SPRU
Science Policy Research Unit

Working Paper Series

SWPS 2016-07 (March)

Assessing Energy Security in a Low-Carbon Context: The Case of Electricity in the UK

Emily Cox

University of Sussex

SPRU Working Paper Series (ISSN 2057-6668)

The SPRU Working Paper Series aims to accelerate the public availability of the research undertaken by SPRU-associated people, and other research that is of considerable interest within SPRU providing access to early copies of SPRU research.

Guidelines for authors

Papers should be submitted to swps@sussex.ac.uk as a PDF or Word file. The first page should include: title, abstract, keywords, and authors' names and affiliations. The paper will be considered for publication by an Associate Editor, who may ask two referees to provide a light review. We aim to send referee reports within three weeks from submission. Authors may be requested to submit a revised version of the paper with a reply to the referees' comments to swps@sussex.ac.uk. The Editors make the final decision on the inclusion of the paper in the series. When submitting, the authors should indicate if the paper has already undergone peer-reviewing (in other series, journals, or books), in which case the Editors may decide to skip the review process. Once the paper is included in the SWPS, the authors maintain the copyright.

Websites

UoS: www.sussex.ac.uk/spru/research/swps

SSRN: http://www.ssrn.com/link/SPRU-RES.html

IDEAS: ideas.repec.org/s/sru/ssewps.html

Research Gate: www.researchgate.net/journal/2057-6668_SPRU_Working_Paper_Series

Assessing energy security in a low-carbon context: the case of electricity in the UK

Emily Cox
SPRU (Science Policy Research), University of Sussex
e.cox@sussex.ac.uk

Abstract

As part of a growing body of research into potential ways of achieving a secure transition to a low-carbon energy system, this paper assesses the future security of the UK electricity system in a low-carbon context. A new mixed-method set of indicators for assessing security of both supply and demand has been developed and applied to a set of three transition pathways for the UK electricity system, all of which seek to reduce UK carbon emissions by 80% by 2050. This paper uses the results to highlight some of the key risks and trade-offs which may emerge under different routes to a low-carbon electricity transition. In particular, the results indicate that a major risk may be experienced by a lack of flexible, responsive supply capacity in low-carbon electricity pathways. A trade-off is also identified between 'affordability' and 'environmental sustainability' objectives. The paper finds that energy security is often conceptualised as the avoidance of *causes of* insecurity (such as insecure fuel imports), but that an equally important aspect of security lies in maximising *responses to* insecurity, for example by increasing the flexibility and responsiveness of both supply and demand.

Key words: energy security; low-carbon transition; electricity systems

1 Introduction

In recent years, energy security has taken a central place on the policy agenda in many industrialised nations. Instability in the Middle East, the rise of 'resource-nationalism' in key fuel exporting nations such as China and Russia, emerging consensus on the seriousness of climate change, and growing global energy demand have all contributed to a rising awareness of the importance of securing energy supplies (Barrett *et al* 2010; Bielecki 2002; Cherp and Jewell 2011; Grubb 2014; Jansen and Seebregts 2010; Kuzemko 2014).

Energy security is highly context-specific (Ang *et al* 2015; Bielecki 2002; Blumer et al 2015; Sovacool *et al* 2012), therefore the analysis in this paper will focus on one country. The UK is chosen as a case study because its energy system is in a major period of transition, causing energy security to become a central feature of energy policy discussions, and unlike many other industrialised nations the UK has a specific energy security strategy (Chaudry *et al* 2011; Department of Energy and Climate Change [DECC] 2012a). This resurgence of interest has been induced by three main drivers (MacKerron 2009; POST 2012; Winstone *et al* 2007). Firstly, increasing concerns over anthropogenic climate change may force a shift to a low-carbon energy economy: in 2008 the UK agreed to legally-binding carbon-reduction targets of 80% on 1990 levels by 2050 (DECC 2008), meaning that dependence on cheap, abundant and flexible fossil fuels may need to be significantly reduced. Secondly, domestic production of oil and gas from the UK Continental Shelf, and of coal from domestic mines, has declined, and the UK is now a net importer of all major fossil fuels (DECC 2013a; Energy Information Administration [EIA] 2014). Finally, the retirement of older power plants has led to steadily declining capacity margins in the power sector (Ofgem 2012a; 2014). Many other industrialised countries, both in Europe and further afield, are experiencing similar pressures on their electricity systems, meaning that the UK can act as a useful basis for exploring energy security in other national contexts.

1.1 Energy security in a low-carbon context

The term 'energy security' has become commonplace in both academic and policy discussions. However, there is a considerable array of overlapping and competing conceptualisations, and despite much literature on the subject the term resists a commonly-accepted definition. Many of the most commonly-cited definitions stipulate that the energy required for an economy or jurisdiction must be physically available, at reasonable prices (Bielecki 2002; International Energy Agency [IEA] 1985; Yergin 2006). However, there has recently been some evidence of a broadening of the energy security discussion; increasing awareness and scientific consensus around climate change has led to an emerging new dimension of 'sustainability' and 'environmental stewardship' (e.g. Ang *et al* 2015; Asia Pacific Energy Research Centre 2007; Elkind 2010; Hughes 2012; Kruyt *et al* 2009; Sovacool and Brown 2010). In 2011, the IEA extended its definition of energy security to "the uninterrupted physical availability [of energy] at a price which is affordable, while respecting environment concerns" (IEA 2011). This new perspective has been challenged by some who argue that the energy security agenda should not be broadened to include environmental sustainability; for instance, Luft *et al* (2011) suggest that this would "open the floodgates" to far too many second-order effects. Whilst this argument is definitely worth bearing in mind, it nevertheless seems somewhat redundant to talk about security without acknowledging its temporal aspects; a system should be secure in both the present-day and into the future, implying that longer-term sustainability is a fundamental part of what we mean by security (Narula and Reddy 2015). Moreover, the practicalities of complying with environmental legislation mean that any aspect of energy policy must now take environmental impacts into account.

1.2 The policy challenges of low-carbon electricity

The energy security literature sometimes displays a bias towards issues concerning fossil fuels, especially oil, despite the fact that electricity now represents an equally significant (and growing) proportion of energy use (Chester 2010). Electricity is an important focus of policies to reduce emissions, partly because technologies for producing electricity from low-carbon sources are often more advanced and cost effective compared to technologies for producing low-carbon heat or for transport. As such, it is often argued that electricity will need to decarbonise more quickly so that heat and transport can subsequently be 'electrified'. It has been suggested that in order to put the UK on a trajectory to meet its carbon reduction commitments, the electricity sector will need to be largely decarbonised by 2030 (DECC 2011; UK Committee on Climate Change 2013). Furthermore, electricity provision creates unique challenges for security, because electricity is costly and difficult to store, meaning that electricity markets are unique in that they require constant and instantaneous balancing of supply and demand (Creti and Fabra 2007; Roscoe and Ault 2010). In the UK, like most industrialised nations, it is seen as imperative that the electricity system can deliver affordable energy in the volume and quality required at any given moment; politicians are reminded of the very real threat to their political legitimacy in the event of electricity shortfalls (RAEng 2014).

Policy recommendations in the UK are sometimes given on the basis of 'improving energy security' and 'reducing carbon emissions', without detailed empirical assessment of future energy security in the context of a low-carbon transition (e.g. DECC 2011; 2012a; 2013b; 2013c; 2014). There may be numerous trade-offs between various objectives as electricity systems undergo this transition (Froggatt and Levi 2009; Jewell *et al* 2014; Jonsson *et al* 2015), therefore there is a real need to understand exactly where these trade-offs may lie, yet there is a lack of existing work which examines these synergies and trade-offs in a systematic and empirical manner. As such, the purpose of this paper is to identify a set of indicators and metrics which are appropriate for assessing the relative security of low-carbon transition pathways, and to use this framework to carry out an empirical assessment using a set of recognised carbon-reduction scenarios for the UK electricity system. This paper therefore makes a contribution by demonstrating a way of turning the rather amorphous literature on energy security into something more practical. Multiple elements of this approach could be generalisable to other country contexts; however, it is always necessary to be aware of the limitations of broad generalisation, and to pay due attention to the particular technical, social and historical context of the country in question.

The following section outlines the methodology which has been employed for an empirical energy security assessment. Section 3 presents the results of the analysis; section 4 then discusses the results, drawing attention to some of the key trade-offs which have been highlighted and some key uncertainties which arise. Finally, section 5 concludes, and offers policy recommendations arising from the research.

2 Methodology

2.1 An analytical framework for assessing low-carbon electricity security

One of the most common means of assessing energy security is through sets of indicators and metrics. It should be noted that there is still much debate over the best means of assessing energy security, and indicator approaches are not immune from shortcomings (see for example Gracceva and Zeniewski 2014; Jewell *et al* 2014; Ren and Sovacool 2014). However, some of the drawbacks can be overcome by avoiding the temptation to attempt to create a generalisable indicator set which is applicable to any situation; instead, the research should identify its specific aim (in this case, assessing UK low-carbon electricity security), and indicators should be developed which are 'fit for a purpose' (Axon *et al* 2013). As pointed out by Gracceva and Zeniewski (2014) and Mitchell and Watson (2013), the choice of security indicators is subjective and often highly political and contested, and therefore a 'one size fits all' approach is undesirable. Instead, it is preferable to offer a 'dashboard' of indicators (Mitchell and Watson 2013), which allows the inclusion of multiple approaches and methodologies (both quantitative and qualitative), and which doesn't attempt to aggregate such disparate methodologies into a single composite index. This approach is useful because it can also assist in the identification of trade-offs and synergies between objectives.

A review of the existing literature found that it is critical to take into account multiple timescales when discussing low-carbon electricity security. Much of the social sciences literature focuses on large-scale, long-term dynamics such as global markets and geopolitics (Chester 2010). On the other hand, there is a body of work from the physical sciences and engineering which focuses on short-term aspects such as second-by-second grid balancing (Boston 2013; Chaudry *et al* 2011; Creti and Fabra 2007). This divide can be conceptualised as a differentiation between gradual 'stresses', such as resource depletion or geopolitical tensions, and sudden 'shocks', such as a technical fault at a plant or a powerline failure (Stirling 2014; Hoggett *et al* 2014). This conceptualisation can be used as the basis for an analytical framework which can assess the security of the UK electricity system in a low-carbon context. The ability to withstand longer-term 'stresses' can be thought of in terms of electricity <u>availability</u>, encompassing aspects such as geopolitical tensions, internal politics and fuel supply source; this dimension is mainly rooted in the social sciences and international relations literature. Meanwhile the ability to respond to short-term 'shocks' can be thought of in terms of system <u>reliability</u>, encompassing aspects such as capacity margins, hour-by-hour system adequacy, and short-term system resilience; this dimension is crucial to electricity security, and is mainly rooted in the physical sciences and engineering literature. Further to this, it is important to consider a price dimension, which (as shown previously) is widely recognised as being fundamental to the pursuit of energy security; this can be thought of as <u>affordability</u>. Finally, the previous discussion on broadening conceptions of energy security suggests that a fourth dimension should be added, that of <u>environmental sustainability</u>. Thus a four-way framework of key characteristics is arrived at – a secure electricity system must ensure that the electricity is 'available', 'reliable', 'affordable' and 'sustainable' (Elkind 2010).

Following from the creation of this analytical framework, a set of indicators which suits the explicit purpose of assessing the electricity security of low-carbon transition pathways was identified from a detailed review of indictors available in the existing literature. In doing so, this paper builds on previous work by Jewell *et al* (2014), which assessed the security of global carbon reduction scenarios according to indicators relating to trade and diversity, and also the work of Jonsson *et al* (2015), which pointed out that there is a real need for a broader framing of energy security which includes qualitative aspects such as social and political dynamics. The indicators were identified by narrowing the vast field of indicators available in the literature (for example, see those identified by Sovacool and Mukherjee 2011) according to those which are appropriate for assessing the security of transition pathways for the electricity system. Indicators were also narrowed down considerably according to data availability constraints. Table 1 presents an overview of the methods used for each indicator. Appendix B gives more detail on the calculations and assumptions for each indicator and metric. Appendix C gives the literature sources from which each indicator is derived.

Table 1: Overview of indicators, calculation methods and data sources

Dim.	Sub-Dimension	Indicator	Overview of methods	Quant/ Qual
Availability	Likelihood of domestic disruption to electricity availability	Approval ratings of generation mix	Results from a nationally-representative public survey (Demski *et al* 2013) are applied to the generation mixes of the pathways, to show proportion of the mix (in Gigawatts [GW] and %) which is 'approved' and 'opposed' by the general public	Quant
		Risk of disruptive opposition	The reasons people protest are complex (e.g. Devine-Wright *et al* 2009), and data is limited; therefore 3 proxies are used on the basis that increased proximity is more likely to result in opposition (Batel *et al* 2013; Devine-Wright 2005): land required for generation infrastructure (weighted 70-30 for onshore-offshore); additional onshore transmission infrastructure required; domestic extraction of primary fuel resources	Quant
		Participation in decisions	Qualitative indicator; uses transitions pathways storylines to assess the level of public participation in energy provision and in decision-making	Qual
	Likelihood of non-domestic disruption to electricity availability	Diversity of fuel types in the electricity mix	Shannon-Wiener diversity calculation: -∑ Pi*(Ln(pi)), as used by DECC (2012b); Lehr (2009); Pfenninger and Keirstead (2015); Stirling (1998)	Quant
		Dependence on fuel imports	Pathways data used to show % of fuel mix from imports for coal, gas and oil Uranium estimates from current stockpile data Biomass estimates using total indigenous biomass potential (estimate from pathways data)	Quant
		Diversity & stability of fuel imports	Insufficient data in pathways for analysis	
Affordability	Cost to the system	Levelised Cost of Electricity (LCOE)	LCOE calculation includes capital costs (pre-development, construction), fixed operating costs (including connection charges, insurance) and variable operating costs (including fuel, carbon costs) (e.g. Pfenninger and Keirstead 2015). Cost data from DECC (2013d) and Mott Macdonald (2010)	Quant
		Transmission upgrade costs	Onshore upgrade costs calculated using Electricity Networks Strategy Group (ENSG) estimates of upgrades required for different levels of new capacity (ENSG 2012) Offshore upgrade costs calculated using estimated unit costs (from National Grid 2013a, Technology Appendix)	Quant
		Distribution upgrade costs	Distribution upgrade costs for the pathways modelled by Pudjianto *et al* (2013)	Quant
	Cost to the consumer	Annual retail bills	Wholesale prices calculated using hourly demand data (from Transition Pathways modelling; see also Barton *et al* 2013) used to create Load Duration Curves; price-setting fuel defined by merit-order stacks; LCOE data used to give average yearly wholesale price; demand weighted seasonally Wholesale prices added to a 'consumer uplift': 19% of bill for supplier costs and margins, 9% social and environmental policies, 20% network charges (DECC 2013e). VAT (5%) not included in estimate.	Quant

Sustainability	Carbon	Carbon intensity	Total carbon intensity = Fuel-type intensity * (fuel-type generation TWh/y / Total generation TWh/y) Baseline estimate from the pathways data (Foxon *et al* 2013) Life-cycle carbon intensity range calculated using range of estimates from global power station data (Moomaw *et al* 2011)	Quant
	Resources	Primary fuels depletion	Qualitative scoring approach from the existing literature and from the indigenous fuels data used in the 'import dependence' indicator. Each fuel is scored from 1 to 10 (1 = no risk of depletion). Scores are applied to the fuel mix in the pathways to give a 'depletion index score' from 1 to 10.	Mixed
		Secondary materials depletion	32 crucial materials are identified from Moss *et al* (2011) and listed from 'highly critical' to 'not critical' according to risk of depletion Generating types are scored from 1 to 10 based on quantity and criticality of secondary materials required, to give a depletion index score (as above)	Mixed
	Water	Water consumption & withdrawals	Data on water withdrawals and water consumption of different types of power generation (Davies *et al* 2013) Projections on types of cooling to be employed in UK thermal powergen in future (Kyle *et al* 2013) These are applied to the generation mix to show water consumption and water withdrawals (in m3 and m3/MWh) Baseline results weighted 70-30 to show greater environmental impact of freshwater vs seawater	Quant
Reliability	System adequacy	De-rated Capacity Margins	Indicative fuel-type margins from National Grid (2012: 30) are applied to the generation mix. Fuel type margin is weighted according to generation mix, and subtracted from peak demand Capacity margin (%) = ((total available capacity-peak demand) / peak demand) * 100 (RAEng 2013)	Quant
	Resilience to sudden and unexpected changes in the supply-demand balance	Flexible supply: Frequency Response capability	Power station data from National Grid (available on request) is used to calculate average Frequency Response (FR) capability of different generation types; this is applied to the fuel mix in the pathways. Maximum and mean FR capability shown for primary FR (<30 seconds) and secondary FR (30 seconds to 30 minutes)	Quant
		Flexible supply: Short-term Operating Reserve & black-start capability	Calculates percentage of generation mix which would be capable of providing short-term operating reserve (STOR) and black-start capability (see National Grid 2011). STOR results shown for short-term STOR (<45 minutes) and long-term STOR (45 minutes to 4 hours)	Quant
		Response & Reserve requirements	Increasing requirements for FR and STOR are calculated on the basis of decreasing system inertia, increasing impact of wind forecasting error, and increased credible in-feed loss due to increase of unit size. All data from National Grid (2011)	Quant
		Flexible demand	Calculates technically and realistically shiftable potential for 2010 (in GW), using data from Sustainability First (AECOM 2011; Dudeney *et al* 2014; Element Energy 2012) Estimates 'realistically shiftable' potential for 2030 and 2050 in % and GW	Mixed

2.2 Applying the set of indicators

The aim of this paper is to apply the set of indicators illustrated above to a set of existing low-carbon transition pathways for the UK electricity system. Transition pathways are especially useful because they generally take a whole-systems view, which explores how all parts of the wider energy system work together. For ease of making comparisons and to reduce the uncertainties which would be caused by attempting to compare pathways from different studies, one set of three pathways was chosen for the application of the security assessment framework. The framework is designed to be applicable to any set of pathways, provided that the raw data is available.

The pathways used for the initial analysis were developed by the Transition Pathways to a Low-Carbon Economy consortium (Foxon 2013) (see Appendix A for more detail on these pathways).[1] The consortium asked what kinds of socio-political governance systems could emerge over the next 40 years, and how the overriding 'governance logic' of the system could affect the transition options taken.[2] From this, the consortium developed three pathways, each of which corresponds to a different governance logic:

- **Market Rules (MR):** this pathway envisages the continued dominance of a market-led system in the UK, in which the government sets high-level goals but otherwise interferes little in the market.
- **Central Coordination (CC):** this pathway envisages that landscape pressures lead to a stronger role for government to deliver carbon reductions, leading to a top-down, centrally-controlled transition.
- **Thousand Flowers (TF):** this pathway envisages a decentralised, bottom-up transition led mainly by civil society and consumers.

These pathways were chosen because their socio-technical, co-evolutionary approach represents a departure from the technological or economic modelling methodologies usually used for creating transition pathways (see for example Anandarajah *et al* 2008; Day 2014; DECC 2010; Strachan *et al* 2008; UK Committee on Climate Change 2008). Energy systems do not usually emerge on the basis of economic rationality; rather, they are the result of a messy combination of socio-technical, political and economic drivers. Furthermore, these pathways offer an opportunity to compare the security of centralised and decentralised options for the electricity system. This is particularly interesting, because it opens up the space to discuss energy security issues in the context of the normative question of how the emerging system *should* look, if we are to achieve a low-carbon, affordable and secure electricity system. It should be emphasised that all transition pathways are constructed on the basis of multiple assumptions (for more on the assumptions of these pathways see Barnacle *et al* 2013; Barton *et al* 2013; 2015; Foxon 2013). The pathways and the results of the security assessment carried out in this paper are not intended to provide predictions of the future, but rather to explore some of the risks and trade-offs which could occur under various alternatives for a low-carbon transition.

[1] http://www.lowcarbonpathways.org.uk/

[2] 'Governance' is defined as the structures and processes influencing the decisions made by various actors, and how these choices give rise to changes within the system (Foxon 2013; Smith 2009)

3 Results

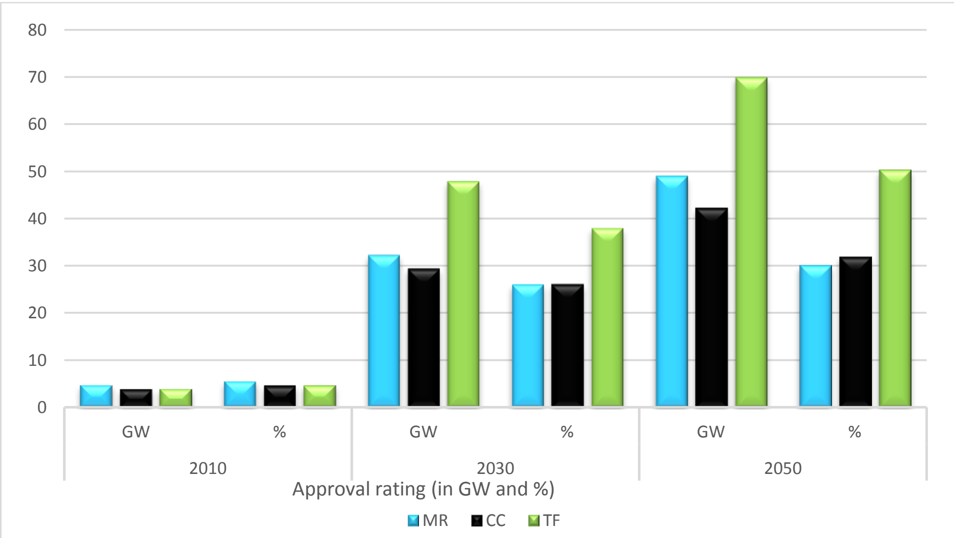
3.1 Availability

3.1.1 Public approval ratings

As pointed out by Pidgeon and Demski, there is often a sense that achieving a transition to a low-carbon energy system will be a purely technical and economic process: "a key assumption is that new technologies, fostered though appropriate market instruments, will lead to the necessary reductions in emissions" (2012: 42). They go on to point out that this is a great oversimplification of the issue. In reality, the constraints upon system transitions are often related to socio-political issues, such as the acceptability of various options (Parkhill *et al* 2013).

Figure 1 shows the weighted proportion of the generation mix which would be 'approved of' by the public, minus the weighted proportion which would be 'actively opposed', extrapolated from the results of a nationally representative survey of the acceptability of generation technologies (Demski *et al* 2013). The results show that public approval improves greatly compared to 2010 for all pathways; this reflects the fact that approval tends to be much higher for renewable energy sources (RES) than for fossil fuels. Lower levels of coal and gas in the TF pathway lead to generally high levels of public approval.

Fig. 1: Public approval ratings of the pathways, in GW and in % of total fuel mix [3]



3.1.2 Risk of direct opposition

High levels of general public support don't always mean that specific projects are approved of, and many installations which have high national approval ratings fail to gain support at the local level, sometimes resulting in the failure of the installation project (Batel *et al* 2013; Devine-Wright 2005). Therefore it is necessary to take a closer look into some of the forms of opposition which can arise. Figures 2 and 3 show the results from three metrics which are used as proxies for possible levels of disruptive opposition: the amount of new generating infrastructure required; the amount of new onshore transmission infrastructure required; and domestic extraction of fuel resources.

[3] The 2010 results differ very slightly between the different pathways. This is an artefact of the Transition Pathways model, which uses 2008 data as the baseline, and therefore this is the case for multiple indicators in this results section.

Figure 2 shows that the pathways are actually fairly similar in terms of land requirements for generation infrastructure. The levels of disruption to be expected due to new capacity are driven overwhelmingly by new additions of wind and solar. The level of onshore transmission upgrades required (figure 2 secondary axis) suggests that the TF pathway will be least vulnerable to this type of disruption, due to lower demand and decentralisation which reduces the need for transmission additions. The CC pathway has high requirements for onshore transmission additions through to 2030, driven by high penetration of nuclear and onshore wind; this could result in disruption due to unpopularity of the pace of change. Figure 3 shows that domestic extraction of fuels (coal, gas and biomass) decreases significantly for all the pathways. Extraction levels are actually very similar for the pathways, despite the emerging differences in fuel mixes; this is because the MR and CC pathways both experience some domestic extraction of gas and coal required for the high penetration of abated gas and coal in these pathways, whilst the TF pathway has much higher biomass requirements.

It is worth reiterating the fact that acceptability and opposition are highly complex and context-specific, and are driven by numerous socio-economic, demographic and psychological factors (Burningham *et al* 2006; Devine-Wright *et al* 2009). For example, location is an extremely important variable, but strong attachment to a location can create either positive or negative sentiment depending on how the project is perceived and framed (Devine-Wright 2011; Moula *et al* 2013). Therefore, high levels of generation and transmission infrastructure and high levels of domestic extraction would not necessarily translate into opposition, especially not if the installations are perceived as positive for the local area. However, a detailed appraisal of the likelihood of opposition is not possible without huge amounts of detailed data on people, attitudes and contexts, which is generally not available in transition pathways data. Therefore the proxies described above are a necessary simplification of a complex issue. For this reason, it is important that this indicator is viewed alongside the other 'domestic disruption' indicators, as all capture slightly different aspects.

Fig. 2: Disruption due to public opposition: additional generation and transmission infrastructure

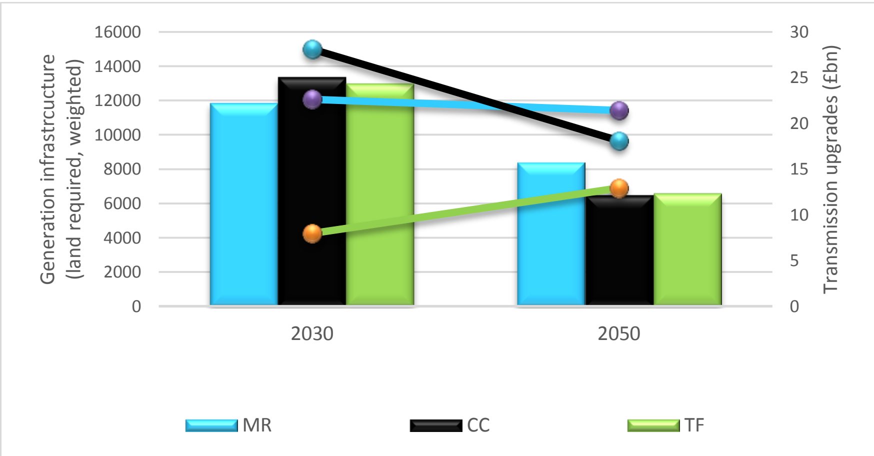
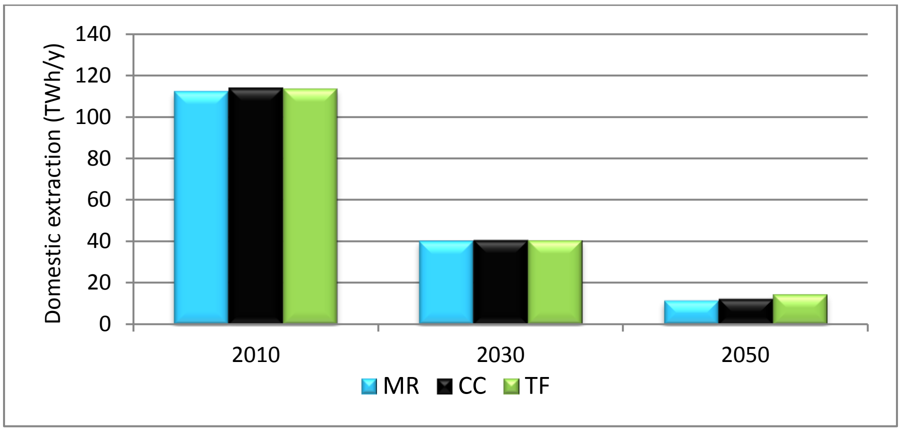


Fig. 3: Disruption due to public opposition: domestic extraction of resources



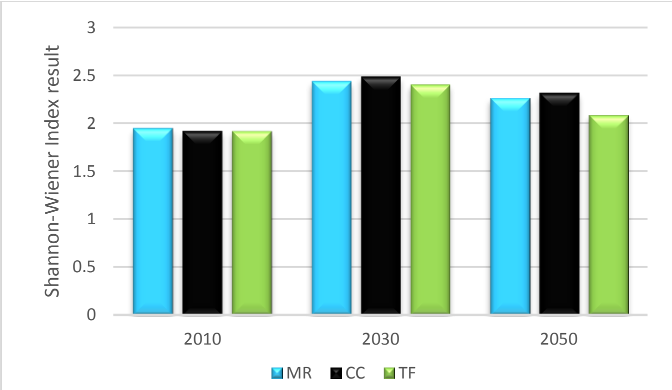
3.1.3 Participation and engagement

Greater levels of public participation in decisions will often lead to higher levels of public acceptance and to reduced likelihood of disruption and delays (Bell *et al* 2005; Cohen *et al* 2014; Jones and Eiser 2009). It is not possible to generate detailed results using the information provided in the pathways, meaning that this aspect of acceptability must rely on the 'storylines' of the pathways. The MR and CC pathways are both organised according to a centralised model in which decisions are mostly taken top-down, with less participation from the general public than the TF pathway. This could create risks, because a system which fails to allow the public to feel that they have a stake in the decisions being made could be more vulnerable to acceptability problems (Fast and Mabee 2015). The TF pathway on the other hand is organised around bottom-up, local and civil-society led decisions, in which people will often have a direct route to the decision-making process for individual plans and choices around energy, and in which citizens will often have a direct stake in their electricity supply via microgeneration or community energy projects. This pathway would potentially be able to mitigate many concerns regarding domestic disruption, because people are more likely to accept something if they have been directly involved in the process from the start or if they have a direct stake in the project (Barton *et al* 2015; Fast and Mabee 2015; Warren and McFayden 2010).

3.1.4 Fuel mix diversity

Figure 4 shows that diversity (measured using the Shannon-Weiner index) increases for all pathways, with the CC pathway experiencing the greatest increase in diversity. The TF pathway scores lowest, reflecting a considerable reliance on biomass as a back-up for intermittent sources. It should be noted that the results from the Shannon-Wiener index are dependent on the level of aggregation used for the different fuel types: increased disaggregation will result in a higher diversity score, therefore diversity scores are of limited usefulness viewed in isolation, and are most useful when making comparisons (Grubb *et al* 2006).

Fig. 4: Fuel mix diversity

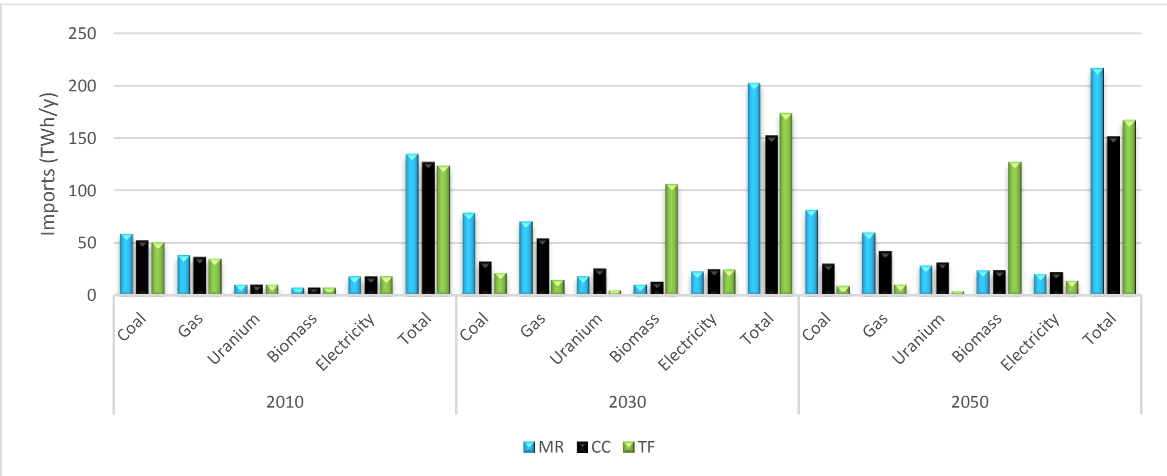


3.1.5 Imports

Figure 5 shows that import dependence increases in all the pathways. The MR pathway has the highest levels of import dependence, driven by rising demand and dependence upon imported coal and gas. The TF pathway, despite achieving significant reductions in overall energy demand, also sees steep increases in import dependence, driven mainly by reliance on imported biomass. These results demonstrate that contrary to received wisdom, dependence on fuel imports does not 'inevitably' decrease as the result of a low-carbon transition.

It is important to note that import dependence per se is a rather poor indicator of energy security, because imports are not necessarily less secure than domestic supplies (Performance and Innovation Unit 2002; Watson and Scott 2009). Therefore it is important to view import dependence alongside results showing the diversity and stability of energy imports. Unfortunately, there is not enough information in the pathways to accurately predict import stability or diversity to 2030 and 2050. There are a vast number of variables which could influence where the UK sources its fuels from in future, the majority of which are impossible to predict. It is the contention of this research that any robust assessment of the energy security of transition pathways would rely on being able to make better projections of the likelihood of disruption to imports. Therefore, if pathways are to be deemed 'secure', it is imperative that they incorporate information about where imports are coming from and the routes taken.

Fig. 5: dependence on imported fuels, in TWh/y

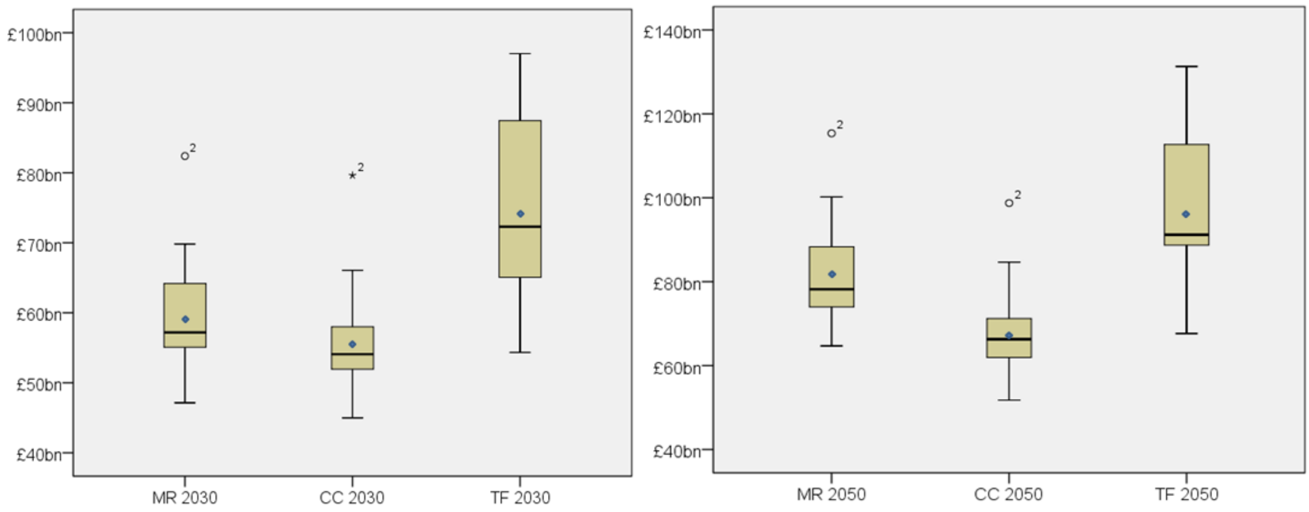


3.2 Affordability

3.2.1 Affordability: Levelised Cost of Electricity Generation

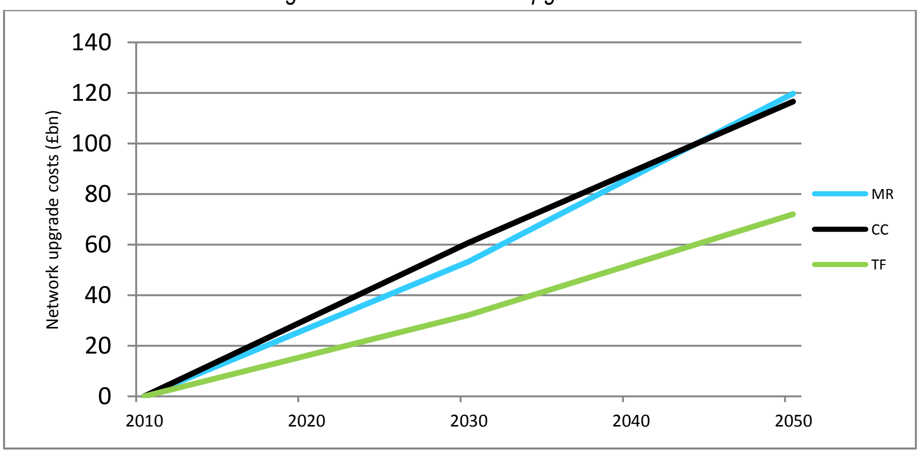
Figure 6 shows that the Levelised Cost of Electricity Generation (LCOE) increases significantly for all the pathways in 2030 and 2050. The TF pathway experiences the most significant increases in generation costs; this reflects the enormous scale of the transition which would be required for such an ambitious phase-out of fossil fuels and nuclear. These high costs are also driven by large amounts of spare capacity and low load factors in the TF pathway, meaning that much of the power generation is only running for limited hours throughout the year; this has the effect of significantly increasing the LCOE. However, this pathway also has by far the biggest range of results, reflecting considerable uncertainty over costs of distributed generation and biomass.

Fig. 6: Levelised cost of electricity generation, £bn



3.2.2 Network upgrade costs

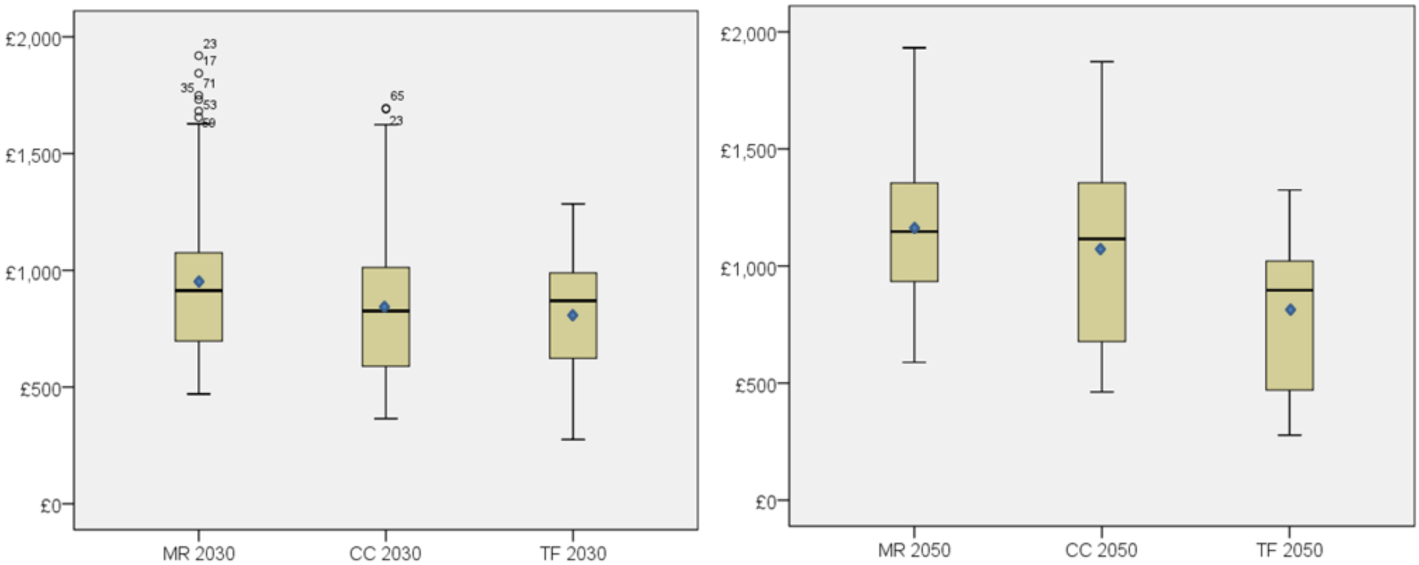
Fig. : Cumulative network upgrade costs



Network costs also increase through to 2050 for all the pathways, as shown in figure 7. Total cumulative network costs in 2050 are expected to be between £70bn and £120bn, whichever route to transition is taken. These costs are at least as high as the costs of generation shown in the previous section; this illustrates the fact that often, policy and public discourse focuses on the costs of generating the power, and doesn't give enough attention to the costs of getting the power to where it's required. It is worth noting that the TF pathway experiences the smallest increase in network upgrade costs, mainly driven by a shift towards distributed generation and reductions in demand.

3.2.3 Annual bills to consumers

Fig. 8: Annual retail electricity bills, 2030 and 2050

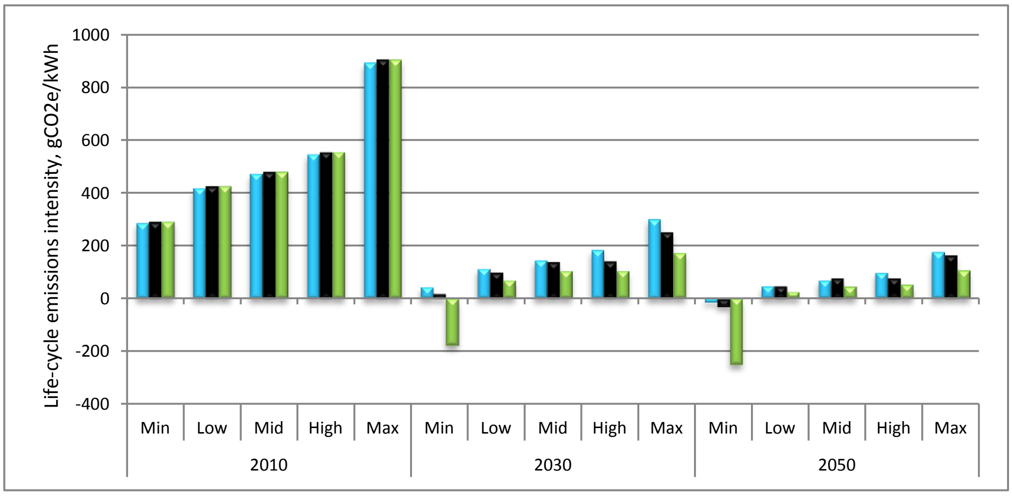


A highly interesting comparison comes when the levelised costs of generation and network costs results are used to calculate the annual bills to consumers (figure 8). Unsurprisingly, in all cases, annual electricity bills are set to increase considerably, reflecting the demands of a transition to a low-carbon electricity system. Once again, the TF pathway looks highly ambitious out to 2030; the bill increases are much higher in the shorter-term for the TF pathway, which could raise severe feasibility issues. However, these results also illustrate the impact of reducing demand; if the same costs per unit are assumed for all pathways, the TF pathway has the lowest bill increases in 2050, despite having higher generation costs. It is worth noting that the demand reductions in the TF pathway are achieved through considerable amounts of behaviour change, leading to greater reductions in overall energy demand than would be achieved through energy efficiency alone.

3.3 Long-term environmental sustainability

3.3.1 Carbon emissions

Fig. 9: Life-cycle carbon intensity



The TF pathway is the most sustainable for the 'life-cycle carbon intensity' metric shown in figure 10. The increasing penetration of small-scale, decentralised energy and RES and a steep decline in the share of fossil fuels in the generation mix all act to reduce emissions. This result may help to highlight trade-offs between the low-carbon agenda and some of the other dimensions explored in this paper. The large range of TF results is due to considerable uncertainty over the potential for negative emissions from biomass.

3.3.2 Resource depletion

In terms of primary fuels, gas and biomass are most at risk from depletion. Global proven reserves of natural gas at the end of 2014 stood at roughly 197 trillion cubic metres (tcm) (Energy Information Administration 2015). BP estimates that this is enough to meet around 55.1 years of global demand under Business-as-Usual (BAU) demand scenarios (BP 2013). However, global gas supply has also increased significantly, and the shale gas boom in the US has somewhat undermined suggestions that we are nearing 'peak gas' (BP 2013; Helm 2011). Biomass is more complicated than non-renewable resources, because it is renewable but can still be depleted, and there is a complex relationship between land for food and land for bioenergy. A report by the UK Energy Research Centre (UKERC) suggests a mid-estimate of global biomass potential between 100 to 600 Exajoules (EJ), dependant on numerous assumptions (Slade *et al* 2011). To put this in context, estimated global proved reserves of natural gas (197tcm) would provide approximately 7,336 EJ (calculated using the Delek Drilling gas volume converter [Delek Drilling 2015]). Therefore it can be seen that even though there is potentially considerable biomass availability under some of the more optimistic assumptions, the reserves are not nearly as large as natural gas. The TF pathway suggests that in 2050 41% of electricity consumption will be from biomass, with only 7% from natural gas. If other countries were to pursue similarly ambitious biomass strategies, this could put serious strain on global biomass feedstock availability.

Coal, meanwhile, is less at risk of imminent depletion; in fact, the main factor which is likely to influence coal production and consumption is the impact of carbon reduction policies rather than depletion of the physical resource (von Hirschhausen *et al* 2010). Coal is still more at risk of depletion than renewable non-depletable fuels, but is generally not considered at risk of global depletion through to 2050. Finally, uranium is generally judged to be at low risk of depletion, although it is still a non-renewable fuel; the OECD Nuclear Energy Agency suggests that "the uranium resource base… is more than adequate to meet projected requirements for the foreseeable future" (2014: 15).

A growing concern for the sustainability of a low-carbon transition is the supply of secondary materials used in power production, such as specific metals and Rare Earth Elements (REEs). Speirs *et al* (2014) note that demand for these materials is likely to increase considerably in the future, especially in the context of increasing penetration of low-carbon technologies such as wind turbines, solar photovoltaic panels and battery-powered vehicles, as well as in other energy components such as the superalloys used in advanced thermal power generation. There has been particular concern over REEs, because their supply is currently limited to relatively few localities: China produces by far the largest quantities of REEs, which raises concerns over potential bottlenecks in the supply chain (Stegen 2015; Umbach 2012). Moss *et al* (2011) assessed the criticality of supply of 32 of the most significant materials for energy generation in the EU through to 2030 under a low-carbon trajectory (table 2).

Table 2: 32 critical materials for power generation (Moss et al 2011)

High	High-Medium	Medium	Medium-Low	Low
REE: Dy, Eu, Tb, Y	Graphite	REE: La, Ce, Sm, Gd	Lithium	Nickel
REE: Pr, Nd	Rhenium	Cobalt	Molybdenum	Lead
Gallium	Hafnium	Tantalum	Selenium	Gold
Tellurium	Germanium	Niobium	Silver	Cadmium
	Platinum	Vanadium		Copper
	Indium	Tin		
		Chromium		

Using the existing literature which has been briefly outlined here, this paper assesses the depletion risk of major generation types, and scores them from 1 to 10 (where 1 indicates no risk of depletion) (figure 10). It is then possible to apply the scores shown in figure 10 to the fuel mixes in the pathways, to show the proportion of each pathway which would be at risk of resource depletion. The graph in figure 11 shows that the depletion scores for the pathways are all actually remarkably similar, despite having very different fuel mixes. All three pathways are more at risk of secondary resource depletion than of primary fuels, reflecting the greater share of RES (and therefore a greater share of REEs). This is actually relatively promising from a security perspective, as there is likely to be higher levels of substitutability for secondary materials; in fact, research is already underway to find substitutes for some of the REEs named above.

Fig. 10: Depletion risk of major generation types

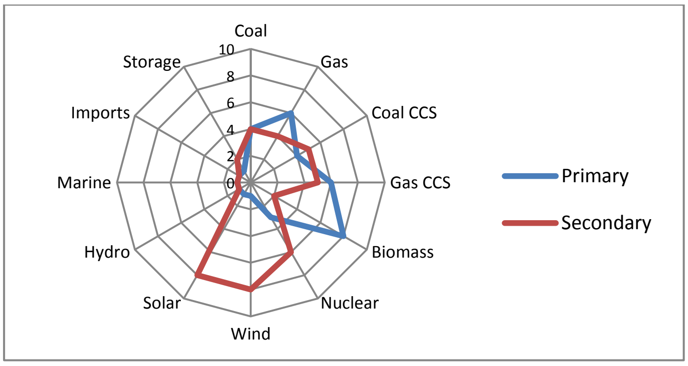
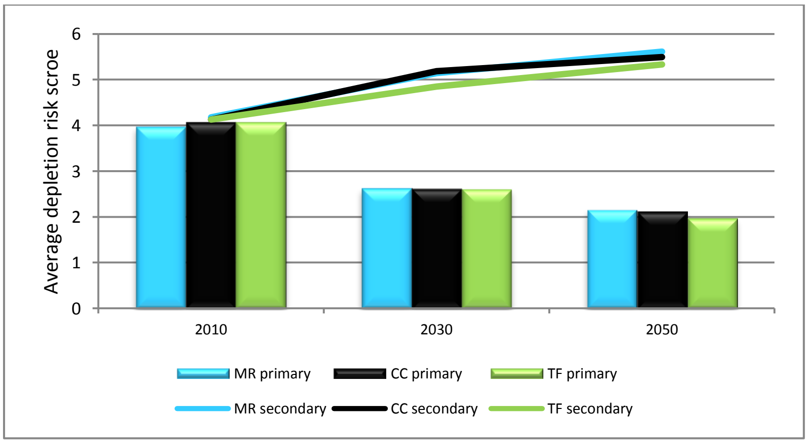


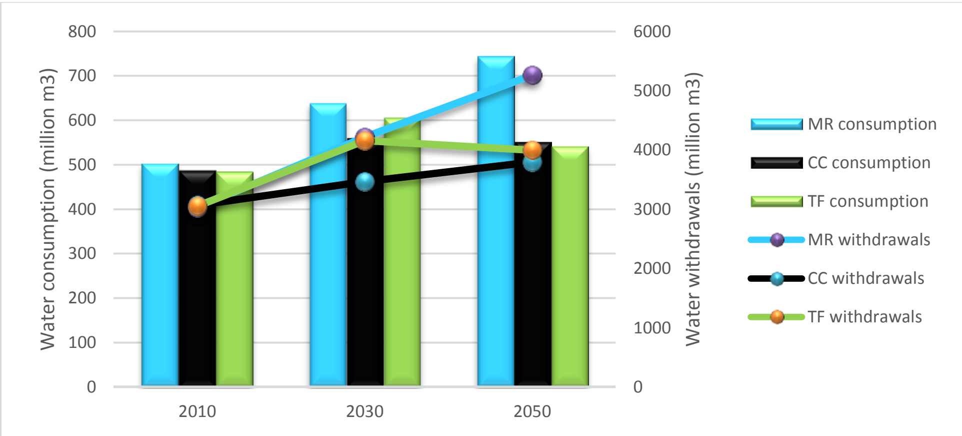
Fig. 11: Primary and secondary resource depletion



3.3.3 Water use

As shown in figure 12, the MR pathway is the least sustainable for the 'water consumption and withdrawals' metrics. This is driven by large amounts of fossil generation in this pathway, which requires cooling water, as opposed to the non-thermal and renewable resources which are relied upon in the other two pathways. It is worth emphasising that life-cycle water requirements are outside the scope of this paper, therefore this indicator does not show water usage for mining or for biomass feedstock production. There is considerable variability in the water requirements of biomass depending on the specific feedstock, but the prevalence of biomass in the TF pathway could result in challenges for life-cycle water requirements.

Fig. 12: Water consumption and withdrawals



3.4 Reliability

3.4.1 Shock resilience: Loss of Load Expectation and de-rated capacity margins

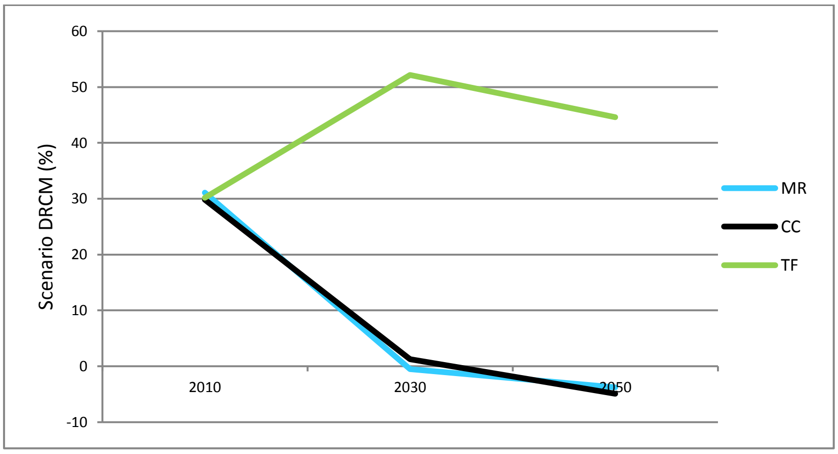
For the electricity system, a common means of assessing system adequacy is by Loss of Load Expectation (LOLE) (DECC 2013f; Ofgem 2013). The LOLE is the reliability standard which is set and maintained by the regulator, and uses a probabilistic approach to represent the number of hours per year when supply will not meet demand.[4] The pathways have all been modelled with hour-by-hour system adequacy in mind (Barnacle *et al* 2013; Barton *et al* 2013), therefore all should be assumed to meet the national reliability standard.

However, the de-rated capacity margins (DRCM) shown in figure 13 illustrate that system adequacy could potentially be a real risk for two of the pathways. Both the MR and CC pathways see DRCM of close to zero in 2030 and negative in 2050, driven by high penetrations of wind and solar. A tight margin suggests that the system could struggle to meet peak demand if the system were to experience an unexpected change in the supply-demand balance, for instance due to a fault at a large power plant. The mismatch between these results and the system adequacy modelling of the pathways suggest that they may have been overly optimistic in their assumptions regarding planned and unexpected outages at thermal plant and peak generation of intermittent sources. These results therefore emphasise the benefits of using more than just one system adequacy metric, because all metrics are dependent upon multiple assumptions.

[4] It is worth emphasising that this is a *probabilistic reliability standard* and not a measure of the actual loss of power which will be experienced by consumers – the actual number and duration of load losses will vary yearly and regionally, and the vast majority of losses of a certain level of load will be managed by the Grid with no impact on power availability to consumers.

Conversely, the TF pathway shows a very high DRCM throughout, reflecting the need for large amounts of spare capacity to back up intermittent RES, and hence low load factors for conventional generation. Therefore the real issue for the TF pathway may be in the feasibility of attracting investment in this spare capacity. Attracting sufficient investment is critical to energy security, but is extremely challenging to assess.

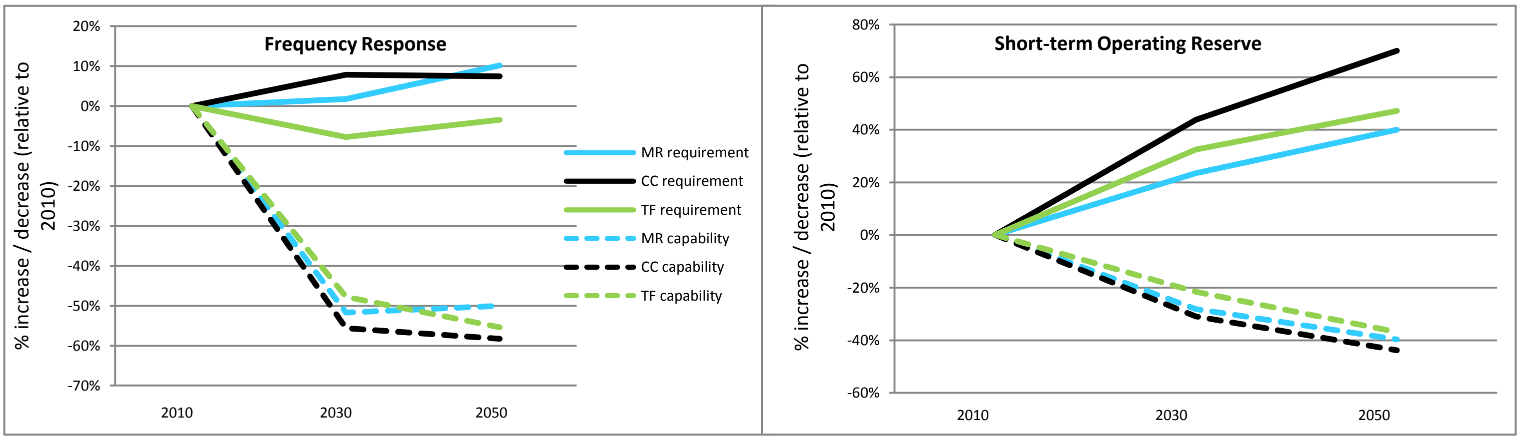
Fig. 13: De-rated capacity margins base case (DRCM), %



3.4.2 Shock resilience: flexible supply

Figure 14 shows a clear disparity between declining capabilities and increasing requirements for frequency response and short-term operating reserve services, for all three pathways. The declining *capability* reflects the increasing penetration of inflexible sources such as RES and nuclear, and also the impact of low load factors; if a plant is switched off at the time of the response or reserve request, it cannot come on-line quickly enough to provide backup services. The increasing *requirement* reflects the impact of increasing wind generation (leading to bigger impact of inevitable wind forecasting errors), decreasing system inertia, and an increase in the credible potential in-feed loss due to an increase in unit size (National Grid 2011; Ulbig *et al* 2014).

Fig. 14 Response and reserve capabilities and requirements[5]



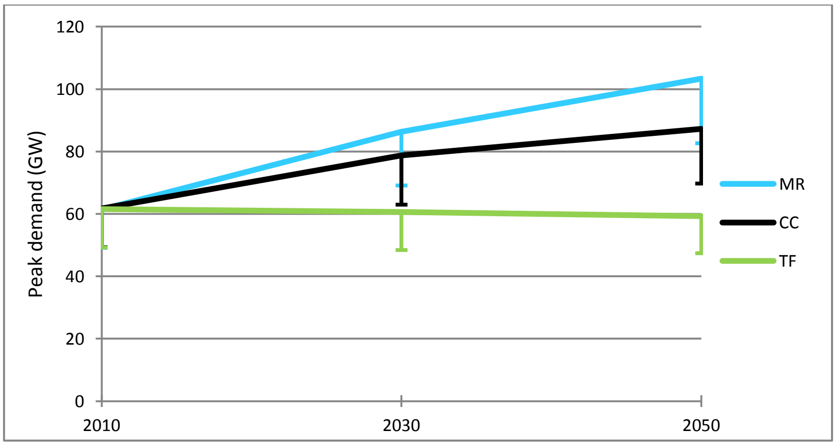
[5] Frequency response = the ability of the system to respond to unexpected fluctuations in electricity frequency, over very short timescales (<30 seconds). Short-Term Operating Reserve (STOR) = the ability of the system to return to normal operating conditions, under slightly longer timescales (< 4 hours).

3.4.3 Shock resilience: flexible demand

One means of mitigating the risks caused by declining response and reserve capabilities would be to increase flexibility of demand. Unfortunately, the demand data in the pathways is limited, and therefore it is very difficult to estimate flexible demand capability. All three pathways include a smart grid by 2050, and therefore it could be assumed that peak load is to some extent already being shifted. However, the pathways creators point out that currently, there is very little data on the actual likely uptake rates of widespread demand-side response, especially for the residential and public sectors (DSR) (Foxon 2015; Hargreaves *et al* 2013). This means that it is difficult to make assured estimates of uptake of more complex DSR technologies such as smart grids for residential areas.

Dudeney *et al* (2014) found that the *technical* potential for shiftable electricity load across all sectors today may be up to ~18GW (out of 54GW peak) on a January weekday winter evening. However, the amount that is *realistically* shiftable is unclear, but is certainly much less. Consumers may be willing to accept some interruption of some household appliances for financial benefit; however, there might be a limited match between what currently contributes to peak demand (lighting, TV, heating, cooking) and most of the shiftable appliances (washing machines, dishwashers etc). If 10% of the electricity load were realistically shiftable (to take a relatively conservative estimate based on figures from Dudeney *et al* [2014], Element Energy [2012] and AECOM [2011]), the MR pathway would still have higher peak demand in 2050 than the other two pathways. The error bars in figure 15 show the impact of a reduction of 20% of peak demand: even under this more optimistic assumption, neither the MR nor the CC pathway reduce their peak demand to the same level as the TF pathway. This corroborates the conclusion from Dudeney *et al* (2014) which suggests that greater gains may be made from reducing overall demand, rather than load-shifting.

Figure 16: peak demand. Error bars show 20% reduction of peak due to shifting



4 Discussion: risks, trade-offs and uncertainties

The results from a broad assessment of future electricity security can help to reveal some of the synergies and trade-offs which may be experienced between different objectives in a transition to a low-carbon energy system. The results show that there are no clear winners; all routes to a low-carbon transition involve vulnerabilities in certain areas, and one of the challenges will be to identify the areas in which we are most prepared to accept compromises.

The results show that the dimension in which all three pathways experience most risk in general is the 'affordability' dimension, whereas the least risky dimension is the 'environmental sustainability' dimension. To some extent, this is to be expected, because the pathways all set out to reduce carbon emissions and the other 'sustainability' indicators (resources and water) appear to improve as the result of a transition away from fossil fuels. The pathways did not, on the other hand, set out to create the cheapest electricity system possible. This high-level overview supports the conventional wisdom that one of the key trade-offs in a transition to a low-carbon electricity system will be between environmental sustainability and affordability. The results indicate that a transition away from high-carbon electricity production results in synergies with some other security objectives: for example, increasing penetration of RES tends to increase diversity and public approval. On the other hand, certain trade-offs between objectives have been identified. For example, the results show that increasing penetration of RES could increase the risk of opposition due to proximity to generation and transmission infrastructure, and could result in reliability risks as discussed in the following paragraph. Furthermore, the results show that contrary to received wisdom, fuel imports do not necessarily decrease in a low-carbon transition, therefore it would probably be wise to abandon the rhetoric of the supposed desirability of fewer imports, and instead focus on improving the resilience of the system to disruption, for instance by improving the diversity and stability of supplies.

The three pathways experience risk in several of the various 'reliability' indicators, mainly due to a lack of flexible, responsive supply capacity (section 3.4). The Market Rules and Central Coordination pathways both have very low capacity margins and a wide divergence between the capability and requirements for short-term system balancing measures. The results for the Market Rules pathway suggest that high demand plus high penetration of intermittent RES may generate risks for system security; meanwhile the results for the Central Coordination pathway suggest that heavy reliance on large inflexible generation technologies such as nuclear and offshore wind may be risky. The only example of secure capacity margins in the three scenarios is in the Thousand Flowers pathway, where is it achieved via large amounts of spare capacity on the system and resultant high generation costs. It is worth noting that all these reliability risks could be mitigated by alternative flexibility options such as DSR, and potentially increased electricity storage and interconnection; the pathways assessed here do not contain enough data to make an accurate assessment of the ability of the system to support significant levels of demand-side flexibility, but this represents an important area for future research.

Reduction of overall energy demand was found to generate security benefits for multiple indicators, and should therefore be a policy priority; this finding supports the literature which suggests that demand reduction can be a win-win for lower emissions and for energy security (Adelle *et al* 2009; Berk *et al* 2006; Froggatt and Levi 2009; Hoggett *et al* 2013; Pye *et al* 2014). However, the Thousand Flowers pathway which capitalises most on these co-benefits achieves highly ambitious demand reductions by maximising consumer engagement and behaviour change as well as simply energy efficiency. Much of the literature focuses on improving security by minimising *causes of* insecurity (Jonsson *et al* 2013), but this paper shows that this approach sometimes neglects the critical issue of maximising *responses to* insecurity, for instance by improving flexibility and responsiveness of both supply and demand.

4.1 Uncertainties and limitations

Four major areas of uncertainty stand out as worthy of note, as they occur in a large number of the indicators:

- **Investment:** realising any transition pathway will be dependent on securing the investment required for infrastructure on both the supply-side and the demand-side. This aspect is often not explicitly addressed in transition pathways outputs, and is highly challenging to assess.
- **Biomass**: the Thousand Flowers pathway especially is heavily reliant on biomass, because it can provide an extremely useful source of flexible low-carbon generation. However, there are high levels of uncertainty over many aspects of biomass supply, including its sustainability and the likely scale and direction of future international resource flows. Closing down these gaps in knowledge may require continued experimentation with existing biomass power generation (e.g. the large conversion project at Drax) in order to explore emerging supply chains.
- **Costs:** it is notoriously difficult to project costs, and like most other cost projections the results here will probably prove to be inaccurate. This dimension is particularly vulnerable to uncertainties which cascade from one indicator to the next.
- **Demand patterns:** several of the assessment results are dependent on information about demand volume; however, it is highly likely that the key indicator in the future will be the *way* in which we use electricity, rather than the amount we use. It is therefore the contention of this research that a robust security assessment of any pathway will require detailed information about future demand patterns.

The results in section 3 offer a very high-level view of the future security of the UK electricity system in a low-carbon context. Clearly, this high-level approach creates limitations of the analysis, both in terms of subjectivity and uncertainty. Multiple assumptions must be made, which in some cases tend to cascade. One important outcome of this analysis is in highlighting three key areas in which improved data or granularity in the inputs or outputs of pathways models would assist in identifying security risks:

- More detailed information on imports, especially regarding country of origin and route of transit.
- Information on demand patterns, potentially including data on consumer behaviour, smart appliances, demand elasticity of electricity, and rebound effects.
- Locational data, especially of generation sites and transmission maps.

5 Conclusions and Recommendations

This paper has presented the initial results from a broad assessment of the security of three low-carbon transition pathways for the UK electricity system. A new framework for the assessment of future low-carbon electricity security has been developed, which seeks to widen the security discussion to include social, economic and environmental aspects. The aim has been to create a 'dashboard' of quantitative and qualitative indicators which can be used without aggregation. This indicator set is designed to be broadly applicable to the security assessment of any set of transition pathways, provided that the raw data is available. The application of these indicators has helped to identify key issues and trade-offs which could occur when undergoing a transition to a low-carbon electricity system, and has helped to identify areas in which data unavailability makes security assessment highly challenging.

The analysis has shown that a major trade-off occurs between sustainability and affordability dimensions. This has major implications for the UK's ability to achieve a 'balanced' trilemma.

This analysis has also shown that increased flexibility on both the demand-side and the supply-side will be imperative to mitigate the security risks of increasing penetration of intermittent generation. As such, policy should immediately recognise the future importance of biomass in providing renewable yet flexible power generation; in particular, more sustainable indigenous forms of biomass, such as energy-from-waste, should be prioritised. Moreover, policy should act now in support of system flexibility, including smart demand-side response, storage and interconnection. Energy security in both policy and the academic literature tends to focus on minimising *causes of* insecurity; this paper has demonstrated that it is just as important to focus on maximising *responses to* insecurity by improving system flexibility.

Acknowledgements

This research was supported under a CASE award, funded jointly by EPSRC and E.ON Technologies (Ratcliffe). Further thanks go to SPRU at the University of Sussex, and especially to Jim Watson (UKERC), Florian Kern (SPRU), Matt Copeland (E.ON) and Andy Boston (Energy Research Partnership) for their insights and continued support. I would also like to thank two reviewers and the editors of the SPRU Working Paper series for their valuable comments.

References

Adelle, C., Pallemaerts, M. and Chiavari, J. (2009) Climate change and energy security in Europe: policy integration and its limits. *Swedish Institute for European Policy Studies, Report No. 4*

AECOM (2011) *Energy demand research project: final analysis.* AECOM Limited, St Albans, Hertfordshire

Anandarajah, G., Strachan, N., Ekins, P., Kannan, R. and Hughes, N. (2008) Pathways to a low-carbon economy: energy systems modelling. *UKERC Energy 2050 Working Paper no.1*

Ang, B.W., Choong, W.L. and Ng, T.S. (2015) Energy security: definitions, dimensions and indexes. *Renewable and sustainable energy reviews,* Vol. 42: 1077-1093

Asia Pacific Energy Research Centre (2007) *A quest for energy security in the 21st Century: resources and constraints.* Institute of Energy Economics, Tokyo

Asif, M. and Muneer, T. (2007) Energy supply, its demand and security issues for developed and emerging economies. *Renewable and Sustainable Energy Reviews*, Vol. 11: 1388–1413

Axon, C., Darton, R. and Winzer, C. (2013) 'Measuring energy security'. In: C. Mitchell, J. Watson and J. Whiting (eds) *New challenges in energy security: the UK in a multipolar world.* Palgrave MacMillan, Basingstoke, pp. 208-237

Barnacle, M., Robertson, E., Galloway, S., Barton, J. and Ault, G. (2013) Modelling generation and infrastructure requirements for transition pathways. *Energy Policy,* Vol. 52: 60-75

Barrett, M., Bradshaw, M., Froggatt, A., Mitchell, C., Parag, Y., Stirling, A., Watson, J. and Winzer, C. (2010) Energy security in a multi-polar world. ESMW Discussion Paper. Available at: http://www.exeter.ac.uk/energysecurity/documents/Energy_Security_in_a_Multipolar_World_Working_Paper_DRAFT.pdf (Last accessed 25.02.2016)

Barton, J., Huang, S., Infield, D., Leach., M., Ogunkunle, D., Torriti, J. and Thomson, M. (2013) The evolution of electricity demand and the role for demand side participation, in buildings and transport. *Energy Policy,* Vol. 52: 85-102

Barton, J., Emmanuel-Yusuf, D., Hall, S., Johnson, V., Longhurst, N., O'Grady, A., Roberston, E., Robinson, E. and Sherry-Brennan, F. (2015) *Distributing power: a transition to a civic energy future.* Realising Transition Pathways Research Consortium

Batel, S., Devine-Wright, P. and Tangeland, T. (2013) Social acceptance of low-carbon energy and associated infrastructures: a critical discussion. *Energy Policy,* Vol. 58: 1-5

Bell, D., Gray, T., and Haggett, C. (2005) Policy, participation and the 'social gap' in wind farm siting decisions. *Environmental Politics,* Vol. 14: 460-477

Berk, M.M., Bollen, J.C., Eerens, H.C., Manders, A.J.G. and Van Vuuren, D.P. (2006) *Sustainable energy: trade-offs and synergies between energy security, competitiveness, and environment*. Netherlands Environmental Assessment Agency, Bilthoven

Bielecki, J. (2002) Energy security: is the wolf at the door? *The Quarterly Review of Economics and Finance*, Vol. 42: 235–250

Bolkesjø, T.F., Tveten, Å,G. and Ilieva, I. (2014) Increased electricity demand flexibility enabled by smart grid: impacts on prices, security of supply and revenues in Northern Europe. *International Association for Energy Economics,* Third Quarter 2014: 43-44

Bolton, R. and Hawkes, A. (2013) 'Infrastructure, investment and the low carbon transition'. In: C. Mitchell, J. Watson and J. Whiting (eds.) *New challenges in energy security: the UK in a multipolar world.* Palgrave MacMillan, Basingstoke, pp. 137-160

Bordhoff, J., Deshpande, M. and Noel, P. (2010) Understanding the interaction between energy security and climate change policy. In: C. Pascual and J. Elkind (eds.) *Energy security: economics, politics, strategies and implications.* Brookings Institution Press, Washington D.C.

Boston, A. (2013) Delivering a secure energy supply on a low-carbon pathway. *Energy Policy,* Vol. 52: 55-59

BP (2013) *BP Statistical Review of World Energy*. BP Plc, London

Burningham, K., Barnett, J. and Thrush, D. (2006) The limitations of the NIMBY concept for understanding public engagement with renewable energy technologies: a literature review. *Beyond NIMBYism Working Paper No. 1.3*

Butler, C., Parkhill, K. and Pidgeon, N. (2013) *Deliberating energy system transitions in the UK.* UKERC, London

Capellan-Perez, I., Mediavilla, M., de Castro, C., Carpintero, O. and Miguel, L.J. (2014) Fossil fuel depletion and socio-economic scenarios: an integrated approach. *Energy*, Vol. 77: 641-666

Carrillo, A.M.R. and Frei, C. (2009) Water: a key resource in energy production. *Energy Policy,* Vol. 37: 4303-4312

Centrica (n.d.) *Energy choices for the UK: seeking affordable, secure and sustainable energy supplies.* Centrica, Windsor

Chaudry, M., Ekins, P., Ramachandran, K., Shakoor, A., Skea, J., Strbac, G., Wang, X. and Whitaker, J. (2011) Building a resilient UK energy system. *UKERC Research Report, UKERC/RR/HQ/2011/001*

Cherp, A. and Jewell, J. (2011) The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. *Current Opinion in Environmental Sustainability,* Vol. 3: 1-11

Cherry, T.L., Garcia, J.H., Kallbekken, S., Torvanger, A. (2014) The development and deployment of low-carbon energy technologies: the role of economic interests and cultural worldviews on public support. *Energy Policy,* Vol. 68: 562-566

Chester, L. (2010) Conceptualising energy security and making explicit its polysemic nature. *Energy Policy* Vol. 38: 887-895

Cohen, J.J., Reichl, J. and Schmidthaler, M. (2014) Re-focussing research efforts on the public acceptability of energy infrastructure: a critical review. *Energy*, Vol. 76: 4-9

Creti, A. and Fabra, N. (2007) Supply security and short-run capacity markets for electricity. *Energy Economics*, Vol. 29: 259–276

Davies, E.G.R., Kyle, P., and Edmonds, J.A., (2013) An integrated assessment of global and regional electric water demands for electricity generation to 2095. *Advances in Water Resources*, Vol. 52: 296-313

Day, G. (2014) Modelling the UK energy system: practical insights for technology development and policy making. Energy Technologies Institute, Loughborough

DECC (2008) *The Climate Change Act*. The Stationary Office, London

DECC (2010a) *2050 Pathways Analysis.* Department of Energy and Climate Change, London

DECC (2011) *Planning our electric future: a white paper for secure, affordable and low-carbon electricity.* Department of Energy and Climate Change, London

DECC (2012a) *Energy Security Strategy.* Department of Energy and Climate Change, London

DECC (2012b) *UK energy sector indicators.* Department of Energy and Climate Change, London

DECC (2013a) *Digest of United Kingdom energy statistics 2014.* Department of Energy and Climate Change, London

DECC (2013b) *More interconnection: improving energy security and lowering bills*. Department of Energy and Climate Change, London

DECC (2013c) *Developing onshore shale gas and oil: facts about 'fracking'.* Department of Energy and Climate Change, London

DECC (2013d) *Electricity generation costs 2013*. Department of Energy and Climate Change, London

DECC (2013e) *Estimated impacts of energy and climate change policies on energy prices and bills.* Department of Energy and Climate Change, London

DECC (2013f) *Annex C: Reliability Standard Methodology.* Department of Energy and Climate Change, London

DECC (2014) *Annual Energy Statement 2014.* Department of Energy and Climate Change, London

Delek Drilling (2015) Natural gas volumes converter. Available at: http://www.delekenergy.co.il/?pg=calc&CategoryID=198 (Last accessed 10.03.2016)

Demski, C., Spence, A. and Pidgeon, N. (2013) *Transforming the UK energy system: Public values, attitudes and acceptability - Summary findings from a survey conducted August 2012.* UK Energy Research Centre, London

Devine-Wright, P. (2005) Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy. *Wind Energy,* Vol. 8: 125-139

Devine-Wright, P. (2011) Place attachment and public acceptance of renewable energy: a tidal energy case study. *Journal of Environmental Psychology,* Vol. 31: 336-343

Devine-Wright, P., Walker, G., Barnett., J., Burningham, K., Infield, D., Devine-Wright, H., Evans, B. and Wheatley, A. (2009) Beyond NIMBYism: A Multidisciplinary Investigation of Public Engagement with Renewable Energy Technologies: *Full Research Report, ESRC End of Award Report, RES-152-25-1008-A.* ESRC, Swindon

Drysdale, B., Wu, J. and Jenkins, N. (2015) Flexible demand in the GB electricity sector in 2030. *Applied Energy*, Vol. 139: 281–290

Dudeney, C., Owen, G. and Ward, J. (2014) *Realising the resource: GB electricity demand project overview.* Sustainability First, London

E3G (2014) *Energy, climate and European reform: 7 propositions for the new Commission.* E3G Consulting, London

Energy and Climate Change Committee (2011) *UK energy supply: security or independence?* UK Energy and Climate Change Committee, London

EIA (2014) *UK became a net importer of petroleum products in 2013.* US Energy Information Administration, Washington DC

EIA (2015a) International energy statistics: natural gas reserves. Available at: http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=1&pid=7&aid=6 (Last accessed 17.02.2016)

EirGrid/SONI (2011) *Ensuring a secure, reliable and efficient power system in a changing environment.* EirGrid, Dublin

Element Energy (2012) *Demand-side response in the non-domestic sector.* Element Energy, Cambridge and De Montfort University, Leicester

Elkind, J. (2010) "Energy security: call for a broader agenda". In: C. Pascual and J. Elkind (eds.) *Energy Security: economics, politics, strategies and implications.* Brookings Institution Press, Washington D.C.

ENSG (2012) *Our electricity transmission network: a vision for 2020.* Electricity Networks Strategy Group, London

European Commission (2014) *European energy security strategy.* European Commission, Brussels

European Council (2011) *Conclusions on Energy.* European Council, Brussels

Falk, J. (2011) 'Rethinking energy security in a time of transition'. In: L. Anceschi and A. Symons (eds.) *Energy security in the era of climate change: the Asia-Pacific experience.* Palgrave Macmillan, Basingstoke, pp. 240-254

Fast, S. and Mabee, W. (2015) Place-making and trust-building: the influence of policy on host community responses to wind farms. *Energy Policy,* Vol. 81: 27-37

Foreign Policy (2014) Fragile States Index. Available at: http://foreignpolicy.com/fragile-states-2014/ (Last accessed 16.01.2016)

Foxon, T.J. (2013) Transition pathways for a UK low carbon electricity future. *Energy Policy,* Vol. 52: 10-24

Foxon, T.J. (2015) Tyndall Manchester seminar series. *Realising Transition Pathways.* 19 February 2015, George Begg building, Manchester University

Foxon, T.J., Pearson, P.J.G., Arapostathis, S., Carlsson-Hyslop, A. and Thornton, J. (2013) Branching points for transition pathways: assessing responses of actors to challenges on pathways to a low carbon future. *Energy Policy*, Vol. 52: 146-158

Froggatt, A. and Levi, M. (2009) Climate and energy security policies and measures: synergies and conflicts. *International Affairs,* Vol. 85 (6): 1129-1141

Frondel, M. and Schmidt, C.M. (2014) A measure of a nation's physical energy supply risk. *The Quarterly Review of Economics and Finance,* Vol. 54: 208-215

Gholz, E. (2014) *Rare earth elements and national security.* Council on Foreign Relations, New York

Gracceva, F. and Zeniewski, P. (2014) A systemic approach to assessing energy security in a low-carbon EU energy system. *Applied Energy,* Vol. 123: 335-348

Greenberg, M. and Truelove, H.B. (2011) Energy choices and risk beliefs: Is it just global warming and fear of a nuclear power plant accident? *Energy Policy*, Vol. 31(5): 819-831

Greenleaf, J., Harmsen, R., Angelini, T., Green, D., Williams, A., Rix, O., Lefevre, N. and Blyth, W. (2009) *Analysis of impacts of climate change policies on energy security.* Ecofys, London

Greenpeace (2005) *Decentralising power: an energy revolution for the 21st Century.* Greenpeace UK, London

Grubb, M. (2014) *Planetary Economics: energy, climate change and the three domains of sustainable development.* Routledge, Abingdon

Grubb, M., Butler, L. and Twomey, P. (2006) Diversity and security in UK electricity generation: the influence of low-carbon objectives. *Energy Policy,* Vol. 34: 4050-4062

Grünewald, P. (2012) Electricity storage in future GB networks: a market failure? Paper presented at the BIEE 9th Academic Conference, 19-20 September 2012, Oxford

Hargreaves, T., Nye, M. and Burgess, J. (2013) Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. *Energy Policy* 52: 126–134

Hayashi, M. and Hughes, L. (2013) The Fukushima nuclear accident and its effect on global energy security. *Energy Policy*, Vol. 59: 102-111

Helm, D. (2011) Peak oil and energy policy: a critique. *Oxford Review of Economic Policy,* Vol. 27 (1): 68-91

Hoggett, R., Bolton, R., Candelise, C., Kern, F. and Mitchell, C. (2014) Supply chains and energy security in a low-carbon transition. *Applied Energy*, Vol. 123: 292-295

Hoggett, R., Eyre, N. and Keay, M. (2013) 'Demand and energy security'. In: C. Mitchell, J. Watson, and J. Whiting (eds) *New challenges in energy security: the UK in a multipolar world.* Palgrave MacMillan, Basingstoke, pp. 92-115

House of Lords (2015) *The resilience of the electricity system: 1st report of session 2014-15.* House of Lords Science and Technology Committee, London

Hughes, L. (2012) A generic framework for the description and analysis of energy security in an energy system. *Energy Policy,* Vol. 42: 221-231

Humphries, M. (2013) *Rare earth elements: the global supply chain.* Congressional Research Service, Washington D.C.

IEA (1985) *Energy Technology Policy*. OECD/IEA, Paris

IEA (2011) *World Energy Outlook 2011.* OECD/IEA, Paris

IEA (2013) *Resources to reserves 2013: oil, gas and coal technologies for the energy markets of the future.* OECD/IEA, Paris

IEA Clean Coal Centre (2014) *Coal reserves in a carbon constrained future.* IEA Clean Coal Centre, London

IMechE (2012) *Electricity storage*. Institute of Mechanical Engineers, London

Jamasb, T. and Pollitt, M. (2008) Security of supply and regulation of energy networks. *Energy Policy,* Vol. 36: 4584-4589

Jansen, J.C. and Seebregts, A.J. (2010) Long-term energy services security: What is it and how can it be measured and valued? *Energy Policy*, Vol. 38:1654–1664

Jewell, J., Cherp, A. and Riahi, K. (2014) Energy security under de-carbonisation scenarios: an assessment framework and evaluation under different technology and policy choices. *Energy Policy,* Vol. 65: 743-760

Jones, C.R. and Eiser, J.R. (2009) Identifying predictors of attitudes to local onshore wind development with reference to an English case study. *Energy Policy,* Vol. 37: 4604-4614

Jonsson, D.K., Johansson, B., Månsson, A., Nilsson, L.J., Nilsson, M. and Sonnsjö, H. (2015) Energy security matters in the EU Energy Roadmap. *Energy Strategy Reviews,* Vol. 6: 48-56

Jonsson, D.K., Månsson, A. and Johansson, B. (2013) Energy security and climate change mitigation as combined areas of analysis in contemporary research. *Energy Studies Review,* Vol. 20 (2): 90-113

King, C.W., Holman, A.S. and Webber, M.E. (2008) Thirst for Energy. *Nature Geoscience,* Vol. 1: 283-286

Koch, H. and Vögele, S. (2009) Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecological Economics,* Vol. 68: 2031-2039

Krishna-Hensel, S.F. (2012) *New security frontiers: critical energy and the resource challenge*. Ashgate Publishing Ltd, Farnham

Kruyt, B., vanVuuren, D.P., deVries, H. and Groenenberg, H. (2009) Indicators for energy security. *Energy Policy,* Vol. 37: 2166-2181

Kuzemko, C. (2014) Politicising UK energy: what 'speaking energy security' can do. *Policy & Politics,* Vol 42 (2): 259-74

Kuzemko, C. and Bradshaw, M. (2013) 'Energy security: geopolitics, governance and multipolarity'. In: C. Mitchell, J. Watson, and J. Whiting (eds) *New challenges in energy security: the UK in a multipolar world.* Palgrave MacMillan, Basingstoke, pp. 22-43

Kyle, P., Davies, E.G.R., Dooley, J., Smith, S.J., Clarke, L.E., Edmonds, J.A. and Hejazi, M. (2013) Influence of climate change mitigation technology on global demands of water for electricity generation. *International Journal of Greenhouse Gas Control,* Vol. 13: 112-123

Le Coq, C. and Paltseva, E. (2009) Measuring the security of external energy supply in the European Union. *Energy Policy,* Vol. 37 (11): 4474-4481

Lehr, U. (2009) More baskets? Renewable energy and energy security. *GWS Discussion Paper 2009/8*

Lilliestam, J. and Ellenbeck, S. (2011) Energy security and renewable electricity trade: will Desertec make Europe vulnerable to the "energy weapon"? *Energy Policy,* Vol. 39 (6): 3380-3391

Luft, G., Korin, A. and Gupta, E. (2011) 'Energy security and climate change: a tenuous link'. In: B. Sovacool (ed.) *The Routledge handbook of energy security.* Routledge, Abingdon

MacKay, D.J.C. (2009) *Sustainability – without the hot air*. UIT Cambridge Ltd, Cambridge

MacKerron, G. (2009) Lessons from the UK on urgency and legitimacy in energy policymaking. In: I. Scrase and G. MacKerron (Eds.), *Energy for the Future.* Palgrave MacMillan, Basingstoke

McDermott, G.R. and Nilsen, Ø.A. (2012) Electricity prices, river temperatures and cooling water scarcity. *IZA Discussion Paper No. 6842*

Mitchell, C., Watson, J. and Whiting, J. (2013) *New challenges in energy security: the UK in a multipolar world.* Palgrave MacMillan, Basingstoke

Mitchell, C. and Watson, J. (2013) 'New challenges in energy security: the UK in a multipolar world – conclusions and recommendations'. In: C. Mitchell, J. Watson and J. Whiting (eds.) *New challenges in energy security: the UK in a multipolar world.* Palgrave MacMillan, Basingstoke, pp. 238-257

Moomaw, W., Burgherr, P., Heath, G., Lenzen, M., Nyboer, J. and Verbruggen, A. (2011) Annex II: Methodology. In: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge

Moss, R.L., Tzimas, E., Willis, P., Arendorf, J. and Espinoza, L.T. (2011) *Critical metals in the path towards the decarbonisation of the EU energy sector: assessing rare metals as supply chain bottlenecks in low-carbon energy technologies.* JRC Scientific and Policy Reports, European Commission, Brussels

Mott MacDonald (2010) *UK electricity generation costs update*. Mott MacDonald, Brighton

Moula, M., Maula, J., Hamdy, M., Fang, T., Jung, N. and Lahdelma, R. (2013) Researching social acceptability of renewable energy technologies in Finland. *International Journal of Sustainable Built Environment,* Vol. 2 (1): 89-98

Narula, K. and Reddy, B.S. (2015) Three blind men and an elephant: The case of energy indices to measure energy security and energy sustainability. *Energy*, Vol. 80: 148-158

National Audit Office (2014). *Balancing Services.* National Audit Office, London

National Grid (2011) *Operating the electricity transmission networks in 2020.* National Grid Plc, London

National Grid (2012) *Electricity 10-year statement 2012: UK electricity transmission*. National Grid Plc, London

National Grid (2013a) *Electricity 10-year statement 2013: UK electricity transmission*. National Grid Plc, London

National Grid (2013b) Interconnectors. Available at: http://www.nationalgrid.com/uk/interconnectors/ (Last accessed 15.01.2016)

Neumann, A. (2007) How to measure security of supply? *EU Energy Policy blog, September 9th 2007*

Newbery, D. and Grubb, M. (2014) The Final Hurdle? Security of supply, the Capacity Mechanism and the role of interconnectors. *Cambridge EPRG Working Paper No. 1412*

Newbery, D., Strbac, G., Pudjianto, D. and Noël, P. (2013) *Benefits of an integrated European energy market.* Booz and Company, Amsterdam

Nistor, S., Wu, J., Sooriyabandara, M. and Ekanayake, J. (2015) Capability of smart appliances to provide reserve services. *Applied Energy*, Vol 138: 590–597

Nuclear Energy Institute (2015) *Nuclear Fuel Processes.* Available at: http://www.nei.org/Knowledge-Center/Nuclear-Fuel-Processes (Last accessed 12.02.2016)

Nuttall, W.J. and Manz, D.L. (2008) A new energy security paradigm for the twenty-first century. *Cambridge EPRG Working Paper*

OECD Nuclear Energy Agency (2014) *Uranium 2014: resources, production and demand.* OECD Nuclear Energy Agency and International Atomic Energy Agency, Issy-les-Moulineaux

Ofgem (2012a) *Electricity capacity assessment report 2012.* Ofgem / Ofgem E-Serve, London

Ofgem (2012b) *Gas security of supply report*. Ofgem / Ofgem E-Serve, London

Ofgem (2013) *Electricity capacity assessment report 2013.* Ofgem / Ofgem E-Serve, London

Ofgem (2014) *Electricity capacity assessment report 2014.* Ofgem / Ofgem E-Serve, London

Parkhill, K., Demski, C., Butler, C., Spence., A. and Pidgeon, N. (2013) *Transforming the UK energy system: public values, attitudes, and acceptability - Synthesis Report.* UK Energy Research Centre, London

Performance and Innovation Unit (2002) *The Energy Review*. Cabinet Office, London

Pfenninger, S. and Keirstead, J. (2015) Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. *Applied Energy,* Vol. 152: 83-93

Pidgeon, N. and Demski, C. (2012) From nuclear to renewable: energy system transformation and public attitudes. *Bulletin of the Atomic Scientists,* Vol. 68 (4): 41-51

POST (2012) Measuring energy security. *Postnote number 399, January 2012.* Parliamentary Office of Science and Technology, Houses of Parliament, London

Pudjianto, D., Djapic, P., Aunedi, M., Kim Gan, C., Strbac, G., Huang, S. and Infield, D. (2013) Smart control for minimising distribution network reinforcement cost due to electrification. *Energy Policy,* Vol. 52: 76-84

Pye, S., Usher, W. and Strachan, N. (2014) The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets. *Energy Policy*, Vol. 73: 575-586

RAEng (2013) *GB electricity capacity margin.* Royal Academy of Engineering, London

RAEng (2014) *Counting the cost: the economic and social costs of electricity shortfalls in the UK.* Royal Academy of Engineering, London

Ren, J. and Sovacool, B.K. (2014) Quantifying, measuring, and strategizing energy security: determining the most meaningful dimensions and metrics. *Energy,* Vol. 76: 838-849s

Roscoe, A.J. and Ault, G. (2010) Supporting high penetrations of renewable generation via implementation of real-time electricity pricing and demand response*. IET Renewable Power Generation,* Vol. 4 (4): 369-382

Ruttledge, L. and Flynn, D. (2015) Short-term frequency response of power systems with high non-synchronous penetration levels. *Wiley Interdisciplinary Reviews: Energy and Environment*, Vol. 4 (5): 452-470

Slade, R., Saunders, R., Gross, R. and Bauen, A. (2011) *Energy from biomass: the size of the global resource.* UK Energy Research Centre, London

Smith, A. (2009) 'Energy governance: the challenges of sustainability'. In: I. Scrase and G. MacKerron (Eds.), *Energy for the Future.* Palgrave MacMillan, Basingstoke

Sovacool, B. and Brown, M. (2010) Competing dimensions of energy security: an international perspective. *Annual Review of Environment and Resources*, Vol. 35: 77–108

Sovacool, B. (2011) 'Defining, measuring and exploring energy security'. In: B. Sovacool (ed.) *The Routledge handbook of energy security*. Routledge, London, pp. 1-42

Sovacool, B. and Mukherjee, I. (2011) Conceptualising and measuring energy security: a synthesised approach. *Energy* Vol. 36: 5343-5355

Sovacool, B., Valentine, S., Bambawale, M., Brown, M., Cardoso, T., Nurbek, S., Suleimenova, G., Li, J., Xu, Y., Jain, A., Alhajji, A. and Zubiri, A. (2012) Exploring propositions about perceptions of energy security: an international survey. *Environmental Science and Policy*, Vol. 16: 44-64

Speirs, J., Gross, R., Contestabile, M., Candelise, C., Houari, Y. and Gross, B. (2014) *Materials availability for low-carbon technologies: an assessment of the evidence.* UK Energy Research Centre, London

Stegen, K.S. (2015) Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis. *Energy Policy*, Vol. 79: 1-8

Stirling, A. (1998) On the economics and analysis of diversity. *SPRU Electronic Working Paper Series*, *No. 28*

Stirling, A. (2014) From Sustainability to Transformation: towards more reflexive governance of vulnerability. In: A. Hommels, J. Mesman, and W. Bijker (eds.) *Vulnerability in Technological Cultures: New Directions in Research and Governance*. MIT Press, Cambridge MA

Strachan, N., Kannan, R. and Pye, S. (2008) *Scenarios and sensitivities on long-term UK carbon reductions using the UK MARKAL and MARKAL-Macro energy systems models*. UK Energy Research Centre, London

Strbac, G., Aunedi, M., Pudjianto, D., Djapic, P., Gammons, S. and Druce, R. (2012) *Understanding the balancing challenge*. Imperial College / NERA Consulting, London

Strbac, G., Pollitt, M., Konstantinidis, C.V., Konstantelos, I., Moreno, R., Newbery, D. and Green, R. (2014) Electricity transmission arrangements in Great Britain: time for change? *Energy Policy*, Vol. 73: 298-311

UK Committee on Climate Change (2008) *Building a low-carbon economy: the UK's contribution to tackling climate change.* The Stationary Office, London

UK Committee on Climate Change (2012) *Energy prices and bills: impacts of meeting carbon budgets.* The Stationary Office, London

UK Committee on Climate Change (2013) The need for a carbon intensity target in the power sector: open letter to the Rt Hon Edward Davey MP. Available at: https://www.theccc.org.uk/wp-content/uploads/2013/02/EMR-letter-September-12.pdf (Last accessed 20.01.2016)

Ulbig, A., Borsche, T.S. and Andersson, G. (2014) Impact of low rotational inertia on power system stability and operation. Paper presented at the 19th Annual IFAC World Comgress*,* 24-29 August 2014, Cape Town

Umbach, F. (2010) Global energy security and the implications for the EU. *Energy Policy,* Vol. 38: 1229-1240

Umbach, F. (2012) The intersection of climate protection policies and energy security. *Journal of Transatlantic Studies*, Vol. 10 (4): 374-387

van Vliet, M.T.H., Yearsley, J.R., Ludwig, F., Vögele, S., Lettenmaier, D.P. and Kabat, P. (2012) Vulnerability of US and European electricity supply to climate change. *Nature Climate Change,* Vol. 2: 676-681

Victor, N., Nichols, C. and Balash, P. (2014) The impacts of shale gas supply and climate policies on energy security: The U.S. energy system analysis based on MARKAL model. *Energy Strategy Reviews,* Vol. 5: 26-41

Von Hirschhausen, C., Haftendorn, C., Herold, J., Holz, F., Neumann, A. and Rüster, S. (2010) Europe's coal supply: obstacles to carbon capture, transportation and storage. *CEPS Policy Brief No. 223, November 2010*

Warren, C.R. and McFayden, M. (2010) Does community ownership affect public attitudes to wind energy? A case study from South-West Scotland. *Land Use Policy*, Vol. 12: 204–213

Watson, J. (2010) *UK gas security: threats and mitigation strategies.* Sussex Energy Group, Brighton

Watson, J. and Scott, A. (2009) New nuclear power in the UK: a strategy for energy security? *Energy Policy,* Vol. 37: 5094-5104

Whitmarsh, L., Upham, P., Poortinga, W., McLachlan, C., Darnton, A., Devine-Wright, P., Demski, C. and Sherry-Brennan, F. (2011) *Public attitudes, understanding and engagement in relation to low-carbon energy: a selective review of academic and non-academic literatures.* Report for RCUK energy programme. Research Councils UK, Swindon

Winstone, R., Bolton, P. and Gore, D. (2007) Energy security. *House of Commons research paper, no. 07/42.* Houses of Parliament, London

Winzer, C. (2011) Conceptualising energy security. *Cambridge EPRG Working Paper, No. 1123*

Woods, P.S. and Zdaniuk, G. (2011) CHP and district heating: how efficient are these technologies? Paper presented at the CIBSE Technical Symposium, 6-7 September 2011, DeMontfort University Leicester UK

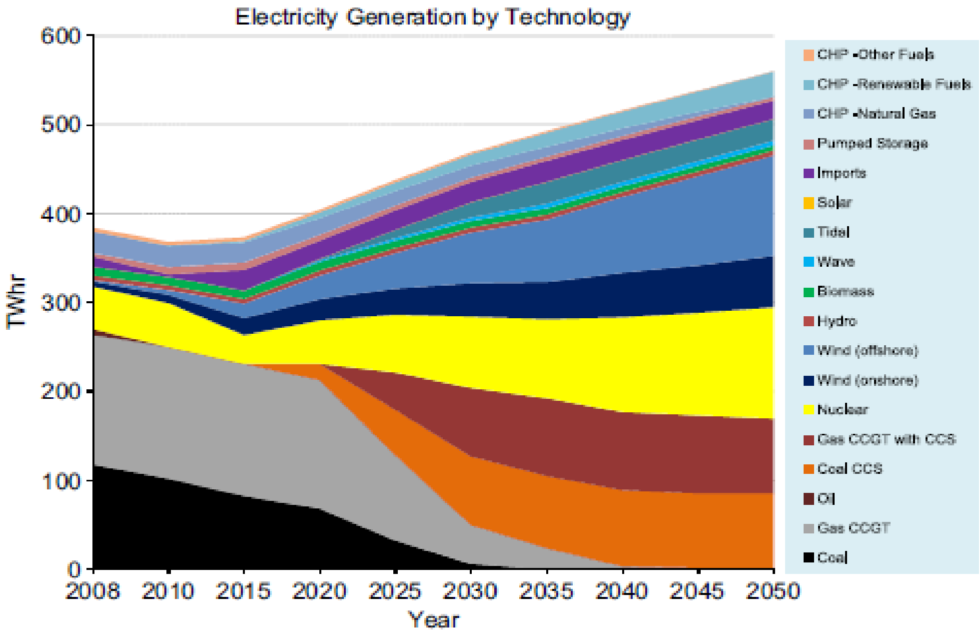
Yergin, D. (2006) Ensuring energy security. *Foreign Affairs,* Vol. 85 (2): 69-82

Appendix A: Transition pathways to a low-carbon economy

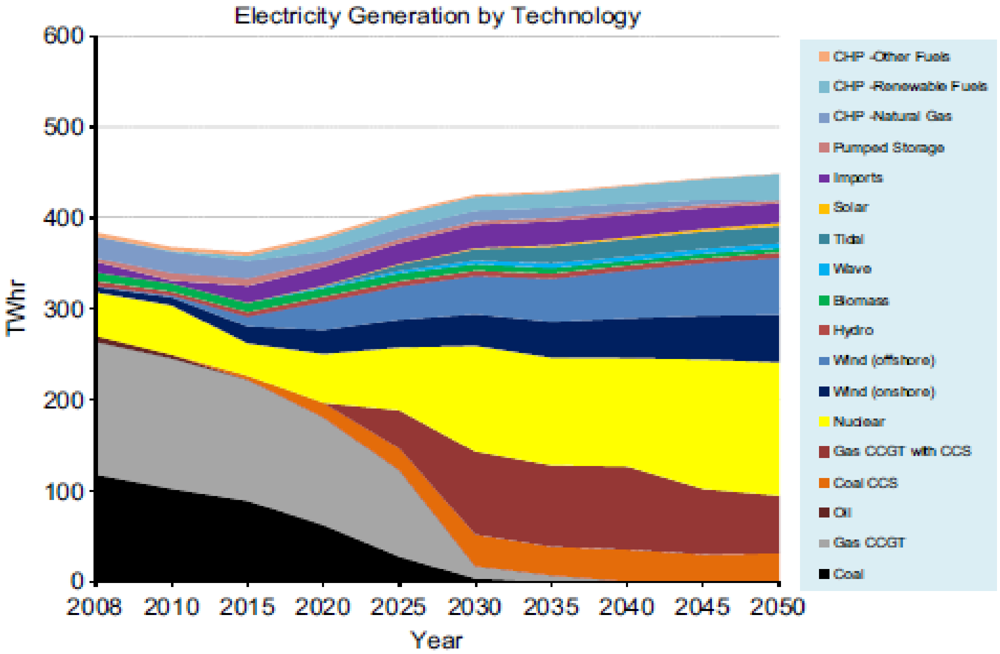
The development and design rationale of the Transition Pathways is described in detail in the Special Issue of *Energy Policy,* Volume 52 (2013). The theoretical background is elaborated in Foxon (2013); more detailed development can be found in Barnacle *et al* (2013) and Barton *et al* (2013; 2015). These papers also provide more detail about the multiple assumptions upon which these pathways were constructed.

All the pathways aim to reduce UK carbon emissions by 80% by 2050. However, the consortium did not assume that all the pathways succeed in doing this; in fact, only the CC and TF pathways succeed, with the MR pathway only reducing overall emissions by 72% in 2050. All pathways assume some electrification of heat and transport; for this reason, despite improvements in efficiency, electricity demand increases in both the MR and CC pathways. The fuel mix for the pathways is illustrated below.

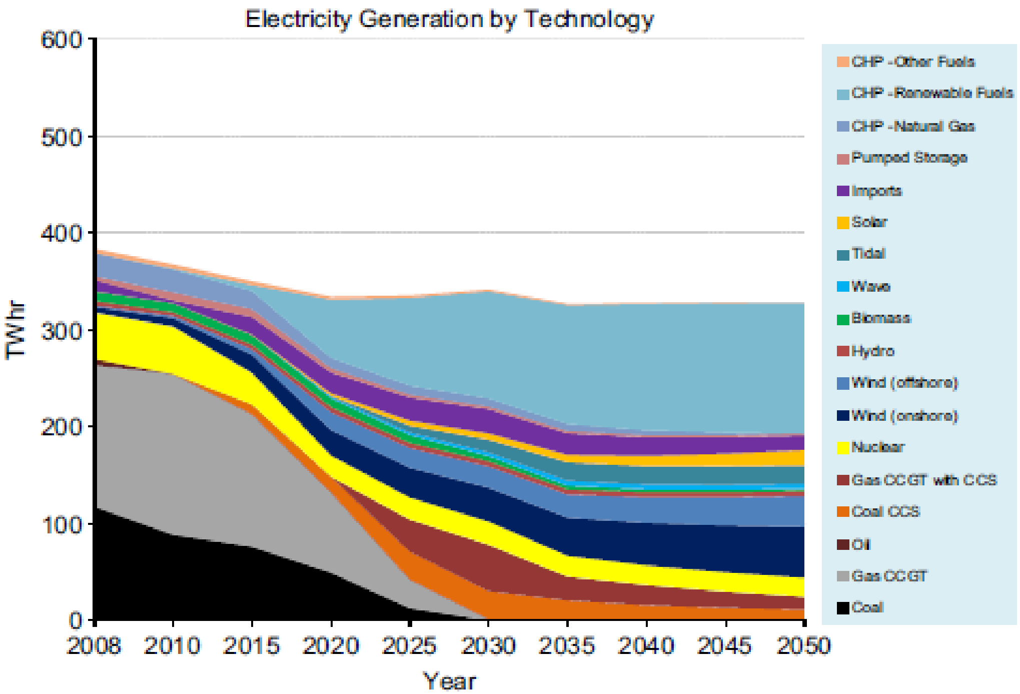
Market Rules:
Large-scale, centralised, market-led
Fossils, nuclear, CCS, wind
Electrification of heating and transport
Large increase in overall energy demand



Central Coordination:
Large-scale, centralised, government-led
Nuclear, wind, energy efficiency
Electrification of heating and transport
Some increase in overall energy demand



Thousand Flowers:
Decentralised, small-scale, civil-society led
Biomass, Combined-heat-and-power, micro-scale RES
Electrification of heating and transport
Reductions in overall energy demand, behaviour change



Appendix B: Indicator methods and example calculations

Indicator / metric	Calculations and examples	Notes, data, assumptions
Public approval ratings	Example: Coal is 'approved' by 19% of population, 'opposed' by 46%. MR pathway has 17.31GW of coal in 2030. (17.31*0.19)+(-17.31*0.46)= -4.6737. Technology totals summed to give pathway total (in GW). This divided by total pathway capacity to give %.	Nationally-representative survey data n=2441; methods given in Demski *et al* 2013
Direct opposition: land requirements	Example: 11.182GW of new nuclear capacity of added between 2010 and 2030 in CC pathway. Average land requirement of nuclear is 1860465m^2/MW. Land requirement = 1118.2*1860465. Technology totals summed to give pathway total in m^2; weighted 70-30 for onshore-offshore	Tech land requirements from publically available data on existing power stations (online) and MacKay 2009. Biomass feedstock not included; covered in 'domestic extraction' CCS assumed same land requirement as unabated generation
Direct opposition: transmission capacity	See 'transmission costs' indicator	
Direct opposition: resource extraction	Levels of domestic extraction of coal, oil, gas and biomass identified in 'import dependence' indicator (in TWh/y).	Includes biomass feedstock Uranium not considered: 'domestic' resources are stockpiles not mined
Public participation	Qualitative indicator; see Section 3.1.3 for details	
Fuel type diversity	Example: pathways in 2010 have 24.93% coal, 35.75% gas, 11.30% nuclear…. SW = (0.2493*(Ln(0.2493)))+(0.3575*(Ln(0.3575)))+(0.113*(Ln(0.113))) etc This gives a minus number, which is inverted to give the diversity index score	Fuel source (e.g. coal, gas, oil) grouped by type. RES disaggregated by type (e.g. wind, solar, tidal). Onshore and offshore wind aggregated together.
Import dependence	Proportion of fuels from imports available in Transition Pathways data (available on request)	
LCOE	CAPEX = Pre-development + Construction costs (in £/MW). Discount rate 10% CAPEX LCOE (£/MWh) calculated in excel using the PMT function, which calculates the yearly financial payment using the capital cost, the economic lifespan of the plant, and the discount rate. This is then divided by the number of load hours (capacity*capacity factor) to give CAPEX LCOE in £/MWh OPEX = (Fixed O&M + Insurance + Connection and UoS charges) + (Fuel + Variable O&M + Decommission). OPEX LCOE: Fixed cost (in £/MW/Year) divided by full load hours and added to the variable OPEX (in £/MWh) Total LCOE (in £/MWh) = CAPEX + OPEX. Total LCOE (in £/MW) = Total/MWh*Load hours. Total LCOE for the capacity in the pathway = Total/MW * Capacity	All cost data from DECC (2013d) and Mott Macdonald (2010). Disaggregated according to large, medium and small-scale, and FOAK and NOAK Newer technologies assumed CAPEX reduction due to learning (using DECC lower estimates) Costs differentiated by technology scale where data available (TF pathway uses small-scale)
Network costs: transmission	Offshore: unit costs for offshore wind farms and interconnectors applied to Round 3 wind sites and planned interconnectors Onshore example: regional upgrade cost estimate (Scotland) of £245098/MW. MR pathway has 66.31GW of new capacity added by 2030, 87% of which centrally connected (57.69GW) Upgrade cost = 245089*57690.	Offshore wind and interconnection sites and unit costs from National Grid Onshore upgrade cost estimates from ESNG (2012:36) Cable distances for interconnection obtained from project planning documents Regional spread of onshore generation assumed to stay constant Distributed generation proportions from central load estimates in pathways data
Distribution costs	See Pudjianto *et al* 2013	
Annual bills	Price-setting fuel calculated using Load Duration Curves (LDC): generation types stacked according to merit order Annual wholesale cost = ∑ (LCOE variable cost for tech X * hours p/a when tech X is setting	Load duration and demand weighted temporally: winter/summer 50/50; peak/off-peak 75/25 Gas price assumed 20% higher in winter

	the price) Full cost = wholesale cost (47%) + network cost (20%) + costs and margins (19%) + social & environmental programs (9%) Annual bill = Average household demand (in MWh) * full cost (in £/MWh)	Merit order given in Pathways data Interconnector prices assumed higher than wholesale cost; sensitivity analysis shows that interconnector price not an important consideration VAT not included
Carbon intensity	Example for MR pathway 2030, with 36.7 TWh unabated gas, 7.5 TWh unabated coal and 37.7 TWh onshore wind. Total output = 467 TWh Mid-estimate life-cycle carbon intensities (50^{th} percentile, 2030): Unabated gas = 469gCO_2/kWh. Unabated coal = 1001gCO_2/kWh. Onshore wind = 12gCO_2/kWh Carbon intensity = (469*(36.7/467)) + (1001*(7.5/467)) + (12*(37.7/467)) etc	Life-cycle emissions intensity range estimates from IPCC (Moomaw *et al* 2011). Raw data low estimates assume negative emissions from biomass CCS mid-range estimate assumed to be mid-way between low and high estimates CHP estimate from Woods and Zdaniuk (2011)
Resource depletion (primary and secondary)	Depletion index score (DIS) for each fuel type established qualitatively (see Section 3.3.2). Application of scores to pathways example: For fuels: ∑((Nameplate capacity*Load factor)/pathway output)*(DIS/100) For renewables: (Nameplate capacity/pathway output)*(DIS/100)	CCS decreases plant efficiency, therefore fuel type output reduced according to efficiency impact for each type CHP fuel requirements halved to account for heat production Coal plant efficiency disaggregated IGCC / ASC
Water	Water usage (million m^3/y) = Fuel water intensity estimate (m^3/MWh) * fuel output (TWh/y) Results weighted for type of plant cooling. Example MR 2030: nuclear = 90% wet-tower, 10% 1-thru, estimated 193m^3/MWh for wet-tower and 4.17m^3/MWh for 1-thru, and a power output of 79.56 TWh: Water withdrawals (million m^3/y) = ((193*79.56)*0.9)+((4.17*79.56)*0.1) Total water usage weighted 70-30 freshwater-seawater (nuclear all seawater) Water intensity (m^3/MWh) = Water usage (m^3) / electricity output (MWh)	Does not calculate life-cycle water intensity (out of scope) Water intensity estimates from Kyle *et al* (2013) and Davies *et al* (2013) Cooling type projections from Kyle *et al* (2013) Onshore-offshore estimates from National Grid 10-yr statement projections Coal disaggregated IGCC / ASC Climate change impacts out of scope
DRCM	Example: coal has capacity credit of 89%, MR pathway 2030 has 6GW coal 2030 MR pathway peak electricity demand = 86.35GW Total available capacity of coal for MR 2030 = 6*0.89 Pathway DRCM = (((∑Fuel 1,2… n)-86.35)/86.35)*100	Capacity credits from National Grid (2012:30) Imports capacity credit 50%. Solar 0%. CCS assumed same capacity credit as unabated Capacity credits assumed to not change over time
Frequency response capability	Example: Unit FR per MW = unit FR capability / unit capacity Pathway FR = ∑ (Output 1,2…n * Unit FR)	Unit FR capability from National Grid plant data (available on request) FR capability calculated for primary FR only FR capability calculated for a large frequency deviation of 0.8Hz Biomass data limited, therefore assumed same FR as coal
STOR capability	Pathway STOR capability (%) = ∑(Capacity of thermal plant / total pathway capacity) Nuclear capacity adjusted for on/off using load factors	Nuclear plant minimum load factor 40%
FR / STOR requirements	Pathway inertia capability (%) = GW capacity of all generation minus wind, marine, solar and imports Credible in-feed loss increase projected by National Grid for 1800MW unit connection. TF pathway assumed smaller unit sizes than CC and MR Wind forecasting error from Nat Grid projections; % increases applied to % increase in capacity in pathway	FR/STOR requirement increase due to wind forecast error and credible in-feed loss: projections from National Grid (2011)
Flexible demand	Pathway peak load plotted to show impact on peak demand of a 20% (optimistic) reduction due to demand shifting Future technical and realistic shiftable potential projections: see Section 3.4.3	

Appendix C: Relevant literature to indicators

	Indicator	Relevant literature
"Availability"	Public approval ratings	Axon *et al* (2013); Demski *et al* (2013); Falk (2011); Hayashi and Hughes (2013); Whitmarsh *et al* (2011)
	Disruptive opposition	Axon *et al* (2013); Batel *et al* (2013); Burningham *et al* (2006); Cherry *et al* (2014); Cohen *et al* (2014); Devine-Wright (2005); Devine-Wright *et al* (2009); Greenberg and Truelove (2011)
	Public participation in decisions	Barton *et al* (2015); Bell *et al* (2005); Cohen *et al* (2014); Fast and Mabee (2015); Johansson (2013); Jones and Eiser (2009; 2010); Sovacool *et al* (2012); Warren and McFayden (2010)
	Diversity of fuel types in generation mix	Axon *et al* (2013); DECC (2012b); Grubb *et al* (2006); Jewell *et al* (2014); Lehr (2009); Pfenninger and Keirstead (2015); Stirling (1998)
	Dependence on fuel imports	Axon *et al* (2013); Frondel and Schmidt (2014); IEA (2011); Jewell *et al* (2014); Kruyt *et al* (2009); Le Coq and Paltseva (2009); Pfenninger and Keirstead (2015); POST (2012); Umbach (2010); Victor *et al* (2014)
	Diversity and stability of fuel exporting nations	Axon *et al* (2013); DECC (2012b); European Commission (2014); Frondel and Schmidt (2014); Jewell *et al* (2014); Jonsson *et al* (2015); IEA (2007); Kruyt *et al* (2009); Le Coq and Paltseva (2009); Lilliestam and Ellenbeck (2011); Neumann (2007)
"Affordability"	Levelised cost of electricity generation (LCOE)	Centrica (n.d); DECC (2012a; 2013d); Greenleaf *et al* (2009); Hayashi and Hughes (2013); Kruyt *et al* (2009); Mott MacDonald (2010); Pfenninger and Keirstead (2015)
	Cost of transmission upgrades	Bolton and Hawkes (2013); Boston (2013); ENSG (2012); Jamasb and Pollitt (2008); National Grid (2011); Strbac *et al* (2014)
	Cost of distribution upgrades	Bolton and Hawkes (2013); Boston (2013); Greenpeace (2005); Jamasb and Pollitt (2008); Pudjianto *et al* (2013)
	Annual retail electricity bills	Centrica (n.d.); DECC (2013e); Elkind (2010); Hughes (2012); IEA (2007); Kruyt *et al* (2009); Sovacool (2011); Sovacool *et al* (2012); Sovacool and Brown (2010)
"Sustainability"	Carbon emissions and carbon intensity	Axon *et al* (2013); Bollen *et al* (2010); Elkind (2010); Falk (2011); Hughes (2012); IEA (2007); Ladislaw *et al* (2009); McCollum *et al* (2011); Sovacool *et al* (2012); Sovacool and Brown (2010); Winzer (2011)
	Primary fuels depletion	Axon *et al* (2013); Asif and Muneer (2007); Capellan-Perez *et al* (2014); Kruyt *et al* (2009); Kuzemko and Bradshaw (2013); Mitchell and Watson (2013); Nuttall and Manz (2008); POST (2012); Sovacool (2011); Sovacool *et al* (2012); Watson (2010); Winzer (2011)
	Secondary materials depletion	Gholz (2014); Humphries (2013); Krishna-Hensel (2012); Moss *et al* (2011); Speirs *et al* (2014); Stegen (2015); Umbach (2012)
	Water consumption and withdrawals for cooling	Carrillo and Frei (2009); Davies *et al* (2013); King *et al* (2008); Koch and Vögele (2009); Kyle *et al* (2013); McDermott and Nilsen (2012); Sovacool *et al* (2012); Van Vliet *et al* (2012)
"Reliability"	De-rated capacity margins	DECC (2011; 2012b); Greenleaf *et al* (2009); House of Lords (2015); National Grid (2012); Newbery and Grubb (2014); Ofgem (2011; 2012a); RAEng (2013)
	Electricity storage and interconnection	European Council (2011); Grünewald (2012); House of Lords (2015); IMechE (2012); National Grid (2013b); Newbery *et al* (2013); Strbac *et al* (2012a; 2012b); World Energy Council (2008)
	Frequency response (FR) capability	EirGrid/SONI (2011); Kiriyama and Kajikawa (2014); National Audit Office (2014); National Grid (2011); Ruttledge and Flynn (2015); Strbac *et al* (2012)
	Short-term Operating Reserve (STOR) capability	EirGrid/SONI (2011); National Audit Office (2014); National Grid (2011); Strbac *et al* (2012)
	Response and Reserve requirements	EirGrid/SONI (2011); National Audit Office (2014); National Grid (2011); Ruttledge and Flynn (2015)
	Flexible demand	Bolkesjø *et al* (2014); DECC (2012a); Dudeney *et al* (2014); Drysdale *et al* (2015); Energy and Climate Change Committee (2011); E3G (2014); Mitchell and Watson (2013); Nistor *et al* (2015); Strbac *et al* (2012)

Recent papers in the SPRU Working Paper Series:

December 2015

Experiments in Climate Governance. Lessons from a Systematic Review of Case Studies in Transition Research. Paula Kivimaa, Mikael Hildén, Dave Huitema, Andrew Jordan, Jens Newig.

Opening the Black Box of Energy Security: A Study of Conceptions of Electricity Security in the UK. Emily Cox.

January 2016

A Triple Helix Model of Medical Innovation: Supply, Demand, and Technological Capabilities in terms of Medical Subject Headings. Alexander Petersen, Daniele Rotolo, Loet Leydesdorff.

Shaping the Agenda of a Grand Challenge: Institutional Mediation of Priorities in Avian Influenza Research. Matthew L. Wallace, Ismael Rafols.

What is Happening to our Universities? Ben Martin.

February 2016

Nonhumans in the Practice of Development: Material Agency and Friction in a Small-Scale Energy Program in Indonesia. Yuti Ariani Fatimah, Saurabh Arora.

March 2016

Technology Development in South Africa: The Case of Wind and Solar PV. Lucy Baker.

The Complex Interactions between Economic Growth and Market Concentration in a Model of Structural Change. Tommaso Ciarli, Marco Valente.

Suggested citation:
Emily Cox (2015). Assessing energy security in a low- carbon context: the case of electricity in the UK. SPRU Working Paper Series (SWPS), 2016-07: 1-36. ISSN 2057-6668. Available at www.sussex.ac.uk/spru/swps2016-07

SPRU – Science Policy Research Unit
University of Sussex
Falmer, Brighton, BN1 9SL,United Kingdom
SWPS Website: www.sussex.ac.uk/spru/research/swps
SPRU Website: www.sussex.ac.uk/spru
SPRU Twitter: @SPRU