Assessing energy security in a low-carbon context

The case of electricity in the UK

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Abstract

This thesis assesses the future security of the UK electricity system in a low-carbon context. Electricity provision is a crucial and ubiquitous component of industrialised societies, and over the past couple of decades a number of fundamental changes to electricity systems have meant that the security of this provision has taken a central place on the policy agendas of the UK and many other industrialised nations. Alongside this, emerging normative, legal and political imperatives to mitigate climate change mean that energy systems will need to undergo a fundamental transition. The overarching aim of this thesis is to assess the future security of the UK electricity system in a low-carbon context, in order to identify the main risks, trade-offs and synergies which may emerge between different objectives in a transition to a low-carbon electricity system. To do this, this thesis develops a set of indicators for assessing the electricity security of low-carbon transition pathways, building on assessment frameworks from the existing literature and utilising a range of both quantitative and qualitative indicators. The indicator set is used to assess the security of three pathways for the UK electricity system, each of which aims to meet the UK's 2050 greenhouse gas reduction target. The indicators are then used as the basis for interview discussions with 25 experts from the UK energy sector, in order to explore the diversity of perspectives in the UK energy community. Finally, the experts' perspectives are used as multiple 'lenses' through which to view the results of the security assessment of the three pathways.

This thesis makes a contribution to knowledge and understanding in three ways. Firstly, it makes a methodological contribution by proposing and testing a set of indicators to measure the security of electricity systems in long-term scenarios of national energy transitions. The thesis takes an interdisciplinary approach and utilises both quantitative and qualitative indicators without aggregation in order to identify synergies and trade-offs. Secondly, this thesis makes an empirical contribution by applying this set of indicators in a novel way to assess the security of a set of low-carbon transition pathways for the UK electricity system: this is the first time that such a comprehensive security dashboard has been used to assess a set of future electricity system scenarios. By including reliability and cost parameters alongside a range of other important aspects of energy security such as diversity, trade and acceptability, this thesis extends the empirical work of existing frameworks to explore the potential

implications of a low-carbon transition on electricity system reliability and costs, and the potential trade-offs between various objectives. Thirdly, this thesis makes a further empirical contribution by identifying the diversity of perspectives amongst UK energy experts; this is a novel contribution to the energy security literature, which contains few empirical studies on experts' perspectives on energy security, and no previously-existing work of this kind in the UK context. Finally, this thesis analyses the impacts of these perspectives on the results of the security assessment, thus providing the first study of this kind to actively incorporate multiple perspectives on energy security into an indicator assessment.

The thesis finds that the three low-carbon pathways tested against the indicator framework all demonstrate a reduction in flexible, responsive supply capacity compared to the 2010 baseline, which could reduce the ability of the system to respond to unexpected perturbations in the supply/demand balance. The results show that demand reduction may be highly beneficial and results in co-benefits across multiple security dimensions (although this thesis has not conducted detailed investigation of the costs and risks of demand reduction, and therefore this issue needs to be analysed further in future research). Increasing the penetration of renewable electricity generation is shown to increase the diversity of the generation mix, and to have a positive impact on greenhouse gas emission reduction and resource depletion; however, it could lead to a reduction in system balancing capability, and does not necessarily minimise dependence on fuel imports. The decentralised transition pathway is shown to have the fewest 'red flags' of security risk in the longer-term; this finding is an interesting addition to the academic and policy literature which has debated the potential security benefits of a decentralised electricity system for the UK. However, this thesis also highlights that there are many areas of uncertainty and potential security risk in a transition to a decentralised electricity system, which may experience some aspects of heightened security risk in the medium-term.

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Acronyms and abbreviations

AD	Anaerobic Digestion
APERC	Asia-Pacific Research Centre
ASC	Advanced Supercritical (coal plant)
BAU	Business As Usual
CAPEX	Capital Expenditure
CC	Central Coordination pathway
CCGT	Combined-Cycle Gas Turbine
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CHP	Combined Heat and Power
CSC	Current Source Converter
DECC	Department of Energy and Climate Change
DRCM	De-Rated Capacity Margin
DSR	Demand-Side Response
ECCC	Energy and Climate Change Committee
EIA	Energy Information Administration
EJ	Exajoule ($1x10^{18}$ Joules)
EMR	Electricity Market Reform
ENSG	Electricity Networks Strategy Group
ETS	Emissions Trading Scheme
EU	European Union
EV	Electric Vehicle
FiT	Feed-in Tariff
FR	Frequency Response
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GW	Gigawatt (1,000,000,000 Watts)
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IEM	Integrated European Market

IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised Cost of Electricity Generation
LCPD	Large Combustion Plant Directive
LDC	Load Duration Curve
LNG	Liquefied Natural Gas
LOLE	Loss of Load Expectation
LV	Low Voltage
MIIS	Mass Impregnated Insulated Subsea cable
MO-ESCo	Municipal Energy Services Company
MR	Market Rules pathway
MVA	Mega Volt Amp
MW	Megawatt (1,000,000 Watts)
MWh	Megawatt Hour
NGO	Non-Government Organisation
OCGT	Open Cycle Gas Turbine
ONS	Office for National Statistics
OPEX	Operating Expenditure
PV	Photovoltaic
R&R	Response and Reserve
RAEng	Royal Academy of Engineering
RES	Renewable Energy Source
STOR	Short Term Operating Reserve
SW	Shannon-Weiner Index
TF	Thousand Flowers pathway
TWh	Terawatt Hour ($1x10^{12}$ Watt Hours)
UKERC	UK Energy Research Centre
VAT	Value Added Tax
VSC	Voltage Source Converter
WRI	World Resources Institute

1 Introduction

This introductory chapter sets out the background to the topic of assessing energy security in a low-carbon context, and outlines the motivation for addressing this topic. The first section of this chapter provides a brief overview of energy security in policy discussions and in the academic literature. Section 1.2 then presents the rationale for bounding the thesis by focusing on electricity in the UK, and provides some essential background information by giving a brief overview of electricity systems, policy and markets in the UK. Section 1.3 then sets out the objectives of the thesis and how they will be achieved. Finally, section 1.4 outlines the structure of the thesis as a whole by providing a brief synopsis of each chapter.

1.1 Introduction to the topic

Over the past couple of decades, a number of fundamental changes to energy systems have led to energy security taking a central place on the policy agendas of many industrialised nations. Instability in the Middle East created new fears about the security of fossil fuel supplies, and since around 2005 concerns have been raised about the rise of 'resource nationalism' in key fuel exporting regions such as China and Russia (Cherp and Jewell 2011; Kuzemko and Bradshaw 2013; Kuzemko 2014; Umbach 2010; Winstone *et al* 2007). China started to pursue bi-lateral fuel deals with producer countries, thus by-passing international markets, rules and norms, whilst Russia enacted a series of reforms whereby the state assumed greater control of energy assets (Kuzemko 2014). This was compounded by the ongoing Russia-Ukraine gas crisis and the stoppage of Russian gas supplies to Ukraine in 2006 and 2009, which was widely seen as an aggressive attempt by Russia to use energy as a weapon in a political conflict (Umbach 2012). Simultaneously, global energy consumption has continued to increase over the past two decades, driven by strong economic growth in emerging economies such as China, India and Brazil (Grubb 2014); this has sparked widespread fears that global fossil fuel production will not be able to keep pace with demand (Cherp and Jewell 2011; Grubb 2014; International Energy Agency [IEA] 2014).

Energy provision plays a fundamental role in everyone's lives; in the words of Sovacool and Brown (2010: 79), "energy services are a ubiquitous component of modern lifestyles, needed to power modes of transport, light factories and workplaces, cultivate food, manufacture and distribute products, and cool and warm residences”. In many industrialised nations, it is seen as imperative that the energy 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 energy shortages or severe spikes in consumer fuel price (Royal Academy of Engineering [RAEng] 2014). Moreover, environmental concerns mean that future energy provision will also need to be environmentally sustainable. Considering the multiple challenges of delivering on these aims, it is hardly surprising that energy security has received so much attention, or that it should continue to receive attention in the future.

Literature addressing energy security in the sense that we know it today first appeared in the late 1970s and early 1980s, partly as a response to the second oil shock in 1979 (Deese 1979; Deese and Miller 1981; Smart 1985). Since then, the term ‘energy security’ has become commonplace in both academic and policy discussions; however, the term tends to resist a generally accepted definition, and often means different things to different people (Bielecki 2002; Chester 2010; Ciuta 2010; Månsson *et al* 2014a; Sovacool 2011). Because of this, the term tends to be open to exploitation by interest groups (Buzan *et al* 1998; Löschel *et al* 2010a; Winzer 2011). There has been a common tendency in the energy literature to focus on supply-side dynamics and fossil fuel resources (Bielecki 2002; Bohi and Tohman 1996; Bordhoff *et al* 2010; Bradshaw 2010; Cherp and Jewell 2014; Frondel and Schmidt 2014; Lefèvre 2010). Perspectives on energy security are often rooted in specific disciplines such as economics, politics or engineering, despite the fact that the issues involved usually cut across multiple disciplines (Cherp and Jewell 2011; Jewell *et al* 2014; Jonsson *et al* 2013). This thesis therefore takes an interdisciplinary approach which recognises the importance of actors and policies as well as technologies, systems and markets. This approach, and the gap in the literature which it aims to fill, is succinctly summarised by Jonsson *et al*:

> “Papers emphasising the economic and technological perspectives are seldom combined with analyses of policy and actors, and vice versa for political science papers… There is a lack of papers using a comprehensive socio-technical perspective in which actors and policies, as well as technology, are equally represented (2013: 104-5).”

Perspectives on energy security have recently become linked to environmental issues, in light of an emerging new paradigm of environmental and social concerns (Elkind 2010; Francés *et al* 2013; Hughes 2012; Mitchell *et al* 2013). Increasing scientific and policy consensus of the imperative to cut carbon emissions has led to the development of the term ‘energy trilemma’, which posits that energy systems needs to balance the three elements of security, cost, and carbon reduction. It is often argued that if one of these aspects is ignored in favour of the others, it has a tendency to catch up in the end; as stated by van Renssen, “In responding to one crisis, it [the European Union] must be careful not to create another: energy security must join, not replace, competitiveness and climate change at the top of the agenda (2014: 757).” The trilemma illustrates a central aspect of the energy security discussion: the fact that there may be certain trade-offs between objectives, as well as potentially certain synergies (Brown and Huntingdon 2008; Froggatt and Levi 2009; Sovacool and Saunders 2014). Therefore there is a need to explore the synergies and trade-offs which may emerge between different objectives in a transition to a low-carbon electricity system. A systematic literature review by Jonsson *et al* (2013) found that the majority of papers which link energy security and climate change only talk about climate change mitigation measures in very general terms; those which are specific tend to focus on energy mix changes, energy efficiency changes, or the introduction of large-scale Carbon Capture and Storage. Therefore there is a real need to assess low-carbon energy security from an analytical perspective which incorporates multiple options for decarbonisation as well as other changes which might occur in a transition from a high-carbon energy system to a lower-carbon one.

1.2 Electricity in the UK

1.2.1 Why focus on the UK?

Energy security is highly context-specific, and energy security concerns are strongly correlated with national energy policies and state imperatives (Ang *et al* 2015; Bielecki 2002; Blumer *et al* 2015; Sovacool *et al* 2012), therefore it makes sense for this thesis to focus on one specific country. The UK is chosen as a case study because its energy system is in a major period of transition (Geels *et al* 2016), driven by a number of factors. The UK is entering a new phase of net fossil fuel imports due to declining domestic production: it has been a net importer of natural gas since 2004 and of oil since 2013 due to declining production from the UK Continental Shelf, and of coal since the mid-1980s (Energy Information Administration [EIA] 2014). Policy concerns over increasing import dependence were compounded by rising oil and natural gas prices from around 2004 onwards; this included an increase in the wholesale price of gas which has contributed to rising energy bills (Bolton 2014; Sauter and MacKerron 2008; UK Committee on Climate Change 2012).[1] Furthermore, the electricity supply infrastructure is ageing and will require a significant proportion of electricity supply capacity to be replaced by the mid-2020s; the retirement of older fossil fuel power plant capacity has led to an erosion of capacity margins in the power sector (Ofgem 2012; RAEng 2013). There are also large parts of the electricity and gas transmission and distribution networks which are in need of replacing or upgrading (Department of Energy and Climate Change [DECC] 2015a; Dodds and McDowall 2013; Energy Networks Strategy Group [ENSG] 2012; Strbac *et al* 2014). Additionally, the UK is under pressure to decarbonise its energy system: the 2008 Climate Change Act (HM Government 2008) established the world's first legally-binding climate change target of an 80% reduction on UK Greenhouse Gas (GHG) emissions on 1990 levels by 2050, and meeting this target will mean that the energy system will need to undergo a major transition. These multiple challenges have meant that energy security has risen rapidly up the public and policy agendas in the UK in recent years, and unlike many other European countries, the UK has a specific energy security strategy (DECC 2012a). Nevertheless, many other industrialised countries, both in Europe and further afield, are experiencing similar pressures on their energy systems, meaning that the UK case can act as a useful basis for exploring energy security in other national contexts.

Policy decisions and recommendations in the UK are frequently made on the basis of 'improving energy security' or 'meeting the goals of the trilemma', without much in-depth empirical assessment of which measures or technologies may help to achieve this (see for example DECC 2012a; DECC 2013a; DECC 2013b; DECC 2014). Therefore, this thesis fills this gap in the literature by systematically assessing the future security of the UK electricity system in a low-carbon context, in order to identify the main risks, trade-offs and synergies which may emerge between different objectives in a transition to a low-carbon electricity system. To do this, this thesis develops a set of indicators for assessing the electricity security of low-carbon transition pathways, building on assessment frameworks from the existing literature and utilising a range of both quantitative and qualitative indicators. 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

[1] These price increases have not been constant and have shown much volatility. Gas and oil prices generally dropped in 2008 as the result of the financial crash, but increased sharply again until the next oil price crash in 2014.

in question. Therefore whilst the methodological approach is designed to be generalisable, the empirical findings may not be.

1.2.2 Electricity in the UK

As noted by Chester (2010), the energy security literature displays a prevalent focus on securing supplies of oil and gas, despite the fact that electricity is now one of the most dominant forms of energy supply. Projections suggest that electricity will be the fastest growing energy sector in the future (IEA 2014), and electricity and heat production is the largest single source of greenhouse gas emissions globally (Intergovernmental Panel on Climate Change [IPCC] 2014). Efforts are already underway to electrify heating and transport systems in order to make deeper cuts to emissions from these sectors in the future, meaning that findings relating to electricity security could eventually become a key component of efforts to decarbonise heating and transport (DECC 2011a; UK Committee on Climate Change 2013). Therefore there is considerable need to look in more detail at the challenges of improving the security of the electricity system in a low-carbon context.

The majority of UK electricity is produced by burning gas and coal, with smaller but significant proportions from nuclear and renewables. Figure 1.1 shows the evolution of the UK electricity mix over the past 33 years. In recent years, the gas-fired proportion of the electricity mix has fallen significantly due to rising gas prices and falling coal prices, whilst the coal-fired proportion rose to its highest level since 1996 in 2012 and then dropped again as electricity consumption continued to fall and as coal-fired power stations closed or converted to biomass. The amount of electricity generated from wind and solar has grown enormously in the past few years, from 10.3 Terawatt-Hours (TWh) in 2010 to 36.1 TWh in 2014. Renewables including hydro and biomass provided 19% of electricity consumption in 2014. Overall electricity consumption has fallen since 2000, mainly due to a marked decrease in consumption from the industrial sector; domestic electricity consumption also fell, due to energy efficiency measures, mild winters and the economic downturn. Installed generation capacity has grown steadily over the past 20 years, from 82.1 Gigawatts (GW) in 2005 to 96.8GW in 2014; this reflects a decline in conventional thermal generation in favour of an increase in intermittent renewables (all information in this paragraph from DECC 2015b).

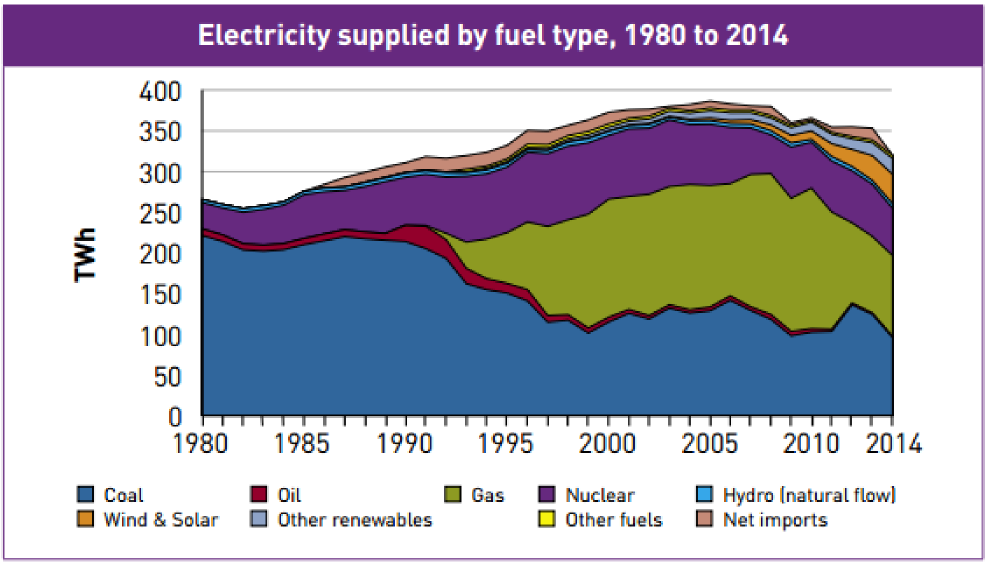

Figure 1-1: Electricity supply in the UK, in TWh/y (DECC 2015b)

1.2.3 UK electricity markets

The UK was one of the first countries in the world to privatise its electricity system. The Electricity Act (1989) laid the foundations for a total restructuring of the UK electricity industry, in which the state-owned generation and transmission company was split up and privatised, although some vertical integration remained (HM Government 1989; Simmonds 2002). There are now 30 major power generators, although the market is dominated by the 'Big 6' of British Gas, EDF, E.ON, Npower, Scottish Power and SSE, who together supply around 90% of domestic electricity and gas consumers (Ofgem 2015).

Over the past few years, UK energy policy has moved increasingly towards government interventions (Foxon and Pearson 2013; Pollitt and Haney 2013). The 2009 Low Carbon Transition Plan clearly outlines the shortcomings of the markets and the need for a strategic role for government (HM Government 2009), and the 2011 White Paper 'Planning our Electric Future' begins with the statement:

> "Since the market was privatised in the 1980s the system has worked: delivering secure and affordable electricity for the UK. But it cannot meet the challenges of the future… Keeping the lights on will mean raising a record amount of investment. However, the current market arrangements will not deliver investment at the scale and the pace that we need." (DECC 2011a: 3)

In order to address these issues, Electricity Market Reform (EMR) set out a plan for four major new policy instruments (DECC 2012b; Pollitt and Haney 2013):

1. A new system of long-term contracts in the form of Feed-in-Tariffs with Contracts for Difference (CfD).[2] These are supposed to provide a clear, stable and robust revenue stream for generators of low-carbon electricity. Low-carbon non-renewable supply technologies such as nuclear power and Carbon Capture and Storage (CCS) are now included in the policy support mechanisms.
2. A Capacity Mechanism, which will offer payments by auction for reliable capacity to be available when needed (see DECC 2013c).
3. A Carbon Price Floor, which was originally set to increase from £15.70/tonneCO2e in 2016 to £32/tonne in 2020 and £76/tonne in 2030 (DECC 2012b), but which has since been reformed to be capped at £18/tonne until 2020 as a response to continually low carbon prices in the European Union (EU) Emissions Trading Scheme (HM Revenue and Customs 2014).
4. An Emissions Performance Standard set at an annual limit relative to a baseload level of 450gCO_2/kWh (DECC 2011a).

The underlying logic behind much recent UK electricity policy is clear in the outline of the EMR policy framework. Increased intervention by government is seen as necessary; however, it has been argued that the government's main role has been to reform the markets in order to ensure that they deliver the necessary investment, resulting in a hybrid mix of market-led and government-led approaches (Foxon 2013; Foxon and Bolton 2013). Despite a move back towards government intervention, the market is still seen as central. Concerns over this have been raised by several authors (e.g. Bolton and Hawkes 2013; Foxon 2012; Helm 2009; 2010; Mitchell and Watson 2013a). This overview is provided simply as background information to the case of electricity in the UK; an in-depth examination and critique of UK electricity policy and EMR is outside the scope of this thesis, therefore for more information see Mitchell *et al* (2014) and Pollitt and Haney (2013).

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[2] "A Feed-in Tariff with Contract for Difference (FiT CfD) is a long-term contract between an electricity generator and a contract counterparty. The contract enables the generator to stabilise its revenues at a pre-agreed level (the strike price) for the duration of the contract. Under the FiT CfD, payments can flow from the contract counterparty to the generator, and vice versa." (DECC 2011a: 38)

Although there has been no official update to the 2012 Energy Security strategy or EMR, it is worth noting that a General Election in 2015 led to a change of administration and some shifts in energy policy more generally, illustrated here with some quotes from a major policy speech by the new Energy Minister in November 2015 (Rudd 2015). Energy security is now seen as the “number one priority” for energy policy, with markets seen as the best means of achieving this:

> We want a consumer-led, competition focussed energy system that has energy security at the heart of it and delivers for families and businesses. We want to see a competitive electricity market, with government out of the way as much as possible, by 2025.

There is a major focus on enabling large supply-side technologies such as gas and nuclear power:

> We need to build a new energy infrastructure, fit for the 21st century. Much of that is already in the pipeline – new gas, such as the plant at Carrington, and of course, a large increase in renewables over the next five years and in the longer-term, new nuclear... Climate change is a big problem, it needs big technologies.

There are also new plans to maximise production from the UK’s indigenous fossil resources, including the Continental Shelf and onshore shale gas. The speech also proposed that unabated coal-fired electricity generation be phased out by the mid-2020s in order to help meet carbon reduction targets, on the condition that new gas-fired stations are available to replace this coal capacity.

1.3 Research objectives

1.3.1 Research objectives and research questions

It is clear that in order to meet the UK’s legally-binding carbon targets, and to help mitigate catastrophic climate change, the UK’s electricity system will need to undergo a transition. It is widely believed that there may be security risks and trade-offs between various objectives as we transition. The overarching aim of this thesis is to assess the future security of the UK electricity system in a low-carbon context, in order to identify the main risks, trade-offs and synergies which may emerge between different objectives in a transition to a low-carbon electricity system. This thesis aims to build upon and develop existing assessment frameworks from the energy security literature (for example, Jewell *et al* 2013; 2014), by proposing a set of indicators which is suitable for assessing the security of long-term national electricity scenarios. In doing this, the thesis aims to propose an analytical framework which is potentially applicable to other industrialised countries as well as the UK. The set of indicators will be demonstrated by applying it to an existing set of low-carbon transition pathways for the UK electricity system, in order to identify risks and trade-offs within the various low-carbon electricity systems proposed by the pathways.

Additionally, it has frequently been noted that energy security is open to multiple interpretations. There are significant differences within the energy community regarding what energy security actually means; however, as of yet, there has been relatively little attempt in the literature to explore the perspectives of energy stakeholders. Therefore this thesis carries out an empirical exploration of the diversity of perspectives on energy security amongst key energy policy stakeholders. In this way, instead of simply stating that 'energy security means different things to different people', this thesis aims to generate an in-depth and transparent discussion which does not seek to close down the diversity of views, but instead seeks to open them up to debate and to policy attention. Following from this, a further objective of this thesis is to analyse the possible implications of different perspectives on the results of the security assessment. This thesis provides the first study of this kind to actively incorporate multiple perspectives on energy security into an indicator assessment.

In order to meet the objectives outlined in the preceding paragraphs, three research questions have been identified, as follows:

i. "What indicators are appropriate for assessing the security of low-carbon transition pathways in the UK, and what are the results of such an assessment using a set of existing pathways?"

ii. "What are the reactions of energy stakeholders to the proposed set of indicators, and what does this tell us about the diversity of perspectives in the UK energy community?"

iii. "What impact do stakeholders' perspectives have on the results of the security assessment and on their preferred options for improving electricity security?"

1.3.2 Overview of methodology

In order to answer these research questions, this thesis undertakes an analysis of the future security of the UK electricity system for a selection of low-carbon transition pathways. To do this, the thesis develops a set of indicators for assessing the security of possible long-term national electricity futures. A distinction is made between those indicators applied to the specific case of UK low carbon scenarios, and those potentially applicable to other countries. Indicators are a fairly ubiquitous means of assessing energy security; in fact, the majority of the literature on measuring or assessing energy security does not even discuss alternatives to indicator approaches, but instead discusses *which* indicators or combinations of indicators are most appropriate and how best to use them. For the purposes of this thesis, indicators are used because they capture the multidimensional nature of energy security and reflect the fact that an assessment of energy security may be grounded in multiple overlapping disciplines (Cherp and Jewell 2011; Sovacool 2011). An indicator approach allows for the empirical assessment of a broad suite of energy security aspects, using a mix of quantitative and qualitative indicators according to their suitability for different aspects. As well as facilitating comparison between different scenarios for a future electricity system, this approach can also allow for comparison between the security of current and possible future systems.

The identified set of indicators is then used as the basis for an in-depth discussion with UK energy stakeholders on low-carbon electricity security, using a number of one-to-one semi-structured interviews. Previous studies by Sovacool *et al* (2012), Knox-Hayes *et al* (2013) and Blumer *et al* (2015) have shown that security concerns map very clearly onto contextual and national concerns (as suggested by the wider literature, e.g. Ang *et al* 2015; Bielecki 2002; Blumer *et al* 2015; Knox-Hayes *et al* 2013; Pasqualetti 2011; Toke and Vezirgiannidou 2013), and also that there are distinct differences between energy consumers and energy experts in how energy security is conceptualised, particularly involving differences in the timescales of reference being drawn upon (Blumer *et al* 2015). Therefore the exploration of perspectives carried out in this thesis will focus on one national context (the UK), and will focus on energy stakeholders, in order to explore the views of those who a) have existing knowledge of energy and energy security and the complexities therein, and b) may have some influence on policy processes, either through direct involvement or through participation in research and consultations. The aim of these interviews is to find out more about the diversity of views on energy security, and to understand how different perspectives might impact the results of the empirical assessment and whether certain perspectives would lead to certain pathways or technology options being preferred. In this way, the results from the initial assessment can be viewed in the context of multiple different perspectives and preferences (Stirling 2008a).

1.4 Structure of the thesis

Chapter 2 reflects in detail upon the current state of the academic literature on energy security and outlines the academic context in which the thesis will be situated. The chapter begins with an overview of historical conceptualisations of energy security, and then moves on to introduce some of the more recent explorations of the energy security concept from the existing literature. The chapter finds that conceptualisations of energy security have in some cases broadened to include issues such as social and environmental sustainability and the demand-side, and argues that incorporating such broader issues can help to address emerging risks to energy systems. This chapter also introduces conceptualisations of security and 'risk' from the existing literature, and highlights the subjective and contingent nature of experts' claims to knowledge. The chapter then focuses in more detail on the imperative to reduce energy-related greenhouse gas emissions, and introduces some ideas from energy and climate change literatures regarding the trade-offs and synergies which could occur in the context of a transition to a low-carbon energy system. Finally, this chapter provides some background information necessary for understanding electricity systems and the challenges of balancing supply and demand.

Chapter 3 builds on the risk frameworks in the previous chapter, and on existing frameworks from the energy security literature, to propose an analytical framework for the assessment of electricity security. The chapter explains the 'dashboard' approach used in this thesis, and conceptualises risks to energy systems in terms of short-term 'shocks' and long-term 'stresses'. These foundations are used to propose that an analytical framework comprising four key dimensions of energy security: 'availability', 'reliability', 'affordability' and 'environmental sustainability', is most suitable for assessing the electricity security of low-carbon transition pathways. The chapter also introduces the literature on futures studies, and sets out the basis for the choice of low-carbon transitions pathways which will be used for applying the analytical framework.

Chapter 4 describes and justifies the methodology used in the thesis. The chapter firstly explores ideas of transitions and futures studies, and justifies the selection of three transition pathways which were used as the basis for the security assessment. The chapter uses the analytical framework outlined in chapter 3 to propose a set of indicators for the assessment of the security of these transition pathways, and lays out the methods used for each indicator. This chapter then goes on to describe the methods for interviewing stakeholders which will be used to explore perspectives on energy security, and the methods which will be used to explore the impact of stakeholders' perspectives on the results from the initial security assessment.

Chapter 5 is the first of two results chapters; it presents the results which answer the first research question: ""What indicators are appropriate for assessing the security of low-carbon transition pathways in the UK, and what are the results of such an assessment using a set of existing pathways?"[3] The chapter presents detailed results from the security assessment of the three transition pathways using the set of indicators developed in chapter 4, for the year increments 2010 (using historical data), 2030 and 2050.

Chapter 6 is the second of the two results chapters. It presents the results which answer the second research question: "What are the reactions of energy stakeholders to the proposed set of indicators, and what does this tell us about the diversity of perspectives in the UK energy community?"[4] This chapter explores the data from 25 interviews which were carried out with UK stakeholders from policy, academia, think tanks, Non-Governmental Organisations (NGOs), utilities and network companies. This chapter presents the results of a thematic coding analysis of this interview data, which identifies five key themes which were found to cut across multiple respondents and multiple security dimensions.

The discussion chapter, **Chapter 7,** brings the results from chapters 5 and 6 together in order to answer the final research question: "What impact do stakeholders' perspectives have on the results of the security assessment and on their preferred options for improving electricity security?" The responses from the stakeholder interviews are applied to the security assessment results, in order to highlight key security concerns for the low-carbon

[3] Some of the results from this chapter, and the corresponding research design, have been published as a working paper (Cox 2016a), and have been submitted to the journal *Renewable and Sustainable Energy Reviews*
[4] Some of the results from this chapter, and the corresponding research design, have been published as a research article in *Energy Research and Social Science* (Cox 2016b).

transition pathways using a combination of indicator assessment results and stakeholder interviews.

The final chapter, **Chapter 8,** summarises the main conclusions derived from the empirical findings in chapters 5, 6 and 7, and presents the contributions to knowledge which this thesis has made. The chapter also discusses the main limitations of the research and highlights some areas in which further research could be beneficial. Finally, the chapter offers policy recommendations (primarily for the UK) based on this research, in particular highlighting areas which should be the focus for policies which aim to improve electricity security in the UK in the context of a transition to a low-carbon electricity system.

2 Literature Review

The literature on energy security has blossomed in recent years, in line with the rise of energy security up the political and public agendas in the UK and Europe. The existing literature therefore offers a rich basis for the study of energy security, which will be outlined in this chapter. This chapter finds that despite an extensive and ongoing debate on conceptualisations, meanings and measurements, there have thus far been relatively few attempts in the literature to assess empirically the security of an energy system in a low-carbon context. Although some conceptual literature discusses some of the synergies and trade-offs which could emerge between various objectives in a transition to a low-carbon energy system, there is very little literature which seeks to assess these synergies and trade-offs in a systematic and empirical manner; this thesis aims to address this gap in the literature. There have also been few attempts to assess the security of possible future energy systems over a long time-period; this thesis addresses this gap by exploring energy security in the context of the UK's long-term carbon targets out to 2050. This chapter also discusses approaches which have been used to assess energy security in the existing literature, and notes that conceptualisations of energy security have broadened out in some of the literature to include societal and environmental concerns. This chapter suggests that this broader approach can be used as the basis for assessing the security of an energy system in a low-carbon context. Furthermore, it is found that previous energy security literature has displayed a prevalent focus on the supply-side; this thesis aims to address this gap by taking a whole-systems approach which incorporates the demand-side more fully into a security assessment. This chapter also introduces conceptualisations of security and 'risk' from the existing literature, and highlights the subjective and contingent nature of experts' claims to knowledge.

It is worth emphasising that the focus of this thesis is on the security of the *electricity* system; however, for the purposes of reflecting upon the state of current research, this literature review focuses more broadly on energy security in general. Existing work on energy security can provide much of the theoretical basis for this thesis. However, the main empirical focus will be on the security of the electricity system, therefore this chapter also provides some background information on the security of electricity systems which will be useful to understand some of the unique issues faced, with a focus on the challenges of balancing electricity supply and demand in the context of a low-carbon transition.

Section 2.1 of this chapter summarises existing conceptualisations of energy security, and examines broader notions of the term which begin to take environmental and societal aspects into account. Section 2.2 then looks at theories on ‘risk’, and introduces some frameworks for addressing the plural and conditional nature of energy security and risks to energy systems. Section 2.3 then introduces discussions about low-carbon transitions in which this thesis is situated, and looks in more detail at some of the synergies and trade-offs which could result from the pursuit of a secure, affordable and low-carbon energy system. Finally, section 2.4 provides useful background information on the security of electricity systems.

2.1 Energy security: what does it mean?

2.1.1 Conceptualising energy security

The term ‘energy security’ has become commonplace in both academic and policy discussions. As the focus of this thesis is on energy security in the UK, it is useful to note that the UK Department of Energy and Climate Change (DECC) produced an Energy Security Strategy in 2012 which provides an operational definition of energy security. The opening paragraphs of the Strategy state:

> There is no perfect definition of energy security. When discussing energy security the Government is primarily concerned about ensuring that consumers have access to the energy services they need (physical security) at prices that avoid excessive volatility (price security) (DECC 2012a: 5).[5]

However, as shall become clear throughout this chapter (and as acknowledged in the quote above), despite much literature on the subject the term ‘energy security’ resists a commonly-accepted definition. As Sovacool (2011) points out, energy itself is a politicised and multifaceted topic, with occasionally incommensurable views rooted in diverse disciplines such as physics, economics, engineering, sociology and politics. The numerous available conceptualisations of energy security are thus also commonly grounded within

[5] It is also important to note that the Energy Security Strategy was produced by the previous government administration, a fact which is emphasised in the official policy archives. As explained in section 1.2.3, the Strategy has not been actively replaced, yet many of the policies therein have undergone significant change.

specific academic disciplines (Cherp and Jewell 2011; King and Gulledge 2013; Månsson *et al* 2014a).

Many of the most commonly-cited definitions of energy security focus simply on two main components of 'availability' and 'affordability'; the same two components which feature prominently in the UK Energy Security Strategy definition above. They stipulate that the energy required for an economy or jurisdiction must be physically available, at reasonable prices (Bielecki 2002; IEA 1985; Yergin 2006). As noted by Hoggett *et al* (2014), there is a common tendency within the literature to focus on supply-side dynamics (see for example Bielecki 2002; Bohi and Tohman 1996; Bordhoff *et al* 2010; Lefèvre 2010; Winzer 2013), in some cases becoming even more specific and concentrating on the physical fossil fuel resources alone (Bradshaw 2010; Frondel and Schmidt 2014). This is partly owing to industrialised nations' shared history of reliance on hydrocarbon resources (Axon *et al* 2013), and perhaps also due to the fact that the majority of energy security literature originates from import-oriented regions such as the EU and US (Jonsson *et al* 2013; King and Gulledge 2013). The IEA states that ''energy security always consists of both a physical availability component and a price component, (but) the relative importance of these depends on market structure'' (IEA 2007: 32). Additionally, Chester (2010) and Cherp and Jewell (2014) note that there is a common bias in the energy security literature towards issues concerning fossil fuels, especially oil (largely due to the fact that energy security has its roots in the oil shocks of the 1970s), despite the fact that electricity now represents an equally significant (and growing) proportion of energy use.

The supply-side bias sometimes manifests itself in a perception that energy security is equivalent to reducing dependence on fuel imports. For example, the literature often refers to 'reducing control' by others, or to limiting the ability of fuel-exporting nations to gain political leverage through their exports (Bordhoff *et al* 2010; Greene 2010; Umbach 2010). However, there is no clear empirical correlation between reducing imports and reducing energy disruption (Chaudry *et al* 2011; Francés *et al* 2013; Stern 2004; Watson 2010). It is noted by Jonsson *et al* (2013) that although import dependence is one of the most commonly-cited energy security issues in the existing literature, there is relatively little research on the potential security *benefits* of mutual dependency. It is therefore argued by some that in a globalised economy, complete independence from imports is essentially neither foreseeable nor desirable (Energy and Climate Change Committee [ECCC] 2011; Pascual and Zambetakis 2010; Yergin 2006).

Others point out that security is not just about reducing *risks* to energy systems, it also entails improving their *resilience* to threats; the combination of these two factors is often termed ‘vulnerability’ (Cherp and Jewell 2014). Many therefore point out that diversity of supply can act as a hedge against supply and price disruptions (Cooke *et al* 2013; Hoggett 2013; Urciuoli *et al* 2014; Watson 2007; Watson and Scott 2008). It is even argued by some that the uncertainties surrounding energy security are so pervasive that the only sure way of maximising energy security is to maximise diversity (Bradshaw 2010; Grubb *et al* 2006; Stirling 1994; 1998). However, as shall be evident throughout this thesis, diversification is but a single facet of a far more complex subject; an amount of diversity may well be a necessary feature of a secure energy system, but it is not sufficient to ensure energy security by itself (Cherp and Jewell 2014; Christoff 2011; Gracceva and Zeniewski 2014; Ranjan and Hughes 2014; Stirling 2010).

2.1.2 A broader view

In some of the energy security literature, there has been 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’. It is widely accepted that there is a fundamental imperative to substantially reduce energy sector emissions in order to avoid the worst effects of anthropogenic climate change, and emissions-reduction legislation is in place in the UK and EU (European Union 2009; HM Government 2008). According to Symons (2011), it appears that energy studies must begin to take account of environmental externalities. In 2007, the Asia Pacific Energy Research Centre argued that energy security consists of four dimensions – availability, affordability, accessibility, and acceptability, with acceptability referring to environmental and societal concerns (APERC 2007).[6] Kruyt *et al* (2009) then pointed out that the vast majority of metrics and indicators for assessing energy security still relate to availability and affordability, and argued that a broadening of the scope of study into issues relating to ‘accessibility’ and ‘acceptability’ would lead to a more comprehensive view of energy security. 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) (although it is interesting to note that the IEA later removed the

[6] The APERC definition was actually borrowed from the public health literature; see Cherp and Jewell (2014) for a detailed critique of this categorisation.

environmental component, and it does not appear in their current definition on their website [IEA 2017]). Elkind (2010: 128-9) wrote that traditional definitions now need to be broadened to include environmental sustainability, for three reasons:

- “Energy infrastructure is long-lived, [meaning that] current decision-making is creating the environmental reality that will shape people’s lives for decades to come…
- “Promoting energy security without including sustainability will promote the use of technologies that will exacerbate climate change…
- “Climate change will affect systems profoundly.”

This broadened perspective has been used widely in the more recent energy security literature (see Ang *et al* 2015), and as the basis for a number of empirical assessments (e.g. Francés *et al* 2013; Gnansounou 2011; Hughes 2012; Mitchell *et al* 2013; Sovacool and Brown 2010). Moreover, it is supported by qualitative studies into global perspectives on energy security, which find that among both elites and the general public there is widespread concern for both environmental and societal sustainability, and that people generally perceive sustainability to be one of the key dimensions of a secure energy system (Sovacool *et al* 2012; Sovacool and Mukherjee 2011).

This broader 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. There is an ongoing debate in the literature about the benefits and drawbacks of including aspects such as GHG emissions into conceptualisations of energy security: many studies view environmental impacts as a separate issue, perhaps to be considered *alongside* energy security but not as part of the concept itself (e.g. Cherp and Jewell 2011; Froggatt and Levi 2009; Jewell *et al* 2014; Pfenninger and Keirstead 2015). However, as pointed out in Elkind’s third point above, climate change may itself become a fundamental facet of energy security as the result of climate change impacts such as floods, heatwaves and storms. For example, in late 2015 many parts of the UK experienced significant disruption to electricity supplies due to flooding caused by several consecutive storms. One storm alone caused loss of power to several tens of thousands of homes after a substation was flooded; importantly, it was reported that researchers had calculated that this storm severity was made approximately 40% more likely by climate change (Pidd *et al* 2016; Vidal 2015). Previously, storms in December 2013 caused around 750,000 homes across the UK to lose power; around 500 households were without supply for more than five days (Macalister 2014; RAEng 2014). Warmer temperatures in summer could also be a risk in the future for the UK's generation and network infrastructure: the severe blackout in North-east America in 2003 was caused by transmission lines sagging in the heat, and some power stations in Europe have experienced problems caused by rising temperatures of cooling water (RAEng 2014; McDermott and Nilsen 2012). Additionally to the physical impacts of climate change, the practicalities of complying with environmental legislation mean that any aspect of energy should now take environmental impacts into account. The UK is one of the only industrialised nations with a unilateral legally-binding emissions target (HM Government 2008), and is also subject to EU climate legislation (European Union 2009). For policy-makers who are legally committed to carbon reduction targets, it may be unwise to examine 'security', 'affordability' and 'environmental sustainability' separately, because the future energy system must meet all these aims. As pointed out by Logan and Venezia (2007: 1):

> "We would benefit by reconsidering what energy security means to us today. The traditional definition of sufficiency, reliability, and affordability now seems incomplete. Environmental sustainability, geopolitical factors, and social acceptability are clearly elements that need to be added to our energy security calculus."

2.1.3 A slippery concept…

It is becoming clear that energy security is complex and resists a commonly accepted definition. In an analysis of existing definitions and conceptualisations of energy security, Chester finds that:

> "An examination of explicit and inferred definitions finds that the concept of energy security is inherently slippery because it is polysemic in nature, capable of holding multiple dimensions and taking on different specificities depending on the country (or continent), timeframe or energy source to which it is applied." (2010: 887)

The 'slipperiness' of the concept means that it is open to exploitation by interest groups (Löschel *et al* 2010a). Energy security is an arena in which different voices seek to 'securitize' their particular understanding of key risks and threats (Buzan *et al* 1998). As pointed out by Joskow:

> "There is one thing that has not changed since the early 1970s. If you cannot think of a reasoned rationale for some policy based on standard economic reasoning then argue that the policy is

> necessary to promote ‘energy security’” (Joskow 2009, cited in Winzer 2011: 2).

Compounding this is the fact that perspectives on energy security are highly context-dependent (Ang *et al* 2015; Bielecki 2002; Sovacool *et al* 2012). Cross-national surveys and studies have found that demographic and national characteristics have a very significant role to play, and that energy security concerns are strongly correlated with national energy policies and state imperatives (Knox-Hayes *et al* 2013; Pasqualetti 2011; Sovacool *et al* 2012; Toke and Vezirgiannidou 2013). Moreover, it has been shown that energy security concerns are dynamic and evolve as circumstances change over time, reflecting dominant discourses and political economic trends (Ang *et al* 2015; Dannreuther 2015; MacKerron 2009); as noted by Dannreuther, “The broader context of the global political economy has a determining effect on which particular securitization of energy assumes dominance” (2015: 467).

Clearly, energy security means different things to different people. As well as mapping onto national concerns, perspectives may be shaped by the sector or organisation for which people work. The idea that people’s views are usually correlated to the sector in which they work is often referred to as “where you stand depends on where you sit”, or Miles’ Law, after the Truman-era bureaucrat who coined the phrase (Encyclopædia Brittanica 2015). Influential work by Allison (1969) suggested that,

> “Where you stand depends on where you sit… Horizontally, the diverse demands upon each player shape his priorities, perceptions, and issues. For large classes of issues, the stance of a particular player can be predicted with high reliability from information concerning his seat” (1969: 711).

Several empirical studies corroborate Miles’ law, with reference to a diverse range of fields (see Berman *et al* 1985; Vest *et al* 2010; Wilcher 1986). However, Bryan (2003) suggests that it is also necessary to conceptualise where people ‘sit’ as not just a person’s professional position but also the wider context, for instance a person’s emotional ties and previous experience (an idea which is also alluded to by Allison himself [Allison 1969]). Von Borgstede and Lundqvist (2006) surveyed a large number of public and private officers regarding their views on different aspects of the climate issue, and found that acceptance of climate policy measures depends on a) where you sit (i.e. organisational affiliation) and

b) what you do (i.e. professional role), but that “Professional roles have an influence *over and above* organizational affiliation” (2006: 279, emphasis added).

For example, the term ‘energy security’ would mean different things to, say, an economist and an engineer (Bielecki 2002). Cherp and Jewell (2011) identify three perspectives amongst the academic and policy literatures, which have emerged from three distinct academic disciplines (illustrated in figure 2.1): the ‘sovereignty’ perspective (rooted in security studies and international relations), the ‘robustness’ perspective (rooted in engineering and physical sciences), and the ‘resilience’ perspective (rooted in economics and complexity science). This highlights the fact that perspectives on energy security still operate to some extent in disciplinary silos, which are operationalised and reinforced by the academic disciplines within which they reside (Jonsson *et al* 2013). This means that assessments of energy security will generally be subject to the underlying or stated preferences of the author (Cherp and Jewell 2011; Mitchell and Watson 2013b; Valentine 2011). Any choice of indicators or framework will be subject to numerous interpretations and assumptions; therefore the best practice for the researcher is to attempt to be explicit about these assumptions (Axon *et al* 2013; Löschel *et al* 2010b; Mitchell and Watson 2013b; Valentine 2011). Following from this, Axon *et al* developed their idea of ‘indicators derived for a set purpose’:

> “It is evident that different stakeholders, having different objectives, will find different meanings of energy security are appropriate for their own particular needs, and thus best served by their own particular set of indicators. This idea of ‘indicators derived for a set purpose’ is important since it shows us that there is no such thing as a ‘right’ or ‘wrong’ answer.” (2013: 209)

Therefore it is important to bear in mind that any choice of framework or indicators will be specifically designed for the purposes set out in this thesis, and also that there is not necessarily any such thing as a ‘right’ or ‘wrong’ answer. As pointed out by Cherp and Jewell (2014), vital systems and their vulnerabilities are not just objective phenomena; they are also political constructs which are defined and prioritised by different social actors. It is the contention of this thesis that a cogent approach to assessing energy security will take into account not only the assumptions and preferences of the author, but also the opinions of a range of other actors, in an attempt to discover the impact of these on the way that the energy security of a system is assessed and improved.

This review of the extensive literature on conceptualising and defining energy security illustrates that some of the literature has broadened out to include environmental and societal issues in concepts of energy security, although there is still debate on this matter. Moreover, this review has shown that there has hitherto been a focus on supply-side dynamics, therefore it appears that the demand-side should now be incorporated more fully (Hoggett *et al* 2011; 2013; Jansen and Seebregts 2010; Pye *et al* 2014). For this reason, the commonly-used phrase ‘security of supply’ will be rejected in favour of ‘energy security’ or ‘electricity security’.

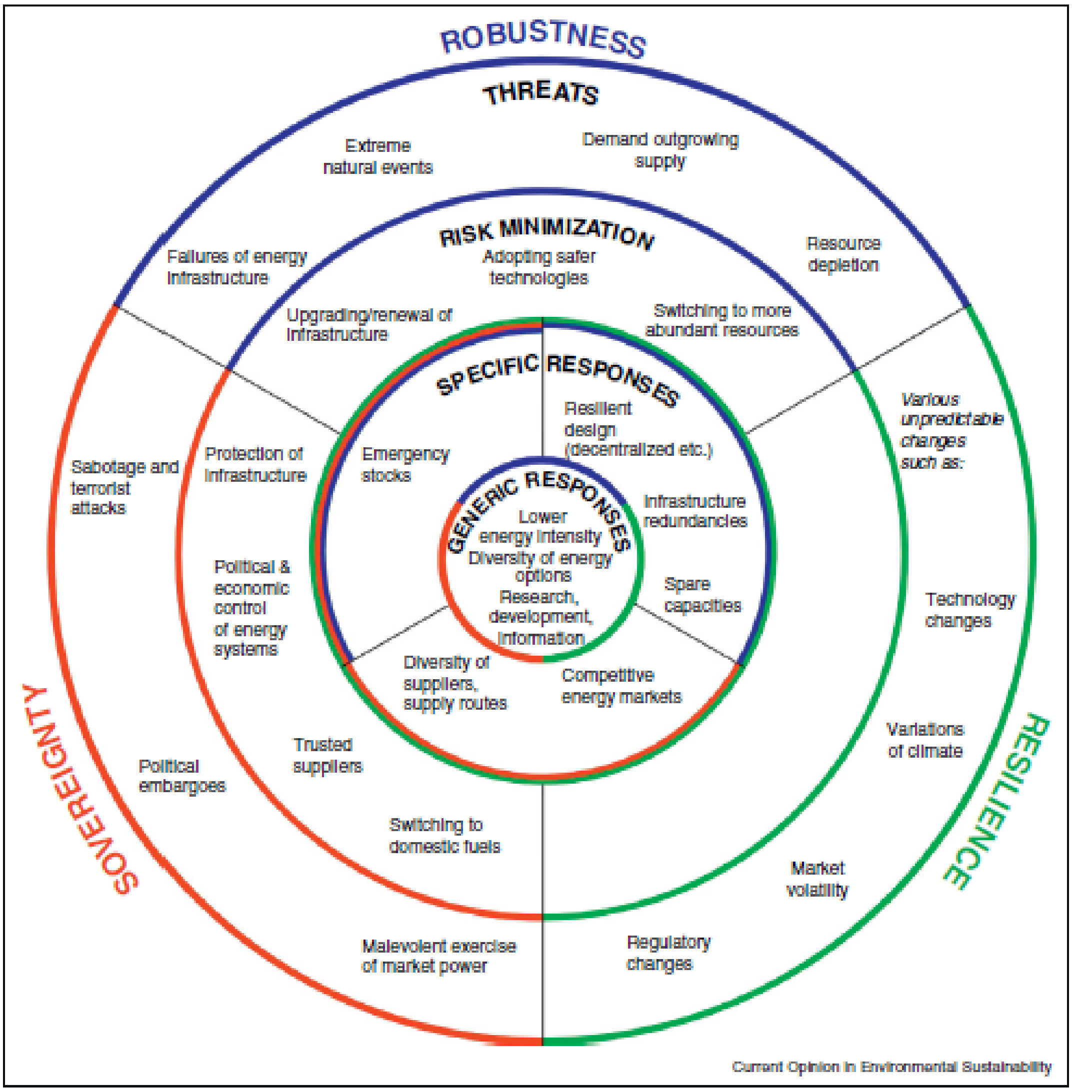

Figure 2-1: Three perspectives on energy security (Cherp and Jewell 2011: 2007)

2.2 'Security' and 'risk'

2.2.1 Conceptualising risk

Energy security cannot be easily or directly measured; therefore most literature focuses on risks to the energy system, treating energy security and energy risk as two sides of the same coin (Francés *et al* 2013). In this sense, the issue of energy security is situated within a rich theoretical literature on risk. Dominant concepts of risk as we know it probably emerged from mathematical theories on probability in the 17th and 18th Century, which attempted to forecast the future on the basis of past observations; in fact, the modern risk analysis techniques employed by insurance companies and market analysts today have barely changed from these early origins (Dannreuther and Lekhi 2000). It was only in the 1920s that discussions on risk turned towards its social qualities, when Frank Knight (1921) sought to explain how individual entrepreneurs and managers were able to gain a profit from the capricious social elements of their markets and competitors. Yet Frank Knight still saw risk as a purely technical, rationalist matter, based within neoclassical economic theories of market equilibrium. Later theorists began to see risk as socially constructed and relating to perceptions which are informed by society and culture (Douglas and Wildavsky 1981; Royal Society Study Group 1992). According to these theories, decisions to minimise risk are usually made not by rational utility-maximisation, but rather in response to rules and norms that constrain and inform appropriate actions (Granovetter 1985; March and Olsen 1984; Meyer and Rowan 1991).

Following from this, 'risk' is defined as "the possibility that human actions or events lead to consequences that harm aspects of things that human beings value" (Hohenemser *et al* 1983; Kates and Kasperson 1983). Risk is therefore both an analytic and a normative concept; perceptions of risk will depend on the preferences and values of those seeking to measure it, and the process of evaluation will depend on the type of risk (Klinke and Renn 2002). In this way, clear parallels begin to become apparent between the literature on risk and on energy security. Risk perception is subject to politics, and decision-makers tend to have subjective viewpoints (Kristensen *et al* 2006); as noted by Renn and Klinke, "As risk analysis and risk management get increasingly caught up in political debates, a new way of looking at and defining the risks of modern technologies becomes necessary" (2004: S41). Many dimensions of risk are "irreducibly qualitative in nature", because different groups of actors place different levels of importance on different aspects of risk (Stirling 1999; 2008b). Stirling sums this up nicely by saying:

> "Different disciplinary perspectives, institutional interests, cultural values and economic priorities will typically influence the interpretation of evidence and analysis in different ways… Contrasting social commitments will thus yield divergent prescriptive bases for governance interventions." (2006: 230).

As pointed out by Stirling (1999), it is generally accepted in the field of risk management that Risk=Probability*Impact Magnitude; however, most issues (including energy security) operate on multiple dimensions, making the delineation of 'probability' and 'impact' highly problematic. Bruijne *et al* (2010), Renn and Klinke (2004) and Urciuoli *et al* (2014) all show that conventional risk management approaches fail to deal with what Taleb (2007) nicknamed 'Black Swans'; that is, events with a low probability but high impact, such as the nuclear disaster at Fukushima power station in March 2011. As such, it can be seen that a broader and more critical conceptualisation of risk and how to manage it is required in order to encapsulate the multifarious issues in assessing the security of an energy system. The preceding sections have demonstrated that despite the clear challenges in approaching a concept as slippery as energy security, decisions still must be made about the future direction of energy systems, especially in the context of a challenging transition to decarbonisation. Policy decisions are being justified on the basis of energy security concerns, and therefore it is crucial to work towards a way of assessing what this means in a manner which attempts to take into account multiple subjectivities. A balance must be struck between assuming that different aspects of security can be easily quantified and weighted using composite indices (which can be inaccurate and misleading), and on the other hand, assuming that security cannot be measured and therefore either adopting overly-simplistic approaches (such as the reduction of energy security into single metrics such as diversity or import dependence), or simply avoiding measuring it altogether (which leaves the concept open to capture by vested interests). The following sections therefore introduce a theoretical framework on risk and uncertainty from the existing literature, which can be used as a lens through which to approach the assessment.

2.2.2 A risk framework

Stirling (1999; 2008b) provides a useful framework for approaching these issues. He points out that conventional risk management relies on sufficient knowledge about the probability and likely impact (or in Stirling's terminology, 'possibilities') of an event; however, this knowledge is sometimes severely limited. A number of alternative situations may therefore arise, in which knowledge about probability, impacts, or both is problematic. These situations are defined by Stirling as areas of ‘uncertainty’, ‘ambiguity’ and ‘ignorance’, and are illustrated by the Uncertainty Matrix in figure 2.2. This framework provides a means of looking at security which takes multiple dimensions and uncertainties into account. Moreover, it explicitly addresses the fact that, as pointed out in section 2.1.1, much energy security literature does not focus only on ‘risks’, but also reducing ‘vulnerability’, for instance by improving the resilience of the system (Cherp and Jewell 2014).

As shown in the illustration, various approaches to analysing risks and vulnerabilities can be seen as falling within different parts of this framework. Conventional risk management approaches usually fall within the top left-hand corner of the quadrant; these approaches tend to encourage single, deterministic policy responses, which is clearly why they are most popular with policy-makers (Stirling 2010). The other approaches discourage single ‘definitive’ results and interpretations. Therefore, Renn and Klinke (2004) advise that analysis of risk should be broadened out so that risk and vulnerability can be assessed under a diverse range of criteria. As an example of this, Gracceva and Zeniewski (2014) note that diversity provides a good means of minimising risk under conditions of ‘ignorance’, but that many other dimensions of energy security extend beyond diversity, and that therefore it is important to address multiple aspects of the Uncertainty Matrix in an assessment of energy security.

This framework can provide a useful starting point for the development of a set of indicators which can take multiple dimensions of risk into account. However, there is an important linguistic issue which arises and is worth clarifying to avoid confusion. The top left-hand corner of the uncertainty matrix is labelled ‘risk’, in order to reflect the fact that the approaches within this quadrant are based on conventional risk management techniques. However, the term ‘risk’ is also often used in its broader sense, to denote all four quadrants of the uncertainty matrix, including vulnerability, and viewing ‘energy security’ and ‘energy risk’ as two sides of the same coin. Throughout the remainder of this thesis, the term ‘risk’ will be used in this broader sense unless otherwise stated.

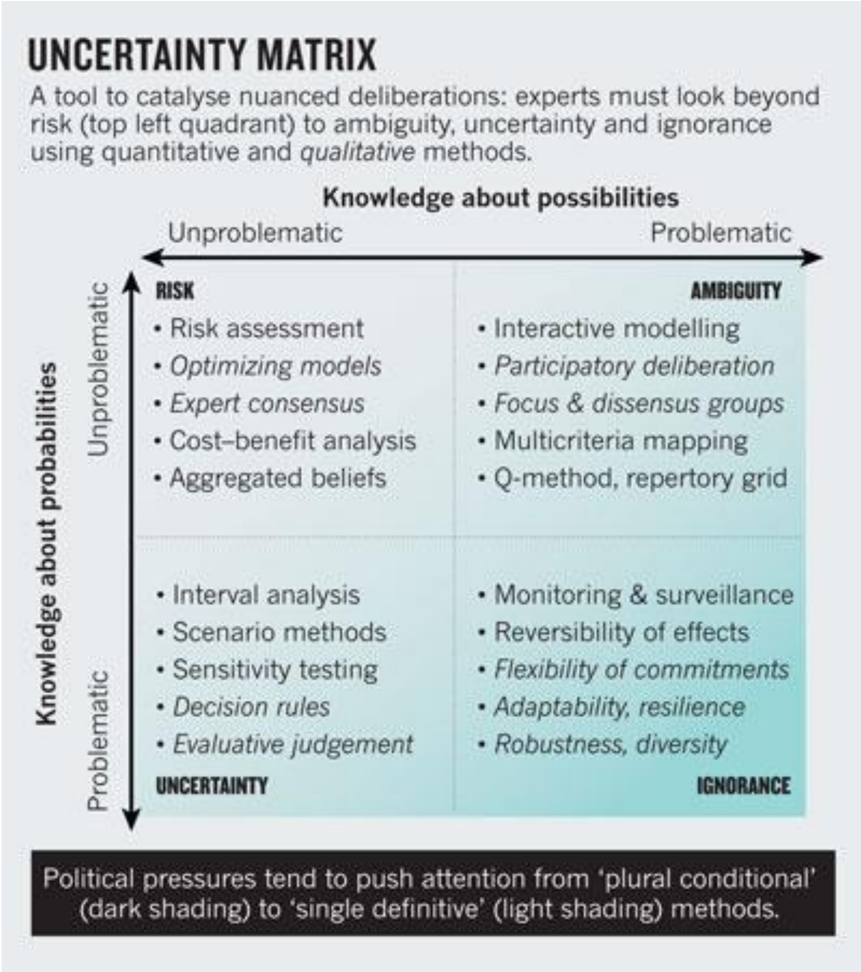

Figure 2-2: The Uncertainty Matrix (Stirling 2010)

2.2.3 Plural conditionality

Following from this, Stirling (2008b) argues that many empirical approaches take an approach in which multiple complexities are reduced to simple parameters of magnitude and probability, and then aggregated across highly diverse dimensions. However, it should be clear from the literature outlined in this section that measuring risk and vulnerability is highly contingent. As pointed out by Scrase and Ockwell (2010) and Millstone (2015), understandings of problems and solutions are always based upon experiences, interpretations and value judgements, which in turn are shaped by social interactions; this holds true for experts, scientists and policy-makers. Thus knowledge is inherently plural and conditional (Stirling 2010). Indeed, as shown in Nobel prize-winning work by Arrow (1963; 1974), it is impossible to definitively aggregate preferences across a diverse and plural society. This is especially true for a slippery concept such as energy security, which may engender a number of competing knowledge claims. Therefore the contention of this thesis is that the measurement of energy security and energy risk in a system should take an approach which recognises that no empirical analysis, no matter how rigorous, is capable of discovering the 'one scientific truth', and that the 'right' answers and solutions depend on the framings of the questions and problems (Stirling 2006).

Instead of continually attempting to reach a consensus of divergent views, it would be far better to accept the inevitability of at least some level of plurality (Stirling 2010). This has been developed by Stirling (2006; 2013) into the approach which he terms 'plural conditionality', as illustrated in figure 2.3. The two quadrants on the bottom row show the dichotomy between the naïve positivist ideal of obtaining the 'one scientific truth', and the caricature constructivist rejection of the whole notion of scientific truth. These approaches can both be rejected at once, because although security and risk are clearly socially constructed and contingent, it cannot be suggested that all claims to knowledge are equally valid – some claims are just simply wrong! The usual response to this falls into the top left-hand corner, which suggests that one knowledge claim will be 'approximately right'. However, this generally sees science as unitary, without the existence of competition over the 'right' answer. Therefore to address these shortcomings, the approach in the top right-hand corner suggests that several competing claims may be equally valid. Elements of this approach can be found in the energy security work by Cherp and Jewell, who state that "Both vital energy systems and their vulnerabilities are not only objective phenomena, but also political constructs defined and prioritized by various social actors" (2014: 419). Drawing on this context, therefore, suggests that an assessment of energy security should acknowledge the multiple issues surrounding the quantification of risk. These assumptions can be used as the basis for a more reflexive approach, which takes into account the realities of multiple competing and disparate preferences and assumptions.

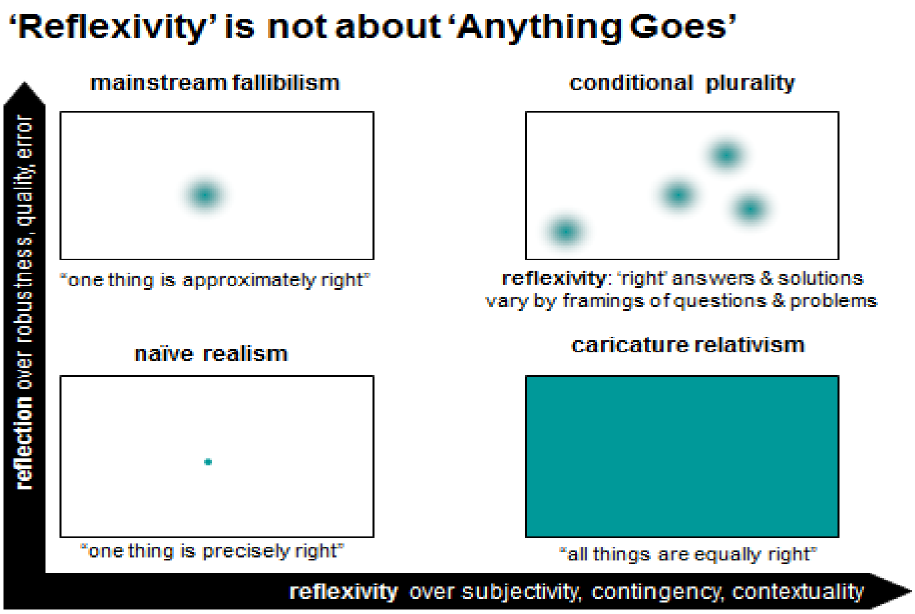

Figure 2-3: Plural conditionality (Stirling 2013)

This thesis aims to assess the future security of an electricity system in a low-carbon context, in order to identify the main risks, trade-offs and synergies which may emerge between different objectives in a transition to a low-carbon electricity system. As such, the following section explains why this thesis takes the low-carbon agenda into account when analysing energy security, and introduces the low-carbon context focusing especially on the synergies and trade-offs which could occur between various objectives. There is a relative lack of literature which seeks to assess these synergies and trade-offs in a systematic and empirical manner, especially in the context of a national electricity system; this thesis aims to address this gap in the literature.

2.3 Energy security in a long-term carbon reduction context

2.3.1 Carbon reduction and the energy 'trilemma'

As part of a response to the threat of climate change, the UK has set a legally-binding target of 80% GHG reduction on 1990 levels by 2050 (HM Government 2008), and the EU has made a commitment to reduce overall GHG emissions from its 28 member states by 20% on 1990 levels by 2020 (European Union 2009). Energy is a primary source of GHGs; in the UK in 2011, around 40% of CO_2 emissions were from the energy supply sector (Froggatt *et al* 2013). Therefore in order to mitigate climate change, the way energy is produced and consumed will need to change entirely within a generation, and eventually the energy sector in the developed world will need to produce close to zero carbon emissions (Froggatt and Levi 2009). Therefore understandings of energy security in the future will likely need to exist within this emerging new paradigm. This has led to the development of the energy ‘trilemma’, illustrated in figure 2.4, which suggests that energy systems need to balance the three elements of security, cost, and carbon reduction (Boston 2013; E.ON 2008). The trilemma illustrates the importance of looking at the climate-security nexus, rather than approaching the two areas in isolation, and of exploring possible synergies and trade-offs between the three objectives (Criqui and Mima 2012; Pfenninger and Keirstead 2015; Sovacool and Saunders 2014). As argued by Ang *et al*,

> “In policy discussions, energy security should not be considered in isolation. Instead, it should be considered in the larger context of the energy trilemma and sustainability to avoid formulating short-sighted policies which address energy security in the short-run but contribute to longer-term problems.” (2015: 1090)

It was suggested in section 2.1 that when considering energy security in the long-term, the physical and legislative impacts of climate change on future energy systems necessitates a broad view of energy security which incorporates the carbon reduction objective as well as societal objectives, demand-side objectives and non-carbon environmental objectives. By taking this broad view, numerous synergies and trade-offs may emerge between different objectives of energy security; furthermore, it allows the thesis to explore the implications of such a broad view of energy security, both on the results of a security assessment and on the ways in which different stakeholders view and conceptualise energy security. The following paragraphs will explore some ideas of where these synergies and trade-offs could lie; as becomes evident, they are potentially very numerous. This reinforces the need for a broader empirical approach which moves beyond simple conceptualisations of energy security as relating simply to physical supply; there is a rationale to incorporate environmental sustainability, society and the demand-side in an assessment of energy security, in order to illustrate and analyse the trade-offs which may emerge between different objectives.

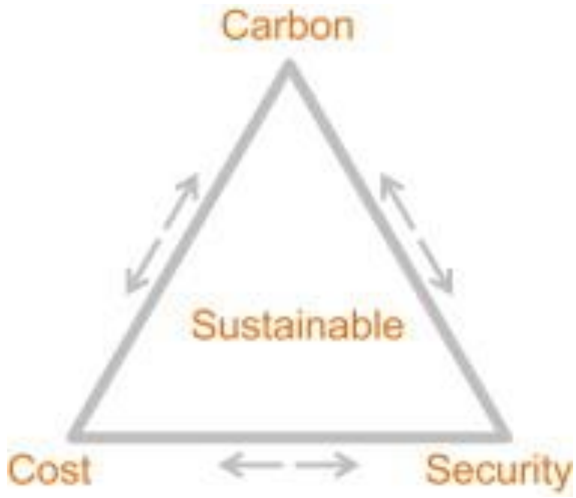

Figure 2-4: The Energy Trilemma (Boston 2013)

2.3.2 Some potential synergies

If security objectives are pursued without mitigating climate change, the negative effects of climate change may actually cause security to diminish in the longer-term (Mayer and Schouten 2011). As shown by Falk, "Energy security bought at the cost of an increasingly chaotic climate may buy neither economic nor social stability" (2011: 248). Therefore it is already apparent that there are potential synergies between objectives; policy-making in Europe and the UK has already begun to explore the potentially large advantages to be gained from exploiting such synergies (Bollen *et al* 2010; Vogler 2013). Societies in the developed world are highly dependent on fossil fuels; this may create an assortment of risks and vulnerabilities, such as dependence on volatile regions, resource depletion, the safety risks of unconventional fossil extraction such as shale gas or deepwater oil, health and safety hazards associated with mining, and price volatility (Adelle *et al* 2009; Criqui and Mima 2012; Kuzemko and Bradshaw 2013; Logan and Venezia 2007).

It is suggested that certain measures could offer 'win-win' solutions. For instance, pursuing energy efficiency and demand reduction measures would reduce the amount of energy we use, thereby for example reducing GHG emissions whilst reducing the risk of physical depletion of resources, and potentially even reducing energy costs for consumers (Adelle *et al* 2009; Berk *et al* 2006; Froggatt and Levi 2009; Greenpeace 2010a; Hoggett *et al* 2013; Pye *et al* 2014). On the supply side, it is argued that a greater share of renewable energy sources (RES) in the energy mix would improve energy security by reducing reliance on fossil fuels and increasing the geographical dispersion of energy supply resources;

moreover, a portfolio using several different types of RES would likely improve diversity (Adelle *et al* 2009; Berk *et al* 2006; Brown and Huntingdon 2008; Diesendorf 2011; Froggatt and Levi 2009; Johansson *et al* 2014; Månsson 2015; Wicks 2009). Furthermore, non-fuel-related measures could potentially provide win-win solutions; for instance, it is argued that improving international agreements and pursuing cross-border energy flows could greatly improve system resilience and could also lower costs (Francés *et al* 2013; Wicks 2009). Greenpeace (2010a) and the Centre for Strategic and International Studies (Ladislaw *et al* 2009) have both produced roadmaps which give examples of how a low-carbon, low-cost and secure energy system can be achieved: following the logic of win-win solutions, both roadmaps advocate a diverse portfolio with a strong emphasis on renewable sources and on reducing overall energy demand.

2.3.3 Some potential trade-offs

Alongside these potential synergies, it is important to accept that there may be unavoidable trade-offs; examining and acknowledging trade-offs can be far more useful for improving energy systems than trying to avoid them altogether (Sovacool and Saunders 2014). In practice, attaining the synergies outlined above is extremely challenging. For example, it has been suggested that the most practical solution for physical security of UK energy supplies would be to mine and burn more domestic coal, as this would reduce reliance on imports and would allow the continued use of existing infrastructure (Bollen *et al* 2010; Chaudry *et al* 2011; Froggatt and Levi 2009). However, coal has extremely high carbon emissions, emitting upwards of 850gCO_2/kWh, compared to around 400gCO_2/kWh for a modern Combined-Cycle Gas Turbine [CCGT] gas plant (ECCC 2010). On the other hand, further switching from coal to gas in the UK could potentially reduce emissions, but would also potentially reduce diversity of fuel sources and increase the supply risks associated with a lack of investment in gas storage in the UK (ECCC 2011; Froggatt and Levi 2009; Jewell 2012). The use of CCS technology would allow for the continued use of coal without the associated high emissions; however, CCS is very costly, and it reduces the efficiency of coal power plants which increases coal supply requirements (Diesendorf 2011; Froggatt 2013; Froggatt and Levi 2009; Johansson *et al* 2014). CCS is also being developed for gas-fired generation; however, the issue is linked to longer-term risks of resource depletion, and some argue that CCS could potentially lock the energy system into using non-renewable resources such as gas which may become depleted (Greenpeace 2008; Vergragt *et al* 2011). The use of unconventional fossil fuels could mitigate the issue of resource depletion; however, unconventional fuels such as shale gas and oil sands bring their own risks, such as increased emissions and various risks to human and environmental safety (see for example Shale Gas Information Platform 2015; Wykes and Heywood 2010).

As shown in the previous section, RES can in theory generate synergies between objectives, yet they also come with their own sets of issues and trade-offs. They are generally not yet cost competitive with thermal generation (if costs of externalities are not factored in), and they still require large amounts of investment both in generation and the networks; these costs will eventually be passed onto consumers, possibly leading to higher energy bills (Berk *et al* 2006; ECCC 2011; Froggatt and Levi 2009; Pudjianto *et al* 2013). Many of the most advanced RES technologies are intermittent, meaning that the electricity may not be available when it is required; this could lead to increased costs, lower levels of spare capacity and increased reliance on backup generation (ECCC 2011; Jewell 2012; Johansson *et al* 2014; Ofgem 2013a; RAEng 2013). The complications of integrating intermittent RES into the existing electricity grid are manifold, and will be discussed at greater length in section 2.4. Moreover, policies designed to stimulate investment in RES, such as a carbon price, would have the effect of increasing the costs of conventional generation in the short-term and may therefore push overall energy prices up (King and Gulledge 2013).

Other low-carbon energy sources could also potentially result in trade-offs. For instance, nuclear power is low-carbon and uranium stocks are relatively plentiful (World Nuclear Association 2014). However, nuclear power is also associated with risks: for example, despite government support in the UK, new nuclear power has been subject to delays and uncertainty caused by the challenges of securing investment for projects with high capital cost in a liberalised energy market (Blyth *et al* 2014; Ellenbeck *et al* 2015; Mitchell *et al* 2014). Another option for fuel switching is biomass, a term which applies to a diverse range of fuel sources including wood pellets, agricultural residues, energy crops, and biogenic waste from landfill, sewage and farming. Biomass is both renewable and non-intermittent, and could therefore provide a useful backup to intermittent RES (Deloitte 2013). However, the climate impacts are highly disputed, especially because (depending on the feedstock used) widespread use of biomass could lead to large-scale land-use change (Frogatt and Levi 2009; IEA 2007; Thornley 2012a; 2012b). Biomass is also subject to a number of other issues, such as competition for agricultural land, concerns over deforestation, and the effects of large-scale export-based monocropping on ecosystems and local communities (Bai *et al* 2012; Coath and Pape n.d.; Thornley 2012a).

The discussion thus far has focused on various fuels and specific practical trade-offs between objectives. Yet there is also a wider, and potentially more intractable, problem. Climate change is a global issue, and therefore suffers from a severe collective action problem. States which reduce emissions unilaterally could potentially put themselves at risk of increasing their energy costs and thereby reducing their competitiveness on international markets (Berk *et al* 2006; Symons 2011). States will tend to prioritise national physical security and lower fuel prices because the effects are more directly felt within their jurisdiction, meaning that physical security and affordability imperatives will tend to trump environmental issues (Dryzek *et al* 2003; Huntingdon and Brown 2004; Toke and Vezirgiannidou 2013). This tendency is compounded by the issue of timescale: most of the risks and impacts of climate change occur on yearly or decadal timescales, and are therefore much more long-term than the technical issues faced when seeking to maximise the reliability of an electricity system, many of which occur every second (Boston 2013; King and Gulledge 2013). States may actually have an imperative to prioritise shorter-term objectives. There is therefore a real need to address empirically the potential trade-offs and synergies in moving to a low-carbon electricity system. The work by Cherp *et al* (2013) and Jewell *et al* (2013; 2014) goes some way towards addressing this gap, by assessing the security of a large number of low-carbon transition pathways for the global energy system, while a more recent paper by Pfenninger and Keirstead (2015) assesses the security implications of three idealised scenarios involving renewables, nuclear and fossil fuels for the UK electricity system. However, these papers display an empirical reliance on diversity and import dependence as the core indicators of energy security, and as shown in section 2.1.1, these indicators are not sufficient. The recent work by Jonsson *et al* (2015) goes a step further, pointing out that there is a real need for a broader framing of energy security which includes qualitative aspects such as social and political dynamics; their paper introduces a more comprehensive suite of energy security aspects and applies them in a low-carbon context. However, their work does not attempt to provide a means for assessing such broader aspects of energy security in a systematic and empirical manner. Thus the requirement for a broader empirical approach is reinforced; environmental sustainability, cost and the demand-side should be incorporated in order to get a grasp on the potential synergies and trade-offs between objectives. As noted previously, any measurement of energy security will be ‘derived for a set purpose’; therefore there is an opportunity to develop a specific set of indicators for systematically and empirically assessing the long-term security of an electricity system in a low-carbon context. There have been few attempts in the literature to assess the security of possible future energy systems over a long time-period.

As explained in the previous chapter, this thesis focuses on the security of the UK electricity system. The following section of this chapter provides some important background information on this topic, particularly relating to the challenges of balancing electricity supply and demand whilst attempting to reduce GHG emissions. Electricity is an interesting case because it encompasses a wide range of timescales over which energy security can operate: system balancing occurs over very short timescales, whereas stresses such as climate change occur over much longer timescales. By assessing the security of electricity systems over the long time-period of the UK's carbon-reduction targets (out to 2050), this thesis explicitly addresses this range of timescales, as will be discussed in more detail in section 3.2.

2.4 Electricity security: background information

2.4.1 Balancing electricity supply and demand

Electricity is difficult and costly to store, meaning that electricity markets are unique in that they require constant and instantaneous balancing of supply and demand (Creti and Fabra 2007; IEA 2004; Roscoe and Ault 2010). This means that electricity security needs to be thought of in terms of different timescales: supply and demand must be balanced over very short timescales to ensure that the electricity is immediately available when and where it is required, as well as securing sufficient overall supplies when averaged over the longer-term (Bolton and Hawkes 2013; Boston 2013; REKK 2009). It must be remembered that most UK citizens are accustomed to constant access to electricity; supply shortfalls in the UK may result in welfare losses and potentially severe consequences for the perceived political legitimacy of the government (de Nooij *et al* 2007; RAEng 2014). Therefore the system is carefully balanced in order to ensure that supply meets demand at all times. Consumers' patterns of working and living mean that the electricity system frequently experiences large pickups in demand, for instance on winter evenings when most people come home from work and switch the lights and kettle on.[7] Thus electricity security involves ensuring both 'system adequacy', i.e. the ability of the system to meet normal variations in demand such

[7] The largest of these was in 1990, when the end of the World Cup semi-final penalty shootout between England and Germany imposed a 2800MW pickup, equivalent to around a million kettles being switched on! (BBC 2006).

as those caused by seasons and working patterns, and 'system resilience', i.e. the ability of the system to deal with disturbances such as unexpected spikes in demand or sudden losses of supply (IEA 2004; Nedic *et al* 2005). As well as this, the system must also be able to attract sufficient longer-term investment to ensure that there will be adequate generation, transmission and distribution capacity in the future (Bolton and Hawkes 2013; Creti and Fabra 2007).

2.4.2 Balancing a low-carbon electricity system

Reducing GHG emissions adds additional challenges to the difficulties of balancing the system (Barnacle *et al* 2013). Some of the most advanced sources of low-carbon electricity such as wind and solar are intermittent, meaning that they cannot be relied upon to be available when they are required. This intermittency means that RES cannot act as a direct watt-for-watt replacement for fossil fuels; in a system with high levels of renewable generation, more resources may need to be available to meet balancing challenges, as explained in more detail in section 2.4.3 (Davis *et al* 2013; Nedic *et al* 2005; Ofgem 2012; Paulus *et al* 2011). Conventional plants may be required to operate at reduced output as they will mainly be used for backup and peaking power (Nedic *et al* 2005; Paulus *et al* 2011; Roscoe and Ault 2010). This is illustrated through the use of capacity factors – a capacity factor is the actual power produced over a period of time, expressed as a percentage of the power that could have been produced if the station or array was running at full power for that period of time (for both conventional and intermittent generation). Increased penetration of intermittent sources reduces the capacity factor of the overall electricity mix; as the capacity factor decreases, the average cost of conventional plant increases, and the efficiency of the plant decreases (Paulus *et al* 2011). These supply-side issues, combined with the challenge of increased overall demand (and possibly higher peak demand) for electricity due to electrification of heat and transport, will represent a significant challenge for balancing the system and integrating high levels of low-carbon capacity.

These difficulties have the effect of reducing the amount of spare capacity which is projected to exist on the system in the future. In 2012, Ofgem suggested that increasing demand and intermittent supply, alongside the closure of some old power stations, could lead to a significant reduction in the overall capacity margin (de-rated to account for intermittency)[8] of the UK electricity system, from around 14% now to around 4% in 2016 in their base case (Ofgem 2012). The Government's 2012 Energy Security Strategy (DECC 2012a) also noted a tightening of de-rated capacity margins, to around 3% in 2030 in their base case,[9] although the report asserts that a tightening of margins is to be expected in a market such as the UK which has in the past had an oversupply of electricity. A recent report by National Grid warns that UK winter capacity margins will be tighter in 2015/16 than they were in previous years, meaning that additional contingency measures (such as those suggested in section 2.4.3) may be required (National Grid 2015a). However, despite several consecutive years of capacity margin warnings and often some rather hyperbolic media reports of a looming 'capacity crunch', there have not yet been any instances of supply shortfalls for consumers.

As well as reducing the spare capacity available, increasing demand and intermittent power generation can put a strain on the transmission and distribution networks. Despite all the discussion around primary energy supply, it is pointed out by Boston (2013) and Jamasb and Pollitt (2008) that the vast majority of actual blackouts are caused by failures on the transmission and distribution networks. There are currently bottleneck areas on the UK transmission grid (for instance, between England and Scotland), and dealing with this in the context of increased load on the system could require a reorganisation of how power is produced and distributed (Hammond and Pearson 2013; Martínez-Anido *et al* 2013). Increased flexible and distributed generation could assist in easing these bottlenecks and reduce the need for network reinforcement (Jamasb and Pollitt 2008; Pudjianto *et al* 2013; Shaw *et al* 2009; see section 2.4.3); however, this would require a large-scale reconfiguration of the grid (Hammond and Pearson 2013). Overall, it is important to recognise that the key negative effect of network reinforcements will be felt via the cost of electricity: network reinforcements or reconfiguration are possible but costly, and the costs will eventually be passed on to the consumer. If the UK is serious about meeting its decarbonisation objectives, these challenges will need to be addressed. As this section has sought to illustrate, the scale of the balancing challenge means that it is imperative to assess the implications of a low-carbon transition on the overall security of the electricity system.

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[8] The de-rated capacity margin is the capacity margin adjusted to take power availability into account, specific to each type of generation (DECC 2011a).

[9] The DECC projections are slightly higher because of differences in assumptions regarding imports and exports from Continental Europe.

2.4.3 Dealing with the balancing challenge

Numerous options are available to help deal with the challenge of balancing supply and demand in a low-carbon electricity system. Overall, these options are termed 'flexible balancing technologies', a broad group which comprises flexible generation, storage, interconnection, and Demand-Side Response (DSR) (Strbac *et al* 2012a).

2.4.3.1 Flexible generation

Flexible generation can be provided using any fuel which can be switched on and off relatively quickly and cheaply. At present, the flexible generation in the UK is mostly provided by gas-fired CCGT and OCGT plants, along with some old oil-fired plants. Because of the challenges of intermittent power generation the government suggests that the UK could see the need for between 26 and 37GW of new gas capacity by 2030 (DECC 2012c). However, CCGT plants produce between 380gCO_2/kWh and 450gCO_2/kWh (ECCC 2010), whereas the UK Committee on Climate Change (2013) recommend that the average emissions intensity of electricity generation needs to decrease to 50gCO_2/kWh. It is therefore clear that the gas-fired proportion of the electricity mix will either need to be scaled back significantly, or CCS will be required in the near future. However, CCS is still not operational in the UK, and still does not offer a zero-carbon source of electricity (Froggatt 2013; IPCC 2005). Instead of relying overly on gas, biomass could represent an additional or alternative option for flexible and reliable generation; however, there are numerous issues and questions surrounding the sustainability of biomass production, especially on the sort of scale that would be required to meet a significant proportion of UK energy needs.

2.4.3.2 Storage and Interconnection

Therefore, other options may need to be considered. Electricity storage would assist in ensuring that power can be accessed when required to deal with system peaks. The UK already has four pumped storage facilities in operation for the storage of electricity; currently, these can only generate at full capacity for short periods of time, but in a context of increased renewable penetration they may need to move towards longer running cycles in the future (SSE 2013). Furthermore, newer forms of electricity storage (such as batteries) can assist significantly in integrating intermittent RES and improving system adequacy;

however, although the cost of these technologies has decreased significantly in recent years they are still relatively expensive (Fuchs *et al* 2012).

Interconnection with Continental Europe and Ireland could also provide a useful means of balancing the electricity system. The UK has three operational interconnectors, with France, the Netherlands and Ireland, with a combined capacity of 3500 Megawatts (MW). Further interconnection is planned or under construction with France (2000MW) and Norway (1400MW), and National Grid is also consulting on plans to connect the UK to Denmark and Iceland. The UK's interconnectors earn their revenue by auctioning electricity capacity, based on price differences at each end of the interconnector; thus when additional supply is needed in the UK, the price should be higher, meaning that electricity will flow from one or more of the other markets to make up the supply shortfall (National Grid 2013a). However, interconnectors have high capital costs, and there is often high uncertainty over whether the benefits of a proposed interconnector will outweigh its initial costs (Turvey 2006). Moreover, the scale of potential interconnection in the future is highly sensitive to assumptions regarding fundamental supply-demand conditions in neighbouring economies (Strbac *et al* 2012a).

2.4.3.3 Demand-Side Response

Thus far, various mechanisms for providing flexible supply have been discussed. But one of the most potentially powerful balancing mechanisms exists on the demand side, in the form of flexible demand and load shifting, otherwise known as Demand Side Response (DSR). Managing demand could reduce peak load and thus reduce the requirement for backup generation (Lockwood 2014; Strbac *et al* 2012a). This can be done by giving consumers the ability to shift their demand away from times when national demand is high. Smart Meters, which communicate consumers' meter readings directly to the supplier, are due for mass roll-out in the UK from now until 2020 (DECC 2012d; HM Government 2011). In the future, automated systems connected to a 'Smart Grid' could mean that devices such as washing machines can automatically shift their use to times of low demand; this tool could theoretically become even more powerful with electrification of heating and transport, for instance by allowing electric vehicles to charge at times of low demand (Greenpeace 2010b). Various studies have suggested that DSR could significantly reduce system peaks, in turn reducing the costs of managing surplus supply and reducing pressure on the networks (Pudjianto *et al* 2013; Roscoe and Ault 2010; Strbac *et al* 2012a). However, the implementation of DSR for residential and public sectors will rely on either widespread active consumer participation for manual shifting, or automated shifting using technology which is not yet commercially available (such as Smart appliances) and a willingness from consumers to allow computerised control of their home devices. Therefore the use of DSR at scale could open up a raft of ethical and practical concerns (Hoggett *et al* 2013; Owen *et al* 2013; Richards and Fell 2013; Stop Smart Meters 2015).

Overall, changes on the demand-side could provide a powerful tool, but cannot provide a panacea. As pointed out in the diversity literature, no single measure is likely to prove sufficient to tackle the trilemma; a portfolio approach, which makes use of a broad range of supply-side and demand-side measures, will be required (Awerbuch 2004; DECC 2012e; Francés *et al* 2013; Kennedy 2013). For this reason, it is important to look at electricity security from a whole-systems perspective; whilst individual measures and technologies on both the supply and demand side are interesting and important, the full security picture only emerges when a holistic approach is taken.

2.5 Summing up chapter 2

This chapter has introduced the existing literature on energy security, outlining the academic context in which this thesis will be situated. Existing conceptualisations of energy security were introduced, along with a look at some of the broader notions which have emerged more recently to include environmental and societal concerns. This chapter has argued that despite normative and legal imperatives to reduce carbon emissions, there has thus far been a lack of empirical effort to assess the security of a future national electricity system in a low-carbon context. There are numerous synergies and trade-offs which could emerge as policy-makers attempt to balance various objectives of energy security; some level of compromise between objectives may be unavoidable, and therefore there is a real need to understand exactly where these compromises may lie. In order to examine these synergies and trade-offs, this thesis builds upon existing assessment frameworks from the energy security literature to propose and apply a specific analytical framework for assessing the security of future electricity systems which is designed to incorporate the broader notions of energy security suggested by some of the literature.

This chapter has also provided an introduction to some of the theoretical concepts which will be drawn upon throughout this thesis. Different conceptualisations of ‘security’ and ‘risk’ from the existing literature were discussed, and it was found that many aspects of risk cannot easily be measured or quantified, and that experts’ claims to knowledge tend to be subjective and contingent. Therefore the chapter introduced a theory which suggests that there are four dimensions of risk, depending on the level of knowledge of probability or impacts; the majority of risk assessments tend to focus on areas where this knowledge is less problematic. The chapter also introduced the ‘plural conditionality’ approach which suggests that instead of continually attempting to reduce or to aggregate divergent views, it would be far better to accept at least some level of plurality: there may be several different answers to a problem, all of which may be ‘approximately right’. This context therefore suggests that an assessment of security should acknowledge the multiple issues surrounding the quantification of risk and vulnerability, and should attempt to take into account the realities of multiple competing and disparate preferences and assumptions.

As a means of bounding the area of study, and as outlined in chapter 1, this thesis will focus on the security of the UK electricity system in the context of the UK’s carbon reduction targets. This chapter has provided some essential background information for understanding the challenges of electricity security in the UK. This chapter has found that a portfolio of both supply-side and demand-side measures will be necessary for the development of a secure, low-carbon electricity system; this means developing a holistic approach to a security assessment which can be used to analyse the whole electricity system, rather than just individual component parts. The following chapter proposes an analytical framework for such a holistic approach to assessing security in a low-carbon context.

3 Analytical Framework

This chapter builds on the literature introduced in the previous chapter to propose an analytical framework for the assessment of electricity security which explicitly addresses issues of risk, uncertainty and subjectivity. Section 3.1 firstly explores issues surrounding the accurate communication of complex data, and introduces and explains the 'dashboard' indicator approach used in this thesis. Section 3.2 then conceptualises risks to energy systems in terms of short-term 'shocks' and long-term 'stresses', and uses these foundations to propose an analytical framework comprising four key dimensions of energy security. Finally, section 3.3 introduces the literature on futures studies, and sets out the basis for the choice of low-carbon transitions pathways which will be used for applying the analytical framework.

3.1 The dashboard approach

As shown in the preceding chapter, any assessment of energy security or electricity security will be based upon numerous assumptions and subjectivities. Stirling (2010) argues that too often, security assessments assume that knowledge about probabilities and impacts are unproblematic. Whilst accepting this line of argument, it is nonetheless important to consider that such conventional risk-based assessments still have some validity, and when used correctly they can yield illuminating information about some of the more quantifiable aspects of energy security. The challenge, then, is to move towards a broader assessment which can incorporate more quarters of the Uncertainty Matrix and thus cover a broader range of possible methods.

As pointed out by Jewell *et al* (2014: 755), it is necessary to use multiple indicators in order to portray an "integrated picture of energy security". However, they also point out that too much data can cause confusion, which could be problematic when analysing or communicating results and could thus affect the policy impact of an assessment. Cherp and Jewell (2013) explore three strategies which are often used in the energy security literature for tackling this issue: interpreting individual indicators; aggregating indicators together into indices using composite metrics; and, presenting indicators either individually or jointly in a manner which facilitates the assessment.

The first option (interpreting individual indictors) can be useful for security assessments of discreet issues, for example ‘customer minutes lost’. But it is less useful for addressing a broader range of risks and vulnerabilities in an integrated way; instead, it is preferable to offer a range of indicators.

The second option (aggregation of indicators) requires more careful consideration. Cherp and Jewell (2013) point out in their paper that even individual indicators often require some level of aggregation. Diversity metrics are a good example of this – for instance, they require decisions over how best to group different fuels, which impacts the results (see indicator 2a, sections 4.4.1.2 and B.2.1). However, aggregated indices go one step further and combine information from multiple diverse security issues into a single number, often using complex mathematics. This can greatly assist in communicating results, especially when seeking to devise a numerical index for comparisons across diverse contexts; however, the complex manipulations of indicators required for aggregation always involves a lot of assumptions, and leads to a risk that they might conceal, rather than highlight, important information (Cherp and Jewell 2013; Jewell *et al* 2014). Moreover, aggregated indices and rankings are found to frequently give conflicting results (Jonsson *et al* 2013; Narula and Reddy 2015). Jonsson *et al* (2013) argue that the energy security literature often takes an approach in which the impacts of competing preferences and biases are ignored in favour of definitive indices which are then aggregated and compared across diverse spatial contexts; as was discussed in section 2.2, this approach makes it challenging to incorporate the inherently plural and conditional nature of knowledge claims, especially regarding a topic as ‘slippery’ as energy security.

As can be seen, a careful balance must be struck between over-simplification of a complex issue, and problematic complexity in analysing and communicating outcomes. Hence the potential usefulness of the third option: presenting indicators either individually or jointly in a manner which facilitates the assessment. As one possible means of navigating this balance, Mitchell and Watson (2013b) propose that a ‘dashboard’ of indicators is used: by this, they mean a type of indicator approach involving a manageable number of indicators which are not weighted or consolidated into composite indices. If one area of the dashboard flags up potential problems (i.e. ‘flashes red’), more information can be gathered where necessary and action can be taken. The ‘dashboard’ can thereby provide an overview of a range of different measures of security, which can be especially helpful to policy-makers (Mitchell and Watson 2013b). Importantly, this approach also removes the need for aggregation of diverse indicators, and enables the identification of important trade-offs between different indicators and thus different objectives for energy security; as noted in section 2.3.3, it is not possible to completely avoid trade-offs and therefore it is vital to attempt to identify them (Sovacool and Saunders 2014). It is important to strike a balance between complexity and reductionism (Jewell *et al* 2014; Mitchell and Watson 2013b); for this reason, the number of indicators should be carefully managed to ensure that a broad range of issues are covered without becoming unmanageable.

As well as considering the issues above, taking such a holistic approach to the development of an energy security assessment also necessitates recognition of the importance of timescales. The following section looks in more detail at timescales, and conceptualises risks to the electricity system in terms of short-term ‘shocks’ and longer-term ‘stresses’. These ideas are then combined with ideas from the literature outlined in this chapter and in chapter 2, in order to propose an analytical framework for the assessment of UK electricity security in a low-carbon context.

3.2 Shocks and Stresses

It should be evident from Chapters 1 and 2 that one of the important aspects to bear in mind when considering energy and electricity security is that much depends on the timescale of reference (Boston 2013; Mitchell and Watson 2013a; REKK 2009; Sovacool and Saunders 2014). In fact, there is a marked divide in the literature between perspectives which focus on the long-term, and those which focus on the short-term. On the one hand, perspectives on *energy* security often take a very large-scale, long-term view, focusing on issues such as geopolitics, resource depletion and climate change (e.g. Bielecki 2002; Bordhoff *et al* 2010; IEA 2007; Kruyt *et al* 2009; Martchamadol and Kumar 2013; Müller-Kraenner 2007; Yergin 2006); these perspectives are usually rooted in social science disciplines such as economics and international relations (Cherp and Jewell 2011). Meanwhile on the other hand, perspectives on *electricity* security often take a micro-scale, short-term view, focusing on issues such as system adequacy, capacity margins and hour-by-hour grid balancing (e.g. Chaudry *et al* 2011; Creti and Fabra 2007; Jamasb and Pollitt

2008; Ofgem 2011; Paulus *et al* 2011); these perspectives are usually rooted in physical science disciplines such as engineering (Cherp and Jewell 2011). It is worth emphasising that these perspectives are not mutually exclusive, and that there are sometimes overlaps between the fields of literature in which they are discussed; nevertheless, this broad differentiation provides a useful basis for the exploration of energy security which explicitly takes timescales of reference into account.

3.2.1 Towards an analytical framework for empirical analysis

The differentiation between long and short term approaches 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 (Dawson *et al* 2010; Hoggett *et al* 2011; Hoggett *et al* 2014; Hughes and Ranjan 2013; Jewell *et al* 2014; Kiriyama and Kajikawa 2014; Mitchell and Watson 2013a; Stirling 2014). Conceptualising electricity security in terms of long-term stresses and short-term shocks can be linked to the literature on defining and measuring energy security; linking these strands of literature can then be used as the basis for an analytical framework for a broader empirical assessment of the security of an electricity system. The ability to withstand longer-term stresses can be thought of in terms of electricity *availability*, 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 *reliability*, encompassing aspects such as capacity margins, hour-by-hour system adequacy, and short-term system resilience; this dimension is crucial to electricity systems, 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 *affordability*. The term 'affordability' is more useful than 'price', because it raises the question 'affordable to whom?' (Cherp and Jewell 2014), and thus encompasses issues such as consumer bills and fuel poverty. Finally, the extensive discussion in chapter 2 regarding climate and environmental concerns suggests that a fourth dimension should be added, that of *environmental sustainability*. It is worth noting that the term 'sustainability' can mean many different things and its definition is the subject of debate, therefore it is important to define how it shall be used in this thesis. In terms of long-term energy security, the main risk areas are climate change (as discussed in 2.1.2), and the depletion of necessary resources for power production such as fuel stocks and water (as discussed in 2.3.3).

Thus it is proposed that an analytical framework of four key dimensions – 'availability', 'affordability', 'reliability' and 'environmental sustainability' (GHG emissions and resource depletion) – is most suitable for assessing the security of low-carbon electricity pathways. [10] This analytical framework could be applied to energy security assessment of any industrialised country, provided that the raw data is available. These four dimensions were first proposed by Elkind (2010). The methodology chapter to follow will demonstrate how this analytical framework can be operationalised using a detailed set of indicators, thus building on existing indicator frameworks from the energy security literature (for example, Jewell *et al* 2013; 2014), with particular focus on proposing a set of indicators which is suitable for assessing the long-term security of national electricity scenarios.

The 'risk' framework outlined in section 2.2 suggests that the methods chosen for assessing security should attempt to provide a mix between 'risk', 'ambiguity', 'uncertainty' and 'ignorance' (as illustrated in the 'uncertainty matrix' in figure 2.2).[11] As shown in section 2.2, many indicators of energy security fall into the top left-hand quadrant of this matrix; however, it is also possible to employ qualitative or societal indicators, as well indicators which can hedge against uncertain risks (for instance by maximising diversity or flexibility). It is also important to carry out sensitivity tests where appropriate, again in acknowledgment of the fact that the required information about risks and their impact is sometimes more or less problematic. Further to this, it is important to continually emphasise the fact that preferences and assumptions affect the way in which energy security is assessed and analysed; different actors will have different views on improving security and minimising risk, and it has been argued in the previous chapter that several answers may all be 'approximately right'. Therefore it would be desirable to look at the way energy security is perceived by different actors and to test the impact of different stakeholders' perspectives on preferred options for improving energy security. As stated by Cherp and Jewell (2014: 220), "The point of conceptualizing a difficult political concept is

[10] It should be emphasised that these dimensions sometimes overlap. In particular, the 'availability' and reliability' dimensions are not necessarily mutually exclusive. For instance, some international relations literature is concerned with short term impacts on prices, whereas some engineering literature is concerned with longer term issues of investment in electricity generation capacity.

[11] Note again the complications caused by the term 'risk'. For the purposes of clarity and simplicity, the rest of this thesis will use the term 'risk' in its more generic form, to refer to a 'risk' in the sense of a hazard; in other words, the opposite of 'security'.

not to eliminate different interpretations but rather to enable their meaningful analysis, comparison and dialogue".

3.3 Low-carbon transition pathways

The purpose of this thesis is to assess the security of possible future low-carbon electricity systems; in order to do this, there needs to be an idea of what a low-carbon electricity system in the UK might look like. In recent years, a large number of studies in the energy field and elsewhere have sought to take a 'futures-based' approach, outlining what the future might look like (Dixon 2011). These analyses can take many forms: McDowall and Eames (2006), in a study on methods used in the field of hydrogen, identified six overlapping types of futures study. These types are shown in table 3.1, which has been adapted to make it relevant to low-carbon energy studies. The distinction between a 'normative' and 'descriptive' method is important. 'Descriptive' methods take today's system as their starting point, and seek to elaborate how the system might evolve in a variety of plausible directions; for example, studies which offer a range of scenarios, some of which may not meet climate change mitigation targets. 'Normative' approaches on the other hand focus on reaching a desired goal or 'vision', and seek to elaborate how best to get there; for example, studies which focus on meeting a specific carbon reduction target. It should be emphasised however that the elements of these six types of futures study are overlapping and not always clear, and that the language is often used interchangeably; for instance, the EU Roadmap 2050 project (European Climate Foundation 2010) states that its aim is to "provide analysis of *pathways* to achieve a low-carbon economy in Europe" (European Climate Foundation 2015; emphasis added). The overlapping nature means that it is not always possible to precisely label a particular approach or study, and some studies use a combination of several approaches.

For the purposes of this thesis, it is important to identify which of these approaches to use, in order to inform the choice of transitions studies which will form the basis for the security assessment. The purpose of the thesis is to assess the security of a *low-carbon* electricity system; therefore it makes sense to choose futures studies which achieve a low-carbon target. For the purpose of this thesis, 'low-carbon' is defined as meeting (or at least attempting to meet) the UK's legally-binding target of an 80% emissions reduction by 2050. For this reason, normative approaches would be more suitable, because of the existence of a set end-goal, and the ‘pathways’ approach is overall probably the most suitable approach for this thesis. Several normative studies take a ‘roadmap’ approach, in which a single ‘ideal’ route for decarbonisation is mapped out in detail; these are less suitable for the purposes of this thesis, because one of the main objectives of this thesis is to identify synergies and trade-offs, therefore it is more useful to make comparisons between a range of possible options. Using a set of different pathways from the same source also allows interesting comparisons to be made, whilst avoiding inaccuracies arising from using raw data from more than one source. The methodology for choosing a set of pathways from the numerous possible options is outlined in the next chapter, in section 4.2.

Table 3-1: Types of futures study. Adapted from McDowall and Eames (2006)

Character	Type	Description	Example
Descriptive	Forecast	Uses formal quantitative extrapolation and modelling to predict likely futures from current trends	IEA World Energy Outlook (IEA 2014)
	Exploratory scenario	Explores possible futures, emphasising drivers; does not specify a predetermined desirable end state	Mountains and Oceans (Shell International 2013)
	Technical scenario	Explores possible future technological systems, emphasising the technical feasibility and implications of different options, rather than exploring how different futures might unfold	‘Sustainability Without the Hot Air’ (MacKay 2009)
Normative	Vision	Describes a desirable and (more or less) plausible future, emphasising the benefits of a low-carbon transition rather than the pathways through which a low-carbon transition might be achieved	World Resources Institute (WRI) Roadmap for a Secure, Low-Carbon Economy (Ladislaw *et al* 2009)
	Pathway	Starts with a predetermined end point (i.e. a desirable and plausible future), and investigates possible pathways to that point	DECC 2050 Pathways Analysis (DECC 2010a)
	Roadmap	Describes a sequence of measures designed to bring about a desirable future	WRI Roadmap for a Secure, Low-Carbon Economy (Ladislaw *et al* 2009)

Using ‘pathways’ rather than an alternative futures approach can help to address some of the drawbacks inherent in other approaches. For instance, Hughes *et al* (2009) suggest that ‘scenarios’ are problematic because they often fail to give adequate recognition of the way in which technology interacts with social, cultural and political systems, and fail to identify actors and key social networks which engender change. ‘Pathways’ on the other hand seek to focus on the co-evolution of actors and technologies in transition processes (Hargreaves and Burgess 2009; Hughes *et al* 2009). Building on transitions literature, pathways recognise the fact that technologies exist as part of a wider socio-technical network of interlinked and interdependent actors, markets, products, institutions and behaviours, and that transitions entail not only a new technology, but also changes in this wider socio-technical network (Berkhout 2002; Bijker 1995; Geels 2002; 2004; Hughes 1987).

It is recognised that it is not possible to predict the future, and as such, transition pathway studies do not aim to accurately model the future system. However, despite the inevitability of such drawbacks, achieving a low-carbon electricity system necessitates a clear direction and early action to move in that direction, because decisions made today will impact upon the electricity system for a long time to come (DECC 2010a). Immediate choices must be made on the basis of a long-term understanding of the development of the system and the challenges and trade-offs involved. Thus transition pathway studies aim to contribute to an ongoing discussion between policy-makers, researchers and stakeholders, in order to better inform the debate about the ways in which the energy system might evolve as we move towards decarbonisation. As such, the use of transition pathways in this thesis does not aim to accurately predict the systems of the future. Rather, the pathways can be used as the basis for a discussion and an illustration of some of the key issues faced in transitioning towards a low-carbon electricity system.

3.4 Summing up chapter 3

This chapter has used the concepts from the existing literature which were outlined in chapter 2 as the basis for an analytical framework for the assessment of the security of low-carbon electricity systems. It was argued that the use of a dashboard approach can facilitate the use of multiple diverse indicators (both quantitative and qualitative) in a transparent manner without the need for aggregation. This approach also allows the reader to focus in on certain indicators and potentially to apply them to other contexts. It was noted that risks to energy systems can be conceptualised in terms of short-term ‘shocks’ and longer-term ‘stresses’; this differentiation was used to develop a four-way framework for a security assessment which explicitly addresses the issues of the energy trilemma and the importance of timescales of reference – electricity should be ‘available’, ‘reliable’, ‘affordable’ and ‘environmentally sustainable’ (with ‘sustainability’ referring to GHG emissions and resource depletion). Finally, this chapter has noted that assessing security in a low-carbon context necessitates an idea of what a low-carbon electricity system might look like; as such, the chapter argued that using ‘pathways’ (as opposed to forecasts, scenarios, or roadmaps) would be most suitable for the purposes of this thesis.

Having set out the theoretical basis for assessing the security of a low-carbon electricity system, the following chapter sets out the methodological approach and the detailed research methods which will be used for this thesis. The next chapter uses the four-way analytical framework outlined here to propose a set of indicators from the existing literature, and sets out the methods used for the systematic application of these indicators to a set of existing low-carbon transition pathways for the UK electricity system. The next chapter also sets out the methodology for engaging with energy stakeholders, in order to explore the diversity of perspectives amongst stakeholders and to test the impact of these perspectives on the results of the security assessment.

4 Methodology

This chapter sets out the methodology for the thesis. Section 4.1 reiterates the research questions and gives an overview of the general methodological approach. Section 4.2 then sets out the choice of existing transitions pathways which will be used as the basis for the security assessment. Section 4.3 explains the methodology for answering the first research question: the development of a set of indicators for the assessment of the security of low-carbon transition pathways. Section 4.4 describes the detailed methods used for calculating or assessing each individual indicator. Section 4.5 then moves on to describe the methodology for answering the second and third research questions: the stakeholder interview method is explained, and the methods used for the analysis of this data. Finally, the last part of section 4.5 sets out the methodology for answering the final research question, by explaining the way in which the results from the stakeholder interviews are applied to the results from the security assessment.

Additionally to this chapter, further details on the methods used are available in the appendices at the end of this thesis. Appendix A shows the initial 'long list' of potential indicators for assessing the security of a low-carbon transition pathway for the electricity system (see section 4.3, later on in this chapter). Appendices B to E show the detailed methods for each indicator in turn, including data sources, main assumptions, calculations where applicable, and details of sensitivity tests which were carried out for some of the indicators. Appendix B gives the methods for the indicators in the 'availability' dimension, appendix C for 'affordability', appendix D for 'environmental sustainability', and appendix E for 'reliability'. Appendix F shows the estimated unit costs which were used to calculate offshore connection costs. Appendix G is a copy of the briefing note which was sent out to interviewees (see section 4.5). Finally, appendix H gives more detail of the results from the application of stakeholder responses to the security assessment results (see sections 4.5.4 and 7.2).

4.1 Research questions and methodology overview

4.1.1 Reiteration of research questions

As explained in section 1.3.1, the overarching aim of this thesis is to assess the future security of the UK electricity system in a low-carbon context, in order to identify the main risks, trade-offs and synergies which may emerge between different objectives in a transition to a low-carbon electricity system. As part of this, this thesis also aims to actively incorporate multiple stakeholders' perspectives on energy security into an indicator assessment, in order to explore the impacts that different perspectives can have on preferred options for improving energy security. In order to meet these objectives, the research questions that this thesis will answer are as follows:

i. "What indicators are appropriate for assessing the security of low-carbon transition pathways in the UK, and what are the results of such an assessment using a set of existing pathways?"

ii. "What are the reactions of energy stakeholders to the proposed set of indicators, and what does this tell us about the diversity of perspectives in the UK energy community?"

iii. "What impact do the stakeholders' perspectives have on the results of the security assessment and on their preferred options for improving energy security?"

4.1.2 Methodology overview

In order to answer the research questions, this thesis undertakes a whole-systems analysis of the future security of the UK electricity system, under a selection of low-carbon transition pathways. The aim is to develop a set of indicators for assessing the security of possible electricity futures, with a selection of indicators which can be applied to low-carbon transition pathways. A variety of indicators is used in order to capture the multidimensional nature of energy security and to reflect the fact that an assessment of electricity security should where possible be grounded in multiple overlapping disciplines. An indicator approach, especially the 'dashboard' indicator approach recommended by Mitchell and Watson (2013b), allows for the empirical assessment of a broad suite of energy security aspects, using a mix of quantitative and qualitative indicators according to their suitability for different aspects.

The indicator set is developed to provide ‘indicators derived for a set purpose’ (Axon *et al* 2013), with indicators chosen on the basis of their suitability for application to low-carbon pathways and for analysing electricity security into the future. Using this indicator set, the thesis carries out an analysis of the UK electricity system in the context of a transition to decarbonisation. A set of 22 quantitative and qualitative security indicators is applied to three existing low-carbon transition pathways for the UK electricity system for the years 2010, 2030 and 2050.

The results from the security assessment are then used as the basis for an in-depth discussion via interviews with stakeholders on low-carbon electricity security. Stakeholders are selected on the basis of their knowledge of energy issues and their involvement with organisations which may have some influence on UK policy processes, either through direct involvement or through participation in research and consultations. The aim of these interviews is to find out more about the diversity of views on electricity security that exists in the UK energy community, in order to create a representation of how different stakeholders think about electricity security. This information is then used to understand how different perspectives might impact the results of the empirical assessment, and whether certain perspectives lead to certain pathways or technology options being preferred.

4.2 Choosing transition pathways

4.2.1 Methodology for choosing transition pathways

The process of developing a robust futures study, especially in the context of a complex, large-scale and interlinked network such as the UK electricity system, is extremely time consuming; therefore, this thesis utilises an existing set of pathways from the literature instead of opting to develop an entirely new set. Section 3.3 outlined the rationale for basing the security assessment of a low-carbon electricity system on *pathways*, rather than forecasts, scenarios, visions or roadmaps. This acts as a useful means of limiting the enormous number of existing futures studies. For the purposes of this thesis, the pathways studies to be used should have four main characteristics:

- They should be to some extent publicly available (i.e. not confidential)

- They should continue at least up to 2050 (in accordance with the generally-accepted timeframe for significant decarbonisation of the energy sector)
- They should aim for an 80% reduction in UK GHG emissions by 2050 (in accordance with the UK's legally-binding emissions reduction targets)
- There should be a set containing more than one indicative future system, so that a comparison can be made between two or more potential pathways and between the current and potential future systems.

Initially, a set of 31 existing futures studies was identified from a review of the existing literature. These were then appraised on the basis of the above criteria. This first selection process eliminated all but six of these existing futures studies. These six were then assessed on the basis of a further three criteria, which were deemed highly desirable (if not absolutely crucial) for the purposes of this thesis:

- Do the pathways show a temporal progression (i.e. do they include several points in time between the present day and 2050)?
- Do the pathways give a range of technological choices (i.e. not focusing exclusively on one technological option such as CCS, wind etc.)?
- Do the pathways include both the supply-side and the demand-side?

This process of elimination left four potential pathways as viable options. These were: the DECC 2050 pathways calculator (DECC 2010a; 2010b); the Transition Pathways to a Low-Carbon Economy (Barton *et al* 2015; Foxon 2013); the UK Energy Research Centre (UKERC) 'Pathways to a low-carbon economy' (Anandarajah *et al* 2008; Strachan *et al* 2008), and the UK Committee on Climate Change 'Building a low-carbon economy' report (UK Committee on Climate Change 2008).

The following stage of the selection process involved looking in more detail at these four remaining possibilities. These four sets of pathways all have relative merits, and would all have been suitable for the purposes of this thesis, but it was decided that the Transition Pathways to a Low-Carbon Economy would potentially yield more interesting results, for the reasons given in the following section. It should be noted that the set of security indicators developed in this thesis is designed to be applicable in a range of situations, and in theory could be used for any set of pathways, provided that the underlying data is available; therefore it would be a very welcome addition to this research if the analysis were carried out for a different set of pathways.

4.2.2 Transition Pathways to a Low-carbon Economy

The Transition Pathways to a Low-Carbon Economy consortium (www.lowcarbonpathways.org) is a network of researchers from the Universities of Bath, Cardiff, Imperial, Loughborough, East Anglia, Leeds, Strathclyde, Surrey and University College London. The consortium aimed to develop their pathways by drawing upon theoretical work from the field of innovation studies, specifically historical transitions in socio-technical networks (see Foxon 2013). This set of pathways sought to move away from a purely technocratic view of the development of the electricity system, and to look instead at the socio-technical, political and economic drivers for a transition to take place, with theoretical foundations which build on the transitions theories of Berkhout (2002), Geels (2002; 2004) and Hughes (1987). In this way, the Transition Pathways study explicitly addresses one of the key drawbacks of scenario approaches which is identified by Hughes *et al* (2009) – the fact that often, there is little recognition of the way in which technology interacts with social, cultural and political systems, and that there is often a failure to identify actors and key social networks which engender change. The Transition Pathways project recognises that the process of making technological choices and actualising a system transition is messy and political, and inherently bound up in the preferences and interests of the actors involved; they therefore fit very well with the overall approach of this thesis, which stresses the importance of actors and policies as well as technologies and markets.

The Transition Pathways 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 pathways taken. The 'governance logic' "represents the actors' assumptions underlying the governance of the energy system, including the relative roles of regulation and market frameworks, and the relative importance attached to the objectives of carbon reduction, energy security and affordability in the energy 'trilemma'" (Foxon and Pearson 2013: 8). From this, the consortium developed three pathways, each of which corresponds to a different dominant governance logic:[12]

- **Market Rules:** this pathway envisages continued dominance of a market-led system in the UK. Landscape pressures on incumbent regime actors lead to market actors making carbon reductions. The main decisions are made by market actors operating

[12] It should be noted that the overriding governance logic in each pathway is not absolute – each pathway involves elements of several different governance logics, but they differ in terms of which one is most prevalent.

freely within a high-level policy framework; the system is dominated by large-scale supply-side technologies which are deemed the most economical to build.

- **Central Coordination:** this pathway envisages that landscape pressures lead to a much stronger role for central government to deliver carbon reductions. The government exerts direct control over the energy system and key actors, working closely with large utilities; the main decisions are made by national government bodies. The system is dominated by large-scale centralised supply technologies and centrally-supported demand reduction measures.
- **Thousand Flowers:** this pathway envisages a growing influence of civil society, which leads to a bottom-up transition. Landscape pressures lead to small-scale low-carbon technologies emerging in niches. The main decisions are made by civil society, community groups and citizens. Widespread engagement with energy issues leads to behaviour change. The system is dominated by small-scale, distributed supply technologies and demand reduction measures.

Figures 4.1 to 4.3 give a technological overview of each pathway, showing the electricity generation mix according to total output, and thus also the level of electricity demand. For more detailed technical and socio-political information on the pathways, see Barton *et al* (2015) and Foxon (2013).

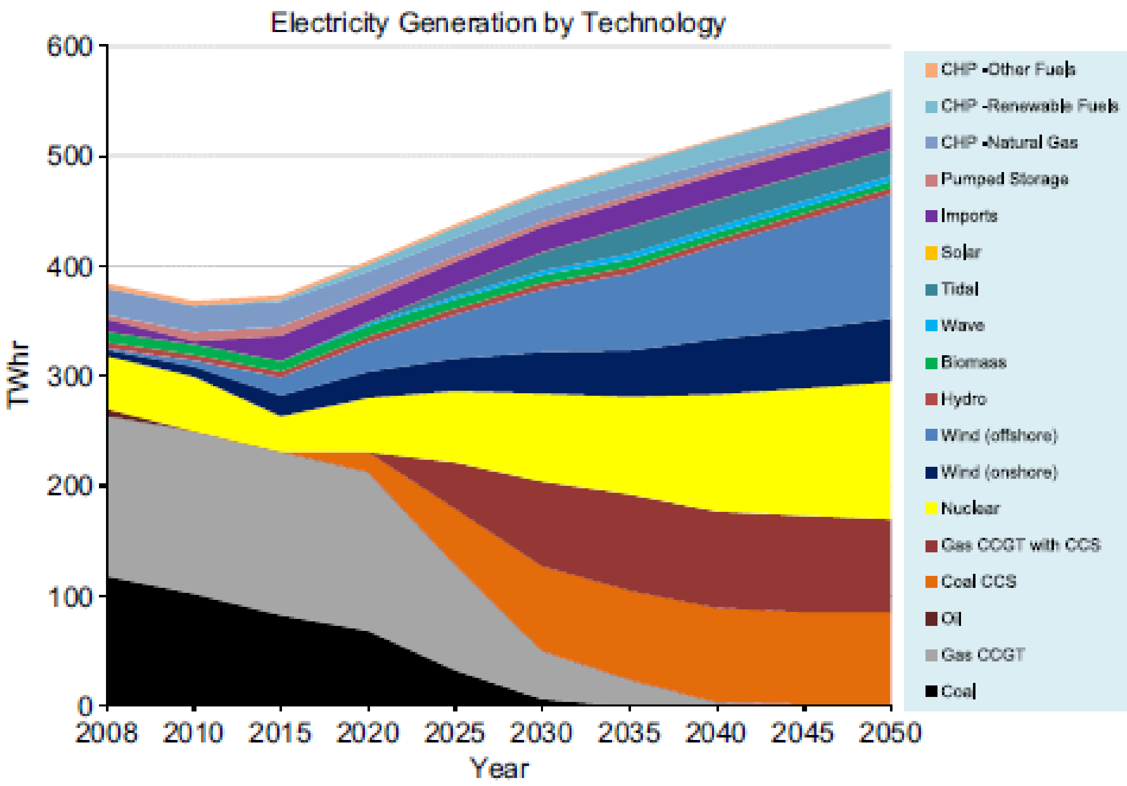


Figure 4-1: Generation mix in the Market Rules pathway in TWh/year, 2008 to 2050

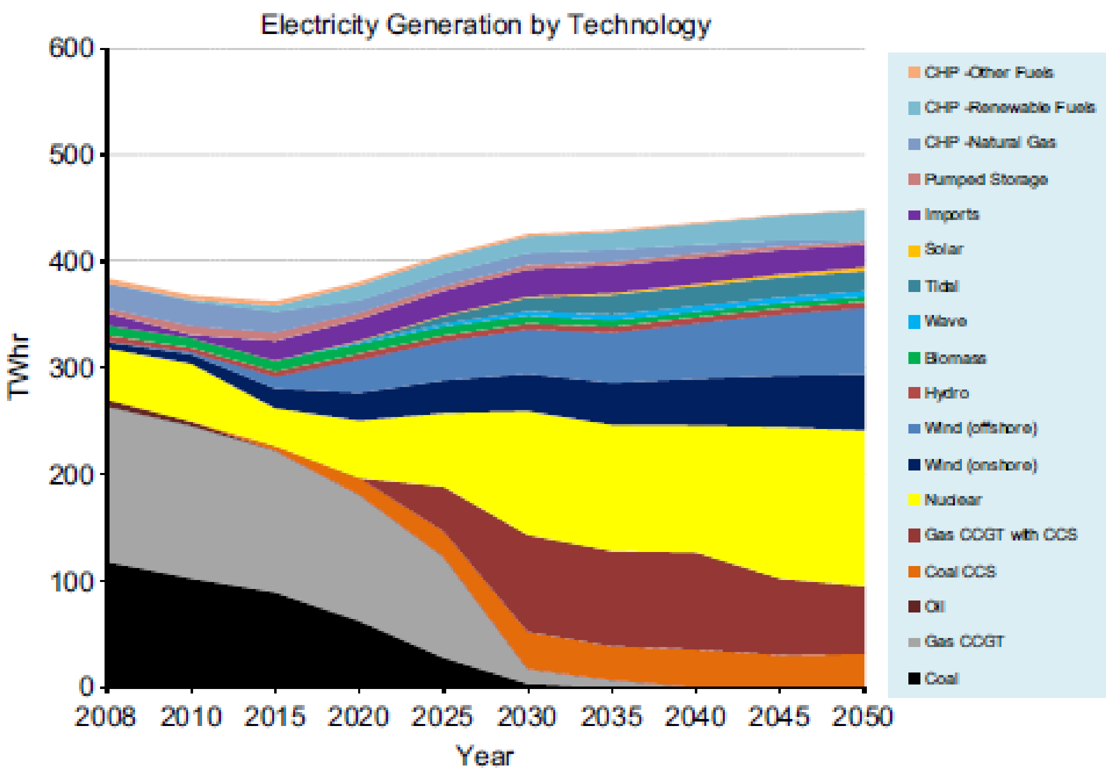


Figure 4-2: Generation mix in Central Coordination pathway in TWh/year, 2008 to 2050

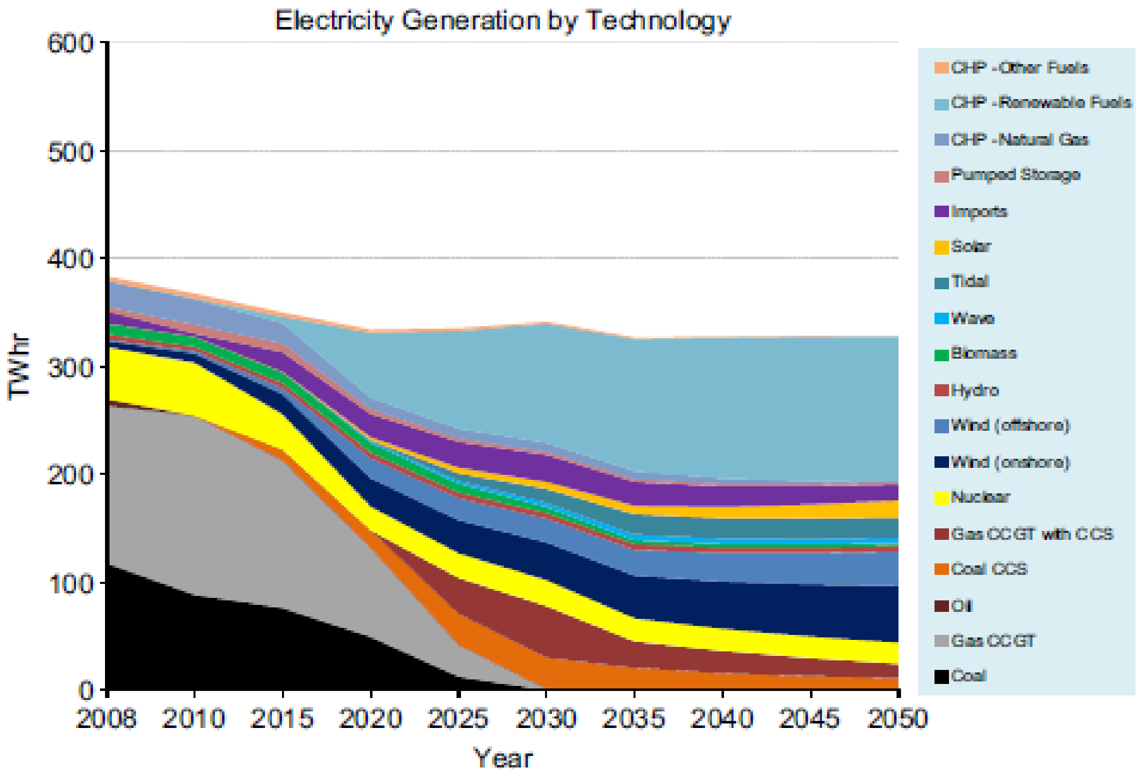


Figure 4-3: Generation mix in the Thousand Flowers pathway in TWh/year, 2008 to 2050

It should be noted that none of the three pathways shown above represents a 'Business-As-Usual' (BAU) case, i.e. what the future electricity system might look like in the absence of marked efforts to reduce GHG emissions by 80% by 2050. A BAU pathway was not available from the pathways modellers, and therefore was unavailable for the security assessment in this thesis; this means that it will not be possible to draw conclusions based on comparing the outcome within the pathway to what might have happened in the absence of policies to meet statutory carbon reduction goals. However, the approach taken in this thesis *does* allow for comparison between the 2010 baseline and the future systems envisaged in the Transition Pathways, thus facilitating comparison between the security of possible low-carbon electricity systems and the existing higher-carbon system.

Furthermore, it is important to note that the Transition Pathways model uses 2008 as the baseline (as shown in the graphs above); however, the security analysis in this thesis is carried out for 2010, 2030 and 2050. There will therefore be some slight differences between the 2010 figures in the results, and the actual electricity system situation in 2010.

The installed gas capacity was around 1% lower in 2010 than in the figures for the three pathways, and nuclear capacity was also 1% lower, whilst wind was 1.5% lower, hydro 1% higher and biomass 1% higher. These differences are small enough to make little difference to the results of the analysis.

4.3 Development of the indicator set

Having set out the transition pathways which will be used for the security assessment, this section now explains the methodology for designing a set of indicators which can be used to assess the security of these (and potentially other) pathways.

4.3.1 Indicator set overview and aims

As shown in Chapter 3, conceptualising electricity security in terms of long-term stresses and short-term shocks can be used as the basis for an analytical framework for assessing the security of low-carbon transition pathways. This framework, which builds upon assessment frameworks from the existing energy security literature (e.g. Elkind 2010; Jewell *et al* 2014), comprises four dimensions which posit that in order to be secure, electricity should be *available, reliable, affordable* and *environmentally sustainable.*[13] These four dimensions can then be operationalised via the use of a more detailed set of indicators, outlined in section 4.4. The results of the assessment are not designed as an attempt to predict the future; rather, the results are intended as an illustration of the synergies and trade-offs which could emerge. The set of indicators avoids using or creating complex composite indicators (as recommended in section 3.1), and uses both quantitative and qualitative methods. Wherever possible, quantitative methods are used, because when used correctly such methods can be succinct, clear and empirically rigorous. However, there are several aspects of energy security which simply cannot be quantified in any meaningful manner; for instance, those relating to politics or society. The majority of indicator approaches simply ignore these aspects (Gracceva and Zeniewski 2014); however, it is the contention of this thesis that they have a valuable role to play, and therefore some more qualitative or descriptive indicators will be included alongside the quantitative data. This thesis therefore builds on the work of Jonsson *et al* (2015), who introduce a more

[13] As explained in section 3.2.1, 'sustainability' in this thesis is used to refer to GHG emissions and resource depletion. For brevity, 'sustainability' will be used henceforth.

comprehensive suite of energy security aspects and make some initial observations regarding their implications in a low-carbon context. Their paper argues that there is a need for a broader framing of energy security which includes qualitative aspects such as social and political dynamics; this thesis attempts to build on this observation by providing a means of assessing such broader aspects systematically and empirically.

Drawing on the basis laid out in Chapter 3, the indicator set developed for the purpose of this thesis has the following aims:

- To offer a range of indicators which captures the multidimensional nature of energy security (the 'dashboard' approach)
- To focus on the transition to a low-carbon electricity system, and to devise indicators fit for this purpose
- To be capable of assessing the security of future electricity system pathways, in order to show the possible security choices which may be made in the future
- To use both quantitative and qualitative indicators
- To illustrate some of the key synergies and trade-offs which may emerge between different aspects of the energy policy trilemma
- To capture both short-term shocks and long-term stresses.

The indicator set is primarily designed to be applicable to the electricity system in the UK, although many of the indicators would also applicable to other nations and jurisdictions, particularly in Western Europe, provided that the raw data is available for that jurisdiction. Again, herein lies an advantage of using a dashboard approach; it may be that some indicators are of limited utility in other countries, or that data for some is unavailable, and therefore it is useful to be able to choose the indicators best suited for the purpose; the choice of indicators, and their applicability to non-UK jurisdictions, is covered in more detail in section 4.4 and in Appendix A. The exercise of application of the indicator set to other countries is outside the scope of this thesis; however, it is intended that the set can be used in further research to assess the security of other low-carbon electricity systems, particularly in Western Europe. It is worth noting that the relatively high level of integration of the European electricity networks in many ways makes Europe a unique case: the European electricity system involves considerable (and growing) cross-border transmission, and the EU is developing an integrated market for electricity, additionally to all the existing fiscal, political and legislative arrangements within the EU. Therefore it is important to bear in mind that analysis based in Europe may have limited applicability elsewhere in the world, especially for developing country contexts.

4.3.2 Developing a set of indicators

Initially, indicators were identified from the list of 372 security indicators provided in Sovacool and Mukherjee (2011: 5347-5352). This was used to generate a 'long-list' of potential security indicators (shown in Appendix A). This list can then be narrowed down considerably due to data constraints; the challenge of working with low-carbon transition pathways and with projections of a future energy system is that data availability and granularity is usually far more limited than it would be for the assessment of a present-day energy system. Furthermore, the indicators can be narrowed down to exclude those which do not relate to the electricity system, because of the electricity focus of this particular study. The indicators are chosen to reflect as much as possible the advice for choosing indicators given by Jewell *et al* (2014). According to their paper, indicators should meet the following criteria:

- They should be relevant to current / historical energy concerns
- They should be sufficiently generic to apply to future systems which are radically different from those of today
- They should be possible to calculate from the data available
- They should provide information which is additional to that provided by the other indicators
- They should reflect key vulnerabilities of vital energy systems
- They should clarify policy trade-offs.

Figure 4.4 shows the four-dimensional analytical framework with the individual indicators therein. The selection of individual indicators and the methods used to calculate/assess each indicator is explained and justified on a case-by-case basis in section 4.4; see also Appendix A for more details regarding the selection process. In order to further organise the indicators within each dimension (and in order to make the methods and results easier to follow), the 22 indicators have been grouped into 9 sub-dimensions; these are shown in table 4.1. Table 4.1 also gives the relevant literature for each indicator – this refers both to literature in which the indicator is proposed (either as a stand-alone energy security indicator or as part of a set), and to literature which discusses, measures or otherwise operationalises the indicator. Further detail on data sources for each indicator is given in table 4.2 at the very end of section 4.4.

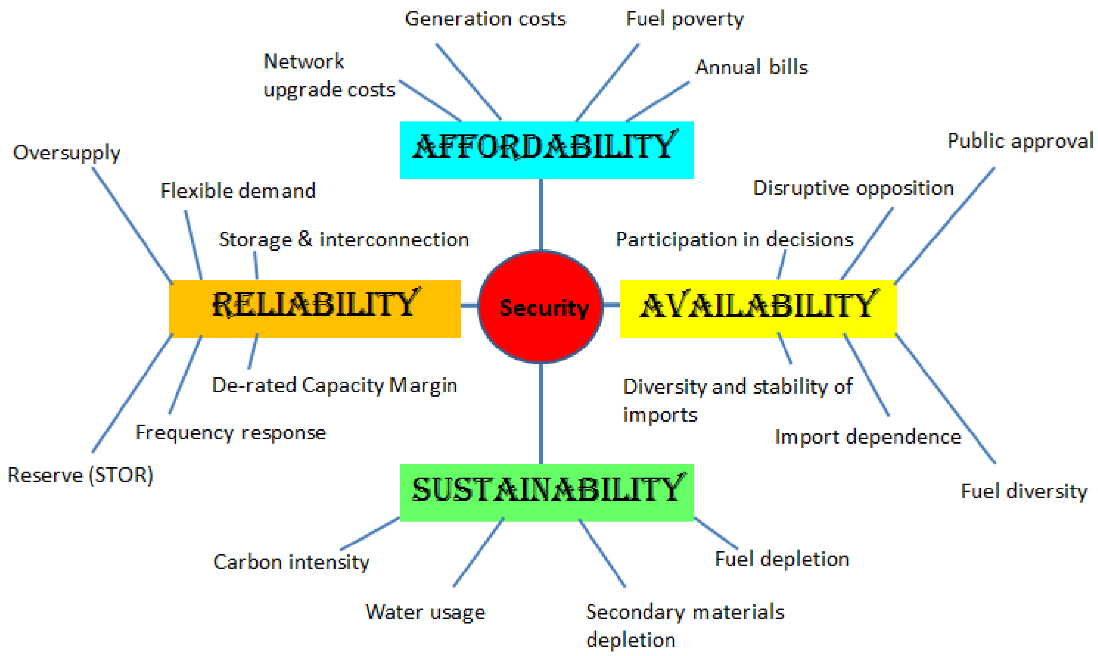


Figure 4-4: Dashboard of indicators for the assessment of a low-carbon electricity system

Table 4-1: Table showing dimensions, sub-dimensions and indicators, including literature for each indicator

	Sub-dimension	Indicator	Literature in which this indicator is proposed or measured
"Availability"	Likelihood of domestic disruption to electricity availability	1a. Public approval ratings	Axon *et al* (2013); Demski *et al* (2013); Falk (2011); Hayashi and Hughes (2013); Whitmarsh *et al* (2011)
		1b. Land requirements	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)
		1c. 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)
	Likelihood of non-domestic disruption to electricity availability	2a. Diversity of fuel types in generation mix	Axon *et al* (2013); DECC (2012a); Grubb *et al* (2006); Jewell *et al* (2014); Lehr (2009); Pfenninger and Keirstead (2015); Stirling (1998)
		2b. 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)
		2c. Diversity and stability of fuel exporting nations	Axon *et al* (2013); DECC (2012a); European Commission (2014); Frondel and Schmidt (2014); IEA (2007); Jewell *et al* (2014); Jonsson *et al* (2015); Kruyt *et al* (2009); Le Coq and Paltseva (2009); Lilliestam and Ellenbeck (2011); Neumann (2007)
"Affordability"	Cost to the system	3a. Generation cost	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)
		3b. Cost of transmission upgrades	Bolton and Hawkes (2013); Boston (2013); ENSG (2012); Jamasb and Pollitt (2008); National Grid (2011; 2013b); Strbac *et al* (2014)
		3c. Cost of distribution upgrades	Bolton and Hawkes (2013); Boston (2013); Greenpeace (2005); Jamasb and Pollitt (2008); Pudjianto *et al* (2013)
	Cost to the consumer	4a. 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)
		4b. Impact on levels of fuel poverty	Axon *et al* (2013); Barton *et al* (2015); Hills (2012); Mitchell and Watson (2013b); Sovacool (2011); Sovacool *et al* (2012); Sovacool and Brown (2010)
"Sust ainabi	GHGs	5a. GHG emissions and intensity	Axon *et al* (2013); Elkind (2010); Gnansounou (2011); Hughes (2012); Kruyt *et al* (2009); McCollum *et al* (2011); Sovacool *et al* (2012); Sovacool and Brown (2010); Sovacool and Mukherjee (2011); Winzer (2011)

	Resources	6a. Primary fuels depletion	Asif and Muneer (2007); Axon *et al* (2013); Capellan-Perez *et al* (2014); Kruyt *et al* (2009); Kuzemko and Bradshaw (2013); Mitchell and Watson (2013b); Nuttall and Manz (2008); POST (2012); Sovacool (2011); Sovacool *et al* (2012); Watson (2010); Winzer (2011)
		6b. Secondary materials depletion	Gholz (2014); Humphries (2013); Krishna-Hensel (2012); Moss *et al* (2011); Speirs *et al* (2014); Stegen (2015); Umbach (2012)
	Water	7a. Water usage for cooling and for biomass feedstock production	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"	System Adequacy	8a. De-rated capacity margins	DECC (2011a; 2012a); Greenleaf *et al* (2009); House of Lords (2015); National Grid (2012); Newbery and Grubb (2014); Ofgem (2011; 2012); RAEng (2013)
		8b. Capacity factors and Oversupply	Barnacle *et al* (2013); Barton *et al* (2013)
		8c. Electricity storage and interconnection	European Council (2011); Grünewald (2012); House of Lords (2015); IMechE (2012); National Grid (2013a); Newbery *et al* (2013); Strbac *et al* (2012a; 2012b); World Energy Council (2008)
	Resilience to sudden and unexpected changes in the supply/demand balance	9a. Frequency response capability	EirGrid/SONI (2011); Kiriyama and Kajikawa (2014); National Audit Office (2014); National Grid (2011); Ruttledge and Flynn (2015); Strbac *et al* (2012a)
		9b. Short-term Operating Reserve (STOR) and black-start capability	EirGrid/SONI (2011); National Audit Office (2014); National Grid (2011); Strbac *et al* (2012a)
		9c. Response and Reserve requirements	EirGrid/SONI (2011); National Audit Office (2014); National Grid (2011); Ruttledge and Flynn (2015)
		9d. Flexible demand	Bolkesyø *et al* (2014); DECC (2012a); Drysdale *et al* (2015); Dudeney *et al* (2014); E3G (2014); ECCC (2011); Mitchell and Watson (2013b); Nistor *et al* (2015); Strbac *et al* (2012a)

4.4 Detailed methods for each indicator

This section gives an overview of the methods employed to assess each indicator, as well as providing a justification of the choice of individual indicators. For each indicator, bullet points show whether the indicator is quantitative, qualitative or mixed, and the units which are used. For each indicator, the extent to which the indicator may be potentially applicable to energy security assessments of other countries and in other contexts is also shown. Table 4.2 at the end of the section gives an at-a-glance overview of the methods used, including the major data sources used and the additional details given in the bullet points for each indicator in this section. Detailed mathematical methods, data sources and assumptions are given in Appendices C to F

4.4.1 Availability

4.4.1.1 Sub-dimension 1: Likelihood of domestic disruption to energy availability

Constraints upon system transitions are often related to socio-political issues, such as the acceptability of various technological options (Parkhill *et al* 2013; Pidgeon and Demski 2012). This sub-dimension therefore takes public levels of acceptance of various forms of energy generation as a proxy for the likelihood of risk of disruption arising domestically in the UK. This sub-dimension of the security assessment views the mitigation of domestic disruption as potentially a three-way strategy – improving overall support, reducing opposition to specific aspects of the energy system or specific new additions, and increasing participation.

Indicator 1a. Public approval ratings

- Quantitative indicator
- Calculates amount of generation mix (in GW and %) which would be ‘approved of’ by the general public
- Potentially applicable to other countries

Public approval ratings are taken from a nationally-representative survey carried out by UKERC, which shows levels of support and of opposition to technologies for power generation (Demski *et al* 2013). The data from this survey is supported by a literature review of academic and grey literature into public opinions of various forms of energy, carried out by Whitmarsh *et al* (2011). The results of the survey are applied to the pathways, to calculate the amount of generation in the pathway (in GW and %) which is likely to be approved of by the general public, and the amount which is likely to be actively opposed. It is worth noting that some technologies are opposed on certain aspects apart from generation; for example, CCGT is generally fairly ambivalent, but extracting the gas by fracking is unpopular. These aspects are covered in the next section, which focuses on direct opposition. The 'public approval ratings' indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK; however, application to other contexts would require additional data because the survey results used here are specific to the UK context.

Indicator 1b. Land requirements (as a proxy for likelihood of disruptive opposition)

- Three distinct metrics (not aggregated)
- Metric 1: Land area required for new and additional generation infrastructure, measured in m^2
- Metric 2: Onshore transmission infrastructure required, using onshore transmission upgrade costs (see indicator 3b) as a proxy, measured in £bn
- Metric 3: Domestic extraction of fuel resources, using data on import proportions as a proxy, measured in TWh/y
- Potentially applicable to other countries

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 project (Batel *et al* 2013; Cherry *et al* 2014; Cohen *et al* 2014; Devine-Wright 2005). Therefore it is necessary to include an indicator which reflects the possibility that risk could occur due to direct opposition to infrastructure. This indicator would be relevant for assessing the energy security of a wide range of pathways, including industrialised countries other than the UK.

Disruptive opposition often occurs due to protests over new infrastructure. People are far more likely to protest against new installations, and communities which live close to older or existing sites are shown to be more supportive than national polls report (Greenberg and Truelove 2011; Pidgeon and Demski 2012). Proximity is important; although people protest against infrastructure for a variety of reasons, one of the most common types of opposition occurs amongst communities who will be directly affected by the infrastructure installation, especially because local communities sometimes experience (or perceive that they are experiencing) disproportionate costs in terms of disruption, inconvenience, aesthetic impacts etc. (Batel et al. 2013; Devine-Wright 2005).

Therefore, the amount of land required for new electricity system infrastructure can be used as a proxy for risk of disruptive opposition to new installations. It should be noted that the type of generation or infrastructure is fairly irrelevant: a long tradition of local protests shows that all new installations are in danger of incurring some sort of opposition. This indicator comprises three distinct metrics for infrastructure land requirements, which are used as proxies for likely levels of disruptive opposition: amount of new generating infrastructure required, amount of new transmission infrastructure required, and amount of domestic extraction of resources. As explained previously, the use of a dashboard approach avoids the aggregation of distinct metrics, therefore these three metrics are kept separate in the analysis.

For generation infrastructure, the additional capacity required is multiplied by the power output per unit of land area for each generation type, to give an approximation of the total area of land required (in m^2). This is then weighted according to whether the installation is on land or out at sea (70-30 weighting) to reflect the fact that land installations are more likely to be the subject of local protests (Jones and Eiser 2010).

For transmission infrastructure, the cost data on transmission upgrades required is used as a proxy. This indicator assumes that the transmission at risk of local opposition will be on land (i.e. underground or overhead High-Voltage Direct Current [HVDC] cables), and therefore uses onshore transmission costs only.

The final metric focuses on domestic extraction of resources (including mining and using agricultural land for biomass); some of the most disruptive protests in recent years have been over domestic extraction, for instance the anti-fracking movement. This indicator uses the pathways data on domestic availability of resources (gas, coal and biomass) in TWh/y as a proxy for risk of disruption to domestic extraction.

It is worth reiterating the fact that acceptability and opposition are highly complex, and are driven by numerous socio-economic, demographic and psychological factors (Bell *et al* 2005; Burningham *et al* 2006; Cherry *et al* 2014; Devine-Wright *et al* 2009). For example, location is an extremely important variable; however, strong attachment to a location can create either positive or negative sentiment towards a new installation, depending on how the project is perceived and framed (Cohen *et al* 2014; Devine-Wright 2011; Fast and Mabee 2015; Moula *et al* 2013). However, a detailed appraisal of the likelihood of opposition is not possible without considerably detailed data on people, attitudes and contexts; 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 of this issue.

Indicator 1c. Public participation in decisions

- Qualitative indicator
- Assesses potential levels of public participation in energy and infrastructure decisions, on a high/medium/low scale
- Potentially applicable to other countries

Increasing people's participation in energy projects can reduce opposition, because people are more likely to object if they feel that energy solutions are being 'imposed' on them from outside (Jones and Eiser 2009). Bell *et al* (2005) also suggest that a democratic deficit in the planning of generation sites could be to blame for much so-called NIMBYism. As such, pathways which incorporate higher levels of citizen participation in the decisions being made will be assumed to militate against some of the acceptability issues outlined in the previous indicators. This indicator uses the overarching logic of the pathway storylines to gauge the levels of public participation in the energy decisions being made. High levels of participation result in low levels of risk for this indicator. The 'public participation' indicator would be relevant for energy security assessments in a variety of other contexts, including in countries other than the UK; however, data is challenging to obtain and is not usually included in electricity mix pathways.

4.4.1.2 Sub-dimension 2: Likelihood of non-domestic disruption to electricity availability

Whereas the previous sub-dimension focused on risks emerging within the UK, this sub-dimension turns the focus toward risks emerging in global markets and supply chains. This sub-dimension includes diversity, which can act as a hedge against unknown and unpredictable risks, a benefit which is especially important when dealing with the enormous uncertainties involved in identifying risks emerging in global energy markets and in international relations.

Indicator 2a. Diversity of fuel types in electricity mix

- Quantitative indicator
- Measures the diversity of the fuel types in the electricity mix, calculated using the Shannon-Wiener diversity index: -∑ Pi*(Ln(pi))
- Diversity index gives a result from 0 (not diverse) upwards
- Potentially applicable to other countries

The Shannon-Wiener (SW) diversity index is commonly used in energy research (Lehr 2009; Pfenninger and Keirstead 2015; Stirling 1998). The SW index increases as both the richness and the evenness of the generation mix increases. The highest possible SW index result depends on the data (see below), but a score of 3 upwards would usually be considered very diverse. It should be noted that this is also an indicator of the resilience in the system which could also help to hedge against domestic disruptions and weather events. This indicator is commonly used in energy security assessments in a variety of contexts, and therefore would be relevant for non-UK-based assessments.

It should be noted that this index is dependent on the level of aggregation used for the different fuel types (Grubb *et al* 2006) (for example, whether or not to group 'coal' and 'coal with CCS' together). Increased disaggregation will result in a higher diversity score. Therefore absolute values from the index are insufficient on their own, and the index is best when used for comparison. The methods and assumptions for the aggregation used are shown in Appendix B.

Indicator 2b. Dependence on fuel imports

- Quantitative indicator
- Measures how dependent the pathway is on imported sources of fuel
- Calculated by the proportion of total fuel supply which comes from imported sources, in TWh/y and %, using pathways data which indicates the proportion of imports in the future
- Potentially applicable to other countries.

Gas and coal import proportions are given in the pathways data. Uranium import levels are not shown in the pathways data, but uranium is easy to stockpile and stockpiles are generally maintained at 'secure' levels, therefore uranium imports use BAU figures for 2030 and 2050. For biomass, import amounts are not given in the pathways data, but they do indicate the biomass potential for the UK at 19TWh/y, which is split equally between electricity, heating and transport and used to indicate the level of biomass which could require imports. Oil imports are not included as the pathways use negligible amounts of oil generation. As noted elsewhere in this thesis, imports are not insecure per se, and much of the likely level of disruption to these imports is dependent on the diversity and stability of exporting nations; therefore this indicator should be viewed in conjunction with indicator 2c. This indicator is commonly used in energy security assessments in a variety of contexts, and would be relevant for non-UK-based assessments. However, vulnerability to risks arising from unstable or non-diverse imports depends on certain contextual factors, including import stability and diversity (see indicator 2c) and access to options such as fuel stockpiles and interconnection; therefore its relevance could vary from country to country.

Indicator 2c. Diversity and stability of fuel imports

- Mixed quantitative / qualitative indicator
- Quantitative indicator used for 2010 data
- 2010 figures show the diversity of fuel imports using SW index (see 2a) and the stability of fuel imports using NSW1, which appends the SW index with a stability parameter.
- For 2030 and 2050, qualitative statements made about possible areas of risk for the pathways
- Potentially applicable to other countries

For diversity of imports in 2010, the origins of existing imports of major fuels (gas, coal, uranium, biomass and electricity imports) are collated to show the proportion of imports and of overall fuel use (in TWh/y) from each country. These are then used to create the diversity measure for 2010, for each of these fuels, in order to illustrate those which currently experience higher diversity.

Additionally to diversity of imports, it is crucial to take into account the stability of the exporting nation (Lilliestam and Ellenbeck 2011; Neumann 2007). To calculate the stability of major exporting nations in 2010, this indicator uses existing data on the origins of major fuels. The import diversity data is appended with information regarding the political stability of the exporting countries, from the Fragile States Index 2014 (Foreign Policy 2014). This is done by including a parameter ‘b’ representing stability into the SW index outlined above, using the Neumann Shannon-Wiener Index (NSW1) (Neumann 2007):

$NSW1 = -\sum Pi*(Ln(pi))*b$

For 2030 and 2050, there is no information available about fuel imports. The source of imports depends on a number of factors which are impossible to assess, including geopolitical relations between states, trade agreements and markets in each individual country and worldwide. It is also not possible to know the stability of exporting states out to 2030 or 2050. The Arab Spring acted as a timely reminder that attempting to project the future political climate of any state is a futile task. Therefore, qualitative statements are all that can be made regarding the situation in 2030 and 2050, based on the calculations for each fuel for 2010.

It is the contention of this research that a more thorough assessment of the energy security of transition pathways would need to be able to make assessments of the likelihood of disruption to imports, either due to a lack of diversity or due to stability problems in the exporting nations. Therefore, if pathways are to be deemed ‘secure’, it is imperative that they incorporate information about global fuel markets and trade routes, and about global geopolitical trends.

The ‘import diversity and stability’ indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK. However, vulnerability to risks arising from unstable or non-diverse imports depends on certain contextual factors, including overall import dependence and access to options such as fuel stockpiles and interconnection; therefore its relevance could vary from country to country.

4.4.2 Affordability

4.4.2.1 Sub-dimension 3: Cost to the System

This sub-dimension carries out quantitative analysis of the costs of realising the three pathways. These costs are assessed separately for each of the major three parts of the energy system: generation, transmission, and distribution.

Indicator 3a. Cost of Electricity Generation

- Quantitative indicator
- Levelised Cost of Electricity (LCOE), measured in £/Megawatt-Hour (MWh)
- Total annual generation costs, measured in £bn
- Potentially applicable to other countries

LCOE uses a widely recognised calculation for the cost of electricity generation. The calculation includes Capital Expenditure (CAPEX) costs (i.e. pre-development and construction), fixed Operating Expenditure (OPEX) costs (i.e. fixed operation and maintenance, insurance and connection charges) and variable OPEX costs (i.e. variable operation and maintenance and fuel). Component data is taken from DECC (2013d) and Mott Macdonald (2010). The calculation takes into account the capacity and load hours of each type of generation. CAPEX is discounted at a rate of 10%. This is then used to show total annual generation costs for the pathways in £bn. The 'cost of electricity generation' indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK; however, application to other contexts would require additional data because the cost figures used here are specific to the UK context.

Sensitivity analyses are carried out to show the impact of:

- Different discount rates (DR Sensitivity)
- Decreasing CAPEX costs due to learning and economies of scale (LC Sensitivity)
- Changes in CAPEX costs based on DECC estimates (CAP Sensitivity)
- Fuel costs
- Carbon price

Indicator 3b. Transmission upgrade costs

- Quantitative indicator
- Calculates costs of necessary additional and upgraded transmission infrastructure, in £bn
- Potentially applicable to other countries

This indicator estimates the cost of upgrading or adding to the transmission network in order to absorb the electricity generation of the pathways. Transmission upgrade costs for offshore wind are calculated using unit costs and existing data about the likely unit requirements of all the Round 2 and Round 3 wind farms (data from National Grid 2013c). Interconnector offshore costs are calculated using unit and cable costs for planned interconnectors (National Grid 2013c; 2013d) and data on individual interconnectors from the websites of the individual projects. Onshore costs are calculated using the estimates of network upgrades that will likely be required for different amounts of new generation, from the Electricity Networks Strategy Group (ENSG 2012). For onshore wind and nuclear, these onshore transmission estimates are weighted according to likely locations of onshore infrastructure, using locations of existing nuclear generation sites and siting estimates of current and future wind installations, from National Grid system maps and projections (National Grid 2012). For all other onshore generation, locations are weighted according to current generation sites (National Grid 2012). This indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK; however, application to other contexts would require additional data because the cost figures used here are specific to the UK context.

Indicator 3c. Distribution upgrade costs

- Quantitative indicator
- Calculates costs of necessary additional and upgraded distribution network infrastructure, in £bn
- Potentially applicable to other countries

Distribution network costs are estimated on the basis of a paper by Pudjianto *et al* (2013), which carries out detailed spatial modelling of the distribution networks for the Transition Pathways through to 2050. This indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK; however, application to other contexts would require additional data because the cost figures used here are specific to the UK context.

4.4.2.2 Sub-dimension 4: Cost to the Consumer

This sub-dimension utilises the information from the previous affordability indicators to estimate the eventual cost to the consumer. This is done both quantitatively and qualitatively. Firstly, a quantitative analysis is conducted of the annual household retail electricity bills of the three pathways. Secondly, this information is used as the basis for a qualitative assessment of the important question 'affordable to whom' (Cherp and Jewell 2014), focusing on fuel poverty and the affordability of the pathways to the most vulnerable groups in society.

Indicator 4a. Annual retail electricity bills

- Quantitative indicator
- Calculates future annual electricity bills to domestic consumers, in £/y
- Potentially applicable to other countries

Annual retail electricity bills are calculated using the wholesale price and a 'consumer uplift' based on an estimated breakdown of an average household bill. This breakdown consists of 19% of the bill for supplier costs and margins, 9% for social and environmental policies, 20% for network charges, and 5% for Value-Added Tax (VAT). The annual bills are calculated without VAT; this is a standard method which makes it easier to compare between countries.

Wholesale prices are calculated by defining the price-setting technology using hourly demand data for the whole year. The load duration curve is first split into horizontal stacks according to the capacity of each fuel, and the estimated merit order as given in the pathways data. The year is split into four time periods: summer and winter peak, and summer and winter off-peak. This is used to calculate the number of hours during the year for which each fuel is setting the electricity price. The LCOE data for total variable costs is then used to show the cost of electricity generation for the price-setting fuel. These prices are multiplied by the number of hours in the year for which each fuel is setting the price, giving an overall wholesale price of electricity.

The wholesale price estimates are then used to estimate the annual electricity bills to consumers. The baseline estimate is calculated using the same consumer uplift as today. Sensitivity tests are then carried out to show the impact of:

- Increasing price of generation for each major fuel by 20% (coal, gas, nuclear, biomass)

- Changes in the merit order of dispatch
- Impact of assumptions r.e. price of imported electricity
- Impact of assumptions r.e. carbon price in 2030 and 2050
- Changes to social and environmental programmes
- Different estimates of wholesale price
- Different network charges (based on transmission and distribution costs, see 3b and 3c)
- Population growth
- Economies of scale
- Changes to the EMR
- Utility profit margins and rent-seeking.

For more detail on all the sensitivity analyses carried out, including the rationale behind each, see Appendix C.

The ‘annual bills’ indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK; however, application to other contexts would require additional data because the cost figures used here are specific to the UK context.

Indicator 4b. Impact on levels of fuel poverty

- Qualitative indicator
- Uses annual bills data and pathways storylines to assess risk of heightened levels of fuel poverty, on high/medium/low scale
- Variable / limited relevance to other countries.

In the absence of detailed information on future incomes which would be required for a quantitative assessment of fuel poverty, a qualitative analysis is carried out using the ‘annual bills’ results, existing information on fuel poverty (Hills 2012) and the pathway storylines. The combination of annual bill data and qualitative analysis allows the identification of ‘high risk’ and ‘low risk’ pathways; more detail is given in Appendix C and in the results in section 5.4.3. Fuel poverty is a particularly prevalent issue in the UK, mainly because of ageing, poor-quality housing stock (compared to some other industrialised countries), combined with cold winters and relatively high income inequality. Therefore this indicator would be of variable or limited relevance to energy security assessments of other industrialised countries.

4.4.3 Long-term environmental sustainability

4.4.3.1 Sub-dimension 5: GHGs

Indicator 5a. GHG emissions and intensity of the generation mix

- Quantitative indicator
- Calculates UK GHG electricity emissions in $MtCO_2e/y$
- Calculates life-cycle GHG intensity of electricity generation in gCO_2e/kWh
- Potentially applicable to other countries

This indicator measures UK electricity emissions in $MtCO_2e/y$, and the GHG intensity of the electricity generation mix per kWh of electricity generated. Both measures are calculated for all GHGs, expressed as carbon dioxide equivalent (CO2e). This indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK.

GHG emissions data is taken directly from the pathways data, and used to show year-on-year and cumulative GHG emissions for the UK energy system. Life-cycle carbon intensity of electricity generation is calculated by adding together recognised carbon intensities of the fuels used, using data from the IPCC (Moomaw *et al* 2011) (again, note that 'carbon intensity' is used here and in the IPCC data as short-hand for carbon dioxide equivalent).

4.4.3.2 Sub-dimension 6: Resources

This sub-dimension focuses on the long-term availability and depletion of fuels and other materials used in power production. Unlike the 'external disruption' sub-dimension (which focuses on markets and supply chains), this sub-dimension focuses on possible future *physical* constraints on resources.

Indicator 6a. Primary fuels depletion

- Qualitative indicator

- Uses existing literature to assess depletion risk of major fuels, and relevance to the fuel mix in the pathways
- Potentially applicable to other countries

The considerable uncertainties in calculating global fuel resources into the future mean that it is outside the scope of this thesis to assess fuel depletion quantitatively. Information from the existing literature is used to assess the risk of depletion of the four primary fuels (coal, gas, uranium and biomass) through to 2050. The pathways are then assessed qualitatively for their level of reliance on depletable fuels. This indicator would be relevant for energy security assessments in other countries. It is particularly suited for security assessments over longer timescales.

Indicator 6b. Secondary materials depletion

- Qualitative indicator
- Uses existing literature to assess depletion risk of major fuels, and relevance to the fuel mix in the pathways
- Potentially applicable to other countries.

As with primary resource depletion, this indicator uses a qualitative method using information from the existing literature to assess the level of risk of depletion of secondary materials used in electricity generation, and explores the extent to which the pathways are reliant on these generating technologies. This indicator would be relevant for energy security assessments in other countries. It is particularly suited for security assessments over longer timescales.

4.4.3.3 Sub-dimension 7: Water

This sub-dimension focuses on the water required for the cooling of power generation facilities, an aspect which is frequently overlooked and yet is likely to become increasingly important in the longer-term. Water requirements are assessed both in terms of overall requirements and intensity.

Indicator 7a. Water usage for cooling and biomass feedstock production

- Quantitative indicator
- Calculates water consumption and water withdrawals for power generation in m^3/y

- Water usage for biomass production not possible to calculate because of lack of available data
- Variable relevance to other countries.

The amount of water required by different types of power generation is given in the literature (Davies *et al* 2013; Kyle *et al* 2013; Van Vliet *et al* 2012). Figures are available for water withdrawals and for water consumption, in m3/MWh. These figures are weighted according to the type of cooling used for the plant, taken from projections by Kyle *et al* (2013). This is then multiplied by power outputs (in TWh/y) to show water withdrawal and water consumption in m^3/y.

The results are then weighted 70-30 to reflect the greater impact of freshwater use vs seawater use, using sites of existing and planned power stations (from National Grid 2012). Sensitivity tests are carried out to show the impact of different assumptions regarding land/sea weighting; more detail of these tests is given in Appendix D.

It is important to emphasise that this is not a life-cycle analysis into the water usage of fuels such as crop-based biomass, or of extraction of fuels such as coal. Data on life-cycle water usage is especially important for biomass, and there are models which are designed to calculate life-cycle water requirements (for example, the FAO-Penman-Monteith model [Zotarelli *et al* 2009]). However, life-cycle analysis of the Transition Pathways would be hindered considerably by a lack of information about biomass feedstock types and country of origin. For a more in-depth analysis of water impacts, it would be desirable to include a life-cycle water assessment; for this, detailed information on feedstocks, fuel types (e.g. brown coal vs lignite, conventional vs unconventional fossils), and country of origin would be required, which is beyond the scope of this thesis.

This indicator would be relevant for assessing energy security in a variety of contexts; however, its applicability would vary between different countries, because some countries are much more prone to water supply problems than others.

4.4.4 Reliability

4.4.4.1 Sub-dimension 8: System adequacy

This sub-dimension focuses on ensuring that the system is adequate to meet demand with the available supply, at all times of the year. The pathways have all been designed with hour-by-hour system adequacy in mind, and all are modelled to meet the UK reliability standard of 3 hours Loss of Load Expectation (LOLE) per year (see section 5.8.1). However, there are other important factors in ensuring system adequacy, including maintaining a secure capacity margin, maintaining adequate capacity factors for dispatchable generation, and providing flexible two-way capacity options such as electricity storage and interconnection with neighbouring countries.

Indicator 8a. De-rated capacity margins

- Quantitative indicator
- Calculates % of generating capacity which could reasonably be expected to be available at time of peak demand
- Potentially applicable to other countries

De-rated capacity margin (DRCM) measures the amount of electricity generating capacity which can reasonably be expected to be available at times of peak demand, and which therefore can be 'relied upon' to be available for meeting system peaks, taking into account planned and unplanned outages and intermittency. Assumed de-rated capacity margins for each fuel ('capacity credit') are given in the National Grid 10-year statement (National Grid 2012: 30). Pathway DRCM is calculated using the following equation (RAEng 2013):

$$\textit{capacity margin (\%)} = \frac{\textit{total available capacity - peak demand}}{\textit{peak demand}} \quad x100$$

This indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK. However, alternative data may be required, as the capacity credit figures used here are specific to the UK context.

Sensitivity tests are carried out to show the impact of changing assumptions regarding:

- Capacity credit of imports (0%, 50% and 100%)
- Capacity credit of wind (5%, 8%, 20%, 40%)
- Capacity credit of CCS (68%, 89%, 110%)

Details of the assumptions underlying these sensitivity tests are shown in Appendix E.

Indicator 8b. Capacity factors and oversupply

- Mixed quantitative / qualitative indicator
- Uses data from the FESA model to show capacity factors for each generating technology in the pathway, in %
- Qualitative analysis is then made of likely areas of risk for oversupply and for investment in dispatchable generation
- Variable / limited applicability to other countries.

As well as ensuring that there is enough generation capacity available to meet demand peaks, an electricity system must also ensure that during times of low demand there is not severe oversupply of electricity. To do this, the capacity factors of each type of generation are adjusted by the FESA model which is used to generate the supply and demand mixes in the Transition Pathways. Barnacle *et al* (2013) and Barton *et al* (2013) note that a key issue for the pathways could be the high amounts of spare capacity required to back up the high penetrations of intermittent RES in the generation mix of the pathways. A significant reduction in capacity factors could be a risk, because it risks making the initial investment in this type of generation capacity economically unviable because of the economic unattractiveness to generators of operating their plants at such low capacity factors.[14] Countries other than the UK may experience different levels of risk arising from oversupply, for instance due to differences in market structure and availability of capacity sharing options such as transnational Grid systems; therefore this indicator would have variable applicability to non-UK contexts.

Indicator 8c. Electricity storage and interconnection

- Mixed quantitative / qualitative indicator
- Calculates total electricity storage + total electricity interconnection in GW nameplate capacity
- Qualitative assessment made of the level of ambition shown in the pathways
- Variable applicability to other countries.

[14] The UK has recently introduced a Capacity Mechanism to attempt to deal with this problem (see DECC 2013c; National Grid 2014a); however, the first out-turn year is in 2018, and therefore it is too early to tell how effective or efficient this mechanism will be.

Storage and interconnection both represent forms of flexible, dispatchable power, which can in theory be called on when required (for instance, at a time of high demand), in order to help incorporate intermittent generation and to help reduce the necessary levels of spare capacity of conventional generation on the system.

The amount of electricity storage and interconnection (in GW) in the pathways is added together. The figures for interconnection are taken from the nameplate installed interconnector capacity, and thus assume 100% imports to the UK during stress periods. The results are then compared against a potential range of interconnection and storage potential suggested in the literature. For example, does the pathway include a significant amount of electricity storage options such as distributed and Grid-level storage? Does the pathway build any new interconnectors? How ambitious are the plans for interconnectors?

This indicator would potentially be applicable to countries other than the UK, but only in certain cases, and may not be applicable to all industrialised country contexts. For some countries, interconnection may be less relevant, either because a transnational Grid system is already in place, or because they are geographically isolated enough to make interconnection unattractive. Furthermore, for some countries with abundant dispatchable low-carbon energy supplies (e.g. hydro-power), storage and interconnection may be less important for Grid balancing.

4.4.4.2 Sub-dimension 9: Shock resilience

This sub-dimension focuses on system resilience, especially resilience to sudden and unexpected changes in the supply/demand balance. No matter how secure the system, it is impossible to completely remove the risk of sudden shocks caused by unpredictable events such as geopolitical tensions, price shocks, or technical faults such as power station failures and line trips. Therefore, an important aspect of system security lies in ensuring that supply-side and demand-side aspects of the system can quickly respond to and recover from such shocks (Kiriyama and Kajikawa 2014).

Indicator 9a. Flexible supply: Frequency response capability

- Quantitative indicator
- Calculates potential maximum and average Frequency Response capabilities of the generation mix, in MWh

- Potentially applicable to other countries.

This indicator uses the capability of the generation mix to provide Frequency Response services to the System Operator as a proxy for the flexibility and responsiveness of the generation mix. Frequency Response (FR) is the ability of the system to react to short-term changes in the frequency (Hz) of supply, over timescales of less than 30 seconds. FR capabilities are calculated by extrapolating from power station data given by National Grid (available on request). From this data it is possible to calculate an average and a maximum FR capability for each type of power station; this is used alongside the recorded unit sizes to calculate FR capability per Megawatt (MW), which is then applied to the generation mix of the pathway. The results show average and maximum primary and secondary FR capabilities, in MWh.

It is important to note that DSR can provide an important source of both Frequency Response and Short-term Operating Reserve (STOR) (Ofgem 2013b). However, as explained in Indicator 9d, it is much more challenging to calculate the potential for DSR in the pathways due to lack of data. For this reason, ‘flexible supply’ and ‘flexible demand’ are assessed separately. Frequency Response and STOR capabilities are used as proxies for flexible supply only.

In the future, the requirements of the system for FR may change; this important consideration is covered in indicator 9c. This indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK, although again the possibility of changing FR requirements should be taken into account. Alternative raw data would be required, as the FR availability figures used here are specific to the UK context.

Indicator 9b. STOR and black-start capability

- Quantitative indicator
- Calculates the proportion of the nameplate generating capacity on the system which could potentially be used to provide STOR and black-start capability, in %
- Potentially applicable to other countries.

FR covers the system if generation is suddenly lost. However, for the system to return to normal, reserve power then needs to come online. STOR is delivered within a maximum of 4 hours (National Grid 2011). All conventional generation can in theory provide STOR; however, some types of plant cannot come online quickly if they are switched off at the time of the STOR request. Therefore this indicator shows results for short-term STOR (within around 45 minutes) and long-term STOR (45 minutes to 4 hours). The results show what percentage of capacity in the pathway would be capable of providing short-term and long-term STOR.

Black-start capability is used in the event of a blackout over a large geographical area. Small off-grid generators (usually liquid fuel) are used to daisy-chain power to start larger generators, until the main plant turbines can be started. In theory, all conventional thermal generation (not including nuclear) can provide black-start power. The indicator shows the proportion of each pathway which would in theory be capable of providing black-start capability, if all compatible plants were fitted with this.

As with FR, requirements for STOR and for black-start may change in future; this is covered in indicator 9c. This indicator would be relevant for assessing the energy security of a wide range of pathways, including countries other than the UK, although again the possibility of changing STOR requirements should be taken into account.

Indicator 9c. Response and Reserve requirements

- Quantitative indicator, to be used alongside indicators 9a and 9b
- Calculates potential increases or decreases in FR requirements (in MWh) and STOR requirements (in %). These are compared with the capabilities calculated in 9a and 9b
- Potentially applicable to other countries.

The requirements for both FR and STOR may increase in a low-carbon electricity system. Requirements may increase due to decreasing system inertia (FR), increasing wind generation and wind forecast error (STOR), and increasing size of the largest generating unit on the system (FR and STOR) (National Grid 2011).

Inertia: when a turbine spins, it creates a build-up of kinetic energy. If the plant stops generating unexpectedly, the turbine does not stop immediately, and the kinetic energy can be used to provide inertia which decreases the need for FR. A shift towards wind and solar power would decrease the amount of natural inertia on the system (Ulbig *et al* 2014). Increasing FR requirements due to decreases in inertia are calculated using the proportion of generation which provides natural inertia.

Wind generation: inaccuracies in wind forecasts mean that with more wind on the system, there is increasing need for STOR to cover these inaccuracies. The increasing STOR requirements due to wind generation are calculated using National Grid data (National Grid 2011) which shows the increases in STOR required for certain levels of wind generating capacity; this is then applied to the wind generating capacity in the pathways.

Increasing unit size: if the biggest unit on the system is of a larger size, the potential loss of power in the event of a unit trip increases, thus increasing the requirements for both FR and STOR to cover this loss. The increasing FR and STOR requirements due to larger unit sizes are calculated using National Grid modelling which assumes the connection of two 1800MW units at Hinkley C within the next decade (National Grid 2011). Sensitivity tests are carried out for the two centralised pathways, to show the potential impact of even larger units than this on the system in 2030 and 2050.

This indicator would potentially be applicable to other countries, especially as requirement levels for FR and STOR may change across different contexts, and are crucial for understanding the level of risk arising from insufficient FR and STOR capacity. However, alternative raw data would be required, as the requirements figures used here are specific to the UK context.

Indicator 9d. Flexible demand

- Mixed quantitative / qualitative indicator
- Calculates technically and realistically shiftable potential for 2010 (in GW); estimates realistically shiftable potential for 2030 and 2050 in % and GW
- Also uses data on electric vehicles (EVs) and heat pumps as a proxy for demand flexibility. Results given in TWh/y and in % of total demand
- Potentially applicable to other countries.

Flexible demand helps to improve resilience by offering increased flexibility and reducing peak load. Reducing the peak means that less generation capacity is required to meet peak demand, meaning that there is potentially less requirement for the types of shock resilience measures described above (Drysdale *et al* 2015). Moreover, an effective system for flexible demand can help the system to respond to shocks, by offering an option for response or reserve from the demand-side rather than the supply-side, and thus mitigating the impact of declining response and reserve capabilities on the supply-side (Nistor *et al* 2015).

Data on flexible demand is not given in the pathways. Current data from the literature (AECOM 2011; Dudeney *et al* 2014; Element Energy 2012; Palmer *et al* 2013) is used to estimate technically shiftable potential and realistically shiftable potential for 2010. This is used alongside peak demand data in the pathways to estimate the reduction in peak demand which could be achieved with conservative and ambitious percentages of shiftable demand.

Pathways data on heat pumps and electric vehicles (EVs) is then used as a further proxy for levels of flexible demand in the pathways. EVs and heat pumps both represent relatively large shiftable electrical loads, especially compared to other appliances which could be used to load-shift such as fridges; therefore they can be used as a rough proxy for flexible demand as a whole.

The ‘flexible demand’ indicator would be relevant for assessing the energy security of a wide range of pathways, including for countries other than the UK. It is particularly relevant for assessing or comparing the security of low-carbon pathways or pathways undergoing major transition, as these could be particularly vulnerable from risks arising from insufficient flexibility.

Table 4-2: Overview of indicators with brief description of methods

'Details' key:
QN: Quantitative. QL: Qualitative. M: Mixed
✓ : Indicator is potentially applicable to other countries

Dimension	**Sub-Dimension**	**Indicator**	**Overview of methods**	**Details**	
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 GW and %) which is 'approved' and 'opposed' by the general public	QN	✓
		Land requirements (proxy for 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	QN	✓
		Participation in decisions	Qualitative indicator, uses pathways storylines to assess the level of public participation in energy provision and in decision-making	QL	✓
	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 Lehr (2009); Pfenninger and Keirstead (2015); Stirling (1998).	QN	✓
		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)	QN	✓
		Diversity & stability of fuel imports	Current (2010) fuel import diversity is measured using Shannon-Wiener index 2010 fuel import stability measured by adding a stability parameter (Neumann 2007): NSW1= -∑ Pi*(Ln(pi))*b , where 'b' represents a stability parameter, derived from the Fragile States Index (Foreign Policy 2014) Insufficient data in pathways for quantitative analysis; therefore qualitative statements made about possible future diversity and stability	M	✓
Affordability	Cost to the system	Generation costs	Calculates LCOE using CAPEX (pre-development, construction), fixed OPEX (O&M, connection charges, insurance), variable OPEX (variable O&M, fuel, carbon price) (e.g. Pfenninger and Keirstead 2015) Cost data from DECC (2013d) and Mott Macdonald (2010)	QN	✓
		Transmission upgrade costs	Onshore upgrade costs calculated using Electricity Networks Strategy Group estimates of upgrades required for different levels of new capacity (ENSG 2012)	QN	✓

			Offshore upgrade costs calculated using estimated unit costs (from National Grid 2013c)		
		Distribution upgrade costs	Distribution upgrade costs for the pathways modelled by Pudjianto *et al* (2013)	QN	✓
	Cost to the consumer	Annual retail electricity bills	Wholesale electricity 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. VAT (5%) not included in estimate.	QN	✓
		Impact on fuel poverty	Qualitative analysis carried out using annual bills estimates, existing literature on levels of fuel poverty in the UK (especially Hills 2012), and the pathways storylines	QL	
Sustainability	GHGs	GHG emissions and intensity	Electricity system GHG emissions taken directly from pathways data (see also Foxon *et al* 2013) Life-cycle carbon intensity (in CO2e) of electricity generation types taken from High, mid and low estimates from IPCC global power station data (Moomaw *et al* 2011) Total carbon intensity = Fuel-type intensity * (fuel-type generation TWh/y / Total generation TWh/y)	QN	✓
	Resources	Primary fuels depletion	Qualitative method using information from the existing literature to assess depletion risk of primary fuels. Pathways assessed qualitatively for their reliance on depletable fuels.	QL	✓
		Secondary materials depletion	32 crucial materials are identified from Moss *et al* (2011) and Speirs *et al* (2014) and listed from 'highly critical' to 'not critical' according to risk of depletion Pathways assessed qualitatively for their reliance on depletable materials.	QL	✓
	Water	Water consumption & withdrawals	Data on water withdrawals and water consumption of different types of power generation from Davies *et al* (2013). Projections on types of cooling to be employed in UK thermal powergen in future from Kyle *et al* (2013). These are applied to the generation mix to show water consumption and withdrawals in m3/y Baseline results weighted 70-30 to show greater environmental impact of freshwater vs seawater. Water usage for biomass feedstock production not possible to calculate because of lack of available data	QN	
Reliabil ity	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)	QN	✓

		Capacity factors & oversupply	Capacity factors (from the Transition Pathways data) and capacity margins (see above) are used to highlight areas of oversupply	M	
		Electricity storage & interconnection	Electricity storage and interconnection nameplate capacities summed together; also compared to plausible storage and interconnection developments	M	
	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 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)	QN	✓
		Flexible supply: Short-term Operating Reserve & black-start capability	Calculates percentage of generation mix which would be capable of providing 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)	QN	✓
		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)	QN	✓
		Flexible demand	Calculates technically and realistically shiftable potential for 2010 (in GW), using data from Sustainability First (Dudeney *et al* 2014); estimates realistically shiftable potential for 2030 and 2050 in % and GW Also uses data on electric vehicles (EVs) and heat pumps as a proxy for demand flexibility. Results given in TWh/y and in % of total demand	M	✓

4.5 Stakeholder interviews

4.5.1 Why analyse stakeholders' perspectives?

One of the challenges of energy security policy lies in the fact that there are significant differences amongst different stakeholders regarding what energy security actually means. However, as of yet, the diversity of views remains rather vague and intangible. The set of indicators developed in the preceding sections offers a useful basis for exploring the perspectives of energy stakeholders, and can provide a starting point for an in-depth and transparent discussion which does not seek to close down the diversity of views, but instead seeks to open them up to debate.

Stakeholder interviews are used to answer the second and third research questions. These interviews enable us to find out more about the diversity of views on energy and electricity security in the UK energy community. Respondents are encouraged to give their perspectives on the choice of indicators, and to give their views on possible additional dimensions and indicators which were not initially included in the set. As noted in Chapter 2, the 'slipperiness' of the energy security concept means that a significant diversity of views may be expected between different actors, even amongst actors who are all experts in the field of energy security. A number of factors may influence perspectives, including potentially the contention by Allison (1969) and others that "where you stand depends on where you sit" (see section 2.1.3). The purpose of the interviews is not to attempt to generate an agreed-upon definition or set of indicators for measuring energy security (which, as shown in Sovacool and Mukherjee [2011] runs the risk of generating an unmanageably large set of issues and indicators). Rather, the purpose is to recognise and clarify the preferences and priorities of different actors and to explore their implications.

The results from the interviews are used to find out what impact stakeholders' views have on the results of the indicator assessment. It may be that certain perspectives, if carried forward into a security assessment, would lead to certain pathways or technology options being preferred. Stakeholder interviews thus allow us to open up the assessment of low-carbon electricity security to the wider energy community. If certain stakeholders feel that a certain indicator or group of indicators is especially important, and one of the pathways or a certain technology scores very badly for this indicator, there is certainly value in flagging this up as an addition to the initial indicator assessment. Similarly, if a certain indicator is generally felt to be unimportant by stakeholders, it is worth noting this for pathways or technologies which appear to be particularly risky for this indicator.

4.5.2 Interview methodology

Semi-structured interviews were conducted with UK energy stakeholders, selected using non-probability sampling. Non-probability sampling refers to sampling techniques which do not select participants on the basis of statistically random samples; studies using non-probability sampling cannot therefore be used to draw generalisations about an entire population. Yet non-probability sampling is commonly used in qualitative research, because it is particularly suited to understanding complex issues relating to human behaviour; it also recognises that some members of the population may be more likely to provide insight into a particular topic, for instance because of their existing expertise (Marshall 1996). For this thesis, stakeholders were selected on the basis of their direct involvement with energy issues (e.g. through their job title or their organisation), and their involvement with organisations which may have some influence on UK policy processes, either through direct involvement or through participation in research and consultations. Initially, purposive sampling was used to contact respondents from a number of pre-defined target organisations (for example, government departments involved in energy security issues). Secondly, snowball sampling was used to fill in any gaps in organisations or sectors where purposive sampling failed to get a response from the desired individual or organisation.

The aim of the interviews was to speak to stakeholders from a range of different types of organisation within the energy sector, in order to gather a range of views from across the spectrum of potentially influential stakeholders. Six desired types were identified as follows:

1. Utilities (e.g. major energy suppliers, smaller suppliers, industry groups)
2. NGOs and civil society (e.g. environmental / consumer interest organisations, energy co-ops)[15]
3. Think tanks and consultancies
4. Government and regulatory bodies (e.g. government departments, Ofgem)
5. Electricity network companies (e.g. National Grid, the Distribution Network Operators)
6. Academia (e.g. universities, research groups)

[15] It should be noted that some of the respondents are from energy co-ops, which could technically be viewed as either 'NGOs' or 'utilities'. However, in light of the fact that employees of energy co-ops are often ideologically driven, and frequently work as volunteers for many years without earning a wage from the organisation, it was decided that they have more in common with NGOs than with the utilities, and are therefore listed as group 2.

From each of these organisations, a number of desired individuals were identified on the basis of their existing knowledge of energy security issues; these were contacted using purposive sampling. Where these individuals were not available, alternatives were identified using snowball sampling. This meant that a number of experts from each type of organisation could be interviewed. Because of the small number of energy experts in the UK, it was not possible to target experts with particular roles within each type of organisation. In total, 25 stakeholders were interviewed; table 4.3 gives anonymised details regarding their position in their organisation and relevant background experience where available. By choosing individuals specifically from a range of different types of organisation, it may be expected (according to Miles' law, discussed in section 2.1.3) that individuals from the same type of organisation would share similar perspectives. On the other hand, perspectives could also be shaped by other contextual factors such as respondents' background experience, personal ties etc., and this could have a stronger influence over peoples' views than the organisation for which they work.

Table 4-3: interviewee details

	Type of organisation	**Position**	**Background / experience**
A	Think tank/ advisory body	Head of Policy	8 years' experience as energy policy advisor (public and private sector). PhD in maths.
B	Academia	Senior researcher	12 years' experience as energy/environment researcher in various universities (UK). PhD in energy policy.
C	NGO	Policy director	15 years' experience as policy advisor and campaigner for environmental NGOs.
D	Think tank/ advisory body	Senior researcher	7 years' experience as environmental/energy consultant (private sector). Previously sales.
E	Think tank/ advisory body	Senior researcher	15 years' experience as environment/energy consultant (public and private sector).
F	Utility	Head of policy	7 years' experience as energy/environment policy advisor and consultant (public and private sector). Previously journalism.
G	Utility	Head of policy	15 years' experience as policy advisor and energy strategist (private sector).
H	Academia	Professor	Over 20 years' experience as energy/ environment researcher in various universities (UK and global). PhD in energy policy.
I	NGO	Chief Economist	Over 20 years' experience as energy/environment researcher and economist (public and private sector).
J	Academia	Senior researcher	8 years' experience as energy/environment researcher in various universities (UK). PhD in energy economics.
K	Academia	Research fellow	11 years' experience as energy/environment researcher in various universities (UK). PhD in energy policy.
L	Utility	Strategy director	Over 20 years' experience as energy policy advisor (private sector).

M	Think tank/ advisory body	Consultant	7 years' experience as energy/environment researcher (public, private and NGO sectors). Previously environmental campaigner.
N	Policy & Regulation	Associate partner	11 years' experience as energy researcher and policy advisor (public sector). Previously law.
O	NGO	Strategy director	15 years' experience as consultant and analyst in the energy sector (public and private sector).
P	Think tank/ advisory body	Senior policy officer	5 years' experience as environmental campaigner and policy advisor (private and NGO sector). MPhil in philosophy.
Q	Policy & Regulation	Civil servant	7 years' experience as civil servant (energy and environment). Previous unknown.
R	Think tank/ advisory body	Executive analyst	13 years' experience as energy/environment researcher and analyst (public, private and education sector). PhD in physics.
S	Network company	Head of policy	14 years' experience as policy advisor and public affairs manager in the energy sector (private sector). Previously politics.
T	NGO	Director	8 years' experience as energy NGO director. Previously journalism.
U	Policy & regulation	Department head	9 years' experience as policy and communications advisor in the energy sector (public sector). PhD in chemistry.
V	Policy & regulation	Civil servant	11 years' experience as director for various energy organisations (public and private sector). PhD in engineering.
W	Network company	Department head	Over 20 years' experience in various roles for network companies (UK and US).
X	NGO	Director	8 years' experience as director of energy NGO. Over 20 years' experience as energy policy advisor (public sector and self-employed).
Y	Utility	Strategy director	11 years' experience as strategy and technology director in energy sector (private sector). Previously chief engineer (private sector).

About one week before each interview, respondents were sent a 2-page briefing note (see Appendix G). The briefing note consisted of an introduction and overview of the thesis research, and the indicator set. The indicators were given to interviewees in a list, rather than the graphical framework image shown in figure 4.4. The reason for this is that the aim of the graphic is to show a broad and balanced view of multiple different dimensions of energy security; offering interviewees this image in advance could thus have resulted in framing effects whereby they became more conscious of this approach than they would have been otherwise, and may have based their opinions accordingly. This thesis aims to identify areas of *imbalance*, therefore indicators were provided in a list. Apart from the briefing note shown in Appendix G, no additional information was provided to respondents; for example, respondents were not made aware of the methods used for calculating indicators, or of the specific set of transition pathways used. All interviews were roughly one hour long, and all were conducted face to face. All interviews were recorded using a Dictaphone and transcribed in full. Interviewees were kept anonymous.

The hour-long face-to-face interviews were structured thus:

1. The first part of the interview elicited opinions on each indicator. Respondents were asked to give a rating of 1 to 5 for each indicator in terms of its importance for assessing electricity security in a low-carbon context. During this process, interviewees were asked *why* they had made certain decisions.

2. Interviewees were asked whether they felt that there were any important indicators missing from the list.

3. Interviewees were asked which measures, policies or technologies they felt are crucial for improving UK electricity security, in both the short-term and the long-term. They were also asked to identify what they see as the main risks to UK electricity security, again over a range of timescales.

It is worth noting that the purpose of the interviews was not to focus on the detail of methods or calculations for individual indicators. If a respondent were to suggest an entirely new dimension or indicator, then this was important to include in the analysis, but the overall focus was on the broad view and perceptions of energy and electricity security. The interviews were carried out during the period January to April 2015. Interviews were conducted *after* the finalisation of the indicator set; as such, the interviews were not intended to contribute to the development of the indicator set, but rather to explore the diversity of actors' views using the indicator set as a basis.

4.5.3 Methods for analysing the results of the interviews

The interview transcripts were coded in accordance with recognised methods for thematic coding analysis (Braun and Clarke 2006; Burnard *et al* 2008; Hsieh and Shannon 2005). The transcripts were first coded according to all key words and topics. These were then grouped in order to find areas of commonality, contention or repetition, and finally the main topics were grouped together into sets of core themes. The transcripts were revisited repeatedly during this process, in order to ensure that important information was not missed and that the main themes were identified. Finally, the respondents were anonymised in the written analysis.

Where respondents have been paraphrased or quoted, the respondents were contacted directly in order to check the information and to avoid misunderstanding or misrepresentation.

4.5.4 Exploring the impact of stakeholders' perspectives on the results of the security assessment

As well as being used to explore the diversity of perspectives in the UK energy community, the data from the interviews can be used to answer the final research question: ""What impact do stakeholders' perspectives have on the results of the security assessment and on their preferred options for improving energy security?" In order to do this, the results from the interviews (presented in Chapter 6) are applied to the results from the security assessment of the three Transition Pathways (presented in Chapter 5), in order to identify the impact of major cross-cutting themes and different emerging views of security on areas of high risk for the pathways. The outcomes and analysis are presented in Chapter 7. Doing this explicitly addresses the plural and conditional nature of energy security, by acknowledging the fact that multiple stakeholders will have competing knowledge claims which should be taken into account where possible when presenting the results from a security assessment.

Furthermore, this process examines in detail some of the indicators which were suggested by respondents as missing from the initial set, to explore whether including them would have been possible or practical, and to ask what impact including them might have had on the overall results of the security assessment. As noted previously, the interviews were conducted after the indicator set had been finalised, therefore the purpose of exploring 'missing' indicators was not to contribute to the construction of the indicator set, but rather to test the set and provide potentially useful insights for further development of the indicator set in future research.

4.6 Summing up chapter 4

This chapter has set out the methodological approach and the detailed research methods which have been used for the empirical work in this thesis. Building on the literature foundations laid out in the preceding chapters, this chapter selected a set of indicators which can be used to assess the security of low-carbon transition pathways, with a case study focus on pathways for the UK electricity system. The chapter selected three existing low-carbon transition pathways to be used as the basis for the application of the set of indicators. This chapter then described in detail the methods which will be used for the application of each individual indicator, including demonstrating the rationale for the choice of each indicator and the literature from which each was drawn. The final part of the chapter then explained the methods for discussing the indicator set with stakeholders in the UK energy community, in order to explore the perspectives of stakeholders on energy security and to explore the impact of stakeholders' perspectives on the results from the initial security assessment.

The following chapter is the first of two results chapters, both of which use the methodology outlined here to carry out empirical research into the security of the UK electricity system in a low-carbon context. The next chapter presents the results from the application of the set of indicators to the three low-carbon transition pathways for the UK electricity system, in order to systematically explore some of the risks, trade-offs and synergies which may occur when attempting to achieve energy security objectives.

5 Results I: Results of the security assessment

This chapter presents the results of the empirical analysis of the security of three selected low-carbon pathways, in order to answer the first research question: “What indicators are appropriate for assessing the security of low-carbon transition pathways in the UK, and what are the results of such an assessment using a set of existing pathways?” The analysis was carried out using the set of indicators developed in Chapter 4, and has applied this set of indicators to the three low-carbon pathways developed by the Transition Pathways to a Low-Carbon Economy Consortium, for the years 2010 (baseline), 2030 and 2050. This chapter presents the results one sub-dimension at a time. Further results from sensitivity tests are presented in the appendices.

As noted in chapter 4, the pathways being assessed do not include a Business-as-Usual (BAU), for reasons which are explained in section 4.2.2. Therefore it is worth reiterating that comparisons are made purely between the three pathways, and are not intended to make any comparisons with any hypothetical BAU pathway. Furthermore, it should be noted that for all indicators, the 2010 results tend to differ only very slightly between the different pathways. This is an artefact of the FESA model which was used to construct the Transition Pathways: the model used 2008 data as the baseline, and therefore shows very slight differences between the pathways in 2010. However, these differences are not great enough to make a significant difference to the overall results, and it should be emphasised that the focus of this assessment is very much on the longer-term transition rather than security of supply in the immediate term.

5.1 Availability Results: domestic disruption

Indicator	**Overview of methods**
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 mix (in GW and %) which is ‘approved’ and ‘opposed’ by the general public
Land requirements	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

(proxy for disruptive opposition)	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
Participation in decisions	Qualitative indicator, uses pathways storylines to assess the level of public participation in energy provision and in decision-making

5.1.1 Public approval ratings

Figure 5.1 shows the approval ratings of the generation mix, in Gigawatts (GW) and % of total capacity. Public approval improves greatly on 2010 levels for all pathways, reflecting higher penetration of Renewable Energy Sources (RES): approval tends to be much higher for RES than for fossils, which is reflected in the high score for the Thousand Flowers (TF) pathway. The approval ratings of the Market Rules (MR) and Central Coordination (CC) pathways also continue to improve. However, as noted in the previous chapter and discussed further later on in this section, public acceptability is complex and much depends on the interaction between approval, opposition and engagement. Moreover, a crucial uncertainty arises from the fact that it is not possible to assess how public opinion will change over time. Therefore more detailed work would probably be required to analyse the public approval levels of the pathways, and care should be taken when drawing conclusions based on the results from this indicator.

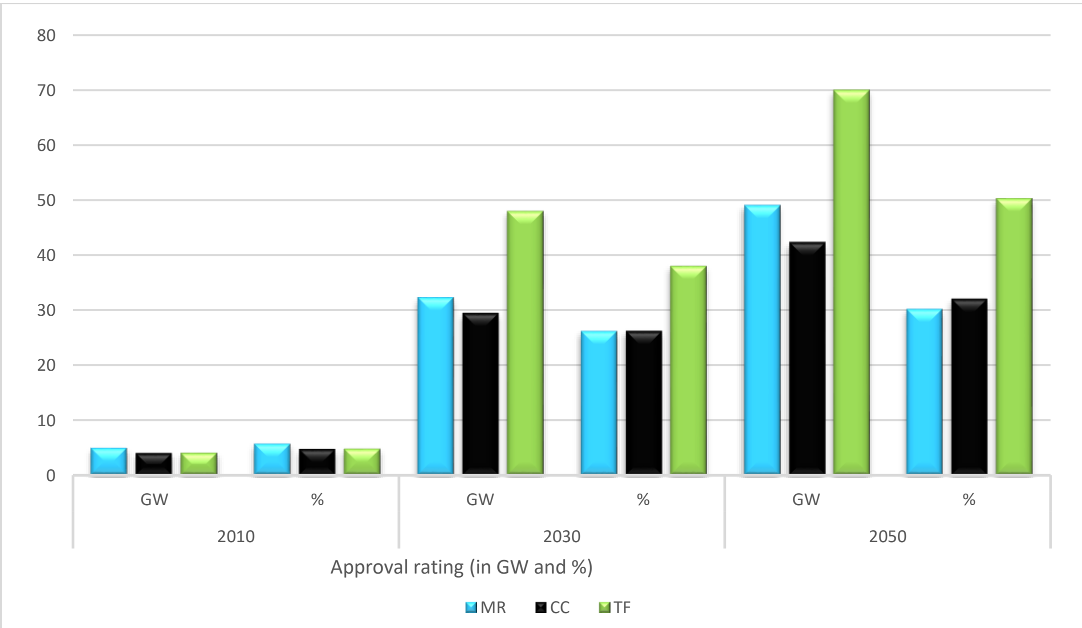


Figure 5-1: Public approval ratings of the pathways, in GW and in % of total fuel mix

5.1.2 Land requirements (proxy for disruptive opposition)

Figures 5.2 and 5.3 show the results from the three indicators showing land requirements of the electricity system, which are used as proxies for levels of risk of public opposition (see section 4.4.1.1). As explained previously, the use of a dashboard approach avoids the aggregation of distinct metrics, therefore these three metrics are kept separate in the analysis.

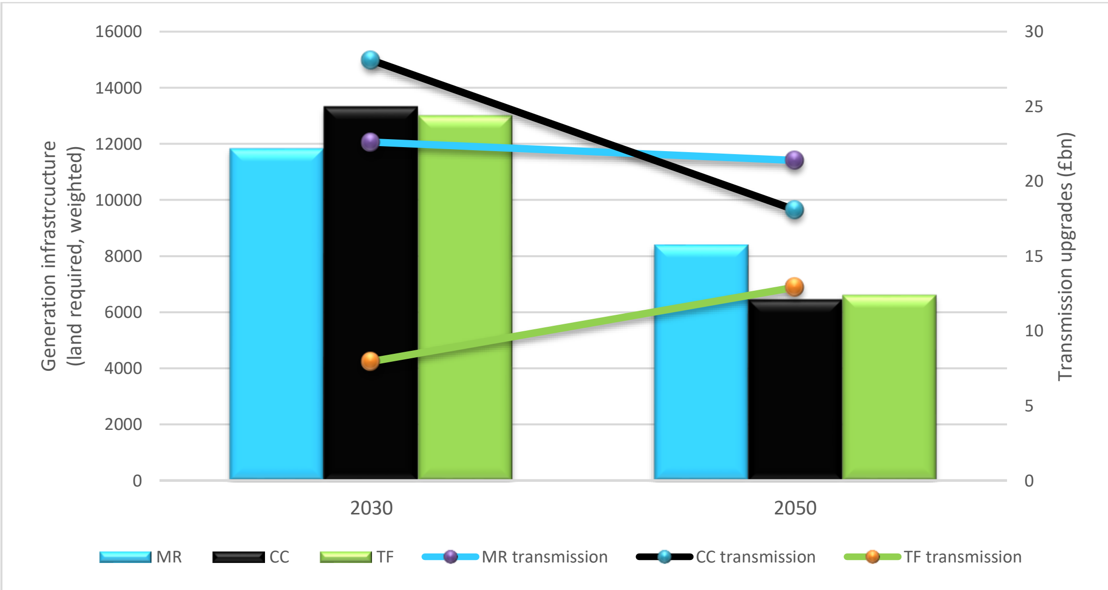


Figure 5-2: Land requirements: generation and transmission infrastructure

Figure 5.2 shows that the pathways are actually fairly similar in terms of additional land requirements for new generation infrastructure. The CC pathway has the highest additional land requirements in 2030, driven by large amounts of wind generation; however, the MR pathway has the highest additional requirements in 2050, driven partly by wind energy again, but also driven by the fact that the MR pathway adds its infrastructure slightly more slowly than the other two pathways. Additional capacity in all three pathways is driven overwhelmingly by new additions of wind and solar, due to the extremely low power output per m^2.

The level of onshore transmission additions required (figure 5.2 secondary axis) suggests that the TF pathway will be least vulnerable to opposition against new transmission infrastructure, due to lower electricity demand which leads to a lower requirement for transmission upgrades, and also a large amount of decentralised generation which generally connects to the distribution network. The CC pathway requires the greatest amount of onshore transmission additions in 2030; by 2050, the transmission requirements for the CC pathway have decreased, but this suggests that the general public will need to get used to a quicker transition to more transmission lines, which could result in more disruption due to unpopularity of the pace of change.

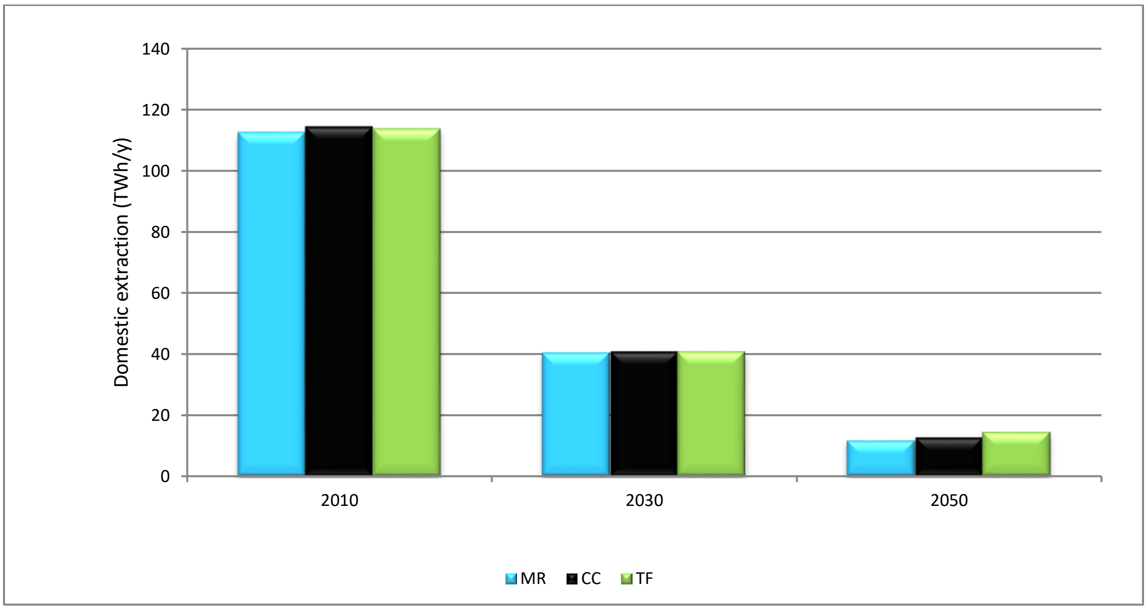


Figure 5-3: Land requirements: domestic extraction of resources

The graph in figure 5.3 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 fossil CCS penetration in these pathways, whilst the TF pathway has much higher biomass requirements. It could be that the unfamiliarity of large-scale domestic biomass production leaves the TF pathway more vulnerable to disruption from opposition to resource extraction, or to local conflicts with non-state actors (Månsson 2015). However, the recent protests against fracking illustrate that although gas and coal themselves are very familiar, new extraction techniques are emerging which are highly vulnerable to disruption. Therefore it is difficult to differentiate between the pathways for domestic extraction.

5.1.3 Participation and engagement in decisions

Table 5.1 shows the level of public participation in decisions being made, under the assumption that greater levels of participation usually lead to higher levels of public acceptance (Bell *et al* 2005; Cohen *et al* 2014; Fast and Mabee 2015; Johansson 2013; Jones and Eiser 2009). People currently perceive the government as having the core responsibility for undertaking the transition to a low-carbon energy system (Butler *et al* 2013). There are very low levels of trust in energy companies, and people don't perceive that the private sector is capable of delivering transition aims in an equitable or effective manner.

Table 5-1: Levels of public participation (from pathways storyline)

MR	CC	TF
Low	Medium	High

It is not possible to generate detailed results using the information provided in the pathways, and these results simply reflect the general storyline. 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 (Barton *et al* 2015). People are generally 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). However, these results are based on a number of assumptions which are not really possible to test with just the information available in the pathways, and considerable uncertainties arise, meaning that care should be taken when drawing conclusions based on the results from this indicator.

5.1.4 Domestic disruption results: key uncertainties and limitations

The results presented in this section don't attempt to predict whether opposition will occur, but rather attempt to measure the likelihood of opposition due to factors such as proximity to new infrastructure. There is one critical uncertainty which arises from all the analyses in this section: there is no way of assessing how public opinion or the opinions of opposition and protesters will change over time. The survey results could only capture one moment in time (in 2012), and the results simply reflect historical trends, leading to significant uncertainties. A number of particular issues are worthy of note:

- Will the availability of CCS result in higher approval ratings for coal and gas generation?
- Will safety advances by the nuclear industry globally ever manage to allay people's fears in the UK and elsewhere in Europe, and what impact will opposition to nuclear in Europe have on the nuclear industry in the UK? What impact will unresolved issues around the disposal of nuclear waste have on public acceptance of nuclear generation in the future?
- Will renewables such as wind and solar (currently the most popular forms of generation) become less popular, for instance due to increasing visual impact, rising costs, or perceptions of decreasing grid stability as is currently being experienced in Germany (Mengewein 2014)?
- The debate over fracking is gathering speed in the UK, and the government has recently changed the law to make it easier to gain planning permission for exploratory drills (HM Government 2015). If fracking goes ahead in the UK on any sort of scale (which may or may not happen), will the popularity of gas decrease as people associate it more with an unpopular form of extraction; or will political framings of the benefits of gas generation succeed in increasing its popularity?
- Could opposition arise against some forms of imports, for instance if biomass imports were perceived to be environmentally problematic?

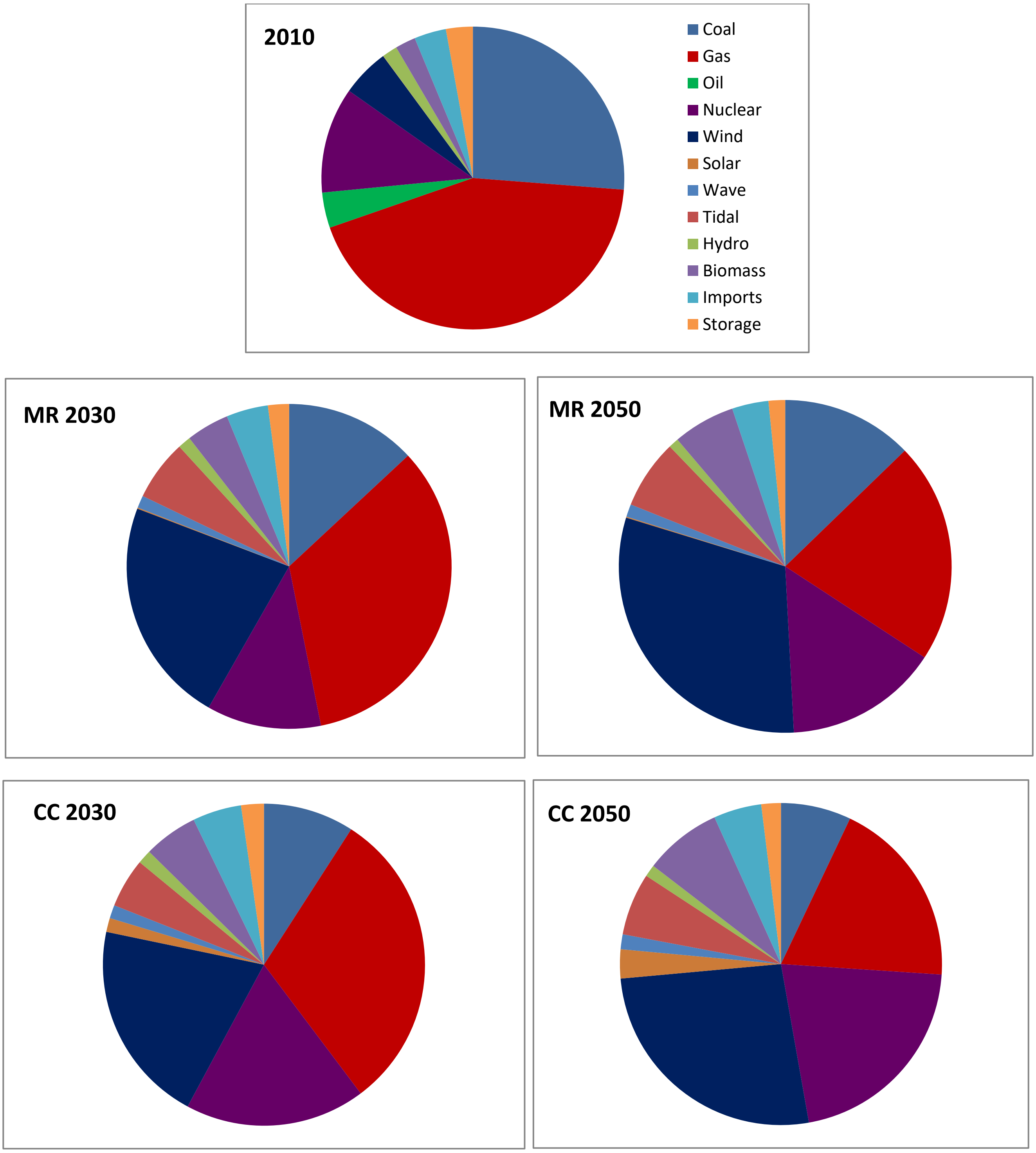
5.2 Availability Results: non-domestic disruption

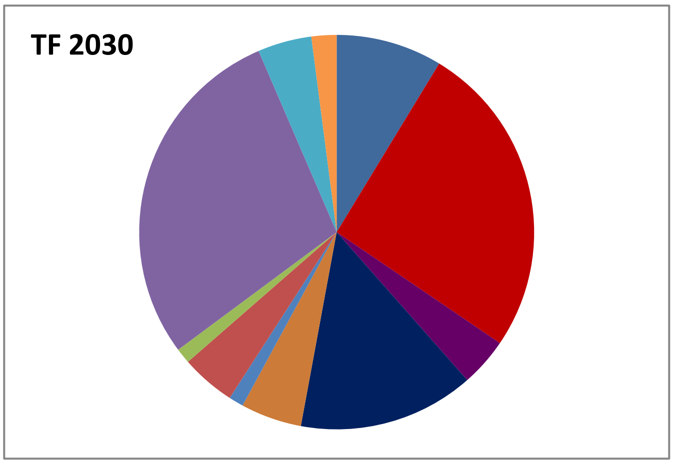
Indicator	**Overview of methods**
Diversity of fuel types in the electricity mix	Shannon-Wiener diversity calculation: -∑ Pi*(Ln(pi)), as used by Lehr (2009); Pfenninger and Keirstead (2015); Stirling (1998)
Dependence on fuel imports	Pathways data used to show % of fuel mix from imports for coal, gas and oil Uranium estimates from current stockpile data Biomass estimates using total indigenous biomass potential (estimate from pathways data)
Diversity & stability of fuel imports	Current (2010) fuel import diversity is measured using Shannon-Wiener index 2010 fuel import stability measured by adding a stability parameter (Neumann 2007**)**: NSW1= -∑ Pi*(Ln(pi))*b where 'b' represents a stability parameter, derived from the Fragile States Index (Foreign Policy 2014) Insufficient data in pathways for quantitative analysis; therefore qualitative statements made about possible future diversity and stability

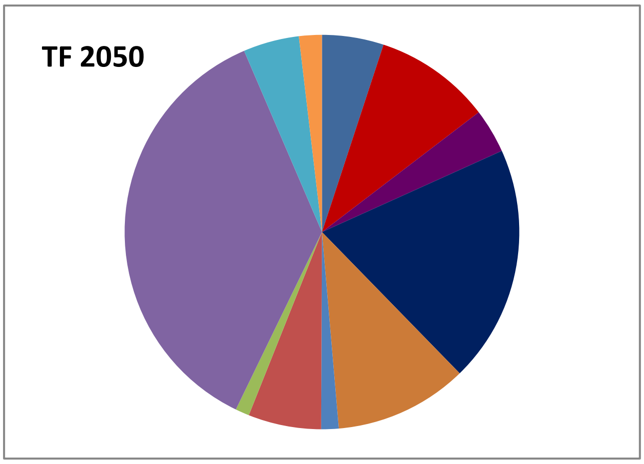
5.2.1 Diversity of fuel types in the electricity mix

The pie charts in figure 5.4 show the generation mix in the pathways. These pie charts are useful because they provide a good overview of the most prevalent fuels in the pathways in 2030 and 2050. The pathways are all roughly the same in 2010, therefore just one graph is presented for 2010 to provide comparison.

Figure 5-4: Generation mix in the pathways



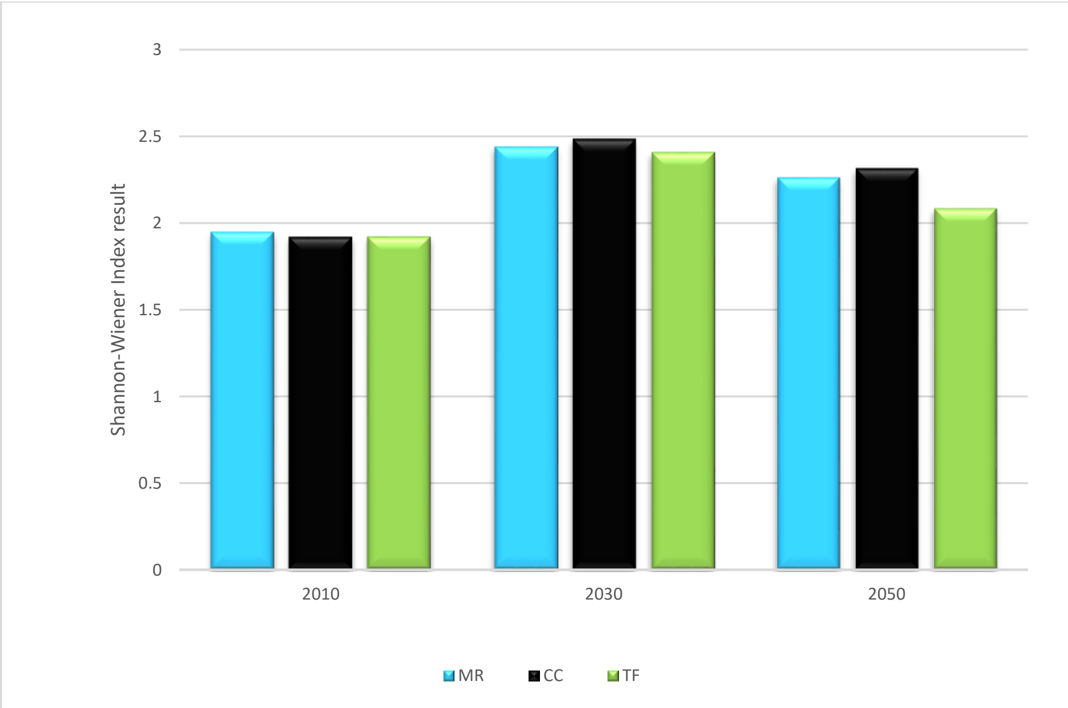




As shown in the pie charts, the prevalence of coal and gas decreases in the future in all the pathways, increasing diversity. The MR and CC pathways both remain reliant on just three or four generation types in 2030 and 2050, although the balance shifts towards increased reliance on wind. The TF pathway on the other hand shows a greater diversity of more minor fuels, but by 2050 is highly dependent on biomass, which makes up a third of its generation mix. This could make the TF pathway vulnerable to disruptions in the biomass supply chain.

Figure 5.5 shows the fuel diversity results using the Shannon-Wiener diversity index. A higher number indicates higher diversity (see section 4.4.1.2). Diversity increases for all pathways, with the CC pathway experiencing the greatest increase in diversity. The TF pathway scores lower than the other two for diversity, reflecting a considerable reliance on biomass as a back-up for intermittent sources.

Figure 5-5: Fuel mix diversity: Shannon-Wiener index results



5.2.2 Fuel imports: dependence, diversity and stability

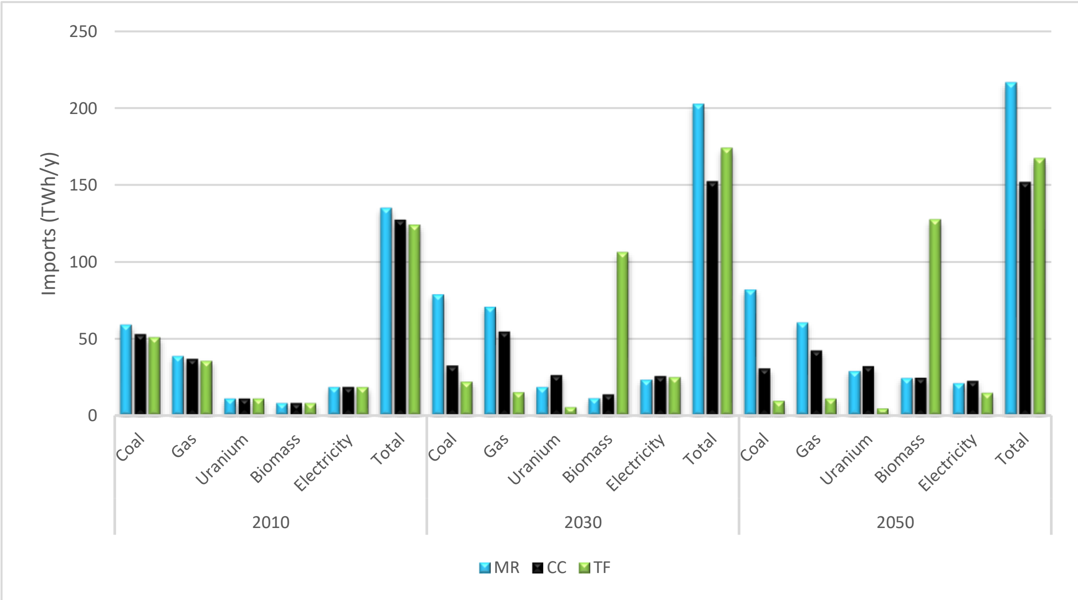
5.2.2.1 Import dependence

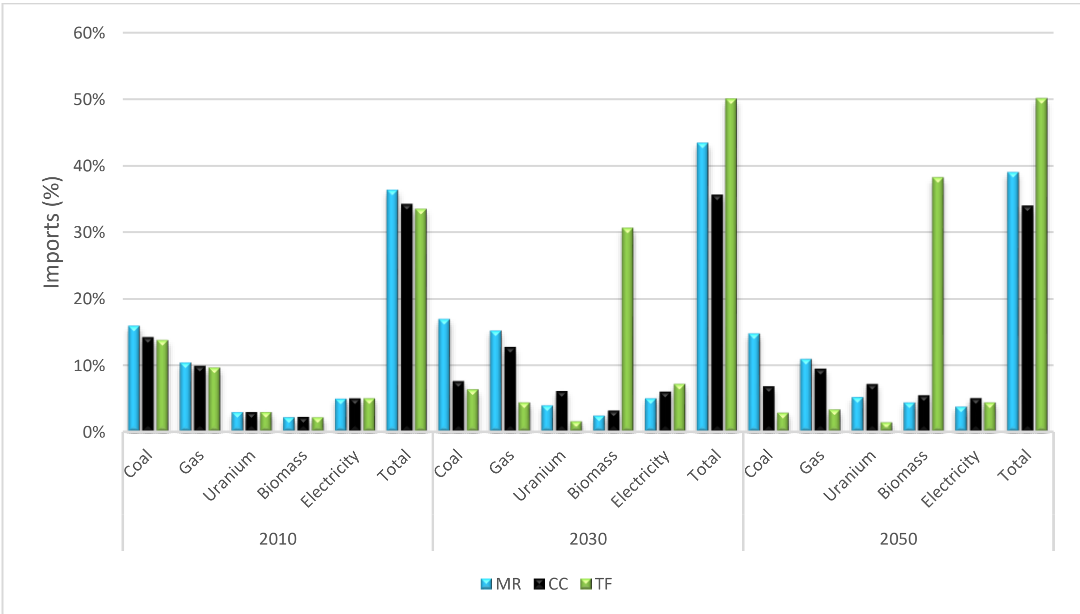
The graphs in figure 5.6 show the dependence of the pathways on imports of each major fuel type. It is important to note that imports are not necessarily less secure than domestic supplies (Johansson *et al* 2014; Performance and Innovation Unit 2002; Watson and Scott 2008): diversity and stability must also be taken into account, as high dependence on non-diverse or unstable imports could indicate a risk of external disruption to supplies (Jonsson *et al* 2015).

The total amount of electricity (in TWh/y) which comes from imports increases in all the pathways. The MR pathway sees the greatest increase in imports, driven by rising demand and dependence upon imported coal and gas. The TF pathway, despite achieving reductions in electricity demand, also sees steep increases in import dependence; this is driven mainly by reliance on imported biomass, as suggested by the pathways data (see Appendix B). These results show that a low-carbon system does not necessarily result in reductions in fuel imports.

When viewed as a percentage, the MR and CC pathways appear less reliant on imports than the TF pathway, due to rising demand in these pathways. The CC pathway actually sees its proportion of import dependence remain roughly stable through to 2050. The TF pathway experiences a steadily increasing dependence on imports; this is driven solely by reliance on imported biomass. These graphs illustrate the importance of viewing results both as absolute values (for example, in TWh/y) and relative values (for instance, in %). For example, the MR pathway relies on imports for a smaller percentage of its overall mix, yet also requires a higher *volume* of imported fuels, which could increase the potential for disruption to these sources.

Figure 5-6: Dependence on imported fuels, in TWh/y and % of total generation output





5.2.2.2 Diversity and stability of fuel imports

Figure 5.7 shows the results from the calculations for fuel import diversity and stability for 2010, for each of the major fuels (coal, gas, uranium and biomass), as well as electricity imports. This method generates lower scores for stability than for diversity across the board (see Neumann 2007). The results for the current (2010) situation show that the imports of major fuels are reasonably diverse; a score of near zero or below 0.5 would indicate vulnerability. Biomass is the most diverse source, and coal also scores well. This implies that pathways with high proportions of biomass and coal would be least vulnerable to disruption due to lack of diversity of imports. Uranium is shown to be the least diverse; however, it should be noted that uranium risks are mitigated by increased stability from stockpiles (see section 5.2.3).

Coal experiences some issues with stability, with a very significant gap between its diversity and stability results; this is to some extent the same with biomass, but the extremely healthy diversity score for biomass helps to mitigate vulnerability. Gas is in general fairly diverse and also fairly stable. Uranium and electricity imports are both less diverse, but have fairly high stability scores, suggesting that vulnerability to external disruption can be mitigated for these fuels. Overall, these results suggest that pathways with large amounts of coal could experience risk and vulnerability caused by lack of stability of exporting nations.

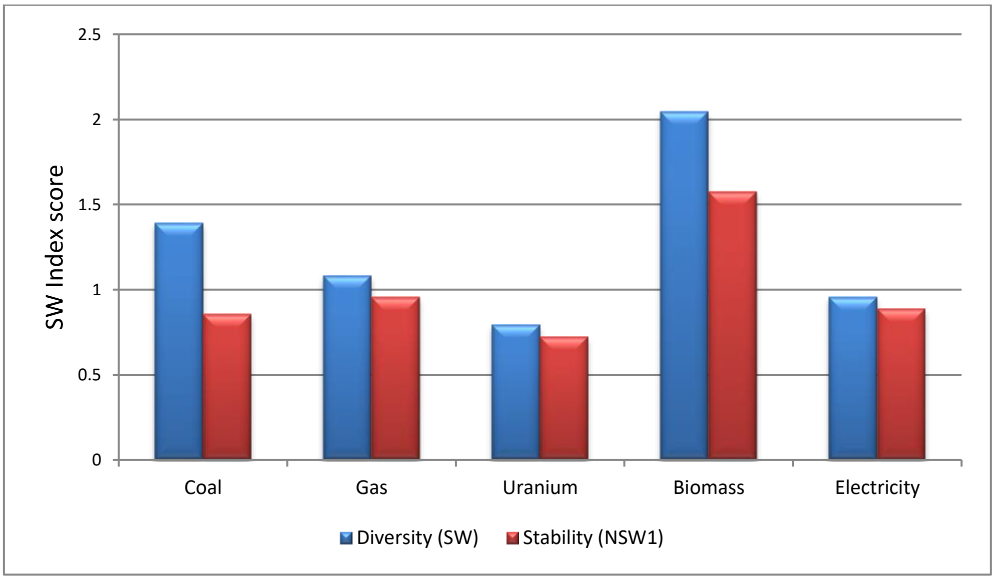


Figure 5-7: Results from Shannon-Wiener diversity index and import stability index

Unfortunately, it is not possible to project future trends of fuel import diversity or stability to 2030 and 2050. There are a vast number of variables which could influence where the UK sources its fuels from in the future, most of which are impossible to project. It is the contention of this research that wherever possible, an assessment of the energy security of transition pathways should be 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 more information about sources of imports and routes of transit.

It is clear from the results that certain fuels are currently more diverse than others, and that certain fuels could be more vulnerable to instability in exporting nations. From this, it is possible to point out some potential risks and vulnerabilities which could lie within the pathways; however, this is highly conjectural.

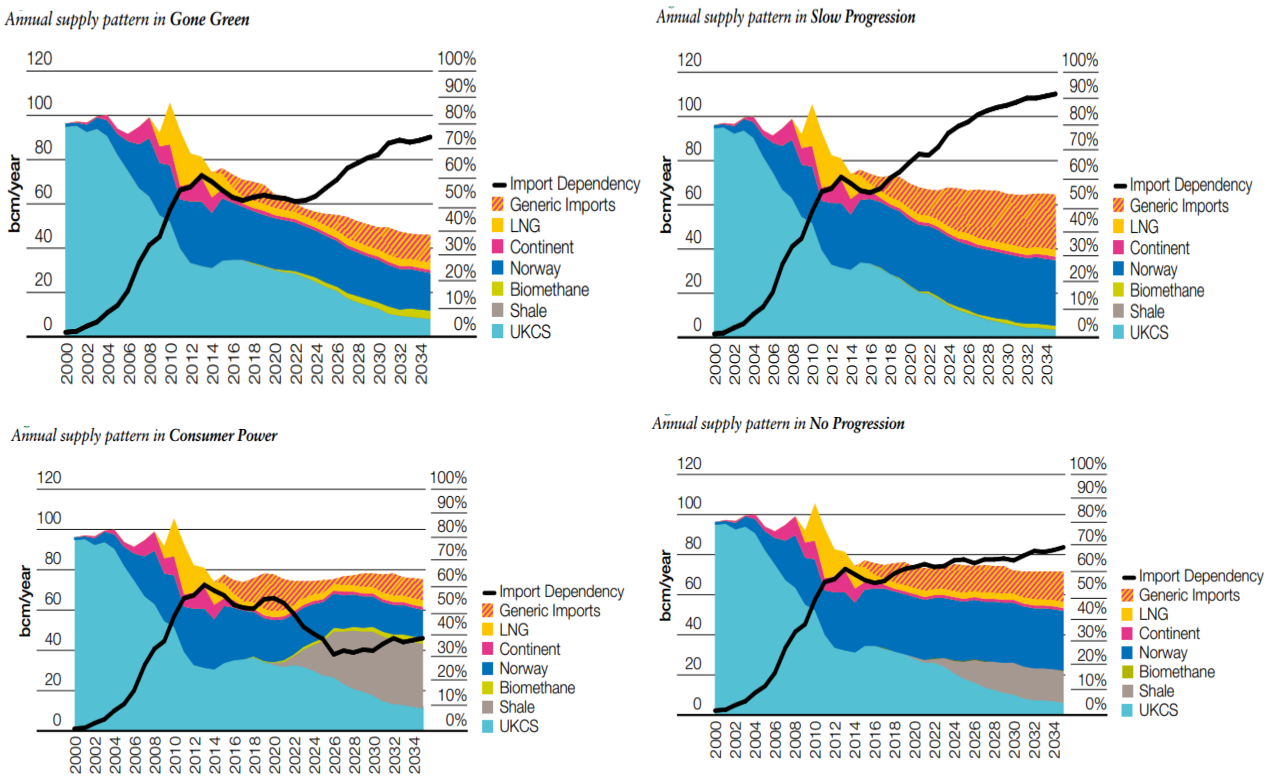
5.2.2.2.1 Coal

Coal imports are currently very diverse, and therefore coal imports could potential be a reliable and diverse source of fuel for the pathways with lots of coal (MR, and to a lesser extent CC). The results from the NSW1 index (diversity plus stability) suggest that coal imports are currently less stable than gas imports, probably driven by reliance on countries such as Russia and Colombia; however, this has not proved to be a problem for securing coal imports in the past, and could also be mitigated in future by increasing coal imports from other areas such as the US and Canada (driven by the shale gas boom), South Africa, Australia or South-East Asia. Unlike gas, coal does not rely on new infrastructure such as terminals to support new trade flows, thus making diversification of suppliers simpler. Overall, it is likely that the key constraint upon UK coal consumption and global coal production will be climate policy, rather than import disruption (von Hirschhausen *et al* 2010).

5.2.2.2.2 Gas

The majority of the UK's gas comes from Europe; the number of supplier countries is fairly low and not particularly diverse, but most are very stable. However, this supply is likely to diminish in the future, as European Continental Shelf reserves deplete and Norwegian reserves stagnate. The graphs in figure 5.8 show National Grid projections of gas supply to 2034 for their four energy scenarios (National Grid 2015b). The graphs show that import dependency is expected to increase in all but one scenario, even if overall gas consumption decreases. They also show that if gas consumption remained stable ('no progression' scenario), imports from both the Continent and as Liquefied Natural Gas (LNG) would need to grow in order to meet demand. As such, this is a vulnerability concern for the pathways which are dependent on gas (MR and CC), because gas supplies would potentially be reliant on less stable areas such as the Middle East. It is also worth noting that security analysts often express concern about the notorious transit choke points of the Strait of Hormuz, the Bab el-Mandab and the Suez Canal (US Energy Information Administration [EIA] 2012), and that although this has mainly been a concern for oil in the past, increasing reliance on LNG from the Middle East could increase the exposure of the UK gas supply to problems at transit choke points (Emmerson and Stevens 2012). There is no guarantee that new sources of LNG, for instance from US shale, would head to Europe instead of to other markets such as in Asia; the eventual destination of gas supplies is determined by consumers' willingness to pay, projections of which to 2030 and 2050 are outside of the scope of this analysis. The National Grid projections also show that import dependency could be mitigated by domestic shale gas in the longer-term, and this represents a key uncertainty over the future of UK gas supplies. However, only one of National Grid's scenarios projects a significant amount of domestic shale gas, and this scenario is not carbon-constrained; moreover, the results for the import dependence indicator suggest that none of the three Transition Pathways utilises significant amounts of domestic shale.

Figure 5-8: Gas supply projections to 2034 showing import dependency (National Grid 2015b)



5.2.2.2.3 Uranium

There is an understandable lack of transparency regarding uranium imports, but the UK is currently listed as having uranium trade arrangements with only 3 countries: Australia, Canada and South Africa (Good Energy 2012; World Nuclear Association 2014). Many uranium deposits are in relatively unstable areas such as Kazakhstan, Niger and Namibia (World Nuclear Association 2014), meaning that an increase in diversity could potentially result in a decrease in stability. Although uranium is generally considered to be a highly secure fuel, the CC pathway which is highly dependent on nuclear could be vulnerable if the uranium trade with any of the three exporting nations were to fail, for instance due to a change of policy in the exporting nation or a spike in price.

5.2.2.2.4 Biomass

Biomass imports are currently very diverse. There are opportunities to grow biomass in most countries worldwide, meaning that diversity is unlikely to become an issue in future. In terms of stability, at present it is likely that the UK will source much of its biomass feedstock for electricity generation from highly stable areas such as Canada, Scandinavia and the US, meaning that stability risk is currently low (Hogan 2013). Nevertheless, the TF pathway relies on a huge amount of imported biomass; this could be vulnerable if other countries were to pursue similarly ambitious biomass plans, or if other sectors such as heating were to become more reliant on bioenergy (Genus and Mafakheri 2014; Welfle *et al* 2014a). In general, the biomass supply chain is unclear in the future, and there is little information about possible future resource flows (Johansson 2013; Welfle *et al* 2014a). The large biomass conversion project at Drax power station may provide some clues in the near future about emerging biomass supply chains: Drax is likely to source the vast majority of feedstock from the US (Lovell 2013), and in fact has started to construct two new Drax-owned pellet mills in Mississippi and Louisiana and dedicated feedstock import infrastructure in the UK (Drax Biomass 2015). However, concerns have been raised already that the upstream supply chain for industrial wood pellets in the US could be at risk of over-development (Rivers 2013). Much of the uncertainty over future biomass supply stems from the fact that biomass represents a fairly small proportion of the UK's energy mix at present; this uncertainty represents a risk for the TF pathway.

5.2.2.2.5 Electricity

Electricity imports are currently not particularly diverse, but they are very stable. The UK currently has electricity interconnection with France, the Netherlands and the Republic of Ireland. The three pathways all include a similar level of electricity imports in the future, probably involving additional connection with France, Ireland, Belgium and possibly Norway. This will increase diversity and also maximise electricity imports from a selection of highly stable nations; as such, there is very little vulnerability for any of the pathways in this area.

5.2.3 Storage and stockpiles

It is worth noting that vulnerability to fuel supply risks is dependent on how easy fuels are to store. For example, uranium was noted in section 5.2.2 to have very low import diversity; however, uranium is generally considered 'secure', because it is cheap and easy to stockpile.[16] Coal requires more space and is therefore more expensive to store; however, large amounts of coal can be stockpiled easily (all it requires is a field and a fence). Gas is more complicated and expensive to store, and a history of easy access to North Sea gas along with a lack of incentives to build storage in the UK have led to comparatively low levels of gas storage (Le Fevre 2013;

[16] According to the Nuclear Energy Institute (2015), a single uranium fuel pellet the size of a fingertip contains as much energy as 17,000 cubic feet of natural gas or 1,780 pounds of coal

Watson 2010). Although new gas storage sites have been proposed, many potential projects are on hold or have been cancelled due to unfavourable economics (National Grid 2013e). Finally, biomass generally has very low energy density per m^2 (MacKay 2009); this means that more space is required to store it, which increases the cost of stockpiling. Moreover, feedstocks such as plant residues and wood pellets need to be dried and kept free of residual moisture build-up; this is not the case for other fuels, and adds significantly to the cost (Ikonen *et al* 2013).

5.2.4 External disruption: key uncertainties and limitations

The uncertainties in this sub-dimension are extremely high, as it is not possible to assess with any degree of robustness the areas where the UK might source its fuel in several decades' time. However, this means that in many ways the primary focus here is not of the results per se, but of the emerging uncertainties which this indicator has helped to highlight. Each of these uncertainties point to areas of security risk, and help to highlight areas in which policy can mitigate risks.

The key uncertainties (in no particular order) are:

- **Biomass**: how much biomass can the UK source indigenously? Where is the rest going to come from, and how secure are the supplies and the supply chains likely to be? (Mainly applies to the TF pathway).
- **Shale gas**: will the US export significant volumes of LNG, and will these supplies come to Europe? Is it likely that significant amounts of UK gas could be sourced through domestic fracking in future? (Applies to all pathways, but less so for the TF pathway in 2050).
- **The Middle East**: how will ongoing political situation in the Middle East evolve? Is there any danger of tensions impacting supplies, especially at important transit choke points? (Mainly applies to gas imports, which is more relevant for the MR and CC pathways).
- **New gas pipelines**: will planned pipelines to transport gas into Western Europe be built, and if so what is the likely timescale? Will these pipelines help to make UK gas supplies more secure? (Again, mainly applies to gas imports, which is more relevant for the MR and CC pathways).
- **Policies on fuel storage and stockpiling**: will policy create incentives to increase storage capacity and stockpiles of key imported fuels (especially gas and, in the future,

biomass), and how much will this add to the cost of the fuels? (Applies to all pathways).

5.3 Affordability Results: cost to the system

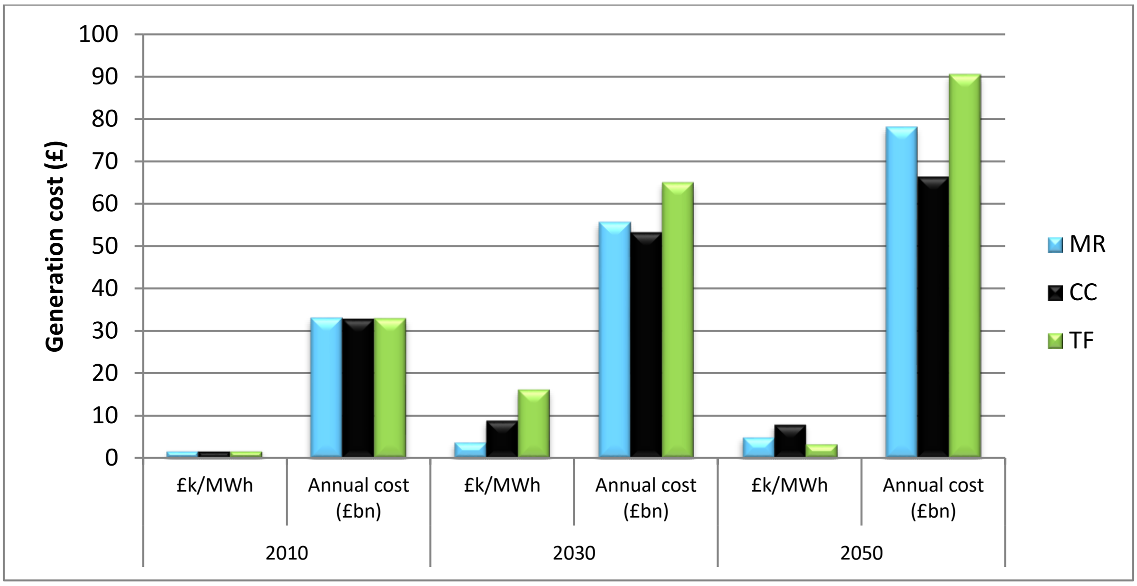
Indicator	Overview of methods
Generation costs	Calculates LCOE using CAPEX (pre-development, construction), fixed OPEX (O&M, connection charges, insurance), variable OPEX (variable O&M, fuel, carbon price) (e.g. Pfenninger and Keirstead 2015) Cost data from DECC (2013d) and Mott Macdonald (2010)
Transmission upgrade costs	Onshore upgrade costs calculated using Electricity Networks Strategy Group estimates of upgrades required for different levels of new capacity (ENSG 2012) Offshore upgrade costs calculated using estimated unit costs (from National Grid 2013c)
Distribution upgrade costs	Distribution upgrade costs for the pathways modelled by Pudjianto *et al* (2013)

5.3.1 Generation costs

Figure 5.9 shows the central estimate of the generation costs for the three pathways, in Levelised Cost of Electricity generation (LCOE) and total annual costs (the range is discussed below). Generation costs increase significantly for all the pathways in 2030 and 2050. The TF pathway has the highest total costs in both 2030 and 2050; in 2050, total annual costs for this pathway are a full £25bn more than for CC. The main reason for this is not because the plants are more expensive; in fact, as shown in the £/MWh results, the TF pathway actually has lower costs per MWh than the other two pathways. Rather, it is because the TF pathway has large amounts of spare capacity (explained in more detail in section 5.8.3); this means that much of the power generation is only running for limited hours throughout the year, which increases the total generation costs. As such, it can be seen that the backup for the decentralised, dispersed and intermittent RES in the TF pathway may come at high cost.

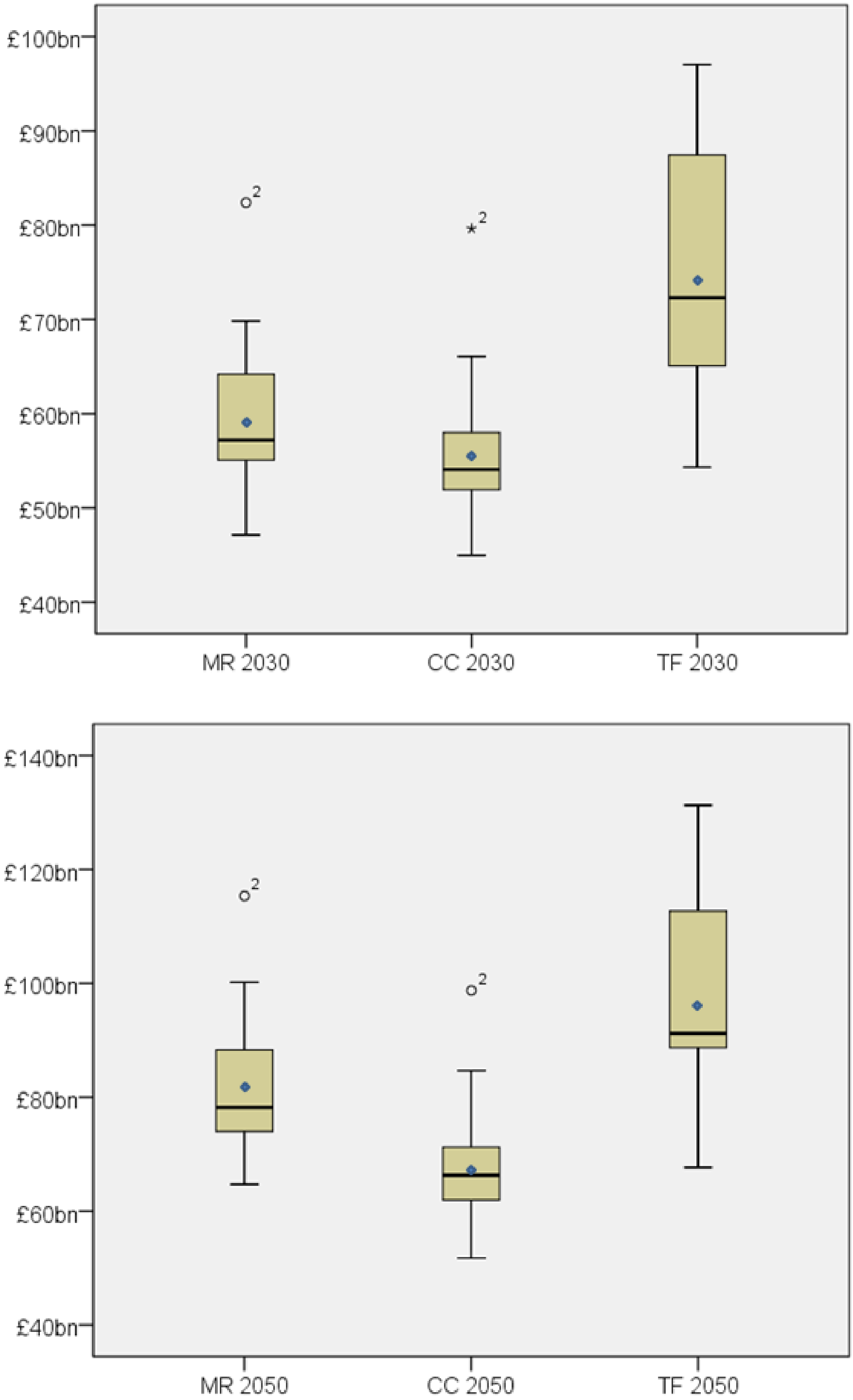
It should be noted that these calculations do not go into detail about other system costs such as the cost of capacity reserve and the cost of balancing. Capacity reserve (i.e. the capacity needed to back up intermittent renewables) is factored into the whole-systems modelling of the pathways, and therefore the cost of capacity reserve is included in the calculations (including the cost implications of reduced running hours for conventional generation used for backup; see Appendix C). System balancing requirements are covered in section 5.9; modelling the costs of this balancing are outside the scope of this thesis, although this could be an interesting area for further research.

Figure 5-9: Cost of electricity generation in £k/MWh, and £bn annual cost



There are large uncertainties in these estimates, mainly because of a lack of publicly available and reliable data. Therefore, several sensitivity analyses were carried out, to show the impact of assumptions regarding discount rates, learning curves, CAPEX estimates, fuel costs, and carbon price. Full details of the methods used and results of these tests are given in Appendix C. The graphs in figure 5.10 show the range of results from the sensitivity tests, illustrating the median, 25th and 75th percentiles (boxes), the upper and lower range of estimates (whiskers), and the mean (blue marker). The graphs show that the range for the TF pathway is considerably greater than the range for the other two pathways, mainly reflecting the uncertainty which accompanies the more ‘radical’ nature of the generation mix in this pathway. However, the MR and CC pathways both have an outlier far above the normal range of the results, representing the outcome which would occur due to a doubling of the discount rate for all generation technologies. Higher discount rates could leave the MR and CC pathways vulnerable to CAPEX increases. Nevertheless, the results from the sensitivity analyses demonstrate that the TF pathway is highly likely to be more expensive than the other two pathways.

Figure 5-10: Sensitivity analyses of £bn annual generation cost, 2030 and 2050



5.3.2 Network costs

Figure 5-11: Total cost of upgrades and additions to the transmission networks

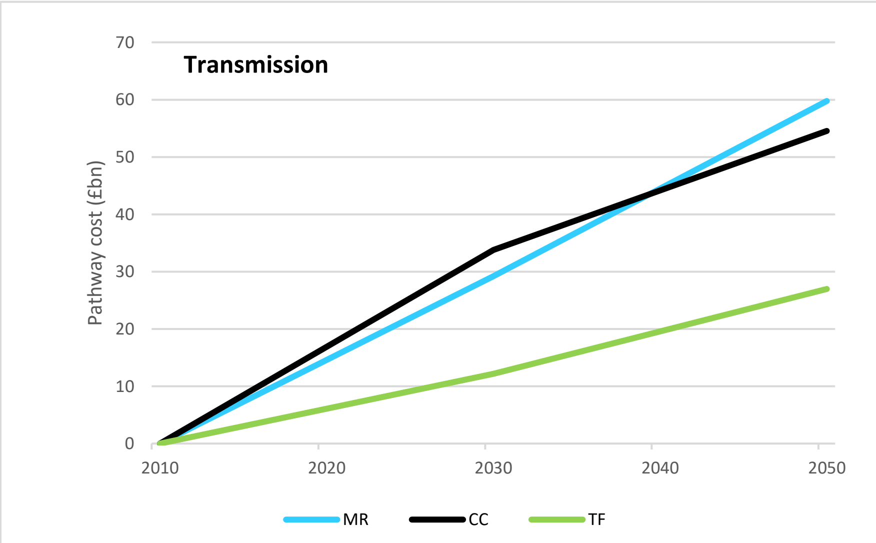
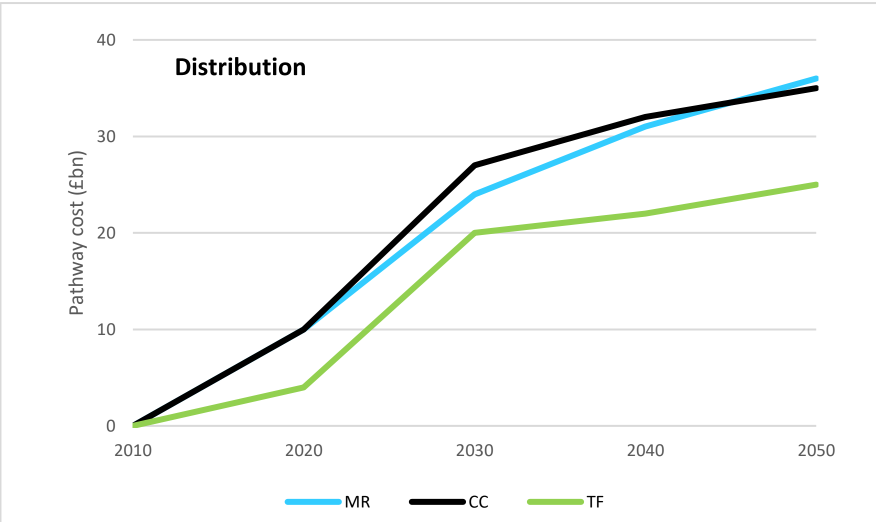


Figure 5-12: Total cost of upgrades and additions to the distribution networks



The graphs in figures 5.11 and 5.12 show the estimated costs to upgrade the transmission and distribution networks in order to connect the supply capacity of the pathways to the grid. As can be seen, network upgrade costs increase for all three pathways. The MR and CC pathways both experience high transmission upgrade costs, driven by high electricity demand, centralised power generation, and high proportions of wind and nuclear in both pathways. Transmission costs for the TF pathway are significantly lower, because of lower electricity demand and decentralisation. Despite decentralisation, the TF pathway also experiences lower distribution upgrade costs, because of lower levels of demand in this pathway, which reduces network loading and thus reduces the necessity for upgrades. These graphs show that decentralisation and reductions in electricity demand can be an extremely effective means of reducing required network upgrade costs.[17] The low network costs for the TF pathway contrasts with the high generation costs for this pathway shown in the previous section. A key challenge for transition pathways should be to attempt to realise the network gains of having more distributed power, whilst avoiding the high levels of spare capacity which lead to such high generation costs. This could potentially be achieved through flexible demand (discussed in more detail in section 5.9.4), or through better linking of distributed systems, for instance by increased use of larger-scale flexibility measures such as interconnection or a national smart grid.

5.3.3 Cost of the system: key uncertainties and limitations

Assessments of future energy costs tend to be so dogged by uncertainties that time and time again they have proven to be inaccurate. As such, it is best to view the results presented above as a high-level overview of some of the key factors which could affect the costs of different pathways to a low-carbon transition, rather than as actual projections of costs in the future.

Some of the core areas of uncertainty are outlined below. For all of these core areas of uncertainty, the sensitivity tests explore the implications of different assumptions (see Appendix C).

- **Raw data**: the LCOE analysis uses publicly available data from DECC (2013d) and from Mott Macdonald (2010). However, this raw data is subject to its own sets of assumptions and uncertainties.
- **Discount rates**: as shown in the sensitivity tests in Appendix C, different assumptions regarding discount rates can have a large impact on generation cost results. However, real-world discount rates vary and tend to be highly commercially sensitive, and therefore there is no public data available.
- **Learning curves:** some technologies experience learning curves, in which costs come down as the technology becomes more mature (Barreto 2001; Gross *et al* 2013; IEA 2000). On the other hand, other technologies (such as nuclear) have been shown to experience the opposite effect (Grubler 2010). There are big uncertainties over the

[17] Note: currently, offshore generators pay for their own cables, they are not paid for by National Grid (Strbac *et al* 2014). However, costs will probably still be passed onto consumers.

extent (and direction) of learning curves, which differ for different technologies, and learning curves are heavily influenced by technology policy both in the UK and internationally (Gross *et al* 2013). Further detailed research would be required to refine the affordability results in relation to detailed analysis and projection of learning curves, which is outside of the scope of this thesis.

- **Fuel costs:** projections of fuel costs are generally inaccurate. For example, the most recent EIA Annual Energy Outlook Retrospective Review (EIA 2015a) shows that forecasts of crude oil and natural gas prices are often wrong by a margin of upwards of 70% (even in some cases just a few years in advance). Fuel costs are highly susceptible to disruptive events such as financial crises or the shale gas boom, which energy analysts in the past have generally failed to predict.
- **Carbon price:** the future carbon price is determined by policy, and recent UK reforms have increased the uncertainties (HM Revenue and Customs 2014). Unlike the other uncertainties herein, this uncertainty could be significantly reduced via consistent and transparent carbon pricing policy.

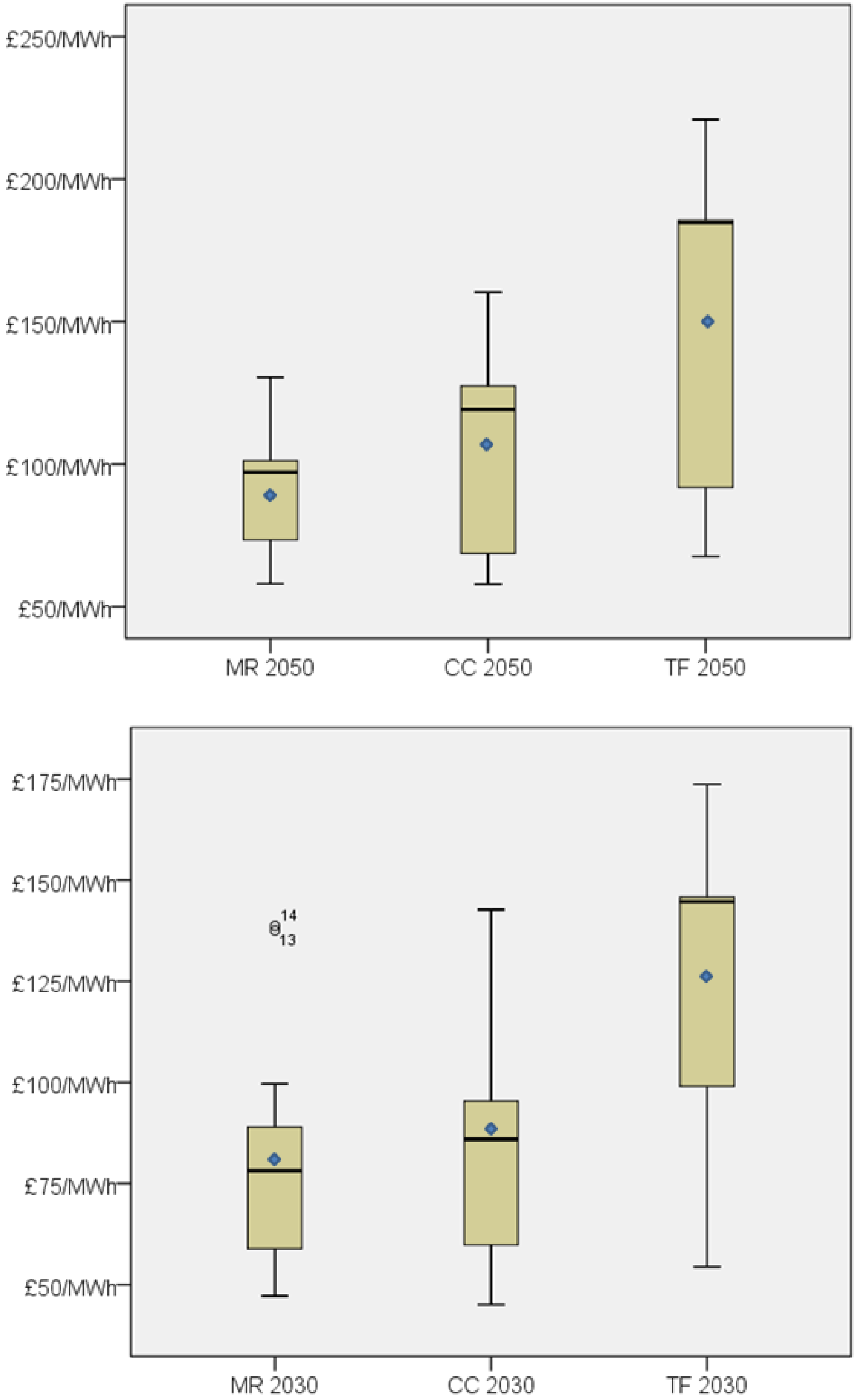
5.4 Affordability Results: cost to the consumer

Annual retail electricity bills	Wholesale electricity 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. VAT (5%) not included in estimate.
Impact on fuel poverty	Qualitative analysis carried out using annual bills estimates, existing literature on levels of fuel poverty in the UK (especially Hills 2012), and the pathways storylines

5.4.1 Wholesale prices

In order to calculate the cost to the consumer, it is first necessary to calculate the wholesale price of electricity for the generation portfolio. This is not the same thing as the LCOE, as it depends on the price-setting technology. The technology which sets the price is determined by the market, and as such the uncertainties are enormous. Therefore, the graphs in figure 5.13 show the results from a set of sensitivity analyses which are further discussed in Appendix C. The results illustrate considerable uncertainties for the TF pathway, mostly stemming from biomass cost uncertainties. This represents increased vulnerability for this pathway, as there is still relatively little concrete information regarding the likely wholesale price of biomass generation in the future. There are also concerns that vulnerability could result from price volatility of feedstock imports (Genus and Mafakheri 2014).

Figure 5-13: Range of results from wholesale price sensitivity analyses, 2030 and 2050



5.4.2 Annual retail electricity bills

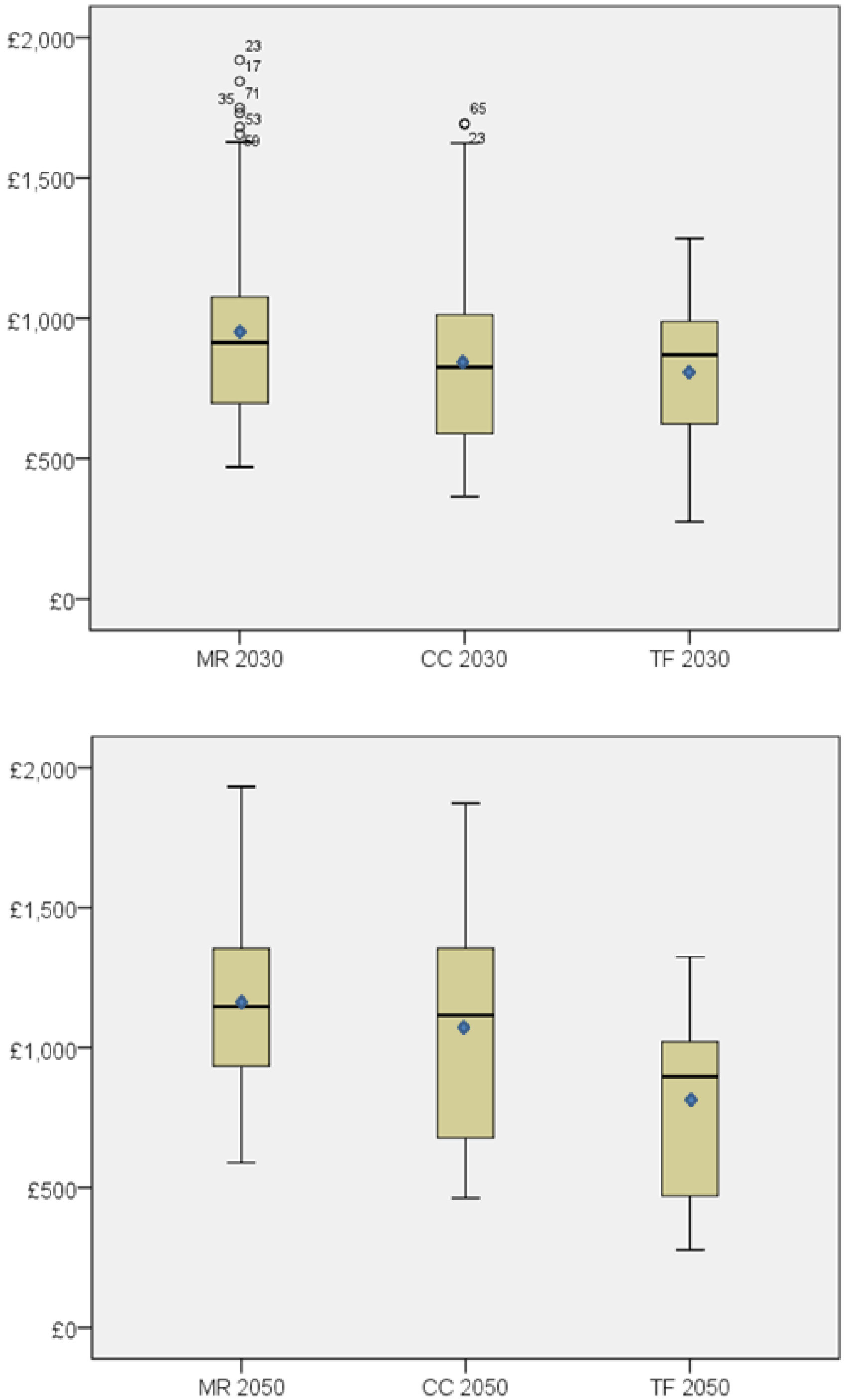
The graphs in figure 5.14 show the range of results for the estimation of annual household electricity bills, including the range returned by the sensitivity analyses (for full methods and results see Appendix C). The high, median and low results in table 5.2 are taken from the upper quartile, median and lower quartile values obtained from the various sensitivity tests. It should be noted that this calculation does not include any discounts consumers may receive for buying their gas and electricity from the same supplier.

Table 5.2 shows that the pathway with the lowest annual bills in 2050, taking into account all the assumptions and caveats discussed previously, is likely to be the TF pathway; this is also the pathway which was found to have the *highest* generation costs. This is because of the impact of reductions in demand in the TF pathway: electricity demand in this pathway remains stable despite considerable electrification of heating and transport, driven by increased consumer engagement and behaviour change (Barton *et al* 2015; Foxon 2013). The results from this indicator clearly show the importance of demand reductions in mitigating bill increases (for more on demand, see section 5.9.4). However, this places a lot of pressure on the TF pathway to achieve ambitious demand reductions, which could require broader changes in social attitudes (Foxon and Pearson 2013). Finally, it is worth emphasising that there is significant overlap within the range of all three pathways; therefore although the TF pathway is found to have the lowest annual bills in 2050, changes to certain assumptions could make this result less definitive.

Table 5-2: Annual bills (£/year, not including VAT)

	2010	**2030**			**2050**		
	Baseline	**Median**	**High**	**Low**	**Median**	**High**	**Low**
MR	£415.68	£912.75	£1073.66	£699.69	£1146.91	£1349.45	£940.30
CC	£392.65	£825.76	£1009.65	£594.82	£1115.82	£1344.99	£678.50
TF	£390.64	£869.51	£983.27	£624.12	£896.85	£1015.02	£470.35

Figure 5-14: Range of results from annual bills sensitivity analyses, 2030 and 2050



5.4.3 Fuel poverty

Table 5.3 shows the annual bill median figures, along with an approximation of the level of fuel poverty risk from the pathway storylines, from the pathways 'storylines' elaborated in the following paragraph. In common with the other affordability indicators, it shows that the CC pathway is the least risky in the medium-term, whereas the TF pathway is the least risky in the long-term.

Calculating the impact of bill increases on levels of fuel poverty in the pathways would necessitate projections of future incomes and income distribution, as well as detailed information on government policies to mitigate fuel poverty. This information is not available in the Transition Pathways data, therefore all that can be done is to look at the pathways storylines and comment on what these might mean for levels of fuel poverty in the future. It is argued by the Hills review (Hills 2012) that redistributive government policies could balance out the impact of rising annual bills, therefore the government control in the CC pathway could potentially counter the impact of rising fuel prices through government policies aimed at reducing the impact on the poor. The free-market logic of the MR pathway, on the other hand, is probably less likely to incorporate these kinds of redistributive policies, meaning that the higher bills in the MR pathway could result in high levels of fuel poverty.

The supporting literature regarding the pathways 'storylines' (published by the TPLCE consortium) suggests that the TF pathway could potentially be expected to mitigate against fuel poverty, for several reasons:

- Lower demand and a focus on energy efficiency leads to people using less, and therefore being less vulnerable to higher prices (Foxon 2013)
- An increase in micro-generation and self-consumption may result in lower vulnerability to price rises (Barton *et al* 2015)
- Barton *et al* (2015) state that the Municipal Energy Services Companies (MO-ESCos) in the TF pathway would have a statutory duty to address fuel poverty and ensure that questions of equity are considered in energy provision.

However, there may be caveats to several of these claims. For instance, poor households may still be vulnerable to higher prices, because they might be less likely to be able to invest in microgeneration and energy efficiency measures. In general, it appears that drawing any conclusions for this indicator based on the information available in the pathways is highly challenging, because of the lack of necessary information in the raw pathways data (e.g. income data), as well as a number of additional uncertainties which are explained in the following sub-section. The pathways storylines can offer a preliminary overview of some of the fuel poverty risks which might be experienced in the pathways, but cannot really provide robust analysis, and considerable detailed modelling work would be required to calculate fuel poverty impacts which is outside the scope of this thesis. Moreover, it is clear from table 5.3 that there is little to differentiate the results below from the results from the 'annual bills' indicator. Therefore, whilst fuel poverty may be an important aspect of energy security, especially from an equity perspective, care should be taken when drawing conclusions based on the results from this indicator.

Table 5-3: Fuel poverty risk

	2030		2050	
	Bills median	**Storyline**	**Bills median**	**Storyline**
MR	**£913**	**Most risk**	**£1147**	**Most risk**
CC	**£826**	**Least risk**	**£1116**	
TF	**£870**		**£897**	**Least risk**

5.4.4 Cost to the consumer: key uncertainties and limitations

As shown in section 5.3.3, projections of future costs have a consistent tendency to be inaccurate (for example, see EIA 2015a). Moreover, it should be noted that the uncertainties inherent in cost analysis tend to cascade, so that one result may be dependent upon a whole host of assumptions, both within this analysis and within the raw data. Therefore once again it is best to view the results presented above as a high-level overview of some of the key risks which could emerge under various routes to a low-carbon transition. The multiple sensitivity tests (explained and analysed in more detail in Appendix C) aim to highlight some of the key uncertainties and to show the sensitivity of the conclusions to various assumptions.

Some of the core areas of uncertainty are:

- **The uncertainties in the LCOE and network costs analysis**: the uncertainties described in section 5.3.3 will cascade into the annual bills projections.
- **Social and environmental programmes**: the scale and direction of social and environmental policies in the UK in the future is highly uncertain; policies have sometimes been subject to change at short notice. The results above are calculated without general tax (VAT), which reduces some of the uncertainty regarding programmes which are paid for out of general taxation. Therefore if the government decided to move some social and environmental programmes out of energy bills and

into general taxation, this would affect the amount that consumers would have to pay on top of their electricity bill for social and environmental programmes.

- **Population growth:** the annual bills calculations are highly dependent on future population assumptions. However, this uncertainty could be mitigated if data on household energy use was available in the pathways; at present, the pathways only include demand data for the UK as a whole.
- **Electricity demand:** an important uncertainty which emerges on both an empirical and a conceptual level is that of *how* consumers use electricity in future. The calculations here are based on the idea that the way consumers use electricity remains similar to today, although the pathways do presuppose the development of a smart grid for the shifting of electrical load. However, the annual bills calculations are still based on the average seasonal demand for the whole of the residential sector, which is highly simplified. The way in which consumers use electricity is likely to change significantly over the next 40 years, with the possible development of smart appliances and remote technology which enables demand-shifting from a distance, and the possibility of affordable home electricity storage solutions and electric vehicles. It would also be necessary to factor in the cost of smart grid infrastructure, which is out of the scope of the estimates given here. For a more comprehensive assessment, patterns of demand would need to be included in the pathway development. This would require explicit model inputs including smart appliances, consumer behaviour, and potential rebound effects.

Finally, one of the major uncertainties to emerge from this analysis is the question of 'who pays', and the issue of incentivising investment in generation capacity and networks. Market and investment structures in the UK are currently under pressure, because the main utilities are suffering from a combination of high corporate debt, low wholesale prices, and reductions in electricity demand (Blyth *et al* 2014; Deane *et al* 2015; Mitchell *et al* 2014). In fact, most countries in the EU are facing debates about whether they are managing to attract enough investment to maintain security of supply (Ellenbeck *et al* 2015), although proposed Capacity Mechanism arrangements in many member states are hoped to alleviate this somewhat (DECC 2013c; Linklaters 2014; Pototschnig and Godfried 2014). Moreover, there are key uncertainties caused by the path dependencies which result from investments in infrastructure with long life-spans, such as power stations and cables (Usher and Strachan 2012).

There is also lot of discussion in the UK at present over the extent to which energy bills should include charges for social and environmental policies such as support for low-carbon generation or help for the fuel poor (a debate which was made notorious by comments attributed to Prime Minister David Cameron in 2013 that he wanted to “get rid of all the Green Crap” from energy bills [Groves and Robinson 2013]). Paying for these charges out of energy bills is naturally regressive, because energy bills are not proportionate to income (Garman and Aldridge 2015; Howard and Frayne 2015); moreover, paying for an expensive low-carbon transition through energy bills may be contentious and thereby may risk losing support for the entire transition plan (Garman and Aldridge 2015).

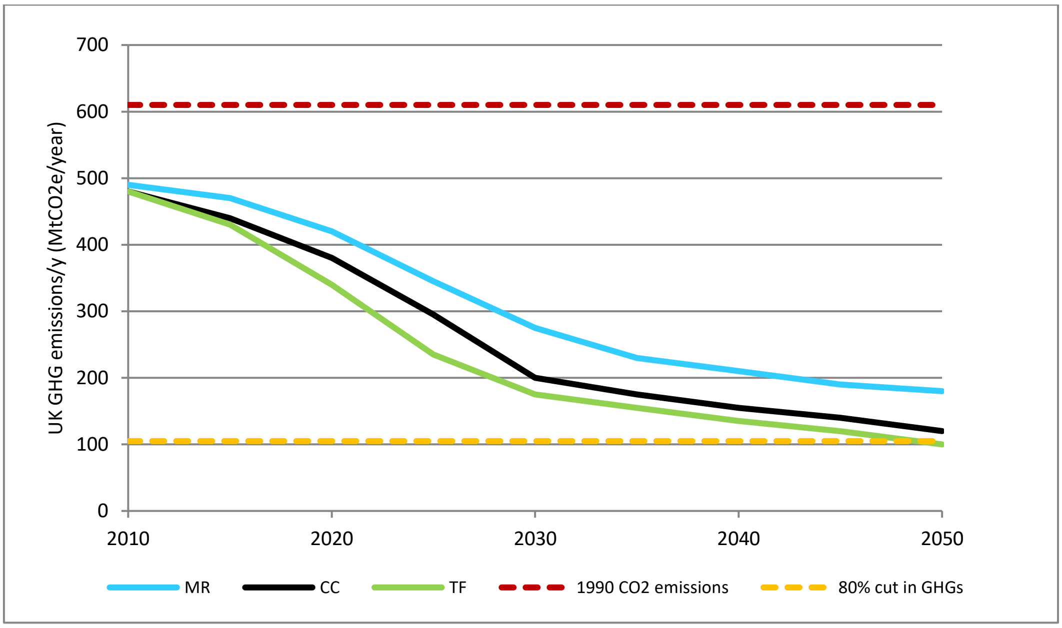
A key risk for all the pathways is that the electricity sector will struggle to secure the level of finance required to realise the transition. The MR pathway, if predicated on current market structures, may struggle to secure finance, particularly because it relies on high-CAPEX, risky projects such as offshore wind, nuclear and CCS (Foxon and Pearson 2013). The CC pathway could cover costs using public funding, although it is not entirely clear whether this would be paid out of energy bills or general taxation, and could generate risks if the public were not accepting of higher costs (Foxon *et al* 2013). The CC pathway could also encounter investment risk if the government were seen to be exercising more control than market actors were willing to tolerate (Foxon and Pearson 2013). Finally, the lower levels of demand in the TF pathway would squeeze margins for producers, unless compensation were available (from a source which is not elaborated in the pathways storylines) or unless the retail price per unit were far higher. It is plausible that increased participation in energy generation could mean that people are willing to pay more for their electricity, but this would increase fuel bills and increase risks of unaffordability and fuel poverty. Hall *et al* (2014) and Barton *et al* (2015) suggest that realising the TF pathway may require new forms of localised finance to become available, for instance through small-scale banks or local credit unions.

5.5 Sustainability Results: GHG emissions

Indicator	Overview of methods
GHG emissions and intensity	Electricity system GHG emissions taken directly from pathways data (see also Foxon *et al* 2013) Life-cycle carbon intensity (in CO2e) of electricity generation types taken from High, mid and low estimates from IPCC global power station data (Moomaw *et al* 2011) Total carbon intensity = Fuel-type intensity * (fuel-type generation TWh/y / Total generation TWh/y)

Figures 5.15 and 5.16 show the baseline estimates for UK GHG emissions and the carbon intensity of the electricity generation mix of the pathways. Both calculations measure GHGs (i.e. not just carbon dioxide), and are therefore expressed in carbon dioxide equivalent (CO2e). It should be noted that the MR pathway only reduces UK CO_2e emissions by 72%, meaning that this pathway actually misses the 80% target by a margin of nearly 80Mt (the Transition Pathways consortium carried out additional work later on to make the MR pathway achieve an 80% reduction, by means of an advanced hydrogen economy and negative emissions from biomass CCS). Figure 5.15 also helps to illustrate the *cumulative* emissions over this period as well as the end target (i.e. the area under the curve); this is crucial, because cumulative emissions are what determines the impact on the climate (Anderson and Bows 2011). The cumulative GHG emissions for the MR pathway for the period 2010 to 2050 are 2810 MtCO_2e, for the CC pathway 2385 MtCO_2e, and for the TF pathway 2170 MtCO_2e. Therefore the cumulative GHG emissions of the TF pathway are only 77% those of the MR pathway and 91% those of the CC pathway. It is worth noting that these figures are estimates, because the emissions data in the pathways is only given in 5-year increments.

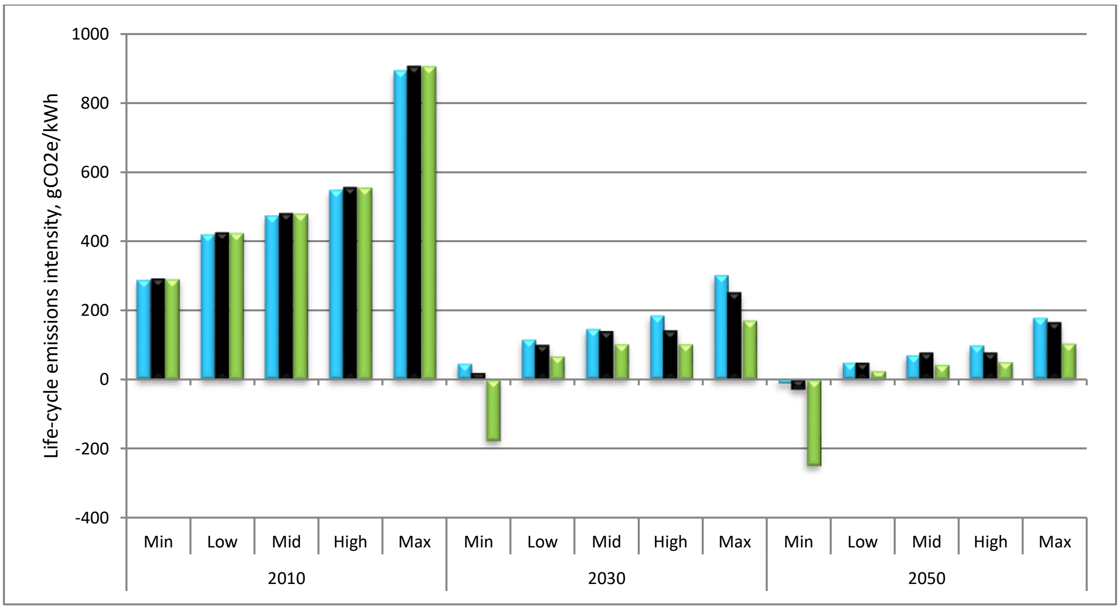
Figure 5-15: GHG emissions



The graph in figure 5.16 shows the range of results of the life-cycle emissions intensity of the electricity generation mix, using a range of emissions estimates from the IPCC (Moomaw *et al* 2011). These results show clearly the enormous level of ambition which would be required to realise these pathways. The MR pathway appears to have the highest emissions intensity in general (although for 2050 the mid-range estimate indicates that the CC pathway has a slightly higher emissions intensity); however, the MR pathway also has the highest electricity demand. Higher demand leads to greater imperatives to reduce carbon intensity, and should in theory create more opportunities for improvements in energy efficiency; the results for the MR pathway suggest that it does not fully capitalise on these opportunities. The TF pathway has the lowest carbon intensity throughout, meaning that less CO_2e is released per unit of electricity produced; this could be argued to be especially ambitious, as the low levels of demand in this pathway mean that opportunities for efficiency savings are more restricted. Therefore, these results seem to suggest that such low carbon intensity, combined with such low demand, is achieved largely because of increased engagement and behaviour change on the part of consumers.

All three pathways show considerable uncertainty between estimates, with the TF pathway in particular returning estimates which differ by orders of magnitude. The uncertainty for the TF pathway is largely driven by biomass, which in theory if aligned with CCS technology in the future could generate significant negative emissions; however, for these gains to be realised, there will need to be significant improvements in biomass power generation and in the production and transport of biomass feedstock. The results show that if the maximum life-cycle estimates are used, all three pathways could generate life-cycle emissions of above 100g CO_2e/kWh in 2050; this is well above the 50g target recommended by the UK Committee on Climate Change (2013). The MR pathway consistently has the highest emissions intensity, due to coal and gas generation; even with CCS, coal and gas have high emissions from plants and from mining and transportation of fuel. It is important to note the distinction between the GHG emissions shown in figure 5.15 and the life-cycle emissions intensity shown in figure 5.16: the life-cycle emissions estimates include GHGs emitted outside of the UK (for instance, via the mining or transportation of resources), whereas the pathways GHG data shown in figure 5.15 only includes emissions released in the UK. Both are important – the UK has a statutory duty to meet targets for UK-only emissions, but mitigation of climate change will necessitate reduction of overseas emissions as well. As shown in figure 5.16, calculating life-cycle emissions intensity entails greater uncertainty.

Figure 5-16: Carbon intensity range of estimates, gCO2e/kWh



5.6 Sustainability Results: Resources

Indicator	Overview of methods
Primary fuels depletion	Qualitative method using information from the existing literature to assess depletion risk of primary fuels. Pathways assessed qualitatively for their reliance on depletable fuels.
Secondary materials depletion	32 crucial materials are identified from Moss *et al* (2011) and Speirs *et al* (2014) and listed from 'highly critical' to 'not critical' according to risk of depletion. Pathways assessed qualitatively for their reliance on depletable materials.

5.6.1 Primary fuels

The following sections show the results from a qualitative review of the literature concerning depletion of the main primary fuels in the pathways: coal, gas, uranium and biomass.

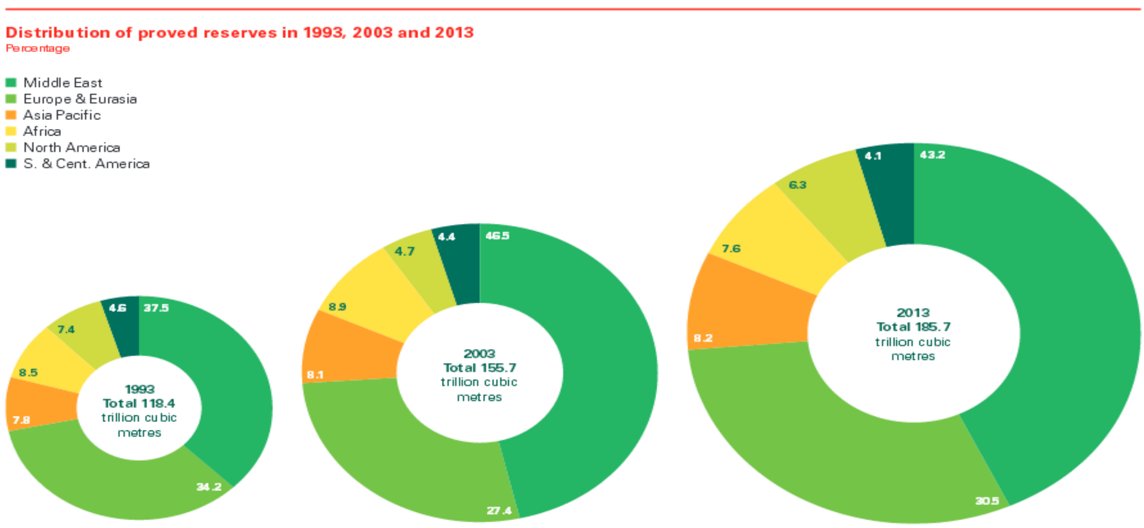
5.6.1.1 Coal

In general, it is accepted that coal reserves are plentiful for the foreseeable future, because 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). Global reserves of coal could last in excess of 100 years (IEA Clean Coal Centre 2014). 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.

5.6.1.2 Gas

Gas represents a more serious risk than coal, although there are considerable uncertainties regarding global economically extractable reserves of gas, especially in the context of potential new sources of unconventional gas. The Energy Information Administration calculates that global proven reserves of natural gas at the end of 2014 stood at 197 trillion cubic metres (tcm) (EIA 2015b). BP estimates that this is enough to meet around 55.1 years of global demand under BAU demand scenarios (BP 2013). Global resources of unconventional gas are estimated at an additional 327tcm, but reserve assessments for unconventional gas are complicated and highly uncertain (IEA 2013).[18] As shown in figure 5.17, although global gas demand has been steadily increasing, the amount of gas held in proven reserves has also increased significantly. The world is unlikely to 'run out' of gas by 2050; however, tighter supply and increasingly concentrated resources could result in higher prices through to 2050. On the other hand, economists such as Helm (2011) argue that a tighter market will simply lead to increased exploration and thus more reserves coming on-line.

Figure 5-17: Global proved gas reserves, 1993 to 2013 (BP 2013)



5.6.1.3 Nuclear

Uranium is plentiful and very easy to store. The OECD Nuclear Energy Agency suggests that "the uranium resource base… is more than adequate to meet projected requirements for the

[18] It is vital to distinguish between *resources* (the amount of gas in the ground), and technically / economically recoverable *reserves.* Typically, a maximum of around 20% of shale gas is recoverable in ideal conditions (Lee 2012).

foreseeable future" (2014: 15). There are probably no serious risks regarding uranium depletion through to 2050, although the analysis still needs to reflect the fact that it is a non-renewable fuel.

5.6.1.4 Biomass

The highly ambitious proportion of biomass generation in the pathways could result in issues relating to the land required for growing feedstocks. Biomass is more complex than non-renewable resources, because it is renewable but can still be depleted. Unlike the wind and the sun, biomass feedstock availability is limited by the land available for growing crops and by the complex relationship between availability of land and water for food and energy production. Intensive or poorly-managed production of feedstock can also reduce soil quality, resulting in declining yields (IRENA 2014). Furthermore, unlike most renewables which only provide electricity, biomass feedstock is also used for cooking, heating and transport, giving rise to competition with other sectors for the resource. As noted in section 5.2.2, it is also possible that many other nations will be competing for biomass feedstocks.

Because of the complex relationship between land for food and land for bioenergy, estimates of future global biomass resource availability are dependent on numerous difficult assumptions, such as population growth, how much land is required to grow food, meat consumption, rates of deforestation, rates of building and urban sprawl, and how much land is left wild or protected. Depending on these assumptions, a report by UKERC (Slade *et al* 2011) suggests a mid-estimate of global biomass potential between 100 to 600 Exajoules (EJ) per year, for all energy requirements (i.e. heating and transport as well as electricity). To put this in context, the World Energy Council estimates that total global primary energy supply will grow to 879 EJ in 2050 (World Energy Council 2013). In terms of the pathways, 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 land availability globally, and could result in constraints on biomass feedstock availability or potentially trade-offs between biomass and other land uses such as agriculture.

5.6.2 Secondary materials

A growing concern for the sustainability of a low-carbon transition is the supply of secondary materials used in the electricity system, such as specific metals and Rare Earth Elements

(REEs). A review of the evidence by UKERC (Speirs *et al* 2014) noted 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 (PV) panels and battery-powered vehicles. 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). Other important metals are also worth flagging up as potentially risky: table 5.4 shows several metals which are considered to be 'critical', along with the low-carbon technologies for which they are required.

Table 5-4: List of critical metals and low-carbon technologies (Speirs et al 2014: 3)

Metal	Low-carbon technology
Cobalt	Lithium-ion batteries
Gallium	Thin-film photovoltaics (PV), Light emitting diodes (LED lighting)
Germanium	Thin-film PV, LED lighting
Indium	Thin-film PV, LED lighting
Lithium	Lithium-ion batteries
Platinum group metals (PGMs)	Hydrogen fuel cells
Rare earth elements (REEs)	Electric vehicles and wind turbines
Selenium	Thin-film PV
Silver	PV (c-Si), concentrating solar and nuclear
Tellurium	Thin-film PV

Moss *et al* (2011) looked in detail at the metals used in energy technologies, and came up with a list of the 32 most significant materials for energy generation in the EU through to 2030 under a low-carbon trajectory. They then assessed the criticality of supply of these 32 materials, on the basis of potential supply-chain bottlenecks which could occur under BAU conditions, resulting from both geopolitical and market-based dynamics. As shown in table 5.5, the most critical materials are the REEs dysprosium, europium, terbium, yttrium, praseodymium and neodymium, as well as the metals gallium and tellurium.

As shown in table 5.4, several of these materials are used in low-carbon generating technologies, most notably wind and solar. Some are also used in other generating technologies, such as in the superalloys used in new fossil fuel power plants (Moss *et al* 2011). From this it is possible to draw up a list of the most critical secondary materials (table 5.6), according to the red, amber and yellow categories. It is worth noting that this analysis focuses solely on metals and REEs; constraints in other materials, for instance used in other parts of the supply chain, were not assessed.

Table 5-5: Criticality of 32 materials for low-carbon energy

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		

Table 5-6: Secondary materials depletion for different generation types

Technology	Red materials	Amber	Yellow
Coal		Rh	Co; Ta
Gas		Rh	Co; Ta
CCS		Rh	Co; Ta; Va; Nb
Biomass			Co
Nuclear		Ha; In	
Wind	Dy; Nd; Pr		
Solar[19]	Te; Ga	Ger, In	Sn
Hydro			
Marine			
Electricity Storage			Co; Cr
Combined heat & power			
Electric vehicles	Nd		

5.6.3 Resource depletion results for the pathways

From the information given in the previous two sections, it is possible to assess the level of risk in the pathways to resource depletion, according to their fuel mixes. It is not really possible to carry out precise calculations of risk of resource depletion without in-depth modelling of global resource availability (which is outside of the scope of this thesis); this could be an interesting area for detailed modelling work in future research.

All three pathways generally reduce their reliance on fossil fuels in 2030 and again in 2050, as they transition towards increased reliance on renewable fuels which are not generally at risk of

[19] For solar, the materials listed apply to existing solar generation technologies, rather than potential future solar technologies.

fuel depletion. The MR pathway does, however, remain reliant on gas throughout the transition, with gas-fired electricity providing around 20% of electricity output in 2030 and around 15% in 2050. Coal also remains somewhat important in this pathway, although again the coal-fired proportion decreases on 2010 levels. It is also important to note that CCS generation gradually replaces unabated generation; whilst this is beneficial for reducing emissions, it also uses more fuel because adding CCS tends to reduce the efficiency of the power plant, thus meaning that more fuel is required for each unit of power generated. The MR pathway also has the highest electricity demand of the three pathways, meaning that more fuel is used overall. Therefore in general, it can be seen that the MR pathway may be at risk of primary fuel depletion, especially of gas.

The CC pathway, similarly to the MR pathway, remains somewhat reliant on gas in 2030 and 2050, and also switches to CCS. However, the CC pathway is much less dependent on gas and coal than the MR pathway, and therefore is probably less at risk of depletion of these fuels. The CC pathway is more reliant on nuclear power, which as shown in section 5.6.1.3 is still a non-renewable resource, but is less at risk of depletion because global uranium reserves are probably plentiful for the next several decades. The CC pathway also has lower electricity demand than the MR pathway.

The TF pathway has much lower electricity demand than the other two pathways, which significantly reduces the fuel use and thereby reduces the risk of fuel depletion. The TF pathway also almost completely phases out fossil fuel use by 2050, meaning that it is not really at risk of depletion of gas or coal. However, the TF pathway is heavily reliant on biomass, which as shown in section 5.6.1.4 is potentially at risk of depletion, because even though it is a renewable resource it is potentially depletable, especially if land use is managed poorly. However, assessing the risk of biomass depletion for the pathway presents significant challenges, because of the large number of important and unknown variables. Moreover, biomass is renewable yet depletable, therefore it constitutes a flow variable (i.e. it indicates change over a period of time), which cannot be compared directly to stock variables (i.e. those which measure quantity at any one time) such as coal, gas or uranium resources. Nevertheless, most energy system models include a biomass constraint to account for the depletable nature of this resource. As explained in section 5.6.1.4, the TF pathway is potentially at risk of biomass feedstock depletion.

Regarding secondary materials depletion, the relatively high levels of coal and gas generation in the MR pathway, nuclear in the CC pathway, and biomass in the TF pathway, could actually help to mitigate the risk of secondary materials depletion, because the most vulnerable generation technologies to this kind of depletion are renewables such as wind and solar. Nevertheless, all three pathways involve increasing amounts of wind and solar generation through to 2050, and therefore may experience increasing risk of depletion of Dysprosium, Neodymium, Praseodymium, Tellurium, Gallium, Germanium and Indium. The increasing electricity demand of the MR pathway may make it more at risk of materials depletion; however, the CC pathway is more at risk of depletion of Hafnium and Indium used in nuclear power. It is important to note that secondary materials are more likely to be substitutable than primary fuels, and recycling of materials could also contribute to the mitigation of secondary materials depletion, although there is considerable uncertainty over whether substitution or recycling can keep pace with growing demand for some of these materials, and there is some concern about potentially long lead times for substitutes (Speirs *et al* 2014; Stegen 2015).

5.7 Sustainability Results: Water

Indicator	**Overview of methods**
Water consumption & withdrawals	Data on water withdrawals and water consumption of different types of power generation from Davies *et al* (2013). Projections on types of cooling to be employed in UK thermal powergen in future from Kyle *et al* (2013) These are applied to the generation mix to show water consumption and withdrawals in m3/y Baseline results weighted 70-30 to show greater environmental impact of freshwater vs seawater. Water usage for biomass feedstock production not possible to calculate because of lack of available data

Figure 5.18 shows both the water *withdrawals* (i.e. water taken from the source and then replaced) and water *consumption* (i.e. water that is not replaced) of the generation mix in the pathways. This is an important distinction, especially when considering water-based generation such as hydro, which has virtually no water withdrawals but some water consumption mainly due to evaporation from the lakes created by dams (Mekonnen and Hoekstra 2011).

Figure 5-18: Total water withdrawals and consumption for electricity generation (million m3)

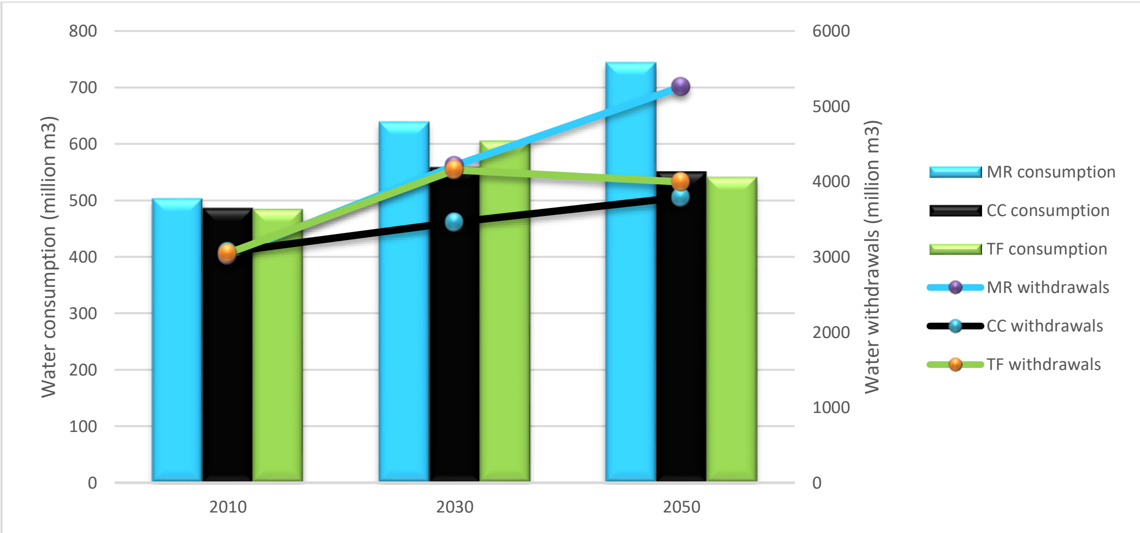


Figure 5.18 shows that the MR pathway has the highest water usage, due to the prevalence of thermal power generation. The CC pathway has the lowest water usage in 2030, and the TF pathway has the lowest in 2050, although the results for these two pathways are very similar. It is crucial to note that the low figure for the CC pathway is influenced heavily by the weighting of freshwater vs seawater, because the CC pathway is reliant on nuclear which in the UK mostly uses seawater. For this reason, sensitivity analyses have been carried out to show the impact of different weightings; more detail is given in Appendix D. The results for water consumption and water withdrawals are broadly similar, largely because of low penetration of hydro.

It is important to note that these results only show primary water use for power generation, for instance in cooling thermal plant; they do not show secondary water requirements such as irrigation for biomass or water for fossil extraction, because this would require data on extraction locations, methods and biomass feedstock types, none of which is available in the pathways data. A life-cycle water usage analysis is therefore outside the scope of this thesis. This is a crucial distinction because all three pathways become increasingly reliant on biomass in order to transition away from fossil fuels, in particular the TF pathway for which biomass is the most prevalent fuel in 2050. This means that the lack of ability to calculate water requirements for biomass feedstock production could have a significant impact on the results, potentially making the TF pathway appear less risky than it actually is. For this reason, robust conclusions are challenging to draw for this indicator without carrying out modelling based on data which is not available. Care should be taken when drawing conclusions based on this indicator,

5.7.1 Sustainability results: key uncertainties and limitations

The three sub-dimensions in the sustainability dimension (carbon, resources and water) highlight considerable uncertainties surrounding biomass. The TF pathway in particular is highly dependent upon biomass, which provides a valuable source of renewable yet flexible generation. However, it is extremely challenging to make accurate estimates of the sustainability of the biomass resources used in this pathway, because of a lack of data regarding the feedstocks used and their location. There is also high uncertainty around levels of global availability of land for biomass, especially considering that other sectors (e.g. food, agriculture, transport, tourism) may be in competition for the same land resource, and also considering that a considerable proportion of the sustainability impact of biomass feedstock will depend on how well the land is managed (see Månsson *et al* 2014b; Welfle 2014a; 2014b).

There are similar uncertainties regarding water requirements of unconventional fossil fuels. Unconventional fuels can delay conventional fossil fuel depletion; however, they sometimes also use large amounts of water, especially when methods such as fracking are employed (POST 2011), thus possibly illustrating a trade-off between water usage and resource depletion. The uncertainties arise because there is no detail in the pathways data regarding whether primary fuels are conventional or unconventional. Finally, the uncertainty around unconventional fossil fuels could lead to a trade-off between affordability and fuel depletion; if the price of electricity increases, this makes it more economical to extract more challenging reserves, thus mitigating resource depletion whilst at the same time increasing affordability risks. Again, this is impossible to calculate because of the lack of fuel type granularity in the raw data.

5.8 Reliability Results: System adequacy

Indicator	Overview of methods
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)

Capacity factors & oversupply	Capacity factors (from the Transition Pathways data) and capacity margins (see above) are used to highlight areas of oversupply
Electricity storage & interconnection	Electricity storage and interconnection nameplate capacities summed together; also compared to plausible storage and interconnection developments

5.8.1 Loss of Load Expectation

One means of assessing the adequacy of the electricity system is by Loss of Load Expectation (LOLE) (DECC 2013f; Ofgem 2013a). The LOLE is the reliability standard which is set by the Secretary of State and implemented by the regulator, using a probabilistic method to represent the number of hours per year in which the System Operator will be required to take additional measures to ensure that power is not lost. The LOLE in the UK is 3 hours per year. It is worth emphasising that this is a 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 System Operator with no impact on power availability to consumers.

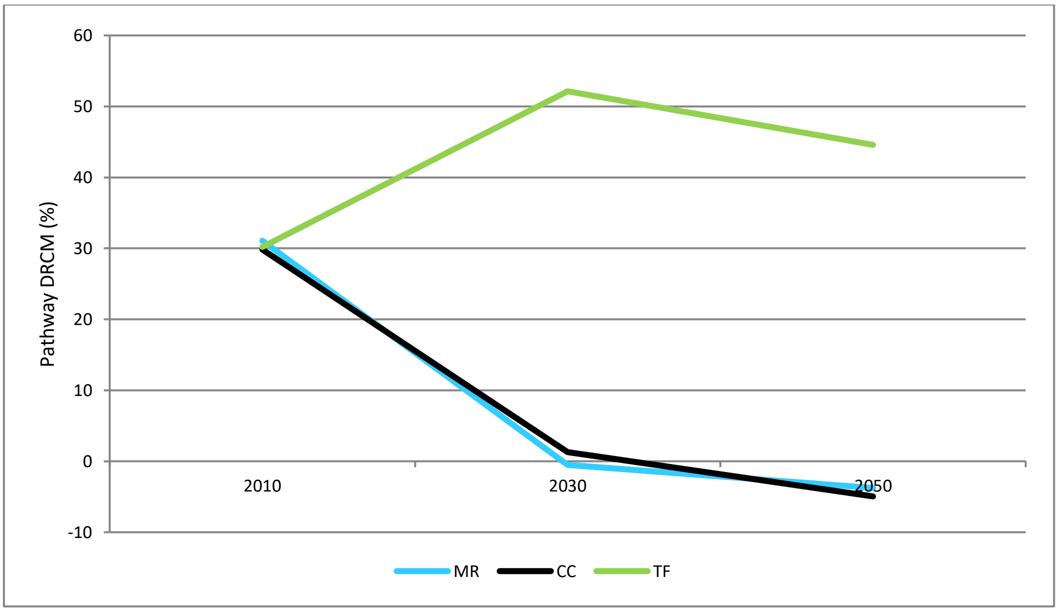
The FESA model used for the Transition Pathways creates generation mixes for the three pathways, which can meet peak demand on a yearly and hourly basis (Barnacle *et al* 2013; Barton *et al* 2013). The pathways have all been modelled with hour-by-hour system adequacy in mind, therefore all can be assumed to meet the national reliability standard.

5.8.2 De-rated capacity margins

Figure 5.19 shows that both the MR and CC pathways see de-rated capacity margins (DRCM) of close to zero in 2030 and negative in 2050. 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 or an unexpectedly cold winter. This appears to contradict the fact that the pathways meet the LOLE standard, therefore it is worth looking in more detail at the possible reasons for this. Firstly, the Transition Pathways data shows that the pathways do not take unexpected outages into account. As shown in section 4.4.4.1, the DRCM calculation *does* take unexpected outages into account (which is one of the reasons why conventional plant, imports and storage are all rated at below 100%); this is important because it could have a big impact on the ability of the system to meet peak demand under stress conditions. Secondly, these results suggest that the pathways may have been overly optimistic in their assumptions regarding peak generation of intermittent sources; it is difficult to assess whether this is the case from the raw data, but this would explain why the de-rated capacity margins are so low. As explained in Appendix E, the peak time availability of renewables is subject to numerous uncertainties and assumptions. These results therefore emphasise the benefits of using more than just one metric for assessing the ability of the power system to meet demand peaks, because all metrics are dependent upon multiple assumptions. Including a calculation of DRCM into the modelling of electricity system pathways would therefore be highly beneficial, and model outputs should be adjusted accordingly if the DRCM is shown to be insecure, especially if the DRCM is below zero.

The low DRCM in the MR and CC pathways may be explained by the large amounts of wind and solar power in these pathways. The CC pathway has increasing penetrations of solar power in the longer term, which is the main driver for the very low DRCM in this pathway in 2050. The TF pathway on the other hand has an extremely high margin, driven by large amounts of dispatchable biomass generation. This high margin suggests that there may be a large amount of electricity which is generated but not required, especially during times of low demand. This may result in the curtailment of renewable capacity. While RES curtailment is not a security indicator in its own right, it impacts the cost of power generation.

Figure 5-19: De-rated capacity margins (base case)



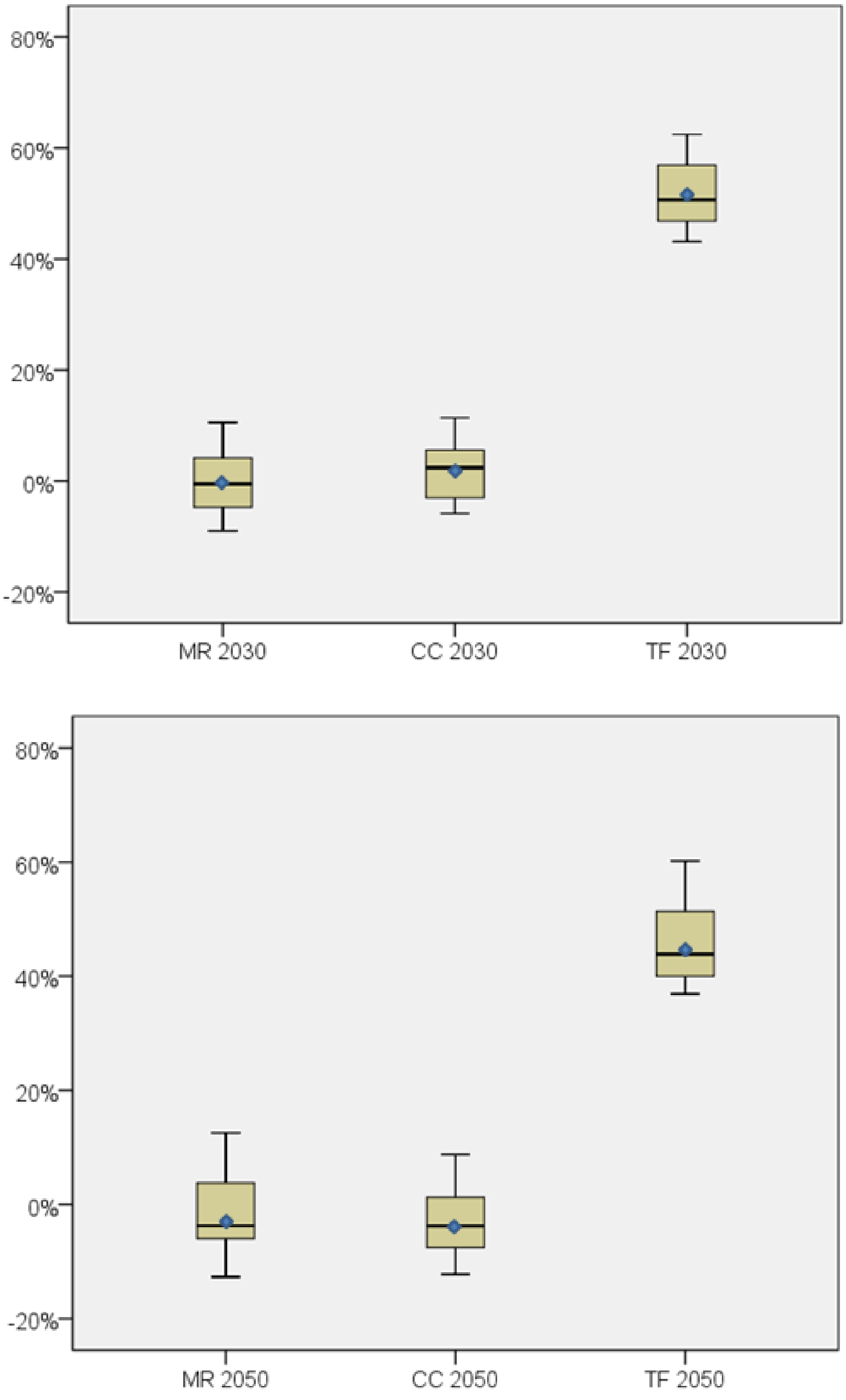
5.8.2.1 DRCM Sensitivity analyses

Putting a figure on the capacity credit[20] of each generation type is not an exact science. Figures vary, especially for RES, and are impacted by issues such as weather forecasting and the geographical dispersion of generation infrastructure. For example, the 'traditional' capacity credit of wind was 5%; however, the National Grid figures (National Grid 2012: 30) raise this to 8% in order to reflect the increasing geographical dispersion of wind arrays.

Because of this, sensitivity analyses have been carried out to show the impact of assumptions regarding the capacity credit of wind, imports, and CCS, full details of which are given in Appendix E. The graphs in figure 5.20 show that the MR and CC pathways are very similar in 2030 and 2050; in fact, their results overlap to the extent that it is not possible to identify conclusive differences between these pathways. Both the MR and CC pathways have an extremely low bottom value for 2030 and 2050, which may represents a vulnerability. This illustrates that, depending on assumptions regarding wind power, imports and CCS, these pathways may not be able to meet peak demand. The TF pathway, on the other hand, shows no overlap with the other two pathways, and has a generally secure DRCM.

[20] Capacity credit = the de-rated capacity margin for each type of generation, or 'fuel-type margin'

Figure 5-20: Range of results from DRCM sensitivity tests, 2030 and 2050



5.8.3 Capacity factors and oversupply

As well as ensuring that there is enough generation capacity available to meet demand peaks, the pathways must also ensure that supply is reduced during times of low demand in order to avoid system overload. To do this, the FESA model adjusts the capacity factors of each type of generation (Barnacle *et al* 2013; Barton *et al* 2013). In order to accommodate increased penetration of intermittent capacity, the remaining dispatchable generation must accommodate this variability, resulting in a decrease in average capacity factors.

The graphs in figures 5.21, 5.22 and 5.23 show the evolution of capacity factors for each type of generation for the three pathways. They show that today's large-scale generators (unabated gas and coal) would have to reduce their capacity factors from an average of between 45 and 60% today, down to zero as they fall down the merit order and are replaced by power plants with CCS or new renewables. New low-carbon thermal generators (gas and coal with CCS, and biomass) will come online with very high capacity factors, but as time passes and more renewable generation is built they will need to reduce their capacity factors also. In the TF pathway, by 2050 the capacity factors of abated gas and coal have fallen to around 20%. Barnacle *et al* (2013) and Barton *et al* (2013) suggest that even if large amounts of demand-side flexibility are introduced, the expected nameplate surplus in the TF pathway may be extremely large.

Low capacity factors could mean less of an incentive to invest in power generation capacity, especially in circumstances where high capacity factors are not available for a sufficient period of time to pay back the initial capital investment of the installation. Figures 5.21, 5.22 and 5.23 indicate that this may be particularly problematic for gas CCS, because its capacity factors begin high and then rapidly fall significantly, which may not give the investors enough time to pay off their capital costs. This is an issue for all the pathways.

To counter these problems, intermittent generation of thermal plants would need to be built into the plans to realise the pathways; the introduction of the UK Capacity Mechanism (National Grid 2014a) is an attempt to address this issue. The main outcome would be on cost; for this reason, the affordability dimension, and especially the generation costs results (shown in section 5.3.1) illustrate this issue more fully, and the impacts of oversupply can be clearly seen in the extremely high total generation costs for the TF pathway. In terms of reliability, the reduction in capacity factor does not represent a risk. However, there is an issue here with the *viability* of the TF pathway (and also the MR and CC pathways to a lesser extent): the risk lies in the possibility that some of the flexible low-carbon thermal generation needed to balance the pathways would not be built, because of the economic unattractiveness to generators of operating their plants at such low capacity factors. It should be noted that the ‘oversupply’ indicator is very much the other side of the coin to DRCM: the TF pathway with its very high DRCM also has the lowest load factors and the most oversupply.

Figure 5-21: Generation-type capacity factors in the Market Rules pathway (Barnacle et al 2013)

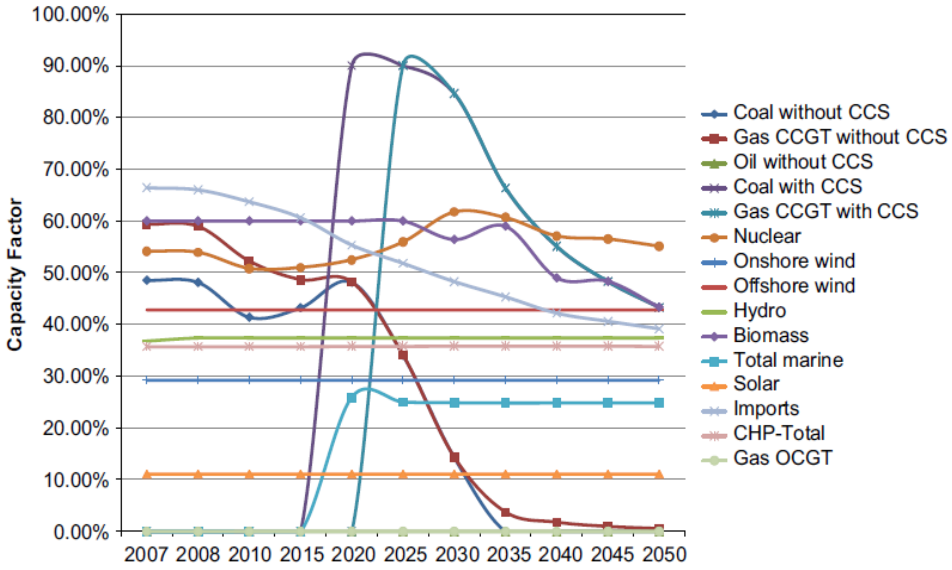


Figure 5-22: Generation-type capacity factors in the Central Coordination pathway (Barnacle et al 2013)

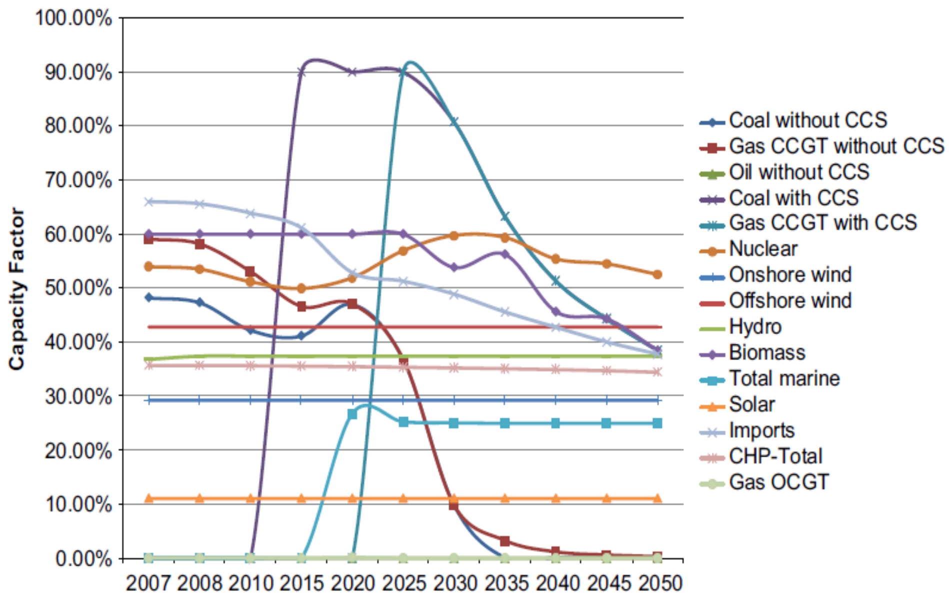
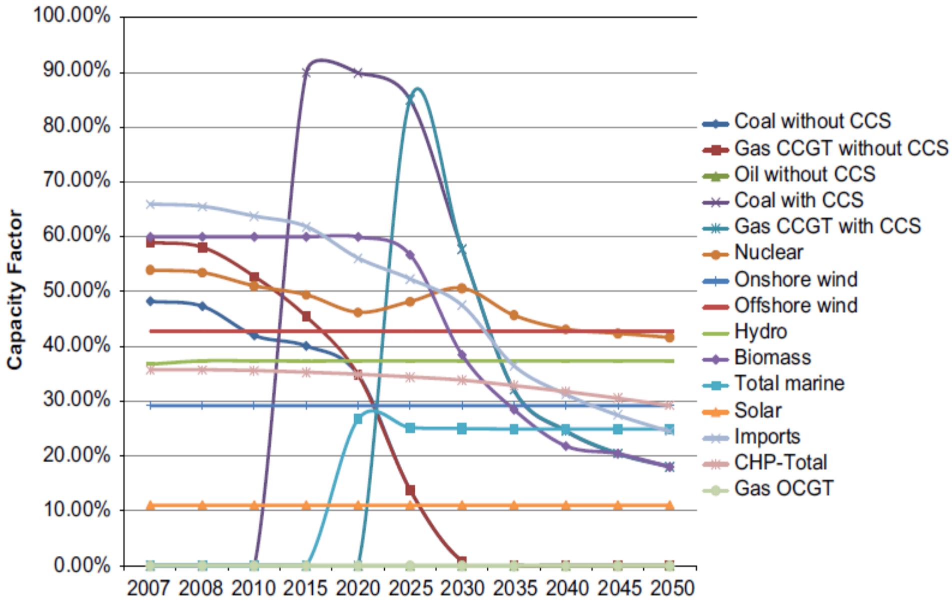


Figure 5-23: Generation-type capacity factors in the Thousand Flowers pathway (Barnacle et al 2013)

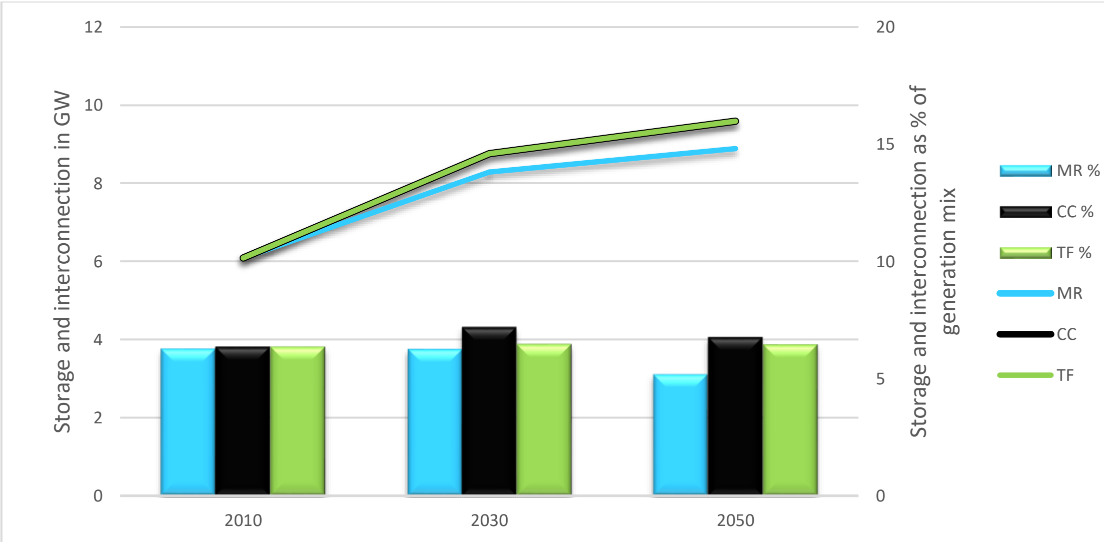


5.8.4 Electricity storage and interconnection

Storage and interconnection can both enable flexibility in electricity production/consumption, and can therefore in theory be called on when required (for instance, at a time of high demand), in order to reduce the necessary levels of spare capacity or conventional generation on the system. Increased flexibility means that the system can incorporate more intermittent sources such as renewables without requiring as much backup for times when the renewable in-feed is low.

Figure 5.24 shows the amount of storage and interconnection in the pathways, both as a relative value (% of the total generation mix) and as an absolute value (in GW). The results for the three pathways are remarkably similar. This can be explained by the fact that all three pathways only include pumped storage, and only include interconnectors which are already built or planned. These pathways therefore experience risk through not fully exploiting the storage and interconnection options which could be available to them. The pathways creators note that they did not explore storage options in any detail, mainly because of concerns about cost (Foxon 2015). In the case of interconnection, the pathways don't seem to consider the full potential of interconnectors to Scandinavia, which is surprising because National Grid is proposing to build a new UK-Norway interconnector for operation in 2020 (National Grid 2013d).

Figure 5-24: Storage and interconnection. Note: CC result in GW is the same as TF result



It is important to note a potential caveat around the reliability of interconnection for providing balancing services to National Grid. This indicator assumes that interconnection can provide a source of flexible supply at times of stress and can provide a useful means of offloading electricity to mainland Europe at times when supply exceeds demand (European Council 2011; House of Lords 2015; National Grid 2014b; Newbery *et al* 2013; Strbac *et al* 2012a). However, there is an active debate on this at present, with considerable uncertainty over what happens when connected countries experience simultaneous stress moments. Some argue that there is the possibility that power could actually flow out of the UK at times of high demand, especially if a large weather system led to low RES in-feed and high demand in several countries at once (House of Lords 2015). In theory, measures could be taken to avoid this happening, although there is uncertainty at present over what these measures might actually look like in practice.

5.8.5 System adequacy: key uncertainties and limitations

The major uncertainty and area for further research which emerges out of these indicators is the question of whether or not sufficient investment is available to realise the ambitious transition envisaged in these pathways. This issue also arose within the affordability dimension (see section 5.4.4). The most important factor that determines whether or not the required investments are available is the underlying business case, i.e. the fundamentals of the electricity market and the details of any subsidy regimes (Blyth *et al* 2014). It therefore appears that one of the key outcomes of the assessment as a whole is that one of the major risks lies within the political and economic feasibility of realising ambitious transition pathways, rather than the (technical) security of the pathways themselves.

5.9 Reliability Results: Shock resilience

Indicator	Overview of methods
Flexible supply: Frequency Response capability	Power station data from National Grid (available on request) is used to calculate average 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)
Flexible supply: Short-term Operating Reserve & black-start capability	Calculates percentage of power generation which would be capable of providing 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)
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)
Flexible demand	Calculates technically and realistically shiftable potential for 2010 (in GW), using data from Sustainability First (Dudeney *et al* 2014); estimates realistically shiftable potential for 2030 and 2050 in % and GW Also uses data on electric vehicles (EVs) and heat pumps as a proxy for demand flexibility. Results given in TWh/y and in % of total demand

5.9.1 Flexible supply: Frequency response capability

This indicator uses the Frequency Response capability of the generation mix in the pathways as a proxy for the flexibility and responsiveness of supply. The graphs in figures 5.25 and 5.26 show the mean and maximum frequency response (FR) capability of the generation mix in the pathways (in MWh). The graphs show the capability of both primary FR (0-30 seconds) and secondary FR (30 seconds to 30 minutes) for the highest probable frequency deviation given by National Grid (0.8Hz for primary, 0.5Hz for secondary), thereby illustrating the ability of the system to respond to shocks of significant magnitude.

All three pathways show significant reductions in FR capability through to 2050. In general, primary FR shows a greater decrease, suggesting that the system’s ability to respond to very short-term deviations in the supply-demand balance is decreasing as a result of increasing penetration of intermittent RES which generally cannot provide any kind of FR. The MR pathway includes large amounts of gas and coal (with CCS), both of which are able to provide FR in much the same way as today; as such, the MR pathway has the greatest FR capability, but it still shows a sharp decline, driven by increasing penetration of RES and of nuclear. Nuclear can provide FR, but the raw National Grid data used for this indicator (available on request) suggest that nuclear provides much lower levels of FR per MW than coal or gas; nuclear tends to be more suited to providing baseload (House of Lords 2015).The generation mix in the TF pathway is less capable of providing FR in 2050 than it is in 2030; this reflects the increasingly rapid phase-out of thermal generation, to be replaced by intermittent small-scale RES. It should be noted that there are large uncertainties caused by lack of data on the Frequency Response capability of dedicated or co-fired biomass generation. The 2011 data used for this indicator only offers data for one biomass plant (at Tilbury), therefore the averages used for biomass are assumed to be the same as coal. This is a significant assumption which is made necessary by lack of data, and is discussed further in section 5.9.6.

Figure 5-25: Mean Frequency Response capability, primary and secondary (MWh)

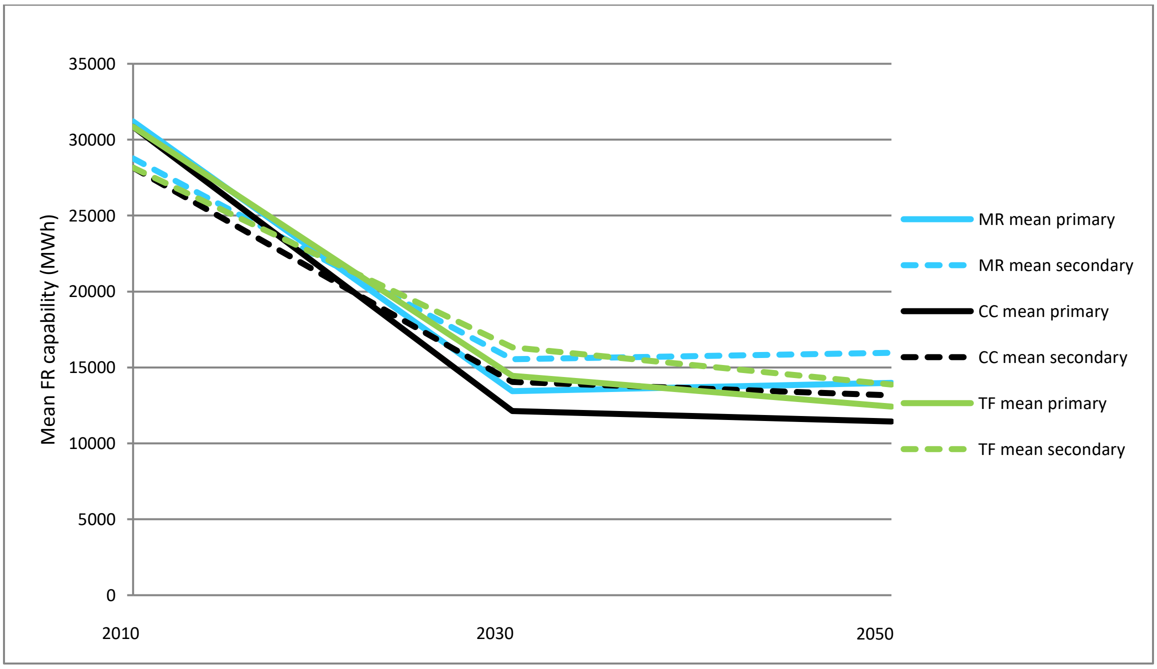
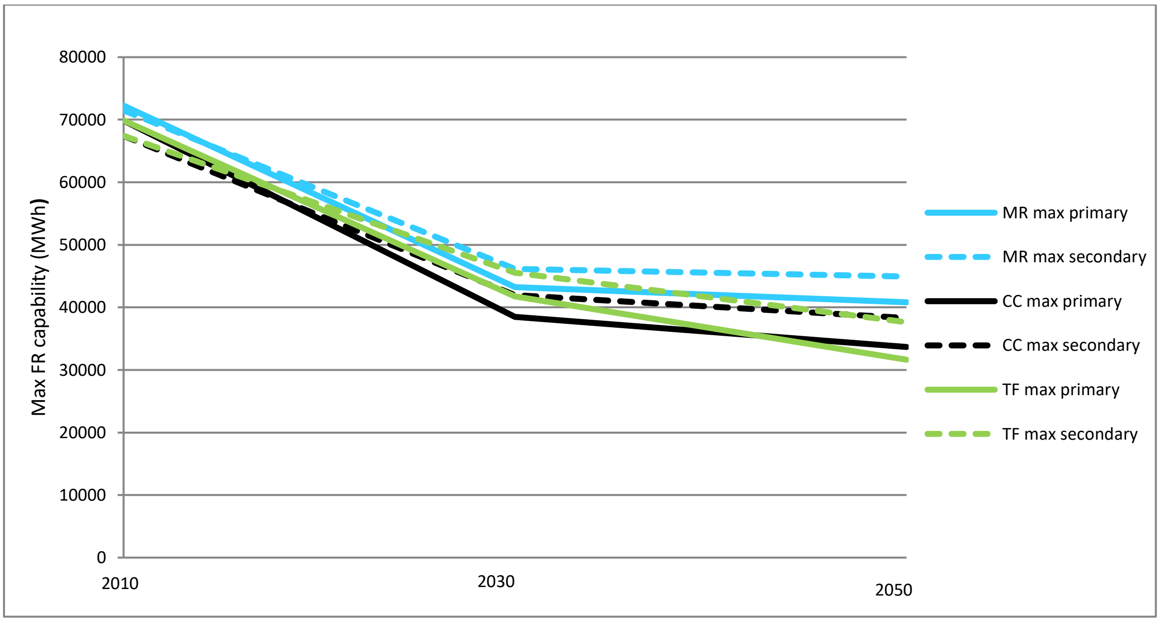


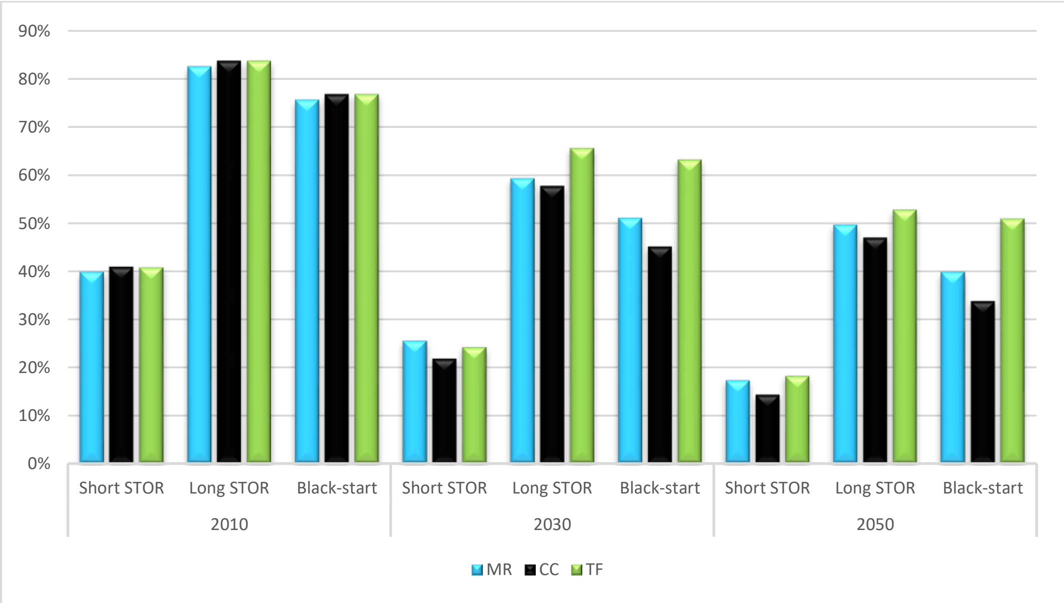
Figure 5-26: Maximum Frequency Response capability, primary and secondary (MWh)



5.9.2 Flexible supply: Short-term operating reserve (STOR) and black-start capability

This indicator uses the STOR and black-start capability of the generation mix in the pathways as a further proxy for the flexibility and responsiveness of supply. Figure 5.27 shows the percentage of power generation in each pathway which is capable of providing three different types of reserve power: short-term STOR (below ~45 mins), long-term STOR (45 mins to 4 hours) and black-start. The reserve capabilities of all three pathways decrease compared to 2010. The CC pathway sees the biggest decrease for all three types of reserve, with the TF pathway generally experiencing the smallest decrease. This is a somewhat surprising result considering that the TF pathway largely phases out gas and coal generation and therefore has far less of what might be thought of as 'conventional' flexible supply, but the result may reflect the large amount of biomass generation in the TF pathway versus the large amount of wind generation in the CC pathway.

Figure 5-27: Short-term STOR, long-term STOR, and black-start capability in % of total generation mix which is capable of offering these services



The CC pathway has the lowest capability for both FR and STOR, reflecting the extremely large amounts of wind power and nuclear power on the system in the CC pathway. Nuclear power cannot provide black-start power, and it cannot provide STOR if the station is switched off at the time of the request, for example for routine maintenance; as explained in Appendix E, this factor is taken into account in the calculations. Wind and solar power cannot provide response or reserve. For all three pathways, the decline in short-term STOR capability is especially pronounced. All pathways show a decline in short-term STOR from around 40% today, to less than 20% in 2050. This could mean that even if the system manages to deal with a short-term shock by restoring the frequency, there may not be enough reserve capability to restore the system back to normal operating status.

5.9.3 Response and Reserve requirements

As shown above, in the future there will likely be changes to the ability of the electricity generation mix to provide FR (response) and STOR and black-start (reserve). Additionally, future electricity systems will likely experience changes to the *requirement* for these services, due to three factors (explained in section 4.4.4.2): a decrease in natural inertia due to declining proportion of thermal plant; an increase in the largest credible in-feed loss due to increasing size of generation units; and an increase in the impact of wind forecasting errors as more wind generation comes onto the system (National Grid 2011).[21] Therefore, this section assesses the requirement for response and reserve services in the Transition Pathways, and compares this to the capability of the system for offering these services which was explored in the preceding sections.

5.9.3.1 Response (FR) requirements

Table 5-7: Increase in response (FR) requirement (% increase, compared to 2010)

		2030		2050	
		Primary	Secondary	Primary	Secondary
MR	Low (inertia only)	1.71%	1.71%	10.11%	10.11%
	High (incl. unit size increase)	77.99%	77.99%	92.69%	67.37%
CC	Low (inertia only)	7.82%	7.82%	-7.39%	-7.39%
	High (incl. unit size increase)	88.68%	88.68%	62.07%	40.77%
TF	Low (inertia only)	-7.84%	-7.84%	-3.45%	-3.45%
	High (incl. unit size increase)	-7.84%	-7.84%	-3.45%	-3.45%

Table 5.7 shows the increase in FR requirements which could be expected in the three pathways. As such, the higher the number, the higher the risk. The table illustrates the enormous influence that an increase in potential unit size (see Appendix E) could have on the FR requirement of an electricity pathway. Including this variable introduces enormous uncertainty to the conclusions. As such, it is recommended that the unit sizes would not be increased without consideration of the impact that this would have on FR requirements, and would therefore probably not occur in the manner shown here. Therefore, the most important conclusions are the ones which consider increases in FR requirement due to declining inertia capabilities, which will be focused on for the rest of this section.

[21] It is worth noting that improvements in wind forecasting in the future could potentially help to reduce forecasting error. However, it is still unlikely that it will become possible to accurately predict wind speeds on the short timescales required for system balancing. Importantly, even if forecasting errors become less common, the *impact* of such forecasting errors will increase as more wind generation comes onto the system.

Figure 5-28: FR requirements and capabilities

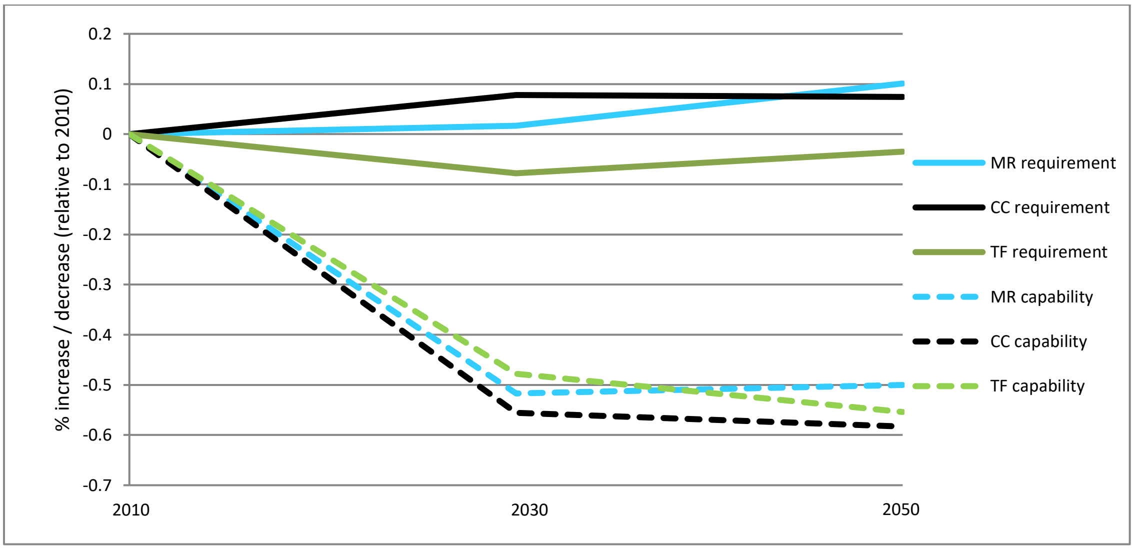


Table 5.7 and figure 5.28 show that the MR and CC pathways both experience very slight increases in FR requirements. The TF pathway actually experiences a reduction in requirements between 2010 and 2050, which would be positive for security. Nevertheless, the graph in figure 5.28 shows an increasing divergence between the *capability* of the three pathways to provide FR, and the *requirement* for FR within the pathways. The CC pathway experiences the largest disparity in 2050. It is worth emphasising that these results simply indicate percentage changes (which are in actual fact fairly small), and that therefore it is difficult to infer from this that the reduction in FR capability would necessarily be large enough to cause security problems. However, the divergence illustrated in figure 5.28 indicates that this could represent a potential security risk for the pathways, and that therefore this area would benefit from more research to improve understanding of how severe these risks could be.

5.9.3.2 Reserve (STOR) requirements

Table 5.8 shows that all the pathways experience significant increases in STOR requirements in both 2030 and 2050. However, those in red (both for the CC pathway) are particularly high at above 50%. The MR pathway experiences the smallest increase in STOR requirement.

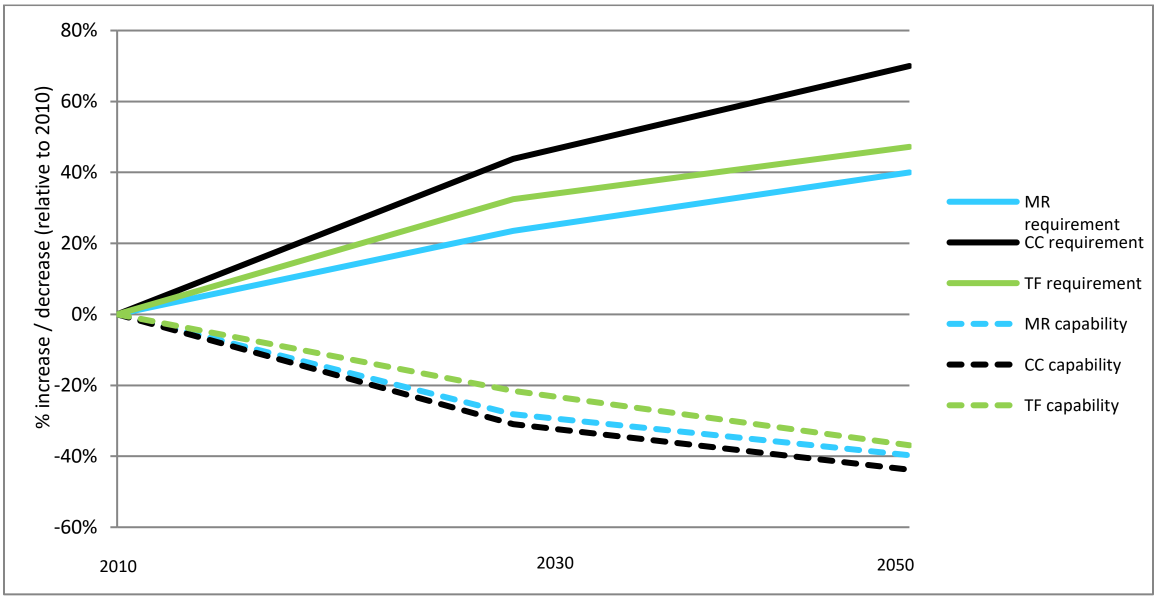
Table 5-8: Increase in reserve (STOR) requirement (% increase, compared to 2010)

	Wind capacity increase		Incl. unit size increase
	2030	2050	2050
Market Rules	23.55%	40%	48%
Central Coordination	43.8%	70%	83.92%
Thousand Flowers	32.5%	47.21%	47.21%

Figure 5.29 compares these changes in STOR requirements with the changes in STOR capability described in section 5.9.2. The STOR capability results show the long-term STOR capability, because this is an overall value which incorporates short-term STOR. As with the FR indicator in section 5.9.1, the unit size increase is not considered here. The graph shows that, similarly to Frequency Response, there is a considerable capability gap in all the pathways between decreasing *capability* to provide STOR, and the increasing *requirement* for STOR due to increasing penetration of wind power. The CC pathway has the biggest capability gap, although the other two pathways also have a fairly significant gap.

This indicator suggests that all three pathways could experience difficulties in responding to shocks, i.e. unexpected short-term changes in the supply-demand balance. It should be noted that possible future increases in reserve requirements due to solar forecasting errors are not included, as there is currently no data available which calculates the impact that this could have. It is feasible that by 2050, solar penetration could be high enough in some of the pathways for this to warrant further consideration.

Figure 5-29: STOR requirements and capabilities



5.9.4 Flexible demand

The preceding 'shock resilience' indicators have shown that the short-term flexibility of electricity generation is likely to decline in a transition to a low-carbon electricity system. Therefore, it would be desirable to make up this flexibility somewhere, and one of the most promising options is DSR. Unfortunately, the demand data in the pathways is limited, and therefore it is very difficult to estimate flexible demand capability. Therefore this indicator examines possible *technical* potential for demand shifting, and to what extent this might be realisable for the three pathways.

5.9.4.1 Flexible demand in the current UK electricity system

The majority of DSR in the UK is currently undertaken by large industrial and commercial consumers who have interruptible contracts, although DSR only accounted for 1% of the successful bids into the first round of Capacity Market auctions in 2015 (Hatchwell 2014). A three-year project by Sustainability First (Dudeney *et al* 2014) set out to assess the potential for DSR in the current UK electricity sector. The project found that the *technical* shiftable potential across all sectors today may be up to ~18GW on a January weekday winter evening, and up to ~10 GW on an August weekend 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, Dudeney *et al* (2014) note that 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.). There may be some scope for the 0.5 million households currently using on-peak electric heating to install insulation and shift their heating use to off-peak.

There have been a number of other useful studies into load-shifting potential in the present-day UK electricity system:

- Element Energy and De Montfort University (commissioned by Ofgem) found peak load-shifting potential in non-domestic buildings of 8 to 30% (Element Energy 2012)
- Smart meter trials have indicated that 7 to 10% of residential load could be shifted without any automation (AECOM 2011)
- Palmer *et al* (2013) found that there is some potential to shift peak household loads using controls on washing machines, tumble dryers and dishwashers. However,

replacing appliances with more efficient ones would do more to reduce the peak than DSR at present (Dudeney *et al* 2014).

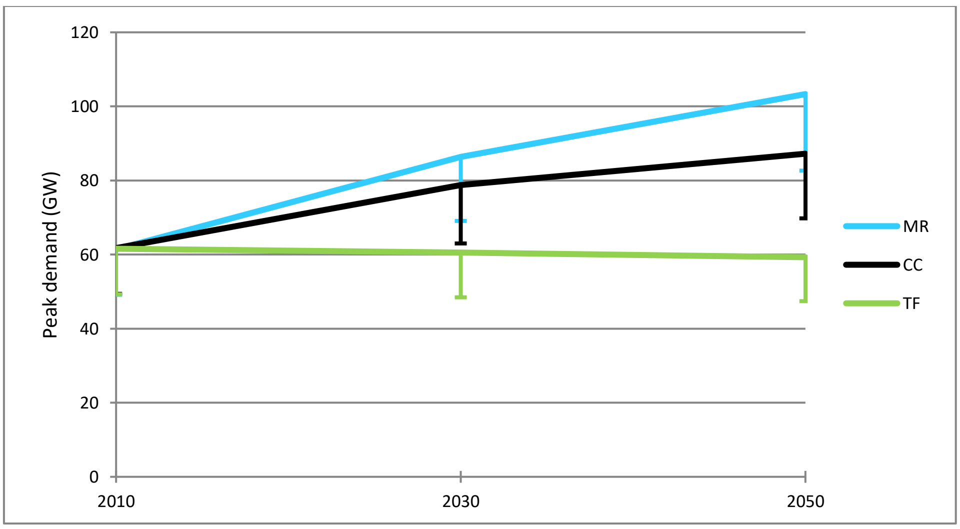
5.9.4.2 Peak load and shiftable potential in the pathways in 2030 and 2050

The level of peak demand in the pathways offers some indication of the amount of load which may technically be shiftable, although it is not possible to say which specific appliances this load consists of. The peak and minimum load for the pathways are shown in table 5.9. The larger the difference between peak and minimum load, the greater the assumed potential for load-shifting. The MR pathway, which has high levels of electrification but low levels of energy efficiency and demand reduction, has the greatest potential for load-shifting. However, there is a clear trade-off here between demand reduction and potential for DSR. DSR could provide valuable services to National Grid in the event of a shock; however, lower peak demand (as evidenced in the TF pathway) would create far fewer challenges for the system in meeting this peak.

Table 5-9: Peak and minimum load

	Market Rules		Central Coordination		Thousand Flowers	
	Peak	Minimum	Peak	Minimum	Peak	Minimum
2010	61.44	23.08	61.75	22.87	61.58	22.77
2030	86.36	26.20	78.76	23.10	60.58	19.78
2050	103.33	30.64	87.23	22.30	59.28	18.85

Figure 5-30: Peak demand. Error bars show 20% reduction of peak due to shifting



If 10% of the electricity load were realistically shiftable (to take a relatively conservative estimate based on the figures from AECOM [2011] and Element Energy [2012] shown above), the MR pathway would still have higher peak demand in 2050 than the other two pathways. The error bars in figure 5.30 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.

5.9.4.3 Could consumers in the pathways be encouraged to shift their demand?

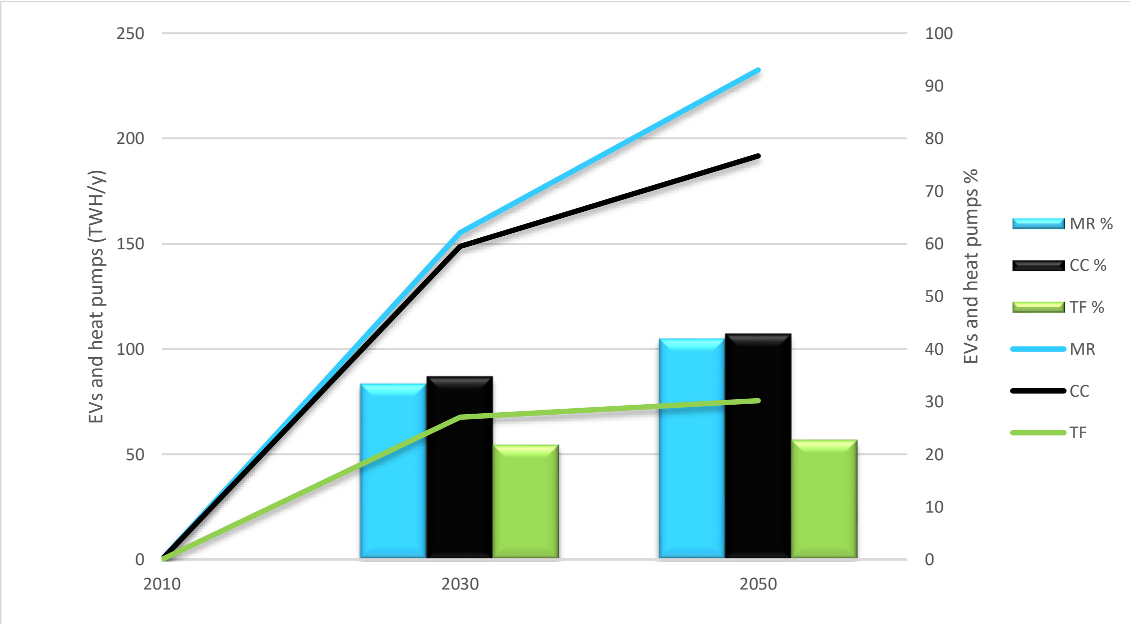
There exist various financial, regulatory and behavioural barriers which could make it challenging to realise the optimistic 20% load-shift scenario outlined above (see Owen *et al* 2013). The three pathways might encounter specific issues:

- **Market Rules**: it is possible that market-based mechanisms, if they developed the right kinds of incentives and removed some of the existing regulatory barriers, could be beneficial; however, this would require the introduction of a clear market incentive for suppliers and DNOs to get involved (Owen *et al* 2013).
- **Central Coordination**: government-led mechanisms, such as the UK smart meter roll-out (see DECC 2012d), could incentivise some load-shifting. However, government-led schemes would likely benefit just as much at the moment from regulating to reduce overall demand (Dudeney *et al* 2014). In the future, the government could mandate load-shifting to be achieved via automation; however, potential might be limited by the fact noted above that peak load is often comprised of less-shiftable services such as cooking.
- **Thousand Flowers**: Dudeney *et al* claim that “local energy schemes are where personal energy, drive and commitment sit to transform the energy sector to low-carbon” (2014:25). Barton *et al* (2015) suggest that ESCos will be critical for achieving demand shifting and overall demand reduction: it is demonstrated by Fang *et al* (2012) that ESCos may be able to deliver demand reductions of between 22 and 35% compared to BAU, which would be crucial for realising the demand reductions in the TF pathway. Automated load-shifting may be used widely by local energy companies in this scenario.

5.9.4.4 Electric Vehicles and Heat Pumps as a means of shifting peak demand

Electric vehicles (EVs) and heat pumps represent very large loads on the system, and therefore represent significant potential for load-shifting, especially because they do not necessarily use power during peak times (other large loads such as cooking are far less shiftable). Figure 5.31 shows that the CC pathway has a higher percentage of EVs and heat pumps than the MR pathway, and also lower peak demand (figure 5.30). The TF pathway has much lower potential for shifting using EVs and heat pumps, but the low peak demand in this pathway suggests that the system would not be as stretched to meet peak demand anyway.

Figure 5-31: Electric vehicles (EVs) and heat pumps



5.9.5 Does decentralisation equal increased resilience?

Some argue that a decentralised system will 'inherently' be more resilient (Farrell *et al* 2004). Greenpeace (2005), Johansson (2013) and Månsson (2015) all argue that a decentralised system will be less vulnerable to a large loss of in-feed, for instance such as that caused by a failure at a nuclear plant, and that decentralisation would minimise the impact of a significant shock such as a terrorist attack. Meanwhile Hoggett (2014) argues that small-scale systems are less vulnerable to supply chain disruption because of shorter and less complex supply chains. On the other hand, decentralisation could bring about different risks. For instance, Barton *et al* (2015) and Wolfe (2008) point out that in a decentralised system, the size and even direction of power flows will be less predictable, and therefore there will be even more need for load balancing. It is also likely that a shift towards electrification of heating and transport will involve significant load clustering, which in a decentralised system would need to be managed locally (Barton *et al* 2015). DNOs do not currently have the experience of managing complex power flows in the same way as National Grid – in order to manage a decentralised system, the DNOs would need to become much more active in managing their networks (House of Lords 2015; Lockwood 2014). If the interaction between the distribution and transmission systems is not managed adequately during this transition, the uncertainties experienced by the transmission operator could become worse (UKERC 2014).

There is also somewhat mixed evidence from mainland Europe: it has been argued that decentralisation can cause problems because of lack of coordination between different network operators (Castle 2006), but on the other hand the large scale of the European transmission system means that a fault in one area can easily cascade into a serious widespread loss of load (RAEng 2014),[22] and therefore decentralisation could actually act as a hedge against more serious cascading outages (UCTE 2006). The debate within the UK is still very much open, as demonstrated by the evidence collected by the electricity resilience enquiry conducted by the House of Lords Science and Technology Committee (House of Lords 2014). This debate seems to point to a possible trade-off between increased overall resilience to the risk of large-scale events, and increased local resilience to the risks of poor system management.

5.9.6 Shock resilience: key uncertainties and limitations

The key uncertainty for this dimension is the role of flexible demand in the pathways. There are multiple variables at work – for example, interruptible contracts for industrial and commercial users, the effectiveness of institutional arrangements, and the behaviour of consumers. It is very difficult to know how resilient a system is to shocks without knowing the capability of that system to shift demand when required. Therefore, in order to fully understand the reliability of a low-carbon electricity system, it would be highly desirable for the pathway or scenario to include detailed data on interruptible contracts, appliances, consumer behaviour, and institutional arrangements for flexible demand.

[22] For example, in 2006, a trip fault which started in Germany led to blackouts in 8 countries and cases of lines tripping as far afield as Tunisia and Morocco (RAEng 2014)

There are considerable uncertainties surrounding future FR and STOR capabilities. The assumptions regarding the FR and STOR capability of plant types comes from data on existing power stations; however, this might change considerably in the future. It is highly likely that response and reserve requirements will increase as more renewables come on-line, and as such, the rest of the power system will probably change to accommodate these requirements. The current system is built so that there is enough response and reserve capability, and it is probable that this would be maintained. All three pathways contain some kinds of responsive generation (in particular gas, coal and biomass), therefore in theory it may be possible to ensure that the response and reserve capability of new plants are maximised in order to accommodate additional requirements.

Finally, similarly to several of the other dimensions examined throughout this thesis, the 'shock resilience' indicators reveal significant uncertainties surrounding biomass generation, in particular the role of biomass for providing Frequency Response and STOR. For instance, the 2011 National Grid data used for the Frequency Response indicator (available on request) only offers data for one biomass plant (at Tilbury). Because of this, the averages used for biomass are assumed to be the same as coal; however, it is uncertain whether this would be the case, especially where CHP is concerned. It is therefore important that the response capabilities of biomass power are better understood and that any new biomass and CHP plant is built with response and reserve requirements in mind. This will ensure that the system can respond to changes in the supply-demand balance, which in turn will help the system to become more flexible and to support the increased penetration of intermittent renewable generation.

5.10 Summing up chapter 5

This chapter has presented the results of an empirical assessment of the security of three low-carbon transition pathways for the UK electricity system. The set of indicators designed in Chapter 4 was applied to the supply and demand data of the Transition Pathways to a Low-Carbon Economy Consortium, for the time increments 2010, 2030 and 2050. In chapter 7, these results will be used to create dashboard analyses of the pathways which flag up areas of risk; the analysis of results and their implications will also take place in Chapter 7.

The following chapter is the second of two results chapters, which uses the indicator set which was applied here as the basis for a discussion on energy security with stakeholders in the UK energy sector. The aim of the following chapter is to identify the key themes which arose from these interviews, in order to understand the diversity of perspectives in the UK energy community, and to elucidate the key areas of commonality and contention. Later, in Chapter 7, the results from these interviews will be applied to the results from the security assessment, in order to explore the impacts that these perspectives have on stakeholders' preferred options for managing electricity security. Operating in the knowledge that energy security is a complex and contested term (as discussed in Chapters 2 and 3), it is important to attempt to understand the possible implications of different perspectives on the results shown here. Instead of seeking to 'close down' the diversity of views around a simple and uncontested set of results, the following chapters of this thesis seek instead to open them up to debate.

6 Results 2: Results from the stakeholder interviews

This chapter presents and analyses the results from the 25 interviews which were conducted with key stakeholders in the UK energy sector, in order to answer the second research question: “What are the reactions of energy stakeholders to the proposed set of indicators, and what does this tell us about the diversity of perspectives in the UK energy community?” The purpose of this chapter is to identify the key themes which arose from these interviews and to elucidate the key areas of commonality and contention, in order to understand the diversity of perspectives amongst UK energy stakeholders. Later on, Chapter 7 will go on to cover the final research question, to explore the impacts that these perspectives have on preferred options for improving electricity security.

Section 6.1 presents an overview of the importance which respondents placed on each indicator, from the ratings given for each indicator on a scale of 1 to 5. Sections 6.2, 6.3, 6.4 and 6.5 then move on to presenting the qualitative outputs of the interviews within each security dimension: availability, affordability, sustainability and reliability. Some of these comments from respondents refer directly to specific indicators; however, several are overlapping, and therefore they are presented according to dimension rather than according to indicator. Finally, section 6.6 uses these outputs to identify five major cross-cutting themes which emerged from the interviews.

6.1 Results from Likert-scale ratings of indicators

Respondents were asked to rate the indicators on a Likert scale according to how important they felt each indicator to be for electricity security in a low-carbon context (with 1 denoting minimal importance and 5 denoting critical importance). The results are shown in figure 6.1, in which each ‘bubble’ represents an indicator, the size of which denotes the mean score for that indicator across all respondents; the larger the bubble, the more important the indicator was felt to be on average. It should be noted that these numbers do not necessarily reflect the complexities and nuances contained within the respondents’ answers (these are analysed in more detail in sections 6.2 to 6.5); however, they can provide a useful overview of the patterns which emerged from the group of stakeholders as a whole.[23]

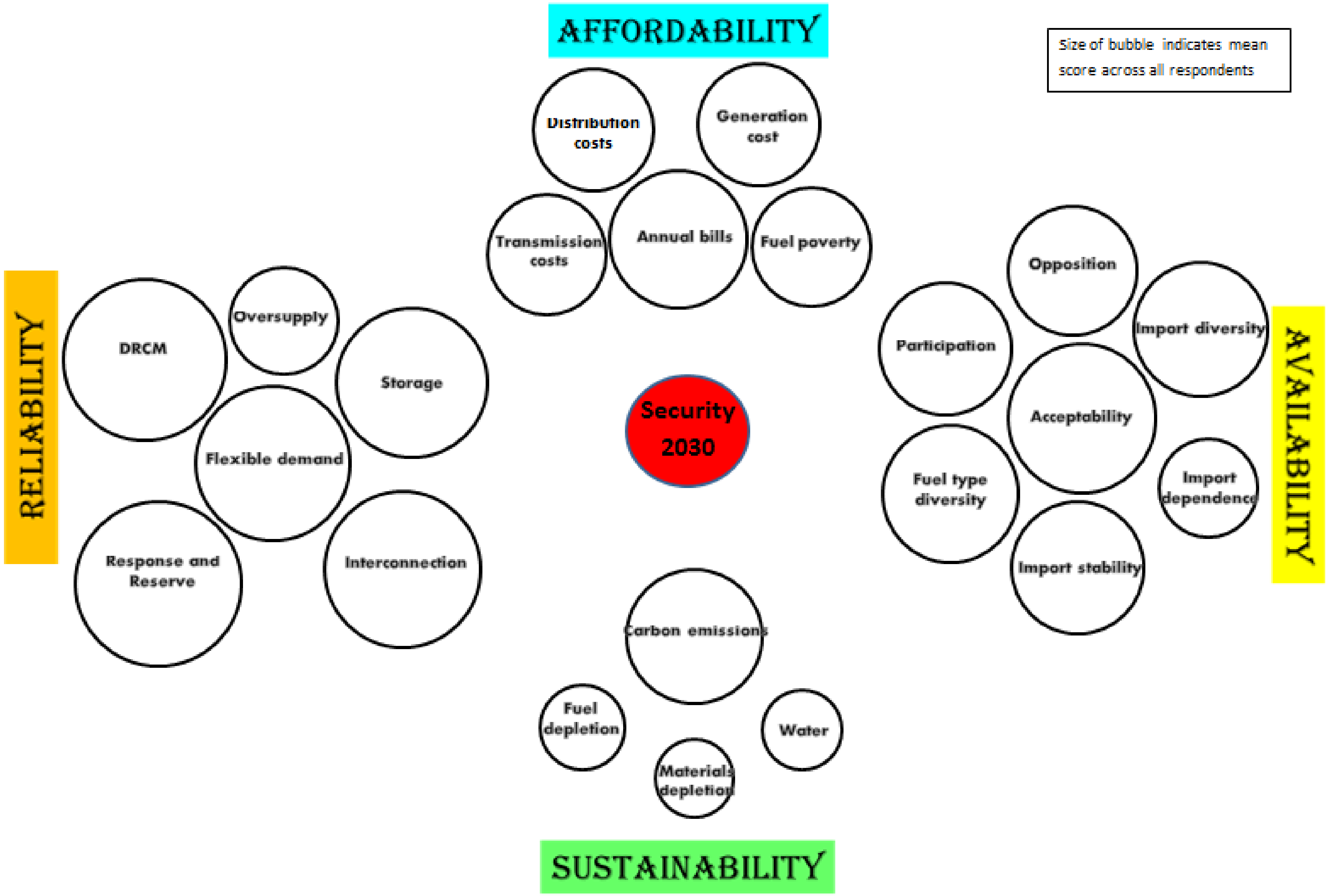
Respondents were asked to rate indicators for the medium-term (2030) and the long-term (2050). However, the interviews were not particularly successful at eliciting differences between the two time-frames; most of the results are very similar for 2030 and 2050, and no clear patterns emerged. This could be for a number of reasons. It could be that respondents were unable to consider how things might change over such long timeframes because of the inherent uncertainty. It might also be because the interview format was not well designed for eliciting considered responses on the differences over timeframes, because the semi-structured format sought to allow for digressions and therefore did not always stick rigidly to discussing each indicator in turn. There was significant variability between the willingness of respondents to differentiate between the two time-frames, but a majority of respondents reported no differences between their ratings for 2030 and 2050. For brevity, and in order to acknowledge the possibility that respondents may have been unable to consider how things might change over very long timeframes, the results are only shown for 2030.

As can be seen from figure 6.1, the 'availability' and 'reliability' indicators were felt to be the most important, whereas most of the 'sustainability' indicators received lower scores. Many respondents felt that the sustainability dimension should be thought of as *separate* to security, whereas many were in agreement that the more traditional security dimensions of availability and reliability are integral to electricity security (again, it is worth noting that 'sustainability' is used in this thesis to refer to GHG emissions and resource depletion, and will likely have been viewed in the same way by the respondents, as they were only provided with the list of indicators and not the names of the four dimensions). However, within these dimensions, not all indicators were felt to be critical to electricity security; notably, 'import dependence', which is often used as an indicator of energy security in the literature (see for example Bordhoff *et al* 2010; Cherp *et al* 2013; European Commission 2001; Greene 2010; Jewell *et al* 2014; Pfenninger and Keirstead 2015; Umbach 2010) was felt to be relatively unimportant. For the 'affordability' dimension, again many respondents felt that affordability issues should be thought of as separate to security; however, the affordability indicators received higher scores on average than the sustainability indicators. This was partly due to a high number of mid-range responses in the affordability dimension, especially relating to transmission and

[23] Note: only 24 out of 25 respondents agreed to rate the indicators on a Likert scale.

distribution costs, and also partly due to a number of low scores for the 'resource depletion' and 'water' indicators. Four of the highest average scores were for indicators relating to the flexibility of the system (response-and-reserve, flexible demand, storage and interconnection). This is interesting because these indicators relate to the ability of the system to *respond to* threats or insecurity; however, a comprehensive literature review by Jonsson *et al* (2013) found that most of the energy security literature focuses on measures which are thought to reduce *causes of* insecurity, such as minimising exposure to imports. The possible reasons for these results, and the nuances within the responses, are explained in more detail in sections 6.2 to 6.6. It should be emphasised that these results are useful simply as an overview of respondents' views; because participants were selected using purposive rather than probabilistic sampling, it is not possible to conduct a robust statistical analysis of the ratings given.

Figure 6-1: Ratings of indicators by interviewees, 2030



6.2 Interview responses: Availability

6.2.1 Acceptability, engagement and opposition

The majority of respondents felt that public acceptability and support is integral to a successful, secure transition. It was noted that actors and decision-makers need a mandate to operate and that the transition needs to be 'politically affordable' (respondents F; G; J; L; O; V, X), and that a lack of public support could create insecurity because infrastructure may not get built in a timely manner (A; D; K; U). One respondent (F) said:

> In order to meet the UK's renewable targets, you are talking about a quite dramatic change in the landscape of the country…. and you are already starting to see the politics get difficult, with the Conservatives essentially trying to block onshore wind developments… And of course the bottom line is, if people do not accept it the politics gets too hard and it won't happen.

However, some respondents argued that public acceptability doesn't seem integral to the concept of energy security, for instance because public opinion doesn't necessarily drive decision-making (E; Q; V; Y), and that it would always be possible to build what is needed, it just might cost more without the public on-board (N; W). It was also noted by many that public approval, engagement and opposition are complex, indirect and non-static measures of electricity security (A; I; N; P; Q; W; Y).

One common theme which emerged was the idea that the transition will mean making difficult choices (E; H; I), a fact which may be poorly understood by the public (C; O; T). It was suggested that there needs to be *better* public engagement around the challenges of developing a secure, affordable and low-carbon energy system (F; J), but that at the end of the day, it all comes down to the extent to which the public accept the trade-offs which may need to be made, for instance if they might need to pay more for a secure system (G; U). It was noted that if people aren't accepting, it would be far more likely that the carbon targets would be the area of the trilemma to suffer (K). Several respondents pointed out that public acceptability is complicated by a widespread fear of letting the 'lights go out' (C; Q; T), and that this makes it politically very difficult to challenge conventional ideas about how electricity is generated and consumed (T).

Several respondents suggested that a secure, low-carbon system with no participation or engagement from the public would be technically feasible, but would reduce the options available and would make low-cost interventions such as demand reduction more challenging, thus probably resulting in a more costly transition (A; O; R; U). This is linked to themes around the co-benefits of participation, such as behaviour change and empowerment for consumers (G; O; T). Some argued that decentralisation is the best means of improving public engagement and buy-in, thus perhaps improving the overall acceptability of the energy mix (B; T; X). One respondent (X) argued that:

> For me, public participation and engagement doesn't really do it as a term, because it conjures up impressions of the sort of consultation process that you go through when you develop any kind of energy project. For me, that is by many leagues insufficient. What we should be looking for is a mixture of community ownership, control, and leadership.

However, others pointed out that there is no research consensus on whether or not a decentralised system would be more secure (E; J; U; V). The UK has a highly centralised market system, which could mean that the lessons from the Continent could be difficult to replicate here, and increased decentralisation could result in fragmentation and some consumers getting 'left out' (B; J). One respondent (Y) said:

> There are lots of people who believe in localism, and to some extent that's true, that the more local it is then the more ownership people have. But how much of a premium are people willing to pay for that ownership? People readily accept that some things need to be centralised.

Participation becomes more crucial for electricity security if the system is decentralised, because in a centralised system power production can often take place in remote locations (D; H; V); this underlines some of the challenges for attempting to create a generalisable set of indicators for the assessment of multiple transition pathways, because the importance of certain indicators depends on the technology mix.

There was disagreement around the impact of direct opposition on security. 10 respondents argued that opposition is highly important, and can have a seriously detrimental impact on security; it was argued that opposition not only impacts on timing, cost and feasibility, but also on the general political dynamics and the political legitimacy for the transition (C; E; J; R; Y). Fracking, onshore wind and nuclear were all mentioned frequently on this subject (D; F; L; O; P; S), although it was also pointed out that the impact of opposition depends on who is doing the opposing (B; E; Y):

> I think that governments listen more to the middle-classes who don't want turbines near their houses than they do to other forms of opposition. If you think of people who've lived near coal-fired power stations their entire lives, generally people who are less well off in big cities, and who've had it pumping over them for decades

> and decades. It depends on who's opposing, as to how important it is.

On the other hand, 10 respondents raised questions over whether opposition would have a material impact on the security of the electricity system. Several respondents said things along the lines of 'with all due respect, protests in the UK never actually stopped anything' (H; S; V; W). One respondent (W) stated that:

> Protesting about existing power stations all seems very totemic, it doesn't actually do a lot… At worse, you have to consult with local opposition about new infrastructure and you don't have to agree with them, and the ultimate decision is taken by the relevant authorities, which is the Secretary of State. I've yet to meet a Secretary of State who would put local opposition over security of supply. They'd probably try to find a way to keep both happy.

It was pointed out that opposition might increase the cost slightly, but developers generally just find a more acceptable way of getting things built or seek redress from the law (D; H; L; M; P; Q). It was also widely noted that there will never be a consensus amongst the public (E; K; N; Q; R). Some respondents argued that opposition is malleable, especially if local people see economic or community benefits from the project (G; J; O; U).

Finally, several respondents picked up on the link between acceptability, engagement and demand-side participation. At the moment, the majority of people act as passive consumers in the UK's top-down system, and only really engage if prices go up dramatically or if someone tries to build infrastructure next to their house (M; P; U; V). However, whichever route to transition is taken, it is highly likely that changes will need to be made on the demand-side: even the two centralised pathways both include large amounts of demand reduction and a smart grid. As noted above, this could bring co-benefits to consumers; however, there was concern amongst the respondents over whether the public would accept this (G; P; V; Y). Concerns were raised that opposition is not just about protests and blocking of planning permission; it's also about a general resistance to the idea of changing behaviour (R; W; X):

> Opposition, I think, also affects the way that we think about electricity use, and so there's a strong, almost ideological opposition to the idea that we should think about anything to do with our demand – we pay our electricity supplier for our electricity, and that instils a sense of a right to use as much as we feel we need. That fundamental assumption, I think, we have to challenge.

6.2.2 Diversity and imports

One of the most commonly-cited indicators for the security of an energy system is diversity. However, the interviews revealed significant levels of disagreement over the importance of diversity as an indicator of electricity security. Numerous respondents suggested that it is 'prudent' to have a range of options to spread the risk, and that the benefits of a 'portfolio' approach have been well recognised, especially in the context of increasing intermittent generation (D; G; K; I; M; N; O; P; Q; R; S; V; X; Y). Respondent V stated:

> To me, this is the nub of the debate. We can't plant the whole of the decarbonisation agenda on one technology, only to find out it can't be deployed or we've misunderstood public acceptability, or we can't get cost reduction.

On the other hand, many respondents expressed scepticism about the importance of the diversity indicator (A; C; E; F; I; J; O; U; Y). Some argued that is a useful but not sufficient indicator, whereas others felt that it is generally not a particularly important factor, as expressed by respondent A:

> It's one of these dogmas at the minute, that everyone says, "future system - diverse, diverse, diverse". I'm less sure about that. I look at France for example, that has what seems to be a very secure system, has been for years and years, and it's about as un-diverse a system as you could get. You need a mix that works…

Several respondents picked up on this point that one technology could in theory simply be more secure than all the others (C; E; J; O; U), with four respondents mentioning the example of France (A; F; J; U). It was argued that at some stage, it will be necessary to narrow it down to technologies which are more mature and more cost effective (A; O); as stated by respondent O:

> It can seem intuitive that you would want a wide range of technologies and a wide range of fuels in order to sort of hedge your risk to supply shocks, but I always have some concerns about that argument because I think it can be used to kind of dissuade oneself from making tough choices… You can end up if you like coming up with a logical construct to support bonkers projects just because we don't have one of those and if we have one of those we will be more diverse.

Many of the respondents noted that the importance of diversity depends very much on the context. The electricity mix in the UK is currently very diverse, and many of the respondents found it unlikely that diversity would ever be an issue for the UK (F; M; U; W); in fact, the results in chapter 5 (section 5.2.1) support this. Moreover, the importance of diversity as an indicator of security depends on the technology mix; for instance, if cost effective storage and widespread DSR are successfully developed, diversity could become much less important as a strategy for integrating intermittent renewables (B; H; W).

A common opinion was that reducing dependence on imports is not an important factor for improving electricity security. It was noted that in the context of a global market, imports are probably a good thing; it will always be possible to get hold of the fuels and materials required as long as the price is paid, and imports can help to reduce costs (F; G; I; J; V; W; Y). Some respondents rejected the rhetoric of not getting fuels from abroad (R; W):

> To say ‘we can’t rely on those pesky foreigners’ is an attitude that’s kind of dodgy anyway, it assumes every other country in the world is ganging up against us, basically paranoia.

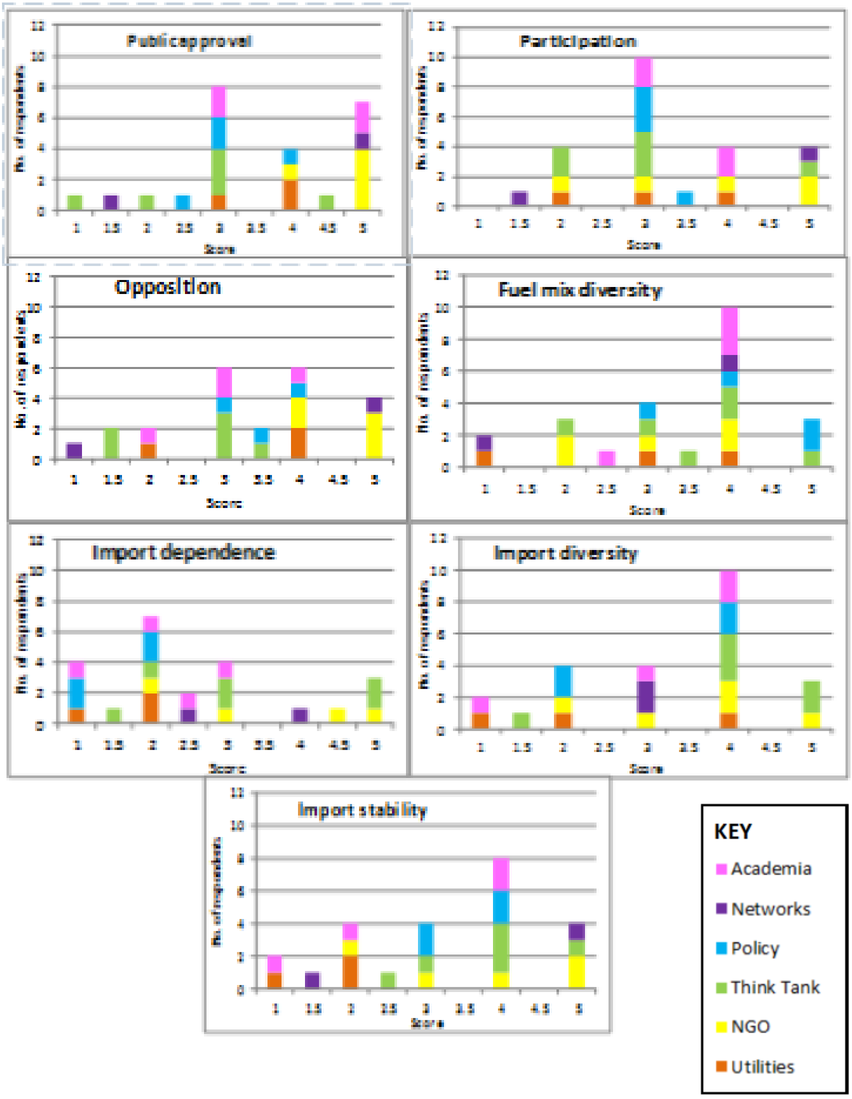
Several respondents said that as long as imports are diverse, the overall level of dependence on imports, and the stability of the exporting nation, is of less importance. The exact balance of the three ‘import’ indicators was not agreed upon, but almost 50% of respondents were explicit about the fact that gains in one of these ‘import’ indicators can make up for shortfalls in others (A; C; D; G; J; K; M; P; S; U; V; W; Y).

Conversely, it was noted that import dependence is what people traditionally think about when they think of energy security (P). It was also noted that politicians in particular see minimising imports as beneficial because they have more control over what happens within the UK (D; Y). As one respondent (T) said:

> Well it's a risk isn't it? It just adds to your risk. You can't control what another country's going to do. So you're increasing risk by relying on imports. And from a business point of view, you want to mitigate, to minimise the risk. So I suppose you're increasing instability by getting it abroad, to various degrees.

This issue is highly linked with concerns over fossil resource dependency, and several respondents argued that reducing reliance on fossil fuels would have a double benefit for electricity security by improving environmental sustainability and decreasing dependence on imports (I; O; Q; T; X). In this respect, a decrease in import dependence was seen as somewhat ‘inevitable’ as the transition is made to a low-carbon economy (H; K; L; O; Q); this is interesting, considering that the results from the security assessment (section 5.2.2) do not support this assumption.

Figure 6-2: Indicator ratings: 'availability' dimension



6.3 Interview responses: Affordability

6.3.1 Costs to consumers and to the system

When analysing the 'affordability' indicators, a divide immediately became apparent between those respondents who felt that affordability is integral to electricity security, and those who felt that affordability is a separate or second-order issue. Clearly, everyone was in agreement that affordability in and of itself is an important goal; however, the question arises over whether this dimension should be included as part of an assessment of electricity security.

Several respondents stated that if people can't pay for their power, they do not have a secure supply (H; N; Q; X; Y). It was also noted that keeping energy affordable is a fundamental part of the wider economy, and that energy security involves "hopefully not screwing the economy by the way that you do this" (Q), and maintaining "economic sustainability" (O). On a similar line, it was also noted that affordability is closely linked to acceptability, and that high prices could cause political instability, which would negatively impact security (C; H; I; L; M; N; O; S). Respondent N said:

> If supply costs get so high that people can't pay their bills then that is going to have a negative impact on security of supply and you will also end up with political things happening that will then destabilize things.

However, it was also pointed out that consumers often don't notice short-term variations in price, and there is probably still room for bills to go up before it creates a serious acceptability risk (D; F; L; M; U; Y). It may not be the price itself which drives insecurity, but rather people's *reactions* to prices and to the pace of change (C; Y):

> But in and of themselves, I don't think affordability drives system security. I think it's the reactions to it that drives levels of system security. Cutting the 'Green Crap' was a choice about where politicians felt they should go; and the political framing around that was coloured by the way some parts of the right wing of the political system have approached the whole issue of climate change, for reasons that are beyond the remit of your immediate project, I suspect. So the affordability has affected system security negatively in the long term.

However, contrary to all this, many respondents argued that affordability is not integral to the concept of electricity security. Affordability was often seen more as a second-order issue (A; D; E; V), or as a trade-off *against* security, because measures to improve security could result in increased costs (K; P; V) and because security of supply is the one thing that people appear to be prepared to pay higher energy prices for (E; K). As stated by respondent A:

> Annual electricity bills fall squarely into the 'cost' side of the trilemma. Now obviously everything's connected in the system, so if bills go up, that might be a sign that the system is getting less secure, but it's a second order sort of impact.

It was suggested that high prices could potentially impact security, for the reasons detailed above, but that they don't tell you very much about the security of the system itself and are therefore not a particularly effective direct indicator of electricity security (A; G; U). Security is seen as 'trumping' both affordability and carbon from a political perspective (C; K; V; W), which could mean that high prices would result in a loss of political consensus for climate mitigation (D; K; P; W). As one respondent (V) said:

> You're not going to not keep the lights on because things are more expensive, ultimately. That would be a very bizarre political decision. But the impact might be more on the rate of decarbonisation more than security. In a political reality, you'd probably sacrifice decarbonisation first.

This makes it important to emphasise the distinction between 'a secure system' and 'a secure *low-carbon* system'; one respondent suggested that affordability is integral to the concept of energy security when talking about a low-carbon transition because of public acceptability issues, whereas when talking about security of supply per se, affordability is not integral to the concept (P). Another common perspective was that it is important to keep prices *efficient* and *reflective*, rather than simply keeping them low. The correct price signals are vital for ensuring that investors have the right incentives to build electricity infrastructure (J; M; N; S; T; U; Y). Respondent U said:

> So the security issues comes more to me in terms of price signals that's telling the market in the long-term to get things built, to get the right sort of things built in the right sort of way.

Finally, fuel poverty was one of the most contentious issues. Some respondents argued that fuel poverty is critical because it can have knock-on impacts right across the board, on demand reduction, energy efficiency, government popularity and public acceptability; fuel poverty can have a wider impact on the general direction of policy, and as a moral argument the issue has considerable potential to engage the public (F; I; J; M; N; O; Q; R; S; X). It was also pointed out that reducing fuel poverty is a sensible strategy for electricity security anyway, because it puts the emphasis on reducing demand and improving energy efficiency, both of which are in theory 'win-wins' for security, affordability and carbon (R). On the other hand, a large number of respondents felt that although reducing fuel poverty is important from a normative perspective, it doesn't have much political salience or material impact on electricity security

(C; D; E; G; H; K; L; P; U; V), especially because the lower end of the income spectrum tends to get ignored by politicians (C; D; H). One respondent (C) said:

> Well the thing about fuel poverty is, it's actually shown almost no ability to influence the politics of energy over quite some time. I mean there's quite a lot of pious commentary about it, but very little real kind of gritty attack on it. I suspect it's because a lot of those people who are genuinely fuel poor don't vote.

Interestingly, it was also suggested that higher energy prices could actually be *beneficial* for electricity security, by encouraging people to reduce waste and to improve energy efficiency; electricity is probably not expensive enough at the moment to really provide an incentive for non-fuel-poor consumers to cut their demand (B; R; T).

6.3.2 Networks and network costs

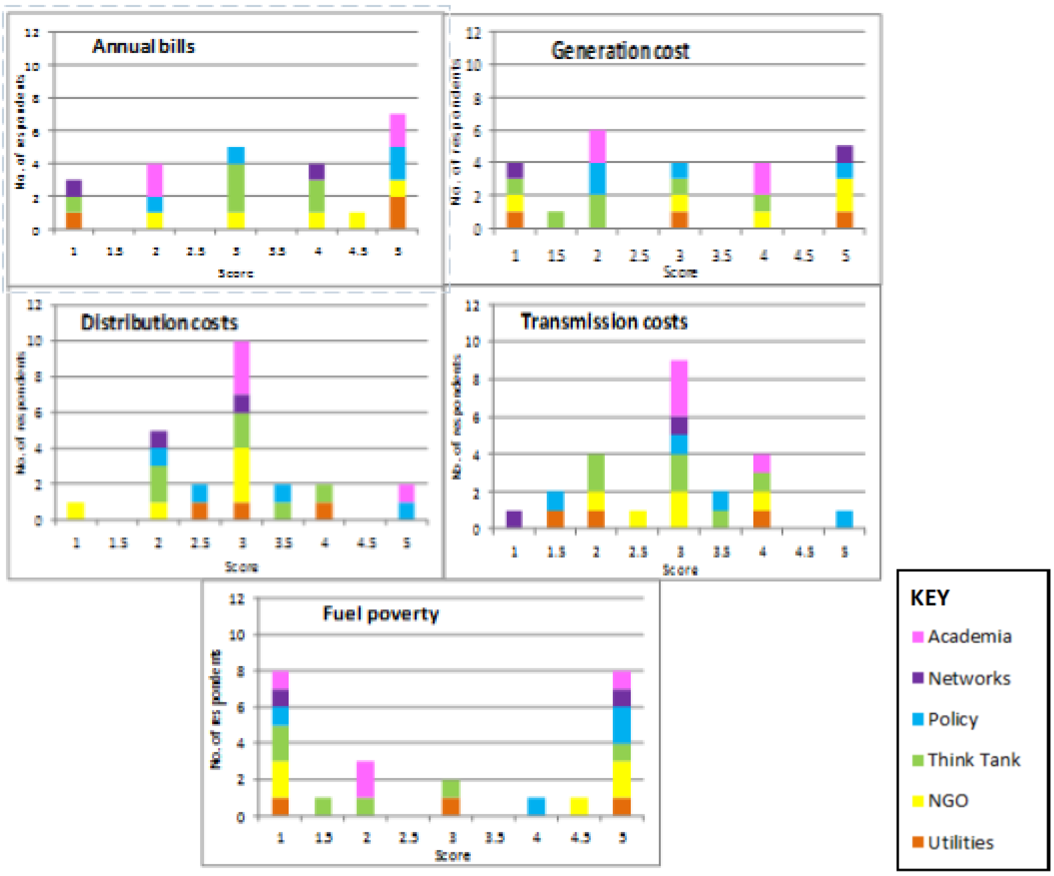
Despite the fact that network costs are included in the security assessment as part of the annual bills calculations, there are numerous interconnected issues to do with network upgrades, several of which relate to network adequacy and the reliability of the electricity system. Therefore the networks are considered here under a unique section; several of the issues raised will also be relevant for the 'reliability' dimension, covered in section 6.5.

Transmission and distribution networks are critical to security; as noted earlier in this thesis, they are the component of the electricity system on which outages generally occur (C; O; W). However, respondents pointed out that unlike the rest of the electricity system, the networks are a heavily regulated monopoly, meaning that there is less risk of failing to attract private investment (L; U; W). Respondent U said: "The cost component attributed to networks I don't feel is going to be a game changer unless it's done really badly, which so far history shows that it hasn't been." The regulated nature of the networks means that cost efficiency is the most crucial aspect for the networks to achieve; expenditure and upgrades will be required, and the challenge is not so much in keeping these low per se, as in keeping them as efficient as possible to maintain the desired level of reliability (G; N; Q; R; S; U; Y). One respondent (S) stated that keeping costs down is "at the heart of what networks do", and that they have seen significant cost cuts since privatisation:

> Network companies are absolutely regulated economically. They are allowed to spend a certain amount; they are given the parameters of their ability to invest. Therefore [cost efficiency] is kind of built-in to the whole process. What we've seen since privatisation in 1990 was… about a 50% real reduction in the cost of the industry due to massive 'squeezing of the lemon'.

The problem with using network costs as an indicator of electricity security is that is doesn't tell you anything about whether the system is the most effective or efficient that it could be (G). At the same time though, it is important to prevent network costs from becoming prohibitively high, because this could present a barrier to the willingness of government and consumers to pay for necessary upgrades, which could cause insecurity (C; G; K; L; M; O; S). However, several respondents noted that public acceptability of high costs might not be a particular problem for the networks, because they only make up a small percentage of the bill (D; K; L; R; U; V; W). Several respondents suggested that decentralisation could be a critical factor in determining the potential future risk to the networks, and that the distribution network is where the greatest changes are likely to be seen in the future (J; L; O; S; V).

Figure 6-3: Indicator ratings: 'affordability' dimension



6.4 Interview responses: Sustainability

6.4.1 Carbon

The question of whether the carbon emissions from electricity generation should be seen as an indicator of the security of an electricity system generated considerable contention amongst the respondents. As shown in the responses from many of the other indicators thus far, the imperative to mitigate climate change is one of the main driving forces behind many of the changes underway in the UK electricity system; however, this also means that many of the measures which could theoretically be used to create a secure electricity system are less useful when trying to create a secure *low-carbon* electricity system. It is worth noting that the entire framing of the interviews was based around assessing the security of transition pathways, in fact the title on the interview briefing note is 'assessing security *in a low-carbon context'*, which creates a framing effect whereby respondents will have instinctively thought about their responses in the context of cutting emissions.

A considerable number of respondents referred to mitigating climate change as a central 'aim' or 'driver' (B; E; I; J; L; Q; R; U; X; Y). One respondent said simply, "We'd rather not fry the planet!" (Q). As one respondent (U) pointed out:

> …if we are still committed to carbon targets but delay action then also there's a security issue in that you have to work a lot faster and harder thus spending a lot more money more quickly and not necessarily having a considered view of the energy system you're trying to build. And that could have knock-on impacts into diversity, into dependence on imports…

On the other hand, many respondents argued that climate change and energy security are two separate issues, and that carbon emissions should be viewed not as an indicator, but as a parallel objective, trade-off or complicating factor (E; F; H; J; K; M; V; W). Several respondents noted that it would be possible to have a very secure system which had very high emissions (A; G; J; K). Respondent W said:

> …ultimately when people make decisions about the trilemma, this [emissions] is the one that gives up in preference to security of supply. But this is the one that we actually have a legal obligation to do, whatever that means...

One issue which was raised repeatedly regarding carbon emissions was the potential for future climate policies to result in stranded assets for the industry (C; D; T; U). The main issue raised here was the future uncertainty, because a secure system will need to attract investments for infrastructure which has very long lifetimes.

An important limitation of this sub-set of interview results concerns the difference between 'carbon emissions' and 'GHG emissions'. The briefing provided to the interviewees (Appendix G) stated that the indicator under discussion refers to 'carbon emissions' (thus implicitly omitting discussion of other GHGs such as methane); however, the security assessment calculations were for CO_2e, which includes other GHGs (the UK carbon targets also relate to CO_2e). The distinction between carbon emissions and GHGs was not mentioned by any of the interviewees, and it is possible that the interviewees may have been using the word 'carbon' as short-hand for all GHGs: carbon dioxide is the primary greenhouse gas, accounting for more than 80% of UK GHG emissions (DECC / National Statistics 2015), and it is not uncommon for policy discussions to conflate carbon and GHGs. However, this was not discussed with the interviewees during the conversations, therefore this represents an oversight and limitation of this part of the thesis.

6.4.2 Resources

The sub-dimension of 'resource depletion' was probably the area of least concern for the group of respondents as a whole. Regarding primary fuels (gas, coal, uranium, biomass), numerous respondents said that resource depletion is not an issue; resources can be made available at a price (C; E; G; H; I; L; O; P; R; U; V; Y). A common theme was that fossil fuels need to stay in the ground, because burning all possible reserves would result in catastrophic climate change (E; H; I; O; P; R; U; V; Y); this is linked to concerns about stranded assets, with one respondent saying "if carbon targets are met then in the longer-term it won't be possible to *give* [fossil resources] away!" (U). There was some scepticism about peak oil: one respondent stated that "we haven't yet scratched the surface in terms of fossil fuel exploration" (P), another stated that "peak oil is mainly nonsense" (L), and four said that the peak oil argument hasn't changed in 40 years despite the fact that (in their view) the Club of Rome got it wrong (C; H; L; P). In general, most of the respondents assumed that there are too many fossil fuels in the ground, rather than too few. However, respondent E also noted that this is still an open debate:

> People sit in different places on resource depletion. Even on our team we disagree. I'm not a peak oil person, basically. Partly because I don't think it's likely that we're going to run out before we kill the climate, and now it's obvious that we have enough to kill the climate. I think we can definitely dig more than enough out of the ground to kill ourselves three times over.

It was also noted that the importance of resource depletion depends on the pathway and the technology mix (a common recurring theme for many of these indicators). There was some disagreement over gas: some respondents stated that resource depletion could be an issue for gas because of its status as a transition fuel (Q; R; S; T; V; W), although others argued that the diversity of potential global gas suppliers means that the UK would always be able to find gas from somewhere (F; J), and that shale gas has somewhat undermined peak gas arguments (O). Respondent O said:

> I am relatively sceptical of peak oil and peak gas arguments simply because I think that over time we are quite a cunning ape, we tend to come up with ever more complex ways of getting at things. I mean shale is used as quite an easy and possibly slightly lazy example of this, but nonetheless it is an example of some relevance. I don't think it is sustainable but I don't actually think we have got a problem finding them.

Regarding secondary materials (Rare Earth Elements etc.), there was slightly more disagreement between the respondents. Some respondents suggested that depletion could be an issue for batteries and for several renewable technologies (G; J; M). However, it seemed that the main concern was not so much *depletion* of these resources, as *access* to resources which are currently highly concentrated (E; I; S; U; Y). However, others argued that the concerns around Rare Earths have been 'overblown' (E; L; C), and that there is potential for finding alternatives (R; V; X). One respondent (C) said:

> Depletion of fuel is a non-issue. Depletion of resources, yes potentially, I think some of the Rare Earths might be impacted. But I think back to the Club of Rome and how they got that wrong, and actually people haven't tried looking for Rare Earths that much, and haven't tried that hard to separate them out, and I think market signals will increasingly be important in delivering material availability outcomes.

6.4.3 Water

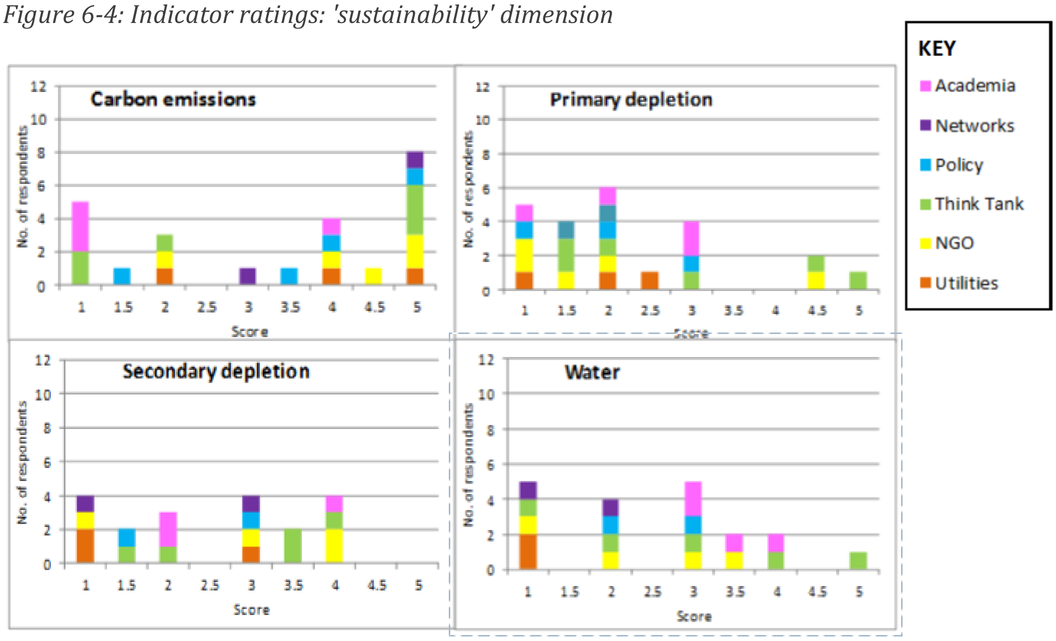
Many respondents stated that they were not aware of any security risks concerning water supply in the UK (A; L; T). The example of France was used to illustrate the fact that the importance of water availability and water temperature as a risk factor depends very much on location (A; E; S); the UK is a fairly damp place with plenty of access to coastline, and water-intensive generation such as nuclear tends to be positioned on the coast (C; D; E; G; I; S). This is an important point for the development of a security assessment, because in theory it would be desirable for any assessment framework to be applicable to other countries and systems.

On the other hand, a number of respondents suggested that water could be an increasing risk factor because of climate change (A; R; S; U; V; Y). One respondent (U) said:

> I don't think the UK is in any danger of running out of water. But the temperature of that water, if you've got any sort of thermal plant taking it out of a river and putting it back, could become problematic. There are new power stations that are already suffering with that, or rather failing to adapt to it would be a better expression.

It was also noted that the level of risk for water, similarly to many other indicators, depends on the technology mix (H; W), especially in the case of high-CCS or high-shale scenarios (J; R) (although one respondent said that after speaking to people throughout the water sector, he no longer felt that there was a serious risk of water shortages due to fracking (P)). Finally, it was noted that decentralised thermal CHP could affect local choices and could potentially create more localised water constraints (C; J); this shows that the importance of water as an indicator depends on the level of decentralisation in the pathway.

Figure 6-4: Indicator ratings: 'sustainability' dimension



6.5 Interview responses: Reliability

6.5.1 System adequacy: capacity margins and oversupply

Clearly, having a reliable system is important, not just for security per se, but also because it links closely with public acceptability for the transition (I; O; S). However, several respondents raised questions over current perceptions of 'adequate reliability', asking whether expectations of a system in which supply always follows demand should remain sacrosanct during the transition (B; N; O; T). The public tend to perceive of a continuous supply of electricity as a “basic human right” (H); however, as the UK transitions to more intermittent renewable sources of generation, and especially if heating and transport become electrified, it will become more and more challenging to maintain this. As respondent B said:

> I just think that you can organise your electricity system in different ways, so that you don’t have to be so far in excess of that peak. I suppose because I’m old enough to have lived when the lights went out from time to time, I lit a candle and read a book. But governments have to be concerned about the public’s response, and the public is not used to power cuts anymore. We’re all spoilt, aren’t we?

This debate over what constitutes ‘adequate’ supply was very apparent in the participants’ responses regarding the capacity margin. Several of the respondents felt that maintaining a healthy De-Rated Capacity Margin (DRCM) is absolutely fundamental to electricity security: if you don’t have the capacity then you don’t have the supply (F; G; K; L; O; Q; T). It was also noted by a large number of respondents that DRCM is the standard metric at the moment, and is a very direct indicator of electricity security (A; D; E; Q; R; V; W). However, DRCM is also a very ‘blunt’ measure, which fails to capture numerous important nuances about the electricity system, including potential ‘hidden margin’ which could be available from flexible demand and additional balancing services if the system were truly under stress (A; C; G; K; N; O; V; W). There was clearly concern that DRCM is frequently used as an indicator of security without any consensus on what constitutes a ‘healthy’ margin (E; F; J; N; S). It was also pointed out that the value of DRCM as an indicator in the future would be highly dependent on future availability of electricity storage, which could have a significant impact on the de-rating factors of intermittent sources in the future (F; H; K; U; X).[24] It was therefore suggested that DRCM will continue to be important, but that the actual calculation itself may have to evolve in order to capture the changing nature of the electricity system (A; D; K; O; W; Y). As one respondent (K) put it:

> De-Rated Capacity Margins is an odd one because I don’t know how much further it’s going to be a particularly useful calculation to do. Like, for example, if there is a load of storage, if there’s a real breakthrough in storage then do you still de-rate wind to 20% or less? Or do you say with storage it’s effectively 50%?

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[24] It is worth noting that Loss of Load Expectation (LOLE), which in many ways is more statistically robust than DRCM and which manages to capture hour-by-hour fluctuations far better than DRCM (respondent N) is included in the security analysis, because all the pathways are created for adequacy on an hourly basis and in theory all meet the LOLE standard (see section 5.8.1).

It was even suggested that a high DRCM could signal poor electricity security, because it could suggest that the system is not efficient or well-balanced (R; X). Many respondents pointed out that minimising oversupply could be crucial for ensuring that there are adequate incentives for investors to build capacity, and for avoiding the risk of stranded assets (E; J; V; X). Respondent J said:

> Minimising oversupply is extremely important. When you make investments, people would assume that you're using that piece of kit. Why else would you make that investment?

Again, this is linked to the public acceptability issue: a common criticism of intermittent generation is the backup required, which could be expected to run at very low load factors (J; N; O). However, respondents also pointed out that policy could intervene to provide incentives for plant owners to run at low load factors (such as the capacity mechanism), and therefore that the risk of oversupply could probably be managed in the longer-term (D; V; Y). As pointed out by respondent W:

> If you don't have enough [capacity], you have to build something and it takes four years. If you have too much, your option is to turn something off, which might upset people and cost a lot of money, but fundamentally you can do it.

One of the main areas of contention seemed to revolve around whether minimising oversupply is integral to the concept of electricity security. Many felt that oversupply is an issue of cost rather than of ensuring that the lights stay on, and therefore not everyone felt that it should be viewed as a part of 'security' (A; F; G; K; I; M); this is similar to many of the indicators in the 'affordability' dimension. One respondent (D) said:

> Oversupply is a problem if you need marginal plant and the market doesn't support their operation. But again, there are quite a few things you can do. I think those risks have been overplayed… I think security works best when it is thought of as more of a physical interruptive thing. Economic factors are murky, and there are many things you can do about them.

6.5.2 Flexibility: response-and-reserve, flexible demand, storage and interconnection

The last set of indicators which were posed to the respondents all related to different options for providing flexibility to the system: flexible generation (response-and-reserve), flexible demand (DSR), electricity storage and electricity interconnection. These were the least contentious of all the indicators: the majority of respondents agreed that flexibility options are important for electricity security, especially in a low-carbon context (J; K; P; T; W). Flexibility is seen as crucial for managing the peaks in demand, which could become much more problematic in future if heating and transport are electrified (B; Q; S; Y). Concerns were raised that the UK system does not currently reward flexibility enough on an ongoing basis (B), and that regulatory barriers could prevent cost-effective flexibility from being realised in a timely manner (U). A majority of respondents mentioned the balance between the different options for flexibility. Many suggested that any level of flexibility gives you more options for keeping the system secure, and that therefore it would be good to pursue many different flexibility options simultaneously (A; D; G; N; O; Q; U; Y). However, the balance of the options depends on their relative costs and feasibility (C; D; G; H; I; J; K; M; W; X).

Flexible generation (for which the indicator set uses response-and-reserve capability as a proxy) was felt by many respondents to be critical for avoiding supply shortfalls and therefore for maintaining public acceptability, especially because it is more controllable and predictable than flexible demand (A; H; I; J; O; S; V; X). One respondent stated that losing response-and-reserve capability would be 'catastrophic' for security (A), and another (S) said:

> If you don't have [response-and-reserve], then there will be more outages. If there are more outages, if the lights go out, the public won't accept the policies going forward. They'll say that's a failure of policy, and then you're gonna have to change radically, and some of those changes could fundamentally contradict the direction you're currently taking.

This discussion is connected to the theme of how conventional perceptions on electricity system management might change in the context of a low-carbon transition. It was posited that flexible generation is thought of as necessary, but only because of a commonly-held perception that a secure system is one in which you have to maintain a certain level of output at all times (T). Respondent P said:

> "The traditional model of having a certain amount of baseload and then you top it up, I'm not sure that'll be as relevant in future. I think we'll move towards more variable supply with strategic reserves."

Regarding flexible demand, several respondents saw this as a massive area of opportunity, although concerns were also raised about its viability on a large-scale. DSR is seen as a priority, partly because the UK already has very active supply-side flexibility whereas the demand-side has been somewhat neglected in the past (I; C; E; M; X). Respondent M said:

> We've had this very active supply side since the beginning of the utility industry; what's been idle is the demand side. If management of demand gets more involved, I think that's the key. So as a priority,

> I would say the demand side, cos we pretty much already have all the tools on the supply side.

Concerns were raised that consumers aren't currently engaged enough for widespread DSR to be realisable, and that automation would be crucial for getting a smart grid to work because consumers can't be relied upon to ramp their demand up and down over very short timeframes (G; J; Y). However, others suggested that DSR could in theory bring all kinds of co-benefits to consumers, such as helping them to improve their efficiency and mitigate the impact of rising costs (O; X), and creating a more 'constructive' engagement between consumers and the energy sector (O; T).

Regarding storage, several respondents suggested that it would be desirable for electricity security in theory, but that it was unlikely to become a reality unless the economics become more favourable (A; F; J; L; M; O; P; Q; W).[25] From this, it can be seen that relying on storage too much for future system security could present a risk in the event that the price remained high. On the other hand, several respondents suggested that there are reasons to believe that the price of storage would come down due to continuing innovation in the field (C; P; T; U). Two respondents suggested that a system with large amounts of storage could be indicative of a very inefficient system which was failing to adequately utilise cheaper flexibility options on the demand-side (A; G). Respondent A said:

> Certainly there's arguments to say that a system that is relying on storage for its security is not a very efficient system, and if you compare to "just in time" supply chains, they take all the storage out of it because it's seen as an inefficiency. But then again, [taking out all the storage] reduces massively your resilience.

Finally, the importance of electricity interconnection as a solution for improving electricity security was also somewhat contentious. Many respondents suggested that to some extent, interconnection would be beneficial for security: it is reliable and proven at scale (F; G; J; R), it allows the value of investment to be spread across borders (O), and it could allow access to renewable resources from Scandinavia and Germany (E; N; Q). However, it was also argued that interconnection brings risks as well as benefits (H; K; L; M; Y). Respondent L said:

> Politicians talk as if it's a panacea. It probably helps at the margin, but it can create as many problems as it solves. Germany is massively interconnected with neighbouring countries, but all the neighbours in the east complain massively that when the wind drops in Germany they've got huge problems running their grids.

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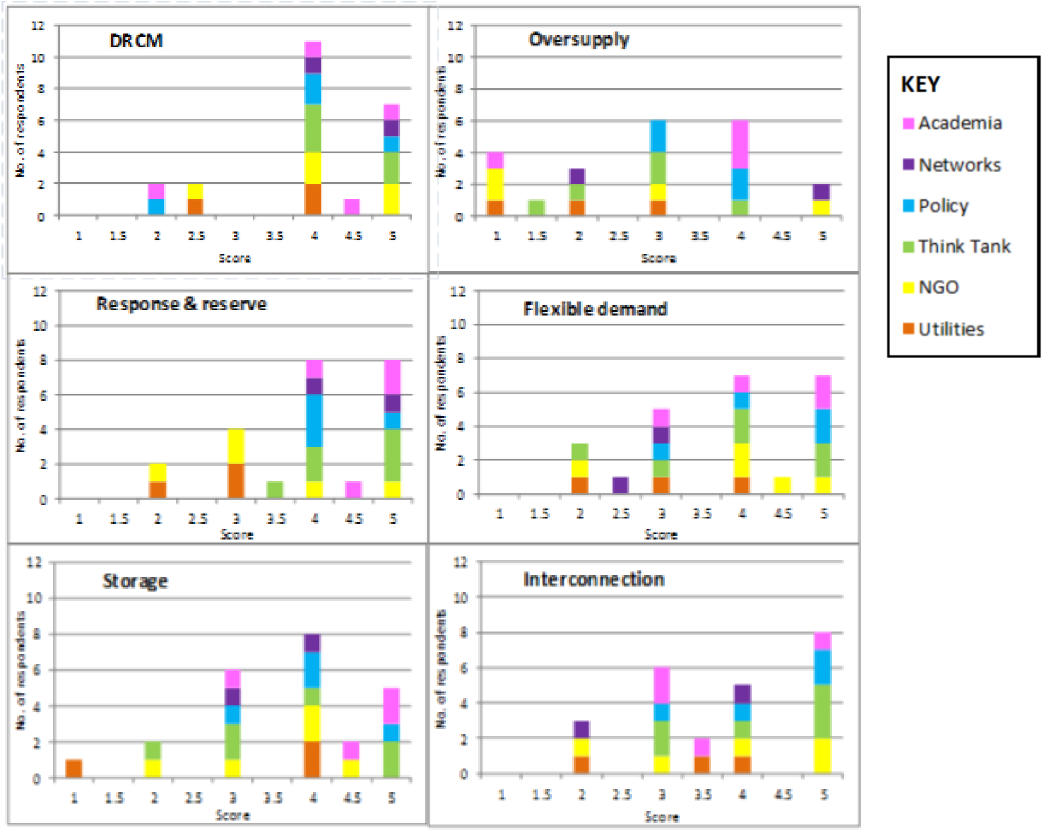
[25] Note: no-one suggested that the UK's existing pumped storage facilities are undesirable or unaffordable; however, the UK is almost completely fully exploited for large-scale pumped storage, and the discussion here centres on an expansion of *new* electricity storage capacity, for instance using batteries.

Concerns were raised about what might happen if numerous interconnected countries experience a stress moment simultaneously, especially because wind speeds in Western Europe are quite correlated, and it was pointed out that there is a need for some protection so that power doesn't all flow out during times of stress (G; L; Q; V; W). As stated by respondent W:

> Interconnection is really about economics rather than security of supply. In theory it makes life more secure and provides more diversity, but then the market responds to that, and the worry is you become more dependent on your imports, and when everyone gets their simultaneous peak and supply crunch you might have a moment where you realise it would have been better to be a glorious island!

Finally, several respondents stated that the value of interconnection for electricity security depends on the market price and fuel mix of the connected country (M; O; P; T; Y). Concerns were raised over the impact of interconnection on carbon reduction; for instance, if the UK were to connect to Germany and import lots of coal-fired power during a stress moment, what impact this might have on the carbon intensity of the UK's power mix (C; P; T). It is worth noting that although this concern was raised by three respondents, interconnection would probably not affect UK emissions unless there was a shift from a production-based emissions accounting system to a consumption-based one; however, none of the respondents mentioned this.

Figure 6-5: Indicator ratings: 'reliability' dimension



6.6 Interview results: Major cross-cutting themes emerging

From the interview responses presented in the preceding sections, a number of key themes emerge. These themes were identified because they were mentioned by several respondents in relation to a number of different indicators and different dimensions, and therefore cut across the four security dimensions covered in the preceding four sections. This section also relates these themes directly to the literature which was introduced in chapters 2 and 3, so that it can be seen to what extent ideas from the energy security literature are evident in the interview responses. The identification of these themes is useful for more than just the exploration of stakeholders' perspectives; later on, in section 7.2, these themes will be applied to the results from the security assessment, in order to establish the impact that respondents' perspectives have on the results.

6.6.1 Theme 1: How broad is too broad?

The analysis of the interview evidence highlighted the fact that there are major challenges in assessing the security of an energy system, because of considerable disagreement over what is necessary for ensuring electricity security. This factor is further complicated by the addition of the carbon reduction imperative. The interview questions were framed around the set of indicators outlined in chapter 4, which deliberately includes affordability and sustainability indicators as well as availability and reliability ones. However, there was considerable disagreement amongst the respondents as to what actually constitutes electricity security, with roughly half of the respondents believing that affordability and sustainability are integral to electricity security, whilst the others believed that affordability and sustainability are separate issues and should be thought of as trade-offs. Importantly, there seemed to be no discernible alignment between experts' perspectives on this issue and the type of organisation for which they work, which goes against the idea that 'where you stand depends on where you sit', as introduced in section 2.1.3. It is interesting to compare this result to debates in the literature: opinions are still somewhat divided over whether environmental sustainability should be viewed as an aspect of energy security (described in detail in section 2.1), but the majority of widely-cited definitions include the affordability dimension (e.g. Bielecki 2002; IEA 1985; IEA 2007; Yergin 2006). For several of the indicators and dimensions discussed (for instance storage, interconnection, demand-side response, public acceptability, network upgrades etc.), many respondents suggested that it would be possible to have a secure system without them, but it would be much more challenging to have a secure *low-carbon* system without them. This is an interesting assertion when compared to the literature, much of which does point out the complications caused by including a carbon reduction imperative (see section 2.3.3), but much of which also argues that decarbonisation would bring multiple co-benefits for security such as an 'inevitable' reduction in reliance on imports and depletable materials (see section 2.3.2). A small number of respondents did refer to these 'inevitable' co-benefits, but the emphasis from the respondents was very much on the trade-offs and complications caused by the carbon reduction imperative. It is also interesting to compare this to the results from the security assessment in chapter 5, which suggest that imports may *increase* as we transition (section 5.2.2), and that dependence on depleting resources could also be an issue, driven by REEs for renewables (section 5.6.2). This debate underlines the importance of differentiating between an assessment of electricity security, and an assessment of *low-carbon* electricity security, and therefore also reinforces the importance of designing 'indicators derived for a set purpose', as explained in section 2.1.3.

This disagreement over what is important or material for assessing security manifested itself noticeably in considerable contention over the majority of the indicators. The analysis revealed that participants seemed to be using different criteria for deciding what is important for security. Two common viewpoints were:

a) The important indicators are those which we have an imperative to address, either for normative reasons or because they represent a current or future risk (according to the subjective viewpoint of the respondent)
b) The important indicators are those which are simple, direct and/or quantifiable.

These different viewpoints were especially apparent in discussions regarding the more contentious indicators, for instance the affordability indicators and domestic disruption indicators. A good example can be found in the responses regarding the most contentious indicator: ‘fuel poverty’ (see section 6.3.1). Respondents who felt that fuel poverty is critically important for security mostly felt that it represents a severe risk for the UK, and therefore felt that improving security will necessitate mitigating fuel poverty. On the other hand, several respondents stated that fuel poverty is too indirect and complex to be much use as part of a conceptualisation or assessment of energy security. Again, there seemed to be no clear pattern between the type of organisation for which respondents work, and which of these viewpoints they supported; for example, as can be seen in section 6.3.1, proponents of the two viewpoints with regard to the ‘fuel poverty’ indicator were fairly evenly spread across all 6 types of organisation. This split between different criteria being used as the basis for viewpoints was also apparent in discussions regarding a large number of other indicators, particularly in the affordability and sustainability dimensions. Meanwhile simplicity and directness were commonly given as key reasons for the inclusion of traditional indicators such as de-rated capacity margins (DRCM), diversity and import dependence, with proponents of each viewpoint once again spread in each case between respondents from different types of organisation.

6.6.2 Theme 2: ‘Traditional’ energy security indicators

This second theme also relates to respondents’ views regarding how to conceptualise energy security. Two indicators which have often been used in the literature to assess energy security are dependence on imports, and diversity (e.g. DECC 2012a; Frondel and Schmidt 2014; IEA 2011; Jewell *et al* 2014; Kruyt *et al* 2009; Pfenninger and Keirstead 2015; Victor *et al* 2014). The literature often refers to ‘reducing control’ by others, or to limiting the ability of fuel-exporting nations to gain political leverage through their exports (Bordhoff *et al* 2010; Greene 2010; Umbach 2010). Others in the literature suggest that diversity acts as a vital hedge against supply and price disruptions (Bradshaw 2010; Cooke *et al* 2013; Grubb *et al* 2006; Hoggett 2013; Stirling 1994; 1998; Urciuoli *et al* 2014; Watson 2007; Watson and Scott 2008). However, there is also considerable scepticism in the literature over the security benefits of minimising imports (Chaudry *et al* 2011; Francés *et al* 2013; Stern 2004; Watson 2010). The literature also notes that a degree of diversity may well be a necessary feature of a secure energy system, but that it is not sufficient to ensure energy security by itself (Christoff 2011; Gracceva and Zeniewski 2014; Ranjan and Hughes 2014; Stirling 2010). Several respondents echoed the idea that these indicators are necessary but not sufficient to capture all the important aspects of energy security, whilst several respondents went a step further and stated that these indicators are not important at all. However, there was disagreement on this point, with many respondents stating that aspects such as import dependence and diversity are some of the major things which spring to mind when they consider energy security; several respondents also spoke of the need to hedge against unpredictable risks by reducing dependence or by increasing diversity. As shown in the responses presented in section 6.2.2, there was no clear pattern between respondents' perspectives on this matter and the type of organisation for which they work. It is interesting to note that both these indicators are in the 'availability' dimension, primarily referring to physical supplies of electricity and/or fuels. Therefore the disagreement over these 'traditional' indicators suggests the need to look beyond this dimension, for instance towards indicators relating to reliability and flexibility. The 'reliability' indicators, especially those relating to flexibility and responsiveness of supply and demand, were generally felt to be much more important than indicators relating to imports and diversity (for instance, as shown in figure 6.1). Stakeholders felt that it is important to improve system resilience by focusing on measures which can *respond to* threats or insecurity (for instance by increasing flexibility), rather than necessarily focusing on reducing *causes of* insecurity (for instance by reducing reliance on imports).

6.6.3 Theme 3: Economic and political feasibility

One of the most common cross-cutting issues emerging from the analysis of the interviews was the importance of securing adequate investment. A majority of respondents noted this as one of the most critical aspects of ensuring energy security on all timescales, and there were concerns that the UK (and in fact most of the EU) is currently at risk of a lack of investment in energy infrastructure. This issue is raised in Blyth *et al* (2014); Deane *et al* (2015); Ellenbeck *et al* (2015); Mitchell *et al* (2014) and Usher and Strachan (2012). There was general consensus that in order for this investment to happen, investors must have confidence that their investments will pay off. This is connected to themes of political feasibility of the transition. There was a common perception that there is currently a lack of political certainty, especially over whether to prioritise certain parts of the trilemma and the fate of the UK's decarbonisation targets as the transition becomes more challenging. Some respondents went a step further and suggested that this political feasibility would only be achievable in the context of 'social feasibility', and that there is a fundamental need for a 'social contract' for the transition; this idea is well grounded in the existing literature, for example Ekins *et al* (2011); Foxon (2012); Mancebo and Sachs (2015); Messner (2015); WGBU (2011). Stakeholders were mostly in agreement with each other regarding the importance of economic and political feasibility. This means that it will be useful to view the security assessment results of the pathways in light of this issue (for instance, by exploring whether any of the pathways perform particularly well or badly for these aspects); this analysis will be carried out in the following chapter, in section 7.2.3.

6.6.4 Theme 4: Context

Another major cross-cutting theme which emerged from the analysis was that of the importance of context. Again, there was broad agreement on this across the different stakeholders, meaning that this theme provides a useful basis for the further analysis of the security of the three pathways, to be carried out in the following chapter. Spatial context was very important to many of the respondents, because many measures can potentially improve electricity security in certain locations, but can generate insecurity if located in the wrong places (such as electricity storage, interconnection, network upgrades etc.). This is especially the case for the reliability and availability dimensions, and several respondents echoed the need for increased locational information in modelling pathways and scenarios, as suggested in chapter 5.[26] It is interesting to compare this to a tendency in the literature to attempt to make security assessment frameworks as universal as possible (see for example Deane *et al* 2015; Gracceva and Zeniewski 2014; IEA 2007; Jewell *et al* 2014; World Energy Council 2012). The results from the interviews therefore raise questions over the extent to which it is desirable or practical to create generalisable indices for comparing the security of energy systems across different spatial contexts, especially when attempting to achieve generalisability on a global scale.

[26] It should be noted here that respondents were not given details of the specific set of transition pathways analysed in this thesis; this point relates to models and pathways in general.

Furthermore, a number of respondents felt that the level of decentralisation of the electricity system is critical for security and for the relative importance of the indicators. In particular, the level of decentralisation of the system was stated to be a major determining factor in the importance of indicators relating to public acceptability and participation, and the four 'flexibility' indicators. This is interesting, because the respondents were not made aware that the set of transition pathways under discussion includes a highly decentralised pathway, thus reinforcing the fact that this is an important line of enquiry for future electricity security. There was no consensus on the relative security merits of centralised vs decentralised systems, and although many respondents made it clear that decentralisation could bring numerous benefits, many others pointed out that lack of experience with widespread decentralisation in the UK could bring unprecedented risks; this issue is covered in more detail in section 5.9.5.

6.6.5 Theme 5: The demand side

In the literature introduced in section 2.3.2, flexible demand, demand reduction and energy efficiency are commonly cited as win-wins for the trilemma, because in theory they can reduce costs and emissions at the same time as making it easier to keep the system secure. This was echoed by the majority of respondents, who mentioned the importance of demand reduction and demand flexibility in relation to a number of indicators. The most important issue to the respondents seemed to be the potential co-benefits of measures to reduce demand. For example, increasing attention to the demand side can in theory improve reliability, availability, affordability and sustainability, ideas which are reflected in the literature (see for example Adelle *et al* 2009; Berk *et al* 2006; Froggatt and Levi 2009; Greenpeace 2010a; Hoggett *et al* 2013; Pye *et al* 2014). Similarly to the other themes covered in this section, there was no pattern which emerged between those respondents who spoke strongly in favour of the importance of the demand-side, and the type of organisation for which they work. As shall be elaborated on in the following chapter (section 7.2.5), it is interesting that this emerged as a cross-cutting theme on which the stakeholders were generally in agreement with each other, especially when viewed in light of the results from the security assessment which suggest that demand reduction can bring about multiple co-benefits in a number of security dimensions.

6.6.6 Does 'where you stand depend on where you sit'?

As can be seen from the discussion above, the results from the interviews do not support the idea that 'where you stand depends on where you sit' (Miles' law). However, the reason for this may be found in the contentions of Allison (1969) and Bryan (2003) discussed in the literature review in section 2.1.3 – the idea that people's perceptions are also determined by the 'baggage' that they inevitably bring to their role (emotional ties, previous experience, sensitivity to certain issues etc.). The fact that the stakeholders interviewed for this study did not conform to Miles' law may simply suggest that there were other contextual factors – other aspects of 'where they were sitting' – which were having a more controlling influence over their decisions than the organisation for which they work. It may be because all the stakeholders chosen for this study possess extensive experience and in-depth knowledge of energy issues, and therefore possess complex, nuanced and widely differing opinions; the qualitative data support this (see sections 6.2 to 6.5). However, it should be emphasised that due to the small number of stakeholders interviewed for this thesis, and therefore the small number of individuals chosen from each organisation, further research with a greater number of participants would be necessary to explore this idea in more depth.

6.7 Summing up chapter 6

This chapter, the second of two results chapters, has presented the analysis of the results from 25 interviews which were carried out with stakeholders from the UK energy community. Respondents were asked to discuss the set of indicators which was developed in chapter 4 and applied in chapter 5, in order to get a grasp on what aspects or dimensions of electricity security are felt to be most important for assessing and ensuring electricity security in a low-carbon context. The interviews also sought to discover the underlying concepts which are used by stakeholders when making or justifying these choices. In this way, this chapter has generated an in-depth and transparent discussion which has not sought to close down the diversity of views, but instead has sought to open them up to debate.

This chapter has presented the results from a thematic coding analysis of the 25 interview transcripts, which identified five major themes which cut across multiple respondents and multiple security dimensions. The results presented in this chapter show that there is a real need to accept the existence of multiple perspectives and at least attempt to take them into account when discussing energy security, instead of focusing down on a small number of simple quantifiable indicators. These results demonstrate that energy security is highly context-specific, and that therefore the challenges of attempting to create generalisable indicator sets are huge. This chapter has shown that some stakeholders focused upon what they perceived to be current risks to the system or areas in which policy has an obligation to act, leading to a preference for indicators such as public acceptability and fuel poverty; meanwhile, others focused on indicators which are simple and direct or more easily quantifiable, leading to a preference for indicators such as diversity and capacity margins. However, certain measures were widely suggested as being sensible for improving energy security by a significant and cross-cutting range of participants: for example, realising the potential co-benefits of measures such as demand reduction and consumer participation; ensuring adequate investment in infrastructure by maximising long-term policy stability and planning; and improving flexibility on both the supply-side and the demand-side, thereby improving system resilience by focusing on measures which can *respond to* threats or insecurity rather than necessarily focusing on reducing *causes of* insecurity. Finally, the results indicated that there is no clearly discernible alignment between the type of organisation for which people work (e.g. supplier, NGO, academia etc.), and the importance which they place on different indicators of electricity security.

The following chapter brings together the results presented here with the results presented in chapter 5. The major themes and additional indicators identified in this chapter will all be applied to the results from the original security assessment in order to discover the implications of different stakeholders' perspectives on what are perceived to be the main security risks and trade-offs for the three Transition Pathways. In this way, the next chapter explicitly addresses the need to open up discussions of security to incorporate multiple perspectives, and aims to take these different perspectives into account when assessing the main risks, trade-offs and synergies which may occur between different objectives in a transition to a low-carbon electricity system.

7 Discussion

This chapter brings together the results presented in chapters 5 and 6, in order to answer the third and final research question: “What impact do the stakeholders’ perspectives have on the results of the security assessment and on their preferred options for improving electricity security?” The aim of this chapter is to discuss the results from both the security assessment of the three Transition Pathways and the results from the interviews, by applying the results from the interview analysis to the results from the initial security assessment. The security of the pathways is also examined in the light of major cross-cutting themes and different emerging views of security, with a focus on key areas of commonality and contention amongst the interviewees, in order to flag up significant areas of high risk / vulnerability (henceforth simply termed “risks”) for the pathways which may be echoed by UK energy stakeholders, and also to identify whether any areas of high risk can be regarded as ‘less important’ to a number of actors. In this way, the chapter highlights the key security risks for the three pathways, using a combination of indicator assessment and the analysis of multiple interviewee perceptions.

Section 7.1 carries out a dashboard analysis of the security of the pathways based on the results presented in chapter 5, which can allow us to view the results for the pathways as a whole without the need for aggregation, and can enable us to identify key areas of security risk for the pathways and key trade-offs between different indicators and dimensions. In section 7.2, these results are analysed in conjunction with the results from the interviews, focusing on the major cross-cutting themes which were identified in chapter 6. Section 7.3 presents the indicators which respondents suggested were missing from the original set of indicators, and examines the impact that including these might have had on the security assessment of the pathways (although it should be noted that the interviews were carried out after the indicator set had been finalised, and therefore could not contribute to indicator selection). Sections 7.1, 7.2 and 7.3 each end with a summing-up of the key points raised in that section, and some of the possible implications that these could have for energy security research and policy.

7.1 Overview of security assessment results

7.1.1 Dashboard analysis

The dashboard analysis presented in figures 7.1, 7.2 and 7.3 are drawn from the results presented in Chapter 5. As shown in the key on the following page, areas of ‘high risk’ are highlighted with a red flag; areas of ‘moderate risk’ with a yellow circle; and areas of ‘low risk’ with a green tick. Results mid-way between these categories are also indicated, using circles coloured half-red or half-green (as illustrated in the key next to figure 7.1). The symbols denoting the level of risk are based on a comparison between the results for the 2010 baseline and the results for either 2030 or 2050, and also a comparison between the pathways. So for example, a ‘high risk’ red flag denotes that the pathway has seen risks grow for this indicator compared with 2010, and is also riskier for this indicator compared to one or both of the other pathways. A ‘low-risk’ green tick indicates that the pathway is less risky for this indicator compared with 2010, and is less risky than one or both of the other pathways. Moderate risk indicates that the risk level is similar compared to either 2010 or the other pathways. Finally, as indicated in the results in chapter 5, it was not really possible to draw firm conclusions for some of the indicators, for example due to lack of available data; these are indicated with a blue question-mark. The results are presented for each pathway, for 2030 and 2050.

Figure 7-1: Dashboard analysis, Market Rules pathway

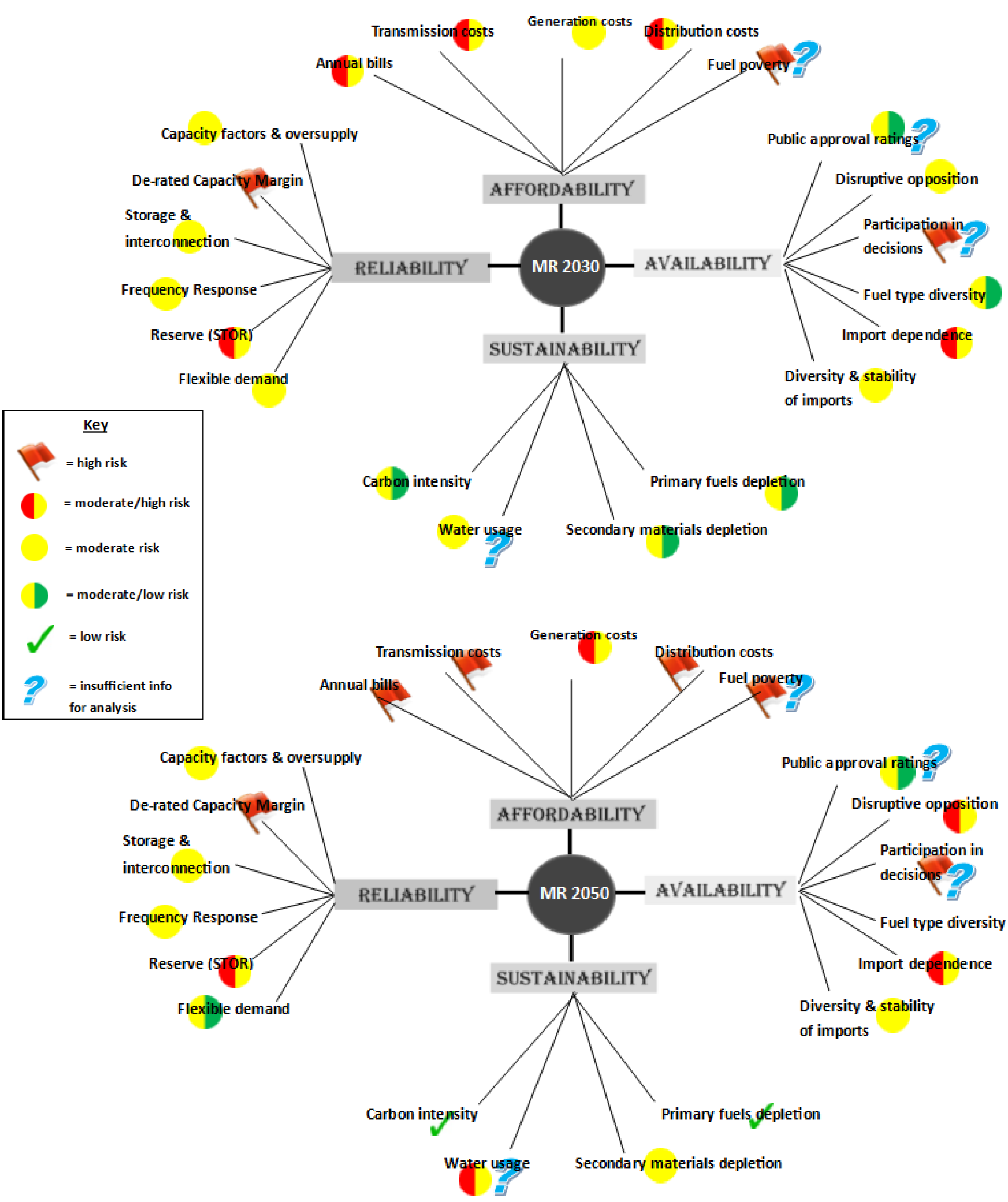
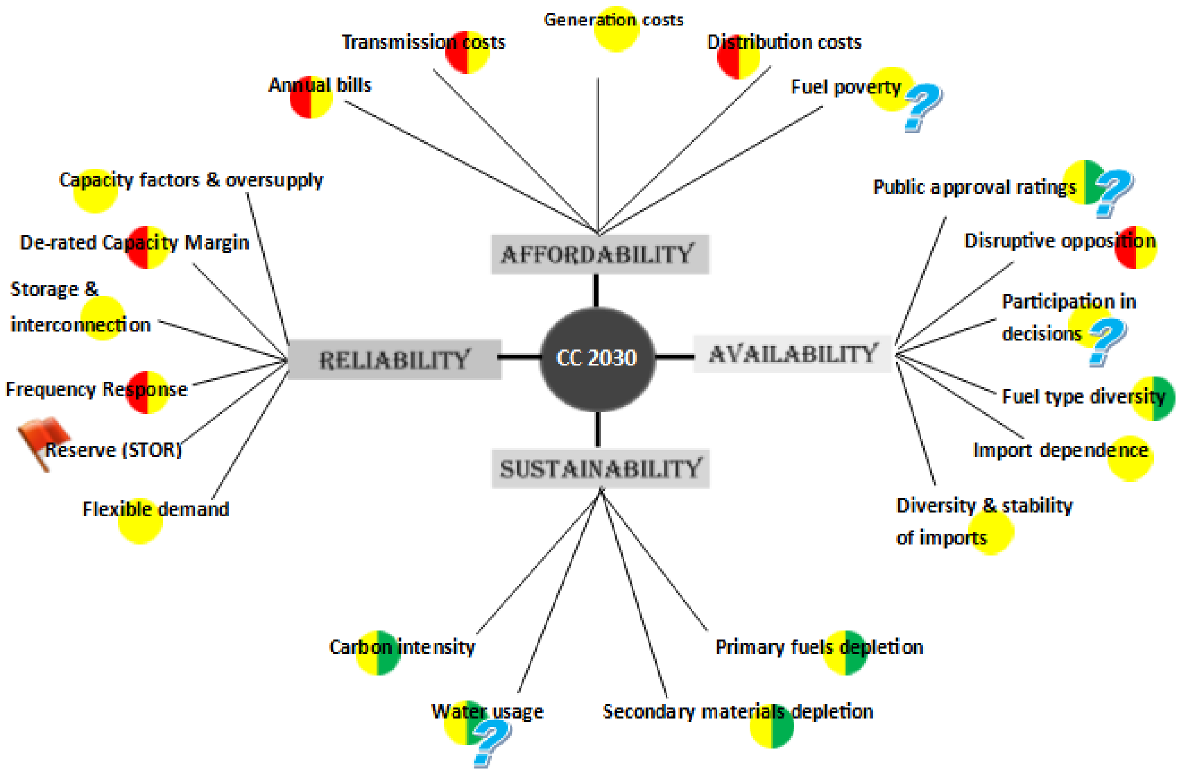


Figure 7-2: Dashboard analysis, Central Coordination pathway



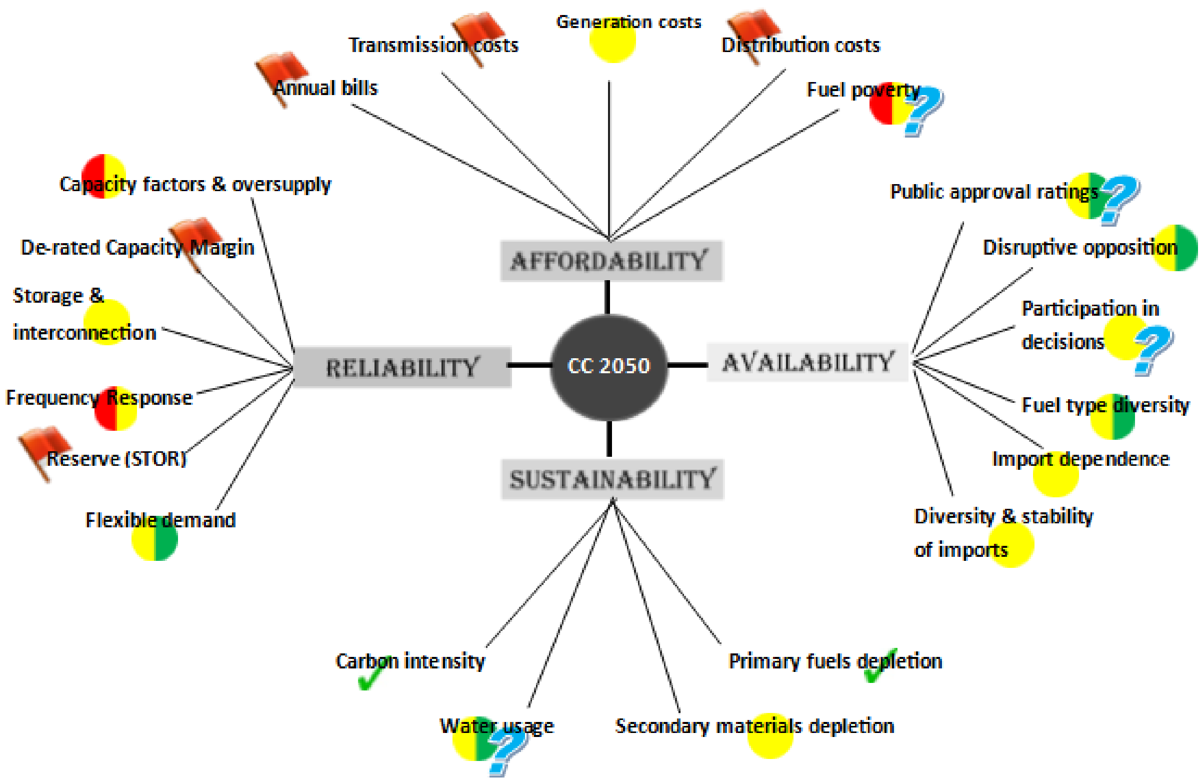
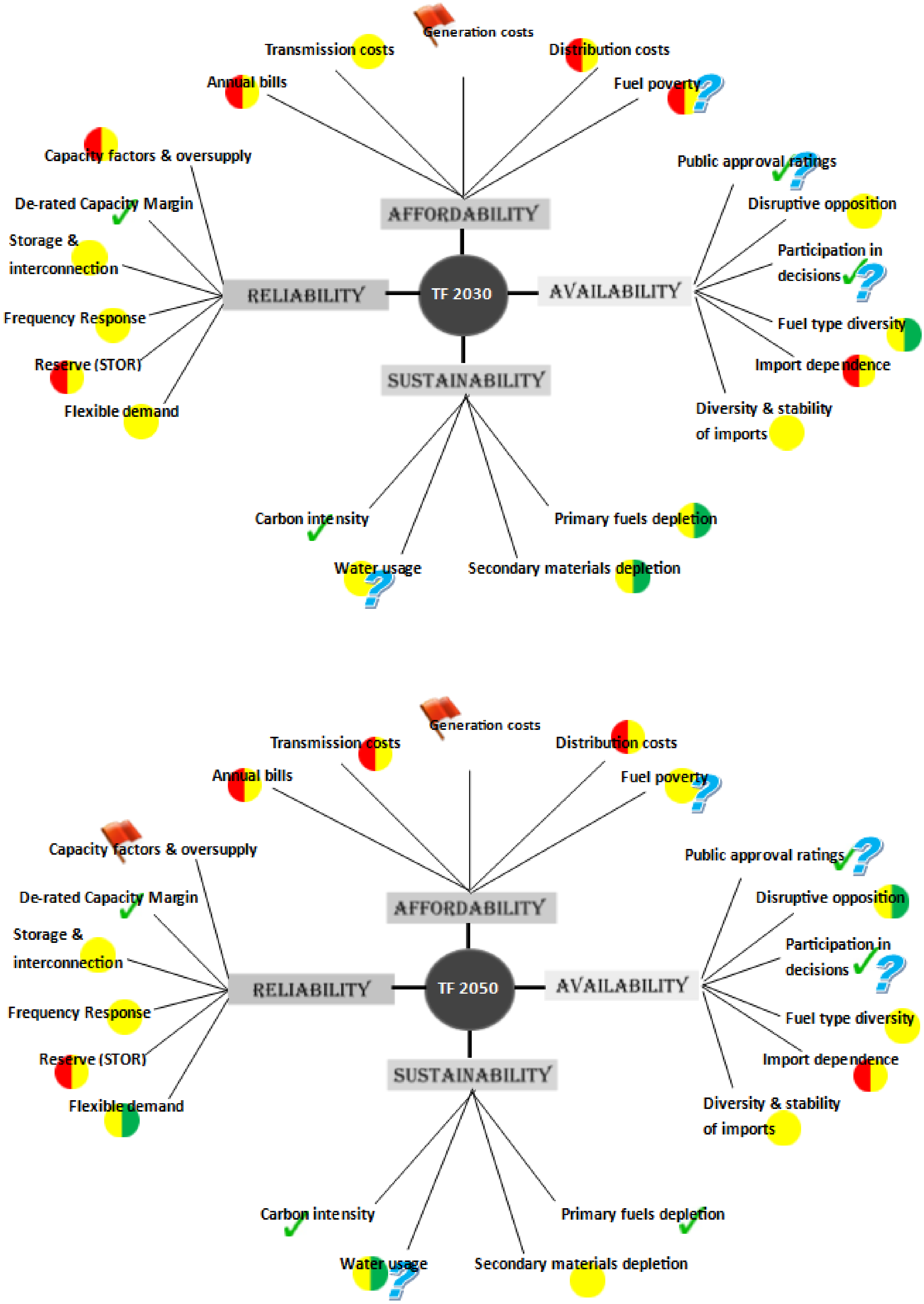


Figure 7-3: Dashboard analysis, Thousand Flowers pathway



7.1.2 Overview of dashboard results: Dimensions and trade-offs

The dashboard analysis shows that the three pathways all have the most ‘red flags’ (denoting high risk) in the affordability dimension, because system and consumer costs increase in all three pathways compared to 2010. Conversely to this, the three pathways have fewest ‘red flags’ in the sustainability dimension (notwithstanding problematic levels of uncertainty in the ‘water usage’ and ‘fuel poverty’ indicators). To some extent, this is to be expected, because the pathways all set out to achieve a transition to a low-carbon electricity system, which also appears to result in benefits (or at least, only moderate risk) for other areas of sustainability such as water, fuel and materials depletion. The pathways did not, on the other hand, set out to create the cheapest electricity system possible, meaning that the affordability indicators illustrate multiple high risks. This high-level overview could point to a trade-off between affordability and sustainability objectives, which if it were the case would have major implications for the UK’s ability to achieve a ‘balanced’ trilemma; however, it is worth emphasising that all three pathways have a fixed carbon constraint, and therefore this result would be in need of further testing via comparison with a non-carbon-constrained pathway (see also section 8.4.2). It is also worth emphasising that there are numerous uncertainties around this finding (see chapter 5), and that therefore this conclusion would benefit from further exploration in future research, for instance via stress testing of this result by asking ‘what if’ questions about the factors that are included in the cost calculations.

Within the reliability dimension, Short-term Operating Reserve (STOR) and to a lesser extent Frequency Response are flagged as high risk areas, because all three pathways experience reductions in STOR and FR capability compared to 2010. However, an increase in the capability for flexible demand (for instance from the residential and public sectors) could somewhat mitigate the security risks of declining flexible generation capabilities. There may also be a trade-off between de-rated capacity margins (DRCM) and generation costs: the TF pathway is the only pathway which doesn’t have low capacity margins, but it does this at high generation expense (although network costs in this pathway are lower because of demand reductions). Finally, the availability dimension reveals slightly complex patterns: the high energy demand and low public participation in the MR pathway leads to risks of domestic disruption and import dependence; the TF pathway succeeds in reducing land requirements for infrastructure and thereby potentially reducing risk of opposition, but also has high levels of imports (driven by biomass feedstock); finally the CC pathway appears to tread the ‘middle ground’ for this dimension, with mostly areas of moderate or moderate/low risk.

7.1.3 Pathway results

7.1.3.1 Market Rules, 2030 and 2050

The dashboard analysis for the MR pathway (figure 7.1) shows that this pathway has multiple 'red flags' in the affordability dimension, especially in 2050: the pathway experiences increasing costs compared to 2010, especially network costs and annual bills. This is largely due to high demand in this pathway, which creates a need for extensive network upgrades and high bills for consumers. The MR pathway experiences high risk for both DRCM and oversupply in 2050, and also for reserve (STOR) capability, mostly driven by the switch to more intermittent electricity generation. On the other hand, it is possible that improvements in flexible demand could mitigate some of these risks; however, this puts a lot of pressure on the pathway to fully realise the benefits of flexible demand. Finally, it appears that this pathway has slightly fewer 'red flags' of high risk in the availability dimension than in the reliability dimension: the pathway experiences high levels of import dependence (driven by reliance on fossil resources while domestic resources are declining), although these risks could probably be mitigated by ensuring stable and diverse imports. Overall, it appears that the MR pathway generally becomes riskier over the longer-term, in particular within the affordability dimension.

7.1.3.2 Central Coordination, 2030 and 2050

The dashboard analysis of the CC pathway (figure 7.2) shows that this pathway is actually rather similar to the MR pathway, with many 'red flags' within the affordability dimension, as well as with DRCM, Frequency Response, STOR and oversupply. Like the MR pathway, this is especially apparent in the longer-term for the CC pathway. This may be partly due to demand projections in this pathway: the CC pathway experiences an increase in electricity demand due to electrification of heating and transport, but it also includes efficiency measures which mitigate demand increases to some extent. However, despite the energy efficiency measures, the CC pathway experiences increasing network costs and annual bills; this may also be due to a reliance on large-scale technologies (which drives up network costs) and expensive low-carbon generating technologies such as offshore wind. The DRCM of this pathway is extremely low in 2050 and it also experiences oversupply in the longer-term, mostly stemming from the transition to increased penetration of intermittent RES alongside inflexible nuclear. The CC pathway has 'red flags' of high risk for STOR capability and moderate/high risks for Frequency Response capability, driven mostly by large amounts of wind power and inflexible nuclear. Although the pathway also sees improvements in flexible demand in the longer-term, there is a concern that the pathway could struggle to maintain resilience in the medium-term if demand flexibility were slow to emerge. Overall, it appears that the CC pathway generally becomes riskier over the longer-term, in particular within the affordability dimension.

7.1.3.3 Thousand Flowers, 2030 and 2050

The dashboard analysis of the TF pathway (figure 7.3) demonstrates significant differences between this pathway and the other two. This pathway appears to experience fewer 'red flags' of high or moderate/high risk than the MR and CC pathways, especially in 2050, and unlike the other two it is not obvious whether there is an overall improvement or deterioration between 2030 and 2050. The results suggest that one of the main problems for this pathway could be the 'transitionary' period in the medium-term. The main 'red flags' for this pathway are generation costs and oversupply; these two indicators are interlinked, because the high levels of spare capacity required for this system to be able to meet demand peaks is reflected in the high total generation cost. However, the TF pathway has lower network costs and lower annual bills than the other two pathways, reflecting the positive impacts of demand reduction. This may also have the co-benefit of improving acceptability: for instance, lower demand results in less requirement for new infrastructure which may reduce the risk of public opposition. However, the analysis also suggests that energy efficiency alone is not enough to generate these co-benefits: the CC pathway has high levels of energy efficiency but electricity demand continues to rise because of electrification of heating and transport, whereas despite electrification the TF pathway keeps electricity demand stable via public engagement and behaviour change. It is worth noting that this pathway is highly dependent on biomass and that there are large uncertainties around biomass for several of the indicators, which increases the general uncertainty over the security of this pathway (see chapter 5). Finally, it is worth emphasising that although the TF pathway has fewer areas of high or moderate/high risk than the other two pathways, especially in the longer-term, it is not really possible to infer from this that a decentralised low-carbon system would be more secure than a centralised one, because of the multiple nuances and trade-offs within the analysis, the multiple uncertainties and assumptions within both the pathways data and the security assessment results (as illustrated throughout chapter 5), and the impossibility of aggregating or weighting the indicators.

7.1.4 Conclusions from the dashboard analysis

This section has derived the following key conclusions from the dashboard analysis. These conclusions will be discussed further in the concluding chapter of the thesis.

- The three pathways all experience many ‘red flags’ within the affordability dimension, compared to very few in the sustainability dimension. Further research would be interesting to test whether this points to a potential trade-off between affordability and sustainability objectives, for instance via comparison with a high-carbon pathway.
- The MR and CC pathways both experience deterioration in their overall security from 2030 to 2050. For the TF pathway on the other hand, the most risky period could be the medium-term ‘transition’ period. This suggests that maintaining a centralised electricity system trajectory could be less risky in the medium-term, but more risky in the longer-term.
- The three pathways all exhibit a reduction in flexible, responsive supply capacity. To some extent, this could be an artefact of the pathways analysed, although the issue appears to stem from increasing penetrations of intermittent and inflexible generation capacity. This risk could be mitigated somewhat by alternative flexibility options such as DSR, storage and interconnection.
- Demand reduction generates security benefits in all dimensions; this finding supports the literature which suggests that demand reduction can be a win-win for lower emissions and for energy security (see section 2.3.2). However, in this analysis, demand reduction was assumed to be cost and risk free, which may not be the case in reality; this thesis has not explicitly investigated the costs and risks of demand reduction, therefore this finding would warrant further investigation in future research.
- Contrary to received wisdom, dependence on fuel imports does not necessarily decrease as the result of a low-carbon transition. Therefore it would 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 imports.
- There are significant uncertainties about biomass generation, particularly regarding feedstock resource flows, sustainability of feedstocks, and its potential contribution to system flexibility (see sections 5.2.2.2, 5.6.1.4 and 5.9.6). The results for the TF pathway therefore exhibit high levels of uncertainty. These gaps in knowledge need closing down if ambitious biomass plans are to be pursued; this may require not only further research, but also further experimentation with existing biomass power generation (e.g. the large conversion project at Drax) in order to explore emerging supply chains.

7.2 Applying the interview results to the security assessment

This section applies the results from the interviews (chapter 6) to the results from the security assessment (chapter 5), in order to establish the impact that different stakeholders' perspectives have on the results of the security assessment. This is done by exploring the possible implications of the five cross-cutting themes from the interviews (which were introduced in chapter 6) for the results of the security assessment of the three Transition Pathways.

7.2.1 Theme 1: How broad is too broad? Affordability and sustainability dimensions

One of the main themes which emerged from the thematic coding analysis of the interview responses was an emerging divide over one critical question: should affordability and sustainability be viewed as part of energy security? There was much disagreement between the respondents on this, as shown in chapter 6. Some respondents suggested that both affordability and sustainability should be thought of as *separate* to security, or as complicating factors or trade-offs. For example:

> A general point is that you've got items in the list [of indicators] which are about cost and also about decarbonisation and it seems to me that under a strict interpretation of the question that you're asking me, those don't have a relevance to security… It seems to me that how much you're prepared to pay for something is a separate question to whether or not something is secure… (Respondent K)
>
> If I think of it traditionally as 'energy security', I think of the issues I mentioned about import stability, import dependence etc. (Respondent P)

It is therefore interesting to examine the impact that taking this narrower view of security would have on the results of the security assessment. If security were seen purely as 'reliability and availability', the MR and CC pathways would have the most areas of high risk in 2030, and the CC pathway would have the most areas of high risks in 2050 (assuming that the 'participation' indicator, which proved to be highly problematic to assess, is not taken into account). The TF pathway has the fewest areas of high or moderate/high risk in both 2030 and

2050. These results are very similar to the results for the broader view of energy security (i.e. including affordability and sustainability). Most of the highest risk areas for the three pathways are in the affordability dimension, meaning that for stakeholders who felt that affordability is not an important aspect of energy security, all three pathways would appear less risky overall.

This thesis has been based around a broad view of energy security which includes affordability and sustainability dimensions, in order to explore the implications of the broader view on both the results of the security assessment and on the ways in which different stakeholders view and conceptualise energy security. It was also posited (see section 2.1.2) that emerging normative and legislative imperatives to mitigate climate change mean that that it is important to take environmental impacts into account; for policy-makers who are committed to carbon reduction targets, it may be unwise to examine 'security', 'affordability' and 'sustainability' separately, because the future energy system must meet all these aims. Nevertheless, there is also an argument to be made to the contrary – that these broader dimensions should be considered to be trade-offs *against* security, and that securitising issues such as environmental sustainability adds unnecessary complications (Jewell *et al* 2014; Luft *et al* 2011; Kuik 2003; Winzer 2011). The interviews showed a split between both viewpoints. The results contribute to this literature by showing that if affordability is *not* viewed as integral to an assessment of electricity security, all three pathways would be seen to have fewer high risk areas, whereas the opposite is true for sustainability.[27]

7.2.2 Theme 2: 'Traditional' energy security indicators

Another major theme which emerged from the thematic coding analysis of the interview responses was a certain amount of scepticism over the usefulness of two indicators which are traditionally used in the literature to assess energy security: import dependence and fuel type diversity (see section 2.1.1). Therefore, it is interesting to examine the impact which removing these 'traditional' indicators of energy security would have on the results of the security assessment.

The MR and TF pathways both have high import dependence; therefore for those respondents who thought this indicator unimportant, there would appear to be one fewer high risk for the

[27] It is worth emphasising that not assessing these dimensions would not mean that the trade-offs disappear; they may simply move to wider discussions about other energy goals.

MR and TF pathways compared with the CC pathway, because the CC pathway has lower import dependence. The respondents suggested that this 'traditional' indicator of energy security is not of critical importance for the pathways; if a well-functioning global market existed for either coal and gas (MR pathway) or for biomass (TF pathway), they suggested that these pathways would still be secure even if they were highly dependent on imports. Respondent A said:

> So import dependence in and of itself, so a high level of imports does not necessarily mean that you'll have low security. But Japan is probably the best example of that because they have basically no indigenous fuels, but even post-Fukushima they have still managed to get the stuff.

It should be pointed out that there was some disagreement on this, with some respondents arguing that reducing import dependence *is* an important factor in improving energy security, for instance because it allows policy to operate within its "sphere of influence" (respondent D). Respondent G summed up two possible sides of this argument:

> Okay, well you could look at imports being a good thing in the sense that if you have a global market and global competition, imports can lower your costs... Equally from a security of supply perspective you could say well actually if we could manufacture these technologies and the supply chain is within the UK then you could argue that that actually helps with security of supply, but it might be a very expensive solution…

Overall, however, respondents felt that import dependence is of fairly low importance for energy security, as shown in figure 6.1. This supports the considerable literature which argues that imports are not insecure *per se* (e.g. Chaudry *et al* 2011; Francés *et al* 2013; Jonsson *et al* 2013; Stern 2004; Watson 2010). This is an important point to make, because numerous energy security assessments still use volume or proportion of imports as a key indicator (e.g. DECC 2012a; Frondel and Schmidt 2014; IEA 2011; Jewell *et al* 2014; Kruyt *et al* 2009; Pfenninger and Keirstead 2015; Victor *et al* 2014).

If the 'fuel type diversity' indicator were not included in the overall analysis of the results, all three pathways would be left without one of their lowest-risk indicators. Therefore the inclusion of this indicator does not have a significant impact on the relative security of the pathways compared to each other. Increasing penetration of RES tends to increase diversity of electricity generation, as the system transitions away from the current reliance on coal, gas and nuclear (Cherp *et al* 2013; Grubb *et al* 2006; POST 2012), although it should be emphasised that this is dependent on the choice of aggregation of generation types (for example, grouping all RES together would result in lower diversity, as noted in section 4.4.1.2). The TF pathway is highly dependent on biomass, meaning that it is slightly less diverse in 2050, but several respondents suggested that a lack of diversity in a pathway does not necessarily make it less secure *per se*. For example:

> I don't think it's important to have that diversity. I'm just looking across to France here, their electricity system is not diverse. No one can say it's not secure. It is secure, full stop. In my view, if you have a technology that works and you're pretty sure about the fuel and the supply of that technology, it doesn't need to be that diverse. (Respondent J)
>
> Diversity of fuel types in the energy mix, I actually don't think it's a problem. We could have a very nuclear heavy system as they do in France, we could have a very renewables heavy system, I see that as a very low risk for transition. (Respondent F)

It should be pointed out that a number of possible methods exist for the calculation of both diversity and import dependence, but that the interviewees were not provided with information on the specific methods used to calculate the indicators; therefore responses relate to import and diversity indicators in more general terms.

Finally, it is worth briefly discussing another 'traditional' indicator, the DRCM indicator. Although the DRCM indicator was felt to be important by some respondents, there was also some contention about its continued usefulness as an indicator of energy security in a low-carbon context, because it fails to capture dynamics such as demand flexibility, embedded generation and short-term intermittency (see section 6.5.1). As stated by respondent V:

> It's a very direct indicator, isn't it? But with a caveat… If you were really going to take executive control of the system under stress, there's probably hidden margin that doesn't emerge from just looking at de-rated margins.

Removing the DRCM indicator would have a noticeable impact on security comparisons between the three pathways, because the TF pathway is at low risk for this indicator whilst the MR and CC pathways are both at high risk. This suggests that care should be taken not to view the DRCM results in isolation, and to bear in mind that positive scores for system flexibility would go a long way toward mitigating the low DRCM in the MR and CC pathways. This result supports a more general point from the literature and from this thesis overall, that indicators may be less useful when viewed in isolation or when aggregated together and that therefore a dashboard approach is more suitable (Jonsson *et al* 2013; Mitchell and Watson 2013b; Narula and Reddy 2015).

The interview results suggest that stakeholders feel that that in a context of increasing penetration of intermittent sources of power generation and increasingly unpredictable demand patterns, indicators of *flexibility* are becoming more important for security than some traditional indicators. As suggested by respondent O:

> I think in future we would need more flexible capacity and I think the priority of quality of flexible capacity will increase in the future… On de-rated capacity too we probably need to explore better what de-rated capacity is available on the demand side, in terms of both automated DSR but also in terms of consumer attitude in terms of price signals.

This is interesting when viewed in light of the existing literature, because it suggests that increased attention should be placed on security indicators which focus on *responding to* insecurity, rather than indicators which relate to reducing *causes of* insecurity, despite the fact that the majority of studies focus on the latter (Jonsson *et al* 2013). If the 'flexibility' indicators of response and reserve, flexible demand, storage and interconnection are considered to be of primary importance, the CC pathway appears to be the most risky. This is especially interesting when comparing with the relatively low import dependence in the CC pathway, because it suggests that the use of 'traditional' indicators could obscure problems with flexibility that may, according to the stakeholders interviewed, be much more important for electricity security.

7.2.3 Theme 3: Economic and political feasibility

A common theme amongst the respondents was the importance of securing investment in infrastructure, and the idea that investment would require long-term stability of policies and political certainty, and that this is closely connected to public acceptability and whether or not decisions are 'politically affordable'. For example:

> I think there is a social contract aspect to sustainability; if you can't bring the public with you then any policy is likely to become at some stage slightly a liability or at risk… You do need to keep in mind that investors will only invest if they think that government will stay the course and governments will stay the course if it does not become a voter liability. (Respondent O)

> I would say that government driving something without public buy in and I think that is a problem at the moment,

> you just have to look at the Tory party on renewables for instance… if the public does not buy in you won't deliver on the demand side you won't deliver on energy efficiency, so the whole system falls over. (Respondent G)

As noted in sections 5.4.4 and 5.8.5, a key risk for all the pathways is that the electricity sector will struggle to secure the level of finance required to realise the transition. However, it is highly challenging to differentiate between the pathways in this regard, as all pathways could potentially engender risks in this area. There is a lack of detailed information in the pathways about future market design. Besides this, evidence from the literature shows that market design is just one determinant of investor behaviour, with an array of other socio-economic and behavioural factors also having an influence (Ellenbeck *et al* 2015). This being the case, it is not really possible to assess the level of investment flows in the pathways, although this issue will be discussed in more detail in section 7.3.

7.2.4 Theme 4: Context

The importance of spatial, temporal, technological and system context was raised repeatedly by the interview respondents, in relation to a number of indicators and dimensions, as shown in the quotes below:

> The principal problem is that when you look that long term, especially 2050, it's very difficult without defining what the energy situation is going to be then to make a coherent comment on the security implications of some of these issues. The other thing is that I think that it really matters whether you assume that low-carbon is high-nuclear or low-nuclear. (Respondent H)
>
> I think [the need for response and reserve] entirely depends on the system that you have. I'm not an engineer, but I could totally imagine that in 2050 we have a system that doesn't have a lot of that and works so dynamically that we don't need it. (Respondent E)
>
> [Diversity] clearly could become a bigger issue if we end up with an all-renewables and gas mix… It's not necessarily an issue, as it depends on what else you're doing. In that scenario, you might have lots of energy storage, lots of clever demand side. I can see some scenarios where diversity does matter. (Respondent W)

This has implications for the practicality of using a generic set of indicators for assessing the security of different pathways or scenarios, because some indicators could be far more salient for certain technologies or systems than for others. The deliberate avoidance of weighting in the assessment makes it difficult to alter the indicator analysis to take these context-specific aspects of individual pathways into account. This is a challenge for energy security assessments in general, because despite the difficulties of generalisation it is desirable to be able to compare multiple options, potentially even in multiple national contexts.

One of the major contextual points raised by respondents revolved around the security implications of a transition to a more decentralised electricity system, as discussed in section 6.6.4. Their responses suggest that the extent of power system decentralisation could be an important deciding factor in determining the future security of a low-carbon electricity system, and can also have a big impact on ways of measuring the security of the system. Interestingly, this occurred despite the fact that the interviewees were not made aware that the Transition Pathways used for this study include a specific decentralised pathway. For example, respondents said:

> I guess it depends on your strategy I would say. I think the centralised energy system model of big power stations, in fairly remote locations, doesn't need as much public participation or engagement. If you are going down a strategy which involves more diffuse tech, such as renewables, wind turbines, solar and things that involve consumers as well so that a highly renewable system needs a lot of demand side response, a much better interconnected system. (Respondent D)

> It depends whether we move from this national, centralised system to a more distributed energy system. Public perception might not even be public in the national sense, as it's understood now, but be public in a regional or local sense. (Respondent B)

The results from the security assessment in chapter 5 support this contention: there are fundamental differences between the TF pathway and the other two pathways, whereas the results from the MR and CC pathways are actually fairly similar. It is also interesting to note that the decentralised TF pathway generally appears to have fewer areas of high risk than the two centralised pathways, especially in the longer-term, although it would be a bit of a leap to state from this that a decentralised low-carbon system would necessarily be more secure than a centralised one. The academic and policy literature has not gone into much detail thus far regarding the potential security implications of a shift to a decentralised system; possible impacts on system resilience and on networks have been discussed (see section 5.9.5), but to the author's knowledge no previous attempts have been made to empirically assess the broader security implications of electricity system decentralisation in the UK, or to examine what kinds of indicators would be most suitable for assessing the security of a decentralised pathway. This thesis makes a contribution to filling this gap in the literature by comparing centralised and decentralised scenarios using a range of indicators; nevertheless, this could be an important area for further research.

7.2.5 Theme 5: The demand side

The importance of demand reduction and demand flexibility was a common recurring theme throughout the interviews, as discussed in section 6.6.5. Respondents especially talked about the potential co-benefits of increasing attention to the demand-side, such as reducing costs, improving acceptability and reducing reliance on resources. This supports the extensive literature which has previously mentioned these co-benefits (e.g. Adelle *et al* 2009; Berk *et al* 2006; Froggatt and Levi 2009; Greenpeace 2010a; Hoggett *et al* 2013; Pye *et al* 2014) and suggests that this is one of the main things which occurs to stakeholders when they think of how best to improve energy security. Again, it is interesting to note that stakeholders were not informed that the three Transition Pathways differentiate significantly in their levels of overall energy demand. Many of the indicators implicitly use the demand-side as part of their calculations: for example, the affordability indicators are all based on demand volume, several of the acceptability indicators are based on required levels of new capacity, and the resources indicators are based on resource demands, which is driven by overall energy demand. However, because of the importance of this aspect to the respondents, it is worth briefly discussing the implications of taking a more demand-side focus on the results of the security assessment. This is especially important considering that much of the literature on energy security is very supply-side focused (Hoggett *et al* 2013).

In terms of maximising the co-benefits of demand reduction, the TF pathway is the least risky pathway. One of the key aspects of this pathway is the steep reductions in overall energy demand which are delivered via increased participation and behaviour change from energy users. Despite not knowing this information about the pathway, respondents stated:

> I think it will be useful to give consumers an ability to more directly engage with the [energy] sector and to actually see a financial benefit from the sector. At the moment it kind of feels like it's purely something that flows out of your wallet to someone else… so trying to come up with a slightly more constructive engagement between consumers and the sector in the future. (Respondent O)

> The transition to a low carbon pathway is going to require us to not only move our electricity system to a low carbon one, but also encourage people to think about how they use electricity, and so actually thinking about electricity efficiency and also demand reduction. (Respondent X)

As shown in chapter 5, the steep demand reductions in the TF pathway also bring about benefits for many of the indicators. To a lesser extent, the CC pathway also achieves reductions in overall energy demand, although the impacts of this on electricity are somewhat taken back by the electrification of heating and transport. However, the demand reductions in the CC pathway are driven by top-down regulations and energy efficiency improvements, which respondents suggested may not bring about the same public acceptability co-benefits. The MR pathway, although it has relatively high levels of shiftable demand (driven by high uptake of electric vehicles and heat pumps), does not achieve significant demand reductions, and does not therefore reap the potential co-benefits. Nevertheless, the co-benefits of demand reduction are already reflected in the results of the security assessment: many of the positive results for the TF pathway (and, to a lesser extent, the CC pathway) are in fact driven almost entirely by demand reduction. Therefore sufficient emphasis has already been placed onto the demand-side in the original security assessment; the results simply reiterate the importance of demand reductions and demand flexibility as a priority for energy policy.

7.2.6 Conclusions from the application of different stakeholder perspectives to the security assessment

This section has illustrated the following key conclusions from the application of the major themes arising from the qualitative interview data analysis to the results of the security assessment:

- The results illustrate the importance of using multiple indicators from multiple dimensions to assess security. The results help to identify trade-offs and priorities; each indicator is much less useful if taken in isolation. Therefore the results reinforce the importance of taking a dashboard approach which incorporates a broad range of indicators whilst avoiding aggregation, as argued throughout this thesis.
- The stakeholders interviewed did not agree on whether to include affordability and sustainability dimensions, and they did not agree on whether to include 'traditional' indicators such as diversity and import dependence. This reinforces the rationale of this thesis that any assessment of energy security should attempt to 'open up' the discussion to take diverse perspectives into account.

- The three pathways were all less risky for several of the indicators which were said to be of minimal importance by the stakeholders interviewed, but more risky for others suggested as being highly important such as system resilience and flexibility. Transition pathways should therefore emphasise system resilience and flexibility in order to ensure energy security within the pathway.
- The ‘traditional’ energy security indicators of import dependence and generation mix diversity were judged to be of relatively low importance by the stakeholders interviewed. Ignoring these two indicators would change the pattern of comparison between the pathways to make the CC pathway appear to be the least secure, because of poor supply-side flexibility in this pathway. This raises the possibility that previous attempts to assess electricity security have been focusing on certain aspects which could lead to a preference for systems which do well for indicators such as import dependence and fuel diversity but which neglect flexibility. These results therefore add weight to the contention that flexibility on both the supply-side and the demand-side should be prioritised when assessing electricity security.
- For those respondents who did not feel that DRCM is an important indicator of security, the general pattern of the MR and CC pathways would appear less risky; however, these two pathways also have less flexibility. Therefore care should be taken not to use DRCM as an indicator in isolation, and to bear in mind that good results for system flexibility would go a long way toward mitigating the low DRCM in these two pathways.
- The level of decentralisation in an electricity system is a critical factor in determining both the level of security risk for a number of indicators, and also the usefulness of several of the indicators used. This result contributes to the literature on low-carbon electricity security, which has thus far not gone into much detail regarding the security implications of significant decentralisation. This result suggests that the extent of decentralisation could be one of the key factors to be considered when approaching questions of both how to measure and how to improve electricity security in the future.
- Many of the positive results for the TF pathway (and, to a lesser extent, the CC pathway) are driven by reductions in overall energy demand. The results therefore add empirical weight to the literature which emphasises the potential ‘win-wins’ of demand reduction.

7.3 Missing indicators

During the interviews, respondents were asked to think about any indicators or dimensions which they felt were missing from the original list provided to them.[28] This can help to highlight important areas which respondents felt had not been covered in enough depth during the rest of the interview. Table 7.1 shows the additional indicators which were mentioned, along with the number of respondents who mentioned them (No.). The codes 'R', 'L' and 'X' denote the potential relevance of these additional indicators to the assessment. Some of those mentioned are relevant and could potentially have been included in an assessment (R), some are less relevant or impossible, as explained by the notes in the table (L), and some are already covered in either the pathways or the security assessment itself (X). For the indicators marked 'R', this section explores the extent to which it would have been possible or desirable to include these additional indicators in the initial set, and also the impact that including them might have had on the results from the security assessment. As noted in chapter 4, the interviews were conducted after the indicator set had been finalised, therefore the purpose of the interviews was not to contribute to the construction of the indicator set, but rather to test the set and to explore potential additions suggested by interviewees, as well as providing potentially useful insights for further development of the indicator set in future research.

[28] This question was also mentioned at the beginning of each interview, so that respondents could consider it throughout the discussion.

Table 7-1: Indicators suggested as missing from the original set

Missing indicator	No.	Relevance	Notes
Political / institutional stability and effectiveness	5	R	
Deliberate attack	3	R	
Physical climate change impacts	3	L	Challenging to assess; also partially covered in the 'GHG emissions' indicator
Energy efficiency	2	R	
Incentives to invest	2	R	Highly challenging to assess
Technological innovation	2	R	Highly challenging to assess
Framings of security in political discourse	2	R	Highly challenging, although obviously important, as noted throughout this thesis
Decarbonisation of heat	2	X	Already modelled in pathways
Loss of Load Expectation	2	X	Already modelled in pathways
Opposition to participation in DSR	2	X	Covered in 'flexible demand', although more detailed information would be beneficial, as noted in section 5.9.4
Supply capacity at other end of interconnectors	1	R	
Availability of key skills (engineers etc.)	1	R	
Local pollution / air quality	1	R	
Green gas for heating	1	X	Already modelled in pathways
Impact of electrification of transport	1	X	Already modelled in pathways
Flexible generation	1	X	Covered as a proxy in 'response-and-reserve'
System operation in context of decentralisation	1	L	Only relevant for one of the pathways
Network reliability and bottlenecks	1	L	Impossible to assess without future network maps
Gas networks	1	L	Impossible to assess without future gas network maps
Space weather	1	L	Not possible to mitigate

7.3.1 Applying the suggested additional indicators to the pathways

7.3.1.1 Policy / institutional stability and effectiveness

A common theme amongst the interview respondents was the importance of policy and institutional stability, which along with a long-term 'plan' or 'vision' were felt to be critical for the transition. This was not included as an indicator mainly because of the impossibility of assessing the likely levels of policy stability in the pathways: there could be arguments made that any of the three pathways or storylines would be more politically stable and effective.

It should be noted that policy could potentially be seen as either a means of mitigating security risks, or alternatively as a *source* of security risks. Three of the five stakeholders who mentioned 'policy stability' as an additional indicator referred mainly to the latter:

> Political interference… I know these factors all go into it but the biggest risk to a low carbon transition for me really is politics and policy. So if you design bad policy showing inefficiency then you make it more expensive than it needs to be and this creates political problems (Respondent F).
>
> New governments can come in and they can tinker or totally change the set-up of the market and that affects investment. There's a massive impact. What people are looking for is some stability or at least [that] they can see the direction (Respondent J).
>
> [A key risk is] lack of long term certainty, so that comes back to the investment signal and that kind of thing (Respondent N).

Meanwhile, the other two respondents used the two views fairly interchangeably. For example:

> It's one of these things that government do, they set a policy and don't think about the long-term consequences of it… I think we need a lot more flexibility in the system than we have now, which does require long-term policy, which I don't necessarily think we have at the moment. (Respondent M)
>
> I talked a little bit about stability and long-term signals and that kind of thing, but ultimately it's the absence of those that are driving a lot of the issues within these things… If that investment is going to happen then those who are going to be building that infrastructure need to have the price signals and stability in order to do so. (Respondent U)

This additional indicator suggestion is interesting because most energy security assessments do not include any similar measure; references to 'political stability' usually refer to the geopolitical stability of key fuel exporters (e.g. Axon *et al* 2013). Policy and regulation are perhaps best viewed not so much as an indicator, but rather as an *overriding process* which has the ability to mitigate any or all of the security risks identified, or alternatively which can generate its own security risks. So for example, a particular pathway might have high risk regarding low capacity margins; policy can act to reduce this risk, for example by putting in extra response and reserve capability or by regulating for increased levels of demand flexibility; on the other hand, policy could create new risks, for instance by making sudden policy changes which 'spook' investors.

7.3.1.2 Incentives to invest

As explained in the previous section, incentives to invest are crucial for realising a transition pathway, regardless of the supply/demand mix. This aspect is similar in many ways to 'policy stability' – it is an overriding factor which has the potential to mitigate numerous security risks if done well, or to destabilise the entire transition if done badly. As pointed out by respondent Q:

> …And if we don't have sufficient incentives in place for capacity to be built, and for all those other things, demand measures etc., ultimately, it's all about investment and kit. Unless we can show a decent prospect of return or an adequate level of risk, then whatever we want just isn't gonna happen.

Interestingly, this was only mentioned as an additional indicator by two of the respondents, despite the fact that investment was a common cross-cutting theme throughout the discussions regarding the initial indicator set (as discussed in chapter 6). Similarly to 'policy stability', this suggests that 'incentives to invest' is perhaps best thought of as an overriding process which has the ability to mitigate (or maximise) any or all of the security risks identified. It is highly challenging to differentiate between the pathways for this aspect: all three pathways could be argued as providing better incentives for investment as a result of the storylines, but this is entirely subjective and impossible to predict in the future.

It is worth noting that policy and regulation can help to mitigate many investment risks. For example, the UK Capacity Mechanism is designed to incentivise investment in generation infrastructure in the context of increasingly low load factors for conventional generation as backup for intermittent RES (DECC 2013c). Respondent L said:

> The main thing I don't see [in the indicator set] is something about how we incentivise thermal plant to be on the system when it's almost never used. That becomes more and more of an issue in the long-term. Obviously we have these Capacity Mechanism arrangements, assuming they continue to work as they're intended to. But the more intermittent renewable generation we have on the system, the more and more important it becomes.

Again, it is highly challenging to differentiate between the pathways for this aspect, because all three pathways could in theory put measures in place to ensure that the required investments are made in an efficient manner. Once again, it is worth noting that the results from the interviews suggest that one of the key aspects of securing sufficient investment is the existence of long-term stability of policies and a 'plan' or 'vision' for the transition.

7.3.1.3 Framings of security in political discourse

To some extent, this aspect is also linked to the 'policy stability' aspect discussed previously. Framings of energy security are discussed in more detail in section 2.1. Framings of security in political discourse can impact upon all levels of the system: for example, they can influence public acceptability, they can influence infrastructure decisions and incentives to invest, they can influence the scale and direction of finance flows, and they can dictate the extent to which there is a 'social contract' for the transition. In this way, similarly to the 'policy stability' and 'incentives to invest' aspects discussed previously, this could be viewed not so much as an indicator in its own right but rather as an overriding process which has the potential to mitigate or increase risks. As noted in chapter 6, an important aspect of the transition is the extent to which people and policy-makers agree on the importance of mitigating climate change; again, this can be heavily influenced by political framings. Respondent C said:

> The way in which media and public debate is framed has a big impact - at the moment, it tends to either be about moments of system failure, or about not having to pay foreign dictators for their hydrocarbons. The way that security is constructed in discourse profoundly affects the climate outcomes that we expect. This is especially evident with nuclear; importing gas from the Middle East is a major fear, but terrorists from the Middle East attacking nuclear power stations are not! This isn't the first time that conventional perspectives on security are leaving us a little bit behind.

The stakeholder interviews have actively explored framings of energy security, and have helped to shed light on the ways in which energy security is framed and perceived by some key stakeholders who may potentially have some influence on policy processes. However, despite the importance of this aspect for security, it is not possible to go further than this and to directly test the evolution of political discourse in the pathways, because there is simply no information available about political discourse in the future, and no way of predicting how political discourse might evolve in the various pathways over the next 40 years.

7.3.1.4 Deliberate attack

Three of the stakeholders mentioned that one possible cause of disruption could be a deliberate attack on critical infrastructure such as a power station, transmission and distribution networks, or control and ICT systems, for instance by criminal or terrorist organisations. Respondents said:

> [These indicators] haven’t gone down the counter-terror route… It’s linked [to cyber-security], from that critical infrastructure perspective. It’s not one that keeps me awake at night, but a lot of people worry about it (Respondent E).
>
> I can’t say anything more about this [terrorism] because I’d have to kill you… (laughs) You can imagine a lot going on with the security services, which I actually can’t tell you about. It’s not so much a low-carbon transition thing, but it is a factor in terms of security, something we spend a lot of time worrying about (Respondent W).

Concerns about this issue have been growing in the UK, largely due to the increasing penetration of sophisticated information technology in the electricity system (Cabinet Office 2011; House of Lords 2015). Increasing reliance on ICT, and the potential for this to constitute a security threat, was a factor mentioned by a small number of interviewees; for example, respondent J said:

> If these [ICT] systems break down, and they can - viruses, security problems, hackers, etc. etc. – that’s a big thing companies need to look at. If systems break down, do they have a backup plan or some way of restoring the system.

However, it may be worth pointing out that some of the energy security literature disputes the importance of this category of risks. For example, Johansson (2013) suggests that deliberate attacks by non-state actors such as terrorists and vandals are fairly rare and aren’t likely to constitute a major security risk; meanwhile Burgherr and Hirschberg (2014) found that maximising public participation and acceptability is more important for security than focusing on technologies which could be at risk of deliberate attack.

The likelihood of disruption from deliberate attack in the pathways is not possible to assess, because of the absence of detailed geographical data about the size of generating units, the location of substations, and transmission and distribution network maps. To some extent, the size of the largest credible in-feed loss could be relevant (see section 5.9.3) – for instance, the MR and CC pathways both see an increase in the size of the largest generating unit on the system, which could increase short-term balancing requirements in the event of the loss of a unit due to an attack (National Grid 2011). However, these large units may also be less vulnerable to attack, as they tend to be better protected. In terms of cyber security, the level of 'smart' technology is very similar across the three pathways, and all three pathways assume the continued existence of the nationwide transmission system through to 2050, therefore it is not possible to differentiate between the pathways in this respect, although this could be an important factor when comparing the security of pathways with significant differences in reliance on ICT systems. It is worth noting that some have argued that a more decentralised electricity system will be 'inherently' more resilient to these types of disruption; references for these claims and counter-claims are given in section 5.9.5.

7.3.1.5 Energy efficiency

It is often suggested that energy efficiency can act as a win-win for all aspects of the energy trilemma, because it can improve the ability of supply to meet demand, can reduce costs for consumers, and can lower GHG emissions (Adelle *et al* 2009; Berk *et al* 2006; Froggatt and Levi 2009; Greenpeace 2010a; Hoggett *et al* 2013). It is interesting to note that only two respondents suggested including energy efficiency as an indicator in its own right. Moreover, these two respondents both suggested it precisely *because* other indicators of energy security are highly linked to energy efficiency:

> I think a secure affordable low carbon system will have a very high level of energy efficiency… I think some sort of indicator linked to energy efficiency would be a good one, because it delivers security of supply, because it lowers consumption, it reduces costs and therefore impacts affordability. (Respondent G)
>
> One solution is energy efficiency – you haven't pulled that out as specific heading, but it probably should be there… There's an important linkage between energy efficiency and building retrofits and fuel poverty and that sort of agenda. (Respondent V)

It is worth emphasising, however, that energy efficiency is a complex and contested subject which is not so easily turned into an indicator. Hoggett *et al* (2013) point out that increasing energy efficiency does not simply equal better energy security, because a disruption to supplies will affect energy services no matter what the level of energy efficiency; one way of looking at it is that a highly efficient economy will be *less* secure because each unit of energy is more valuable and therefore a loss of any one unit is more problematic. Moreover, there are many potential ways of measuring energy efficiency, each of which would have slightly different implications: for example, it could refer to energy intensity per unit of Gross Domestic Product (GDP) (EIA 2015c), energy intensity per unit of Purchasing Power Parity (Suehiro 2007), manufacturing output (or other sector output) per unit of energy used (Green and Zhang 2013), exergy (Gundersen 2011; Laitner 2013), or even the number and reach of policies to improve energy efficiency. Respondent G said "…you can measure energy efficiency in various ways, you can link it to GDP you can link it to various things…", thus suggesting that some sort of indicator relating to energy efficiency would be beneficial, but that it would require careful thought over how to measure it. Hoggett *et al* (2013) actually argue that a more important goal is to reduce overall consumption of energy, a goal which is dependent on a raft of wider social and behavioural practices (Eyre *et al* 2011). If this is taken to be the case, it could be argued that overall energy demand would make a better indicator. However, most indicators already incorporate demand figures as part of their calculations; therefore it would be worth being cautious about including overall demand as an indicator in its own right.

7.3.1.6 Technological innovation

Two respondents suggested that 'technological innovation' should be included as an indicator in its own right. However, neither of these two respondents went into any detail regarding how best to design an 'innovation' indicator:

> One observation – we've said nothing here about innovation and technology. It seems to me that's absolutely vital…. You need to spur that innovation and technological development to deal with these challenges. (Respondent I)
>
> Innovation and R&D I think is an absolutely crucial area, that's more long term but it is about finding choice. And it's not just in technologies it's about systems, the whole smarter agenda, materials, science, because it's those things that can provide that disruptive journey which can really accelerate the transition. (Respondent G)

There are numerous metrics which are used to measure innovation. These can be broadly divided into 'input' indicators such as Gross Expenditure on R&D or number of trained scientists per capita, and 'output' indicators such as numbers of patents or publications (see for example OECD 2015; Statistical Office of the European Communities 1997). There is a large literature which examines and critiques the usefulness of such counting methods for examining the level of innovation in a system or sector; a detailed appraisal is beyond the scope of this section, but for a good overview see Freeman and Soete (2009). However, regardless of whether such metrics are regarded as useful, the detail in the pathways is by no means sufficient to be able to use them in this instance.

In the absence of such detailed input/output data, all that can be done is to take a rather broader view of technological innovation evident in the pathways. All three pathways rely on existing technologies, although some (such as CCS) are not currently deployed at scale in the UK. It is useful to distinguish between incremental and more 'radical' innovations (Freeman 1992): for existing technologies, innovation in all three pathways leads to incremental improvements, whilst the pathways also include several emerging technologies which appear at scale in future decades:

- all three pathways assume that CCS becomes commercially viable (the TF pathway includes CCS on a smaller scale, due to lower proportion of fossil generation);
- all three pathways include the emergence of a Smart Grid for managing electricity demand;
- all three pathways presume widespread electrification of heating and transport;
- all three pathways include the emergence at scale of tidal and wave generation;
- all three pathways include innovations in energy efficient appliances and other demand-reduction technologies (this is especially evident in the CC and TF pathways);
- all three pathways presume incremental efficiency improvements in existing generation technologies;
- none of the pathways includes the emergence of more radical innovations such as nuclear fusion, new types of cost-effective batteries, advanced biofuels for transport etc.

As can be seen from the list above, there is little to differentiate between the pathways in terms of the technological innovation evident in their respective technology mixes. The main differences are that CCS is used much less extensively in the TF pathway, thus meaning that the TF pathway would be at lower risk of being unfeasible if the necessary innovation and cost reduction in CCS did not occur. The CC and TF pathways also include higher levels of buildings efficiency than the MR pathway, implying higher levels of innovation in this area. It is also worth noting that innovation can be important not only for improving the technology itself, but also for reducing costs, known as 'learning curves', an aspect which may be especially important for newer technologies such as wind and solar (Barreto 2001; Gross *et al* 2013; Grubler 2010). This issue is discussed in relation to the pathways in section 5.3.3 and in Appendix C.

Another important aspect of an 'innovation' indicator would be whether there are sufficient incentives for innovation and whether new innovations can find the opportunity to emerge. However, it is highly challenging to assess which of the pathways would be better at incentivising technological innovation. Some economists might argue that a market-led system such as that envisaged in the MR pathway might be better placed to ensure efficient technological innovation, because the market will (in theory) seek the most economically efficient route (Less 2012; Moselle & Moore 2011; Nordhaus 2009). However, others point out that the existence of market failures and externalities mean that the public sector has a vital role to play, because the market won't necessarily account for these when valuing innovations (Gross *et al* 2012; Mowery *et al* 2009). Finally, some suggest that the TF pathway might be better at incentivising bottom-up innovation from consumers and local groups (Barton *et al* 2015; Bolton and Foxon 2015). It becomes very complex to differentiate between the pathways in this respect, because the pathways themselves cannot be easily reduced to 'private' versus 'public': it should be emphasised that both public and private sectors have a role in all three of the pathways, although their relative importance varies. For example, the MR pathway may be market-led but it does not preclude the existence of state support for innovation, especially at the early R&D stage; the CC pathway on the other hand might involve lots of state support for innovation, but private firms will still be needed to commercialise technologies (Balachandra and Reddy 2007).

This discussion shows that it is not simply the *amount* of innovation which matters; a small amount of cleverly targeted innovation which can bring about critical improvements in vital technologies is much more useful than scattered innovations across the board (Irvine and Martin 1984). In this respect, it must be emphasised that concepts of 'innovation' are themselves highly contested (although none of the interview participants mentioned this). As pointed out by Stirling (2009; 2014), concepts of innovation are often reduced to simple questions such as 'how much?', 'how fast?' and 'who leads?', yet this is deterministic and assumes that there is a single best route for innovation. A more plural understanding gives rise to questions such as ‘which way?’, ‘what alternatives?’, ‘who says?’ and ‘why?’ Moreover, innovation is not just about technological invention, nor is it always beneficial (Stirling 2014). The complex and contested nature of innovation as a concept would warrant an extremely lengthy discussion which is outside the scope of this section, but which reinforces the significant challenges which would face attempts to include this as an indicator.

7.3.1.7 Supply capacity at the other end of interconnectors

As discussed in sections 5.8.4 and 6.5.2, interconnection can in theory bring benefits for electricity security by providing additional flexible capacity for dealing with stress periods; however, interconnection could also generate risks, especially if a fault occurs at the other end of the interconnector or if several interconnected countries experience a stress moment simultaneously. Therefore, it was suggested that an indicator of the supply capacity at the other end of the interconnectors could help to reduce some of this uncertainty. Just one respondent suggested this as an additional indicator, stating “I wonder if you need something around generation capacity levels in our interconnecting areas…” (Respondent N).

However, for the purposes of this assessment, all three pathways are remarkably similar in their levels of interconnection, and all include interconnection to the same sets of countries, therefore it wouldn’t be possible to differentiate between these pathways for this indicator. Furthermore, it is worth noting that supply capacity at the other end of the interconnector is not the only factor which determines the effectiveness of the interconnector at improving system security. Electricity imports need to be available at the specific times required; for this, hour-by-hour modelling of transmission flows based on the supply/demand balances of all interconnected countries would be required, which is outside the scope of this thesis. Regulations are also important, because they can help to control what happens during a stress moment, in particular ensuring that international markets are working to effectively distribute power to where it is needed most and helping to ensure that power does not flow out of the UK when it is required (House of Lords 2015). The interaction between System Operators in different countries is also critical: getting this interaction right can help to regulate load flows and can help to mitigate the impact of cascade faults (RAEng 2014). As noted by respondent N, it is also important that the market arrangements in different countries work well together; there is currently some uncertainty over how the various independent Capacity Mechanisms emerging in Western European countries will work together in the context of increased interconnection (ACER 2013; Newbery 2014).

7.3.1.8 Availability of key skills

As noted by one of the respondents, ‘resources’ does not necessarily only apply to physical resources such as fuels and materials. It is also crucial that there is an adequate supply of labour, engineering skills and technological know-how for newer technologies:

> … I don’t know if you can put the skills shortage in there as well. I would say we haven’t got it here, but that’s a biggy, because if you don’t get engineers, the right people trained up, it’s going to be increasingly difficult to run an energy system in the future. (Respondent J)

There is not enough data in the pathways to assess the availability of key skills in the future. Again, this is an area in which policy and regulation can intervene to ensure that the right labour and training incentives are in place to ensure good availability of key skills. It is worth noting that this is potentially an area of greater risk for the TF pathway, because the decentralised nature of the energy system would mean that some level of expertise may need to be available at local level. This could create a barrier to local energy schemes, especially for the operation and maintenance of municipal or community generation assets (Morrison *et al* 2013), although it is possible that Energy Service Companies (ESCos) could mitigate this to some extent (Bertoldi *et al* 2006).

7.3.1.9 Air pollution / local air quality

As pointed out by one of the respondents, mitigating air pollution and maintaining air quality is not just important for environmental and health reasons: in fact, it can have an impact on the ability of power stations to run, because air pollution controls could constrain some fossil generation capacity. For example, the EU Industrial Emissions Directive and its predecessor the Large Combustion Plant Directive (LCPD) have already had an impact on coal generating capacity in the UK, with numerous old coal plants choosing to close instead of complying with the emissions limits (Loyd and Craigie 2011). There is also a Medium Combustion Plant Directive in process in the EU, due to come into force from 2020 onwards (European Commission 2013); this illustrates that the suite of air pollution controls is likely to get more stringent in the future as legislators attempt to minimise the serious health impacts of airborne pollution. Although this was only suggested as an additional indicator by one respondent, it could be argued that the decision not to include air pollution in the initial assessment (see Appendix A) was an oversight, and that this indicator could be useful in future research.

Unlike most of the other additional indicators suggested by the respondents, this would have been possible to include as a quantitative indicator. Treyer *et al* (2014) conduct a life-cycle assessment of various electricity generation technologies for particulate matter and other impacts on human health. Their results show that particulate matter formation is most serious for lignite and hard coal. Adding CCS does improve this somewhat, but coal with CCS is still more damaging than other forms of electricity generation. The next most damaging is gas, followed by geothermal (of which there is none in the pathways), then solar (mainly due to the diesel generators used when building the array), then nuclear (mainly due to plant construction), then all other RES. A full quantitative assessment is outside the scope of this section, but a preliminary overview shows that pathways which are heavily reliant on coal and gas generation (i.e. the MR pathway, and to a far lesser extent the CC pathway) would produce the greatest risks from air pollution. Therefore it could be argued that the MR pathway may also run the greatest risks to plant closures or increasing costs due to air quality controls such as the LCPD (although in the absence of information about specific future regulations this is still fairly speculative). It is also worth noting that this could impact the MR and CC pathways by increasing the cost of fuel supplies from overseas, if for example producer countries implemented more stringent air pollution controls on mining processes.

7.3.2 Conclusions from missing indicators

This section has illustrated the following key conclusions from the analysis of indicators which were suggested by respondents as missing from the initial set of indicators:

- There was no overwhelming consensus regarding indicators which stakeholders felt were missing from the initial set of indicators.
- Out of all the additional indicators which were suggested by the respondents, only ‘energy efficiency’ and ‘air pollution’ would really be possible to measure using available data. However, ‘energy efficiency’ in particular is complex and contested.
- The missing indicators suggested by respondents reinforce the importance of stability of policies, institutional effectiveness, and securing adequate investment. These aspects are difficult to measure and are impossible to assess in the context of

transition pathways into the future as it is possible to envisage a range of plausible political and investment risks for all three pathways.

7.4 Summing up chapter 7

This chapter has brought together the results presented in chapters 5 and 6, in order to assess the impact of stakeholders' perspectives on the results from the initial security assessment. First of all, the results from the initial security assessment (presented in chapter 5) were presented as a dashboard analysis, which enables the identification of trade-offs between various objectives, and thereby acts as a useful precursor for the application of the interview results to the results from the security assessment. In order to do this, the dashboard analyses were examined in light of the results from the interview analysis, in order to flag up significant areas of risk for the pathways which may be echoed by UK energy stakeholders. Finally, this chapter looked in more detail at some of the additional indicators recommended by the interviewees, and analysed what impact including these additional indicators would have had on the results of the security assessment of the three pathways.

This chapter has demonstrated the importance of using multiple indicators from multiple dimensions to assess security. The results help to identify trade-offs; each indicator is much less useful if taken in isolation. Therefore the results reinforce the importance of taking a dashboard approach which incorporates a broad range of indicators whilst avoiding aggregation. This chapter showed that there was generally agreement amongst interviewees over the importance of system flexibility, and it highlighted the risks created by a reduction in flexible and responsive electricity supply in all three pathways. The three pathways were all less risky for several of the indicators which were said to be of minimal importance by the stakeholders interviewed, but more risky for others suggested as being highly important. It could be argued that this suggests the need for more of a focus on system resilience and flexibility in low-carbon transition pathways in general. This chapter also showed that there are big challenges for the development of a generalisable set of indicators for assessing the security of multiple systems in a low-carbon context. These challenges are mainly caused by three factors: a lack of consensus regarding the inclusion of affordability and sustainability dimensions; a lack of consensus regarding the inclusion of 'traditional' indicators of energy security such as diversity and import dependence; and the importance of spatial and technological context on the choice of indicators. These challenges mean that it is important to design assessments in a way which captures the multidimensional nature of energy security, in a transparent manner which does not seek to aggregate diverse indicators.

The dashboard analysis showed that the area of highest risk in general for the pathways is the affordability dimension, whereas the area of lowest risk in general is the sustainability dimension. This could point to a trade-off between affordability and sustainability objectives, which if it were the case would have major implications for the UK’s ability to address all three dimensions of the energy trilemma; however, it was also noted that comparison with a higher-carbon pathway would be needed to test this. The dashboard analysis also found evidence to suggest that maintaining a centralised electricity system trajectory could be less risky in the medium-term, but more risky in the longer-term. This raises some interesting questions about what the priorities should be for policy in the immediate future, because the results suggest that pursuing less risky strategies now could lock the UK into a less secure future if a low-carbon trajectory is maintained. This is especially interesting in light of the interview data which suggested that the extent of power system decentralisation could be a crucial factor in determining both the security of the system going forward and how to assess it. This reinforces the conclusion from both the dashboard analysis and the interviews, that certain ‘low regret’ options such as demand reduction which can generate benefits in multiple dimensions should be a priority.

Finally, this chapter explored some of the indicators which were suggested by respondents as missing from the set of indicators, as a means of testing the set and potentially providing useful insights for further development in future research. The additional indicators suggested by respondents reinforce the importance of policy stability, institutional effectiveness, and securing adequate investment. These aspects are difficult to measure and are impossible to assess for the Transition Pathways studied here; a range of plausible political and investment risks can be envisaged for all three pathways. Of all the additional topics which were suggested by the respondents, only “energy efficiency” and “air pollution” would really be possible to implement using available data, and ‘energy efficiency’ in particular is complex and contested.

The next and final chapter concludes the thesis. The next chapter will reiterate the goals which this thesis set out to achieve, including a summing up of the methods used to achieve these goals. It will summarise the results from chapters 5, 6 and 7 in order to provide answers to the research questions posed, and will describe the contributions to knowledge that this thesis has made. The next chapter will also present the main limitations of this thesis, as well as areas which could prove fruitful for further research. Finally, the following chapter aims to generate practical applications of this research by generating a set of policy recommendations arising from the knowledge created in this thesis.

8 Conclusions

This final chapter presents the conclusions from the thesis as a whole, and describes the contributions to knowledge that this thesis has made. Section 8.1 reiterates the overarching aims of the thesis and the research questions, and briefly outlines the ways in which the research questions were answered. Section 8.2 then provides the answers to these research questions by summarising the results and discussion from the preceding three chapters. Section 8.3 describes the contributions to knowledge that this thesis has made. Section 8.4 then discusses the uncertainties and limitations of the thesis, and outlines areas in which further research would be beneficial. Finally, section 8.5 gives policy recommendations arising from the results.

8.1 Goals of the thesis, and how they were achieved

The overarching aim of this thesis has been to assess the future security of the UK electricity system in a low-carbon context, in order to identify the main risks, trade-offs and synergies which may emerge between different objectives in a transition to a low-carbon electricity system. This thesis has carried out a systematic empirical assessment of the security of three low-carbon transition pathways for the UK electricity system, in order to answer three research questions:

i. "What indicators are appropriate for assessing the security of low-carbon transition pathways in the UK, and what are the results of such an assessment using a set of existing pathways?"

ii. "What are the reactions of energy stakeholders to the proposed set of indicators, and what does this tell us about the diversity of perspectives in the UK energy community?"

iii. "What impact do the stakeholders' perspectives have on the results of the security assessment and on their preferred options for improving electricity security?"

The first research question was addressed in chapter 5. A four-dimensional analytical framework for assessing the security of low-carbon transition pathways for the electricity system was proposed from a review of the existing literature. In order to operationalise this framework, a set of 22 security indicators was developed and was applied to three low-carbon transition pathways for the UK electricity system. It was found that many indicator approaches suffer from problems caused by the aggregation of diverse and distinct indicators, and that a 'dashboard' approach may be preferable because it allows for a manageable number of quantitative and qualitative indicators to be used without aggregation, and allows for trade-offs between objectives to be identified. The framework and methodological approach has been designed to be applicable to any pathway for the electricity system of any jurisdiction, provided that the raw data is available; the set of indicators therein was designed specifically for the purposes of assessing the security of UK electricity systems, although many of the indicators would also be applicable in other national contexts. Herein lies an advantage of using a dashboard approach: it may be that some indicators are of limited utility in other countries, or that data for some is unavailable, and therefore it is useful to be able to choose the indicators best suited for the purpose. Detailed information regarding the applicability of specific indicators to non-UK contexts is given in section 4.4, and in the table in Appendix A.

The second research question was addressed in chapter 6. The theoretical approach of the thesis, set out in chapter 2, suggests that several answers to a question may be 'approximately right', meaning that the perspectives of other stakeholders can therefore provide multiple lenses through which to view the results. Interviews were carried out with 25 experts from the UK energy sector, in order to elicit their opinions on the set of indicators and to explore the diversity of perspectives in the UK energy community. In this way, this thesis has put some concrete empirical material behind the claim that different people think differently about energy security. The qualitative data from the interviews was analysed using thematic coding analysis.

The third research question was addressed in chapter 7. As mentioned above, the perspectives of multiple stakeholders provide a highly useful lens through which to view the results from the initial security analysis in chapter 5. Therefore the results from chapters 5 and 6 were brought together in the discussion in chapter 7: the interview results were applied to the results from the security analysis, in order to analyse the impact of stakeholders' perspectives on the results. This chapter also explored in more detail some of the additional indicators suggested by respondents, assessing whether including these indicators would have been possible or practical, and what impact these additional indicators might have had on the security assessment of the pathways.

8.2 Overview of results

The results from the security assessment of three transition pathways for the UK electricity system showed that the centralised Market Rules and Central Coordination pathways both experience deterioration in their overall security from 2030 to 2050, whereas the decentralised Thousand Flowers pathway experiences some heightened security risks in the medium-term 'transition' period. This suggests that maintaining a centralised electricity system trajectory could be less risky in the medium-term, but more risky in the longer-term. The results demonstrated that demand reduction can bring co-benefits in multiple security dimensions; this finding adds empirical weight to existing claims in the literature, discussed in section 2.3.2. However, in this analysis, demand reduction was assumed to be cost and risk free; this thesis has not explicitly investigated the costs and risks of demand reduction, therefore this finding would warrant further investigation in future research.

It has also been suggested in the existing literature that increasing the penetration of RES will bring about co-benefits in multiple security dimensions (see section 2.3.2). The results from this analysis show that the picture is somewhat more complex, with synergies in some areas but trade-offs in others. Increasing penetration of RES was shown to increase the diversity of the fuel mix, and may also have a positive impact on general public approval. Moreover, increasing penetration of RES has a beneficial impact on fuel depletion risk, and the 'sustainability' dimension was the area of lowest risk in general. However, high penetrations of RES were also shown to generate 'red flags' for the security of the three pathways in other dimensions. For example, it is often suggested that RES will improve security by reducing dependence on imports – not only has this thesis shown that reducing imports is not necessarily important for energy security, but it has also shown that reliance on imports may not necessarily decrease with the introduction of more RES (all three pathways displayed ongoing dependence on either imported fossil fuels or imported biomass). The results show that all three pathways exhibit a reduction in flexible, responsive supply capacity, which could reduce the ability of the system to cope with unexpected perturbations in the supply/demand balance. In particular, high penetrations of wind generation plus high penetrations of nuclear would potentially compromise the resilience of the electricity system, as would high penetrations of intermittent generation plus high electricity demand. These risks could be mitigated somewhat by increasing flexibility on the demand-side, or by increased use of measures such as electricity storage and interconnection. The results from both the security assessment and the interviews suggest that flexibility of both supply and demand should be a greater security priority than reducing imports or even increasing diversity. Much of the literature focuses on improving security by minimising *causes of* insecurity, but this thesis has shown that this approach sometimes neglects the critical issue of improving the capability of the electricity system to *respond to* insecurity, for instance by improving flexibility.

The results from both the initial security assessment and the results when viewed from the perspectives of multiple stakeholders suggest that the decentralised Thousand Flowers pathway is less risky than the centralised Market Rules and Central Coordination pathways, especially in the longer-term. Because of the impossibility of conclusively aggregating or weighting the indicators, it is not possible to state from this that the decentralised pathway is more secure; however, this finding is an interesting addition to the energy security literature and to policy discussions which have sometimes debated the potential security benefits of a decentralised electricity system for the UK but have not yet explored this issue in empirical detail. However, this thesis has also highlighted that there are many areas of uncertainty and potential security risk in a transition to a decentralised pathway, including the finding that the more ‘radical’ decentralised pathway may experience some aspects of heightened security risk in the medium-term. This reinforces the conclusion from both the security assessment and the interview analysis, that certain ‘low regret’ options such as demand reduction which can generate benefits in multiple dimensions should be a priority.

The results have highlighted areas which need more attention in the modelling of transition pathways in future. Firstly, the findings from the reliability dimension have demonstrated that it is necessary to include more than one measure of the ability of electricity supply to meet peak demand. This is because despite being modelled to meet demand on an hourly basis, two of the pathways experience a negative de-rated capacity margin in 2050, thus suggesting that some of the pathways assumptions may have been overly optimistic and that a separate measure of supply adequacy would be useful for minimising the risk of capacity shortfall at peak times. Secondly, the results from the interviews show that one of the most critical areas for security is incentivising adequate investment in infrastructure, and the importance of policy stability in achieving this; this issue is usually not explicitly addressed in transition pathways, and is highly challenging to assess (discussed in more detail in section 8.4.2).

This thesis has explored stakeholder perspectives on energy security, thereby contributing to the existing literature on defining and conceptualising 'energy security'. This part of the research generated five cross-cutting themes which encapsulate the key issues which UK energy experts consider when deciding what is important for security and why, and also ascertained some of the underlying concepts which are used when making or justifying these choices. The interview analysis found that some interviewees focused upon what they perceived to be current risks to the system or areas in which policy has an obligation to act, leading to a preference for indicators such as public acceptability and fuel poverty; meanwhile others focused on indicators which are simple and direct or more easily quantifiable and usable, leading to a preference for indicators such as diversity and capacity margins. The results also demonstrated that the views of the experts interviewed were not necessarily aligned with the type of organisation for which they work (although it should be emphasised that statistical analysis of this hypothesis was not possible with the selection methods used, and this finding simply reflects the results of the qualitative analysis of the interview transcripts). The reason for this lack of alignment may be that all the stakeholders chosen for this study possess extensive experience and in-depth knowledge of energy issues, and therefore possess complex, nuanced and widely differing opinions, thus meaning that they are unlikely to be co-opted by the 'party line' of their various organisations. It could also be that movement between types of organisation could partly explain this result; in the energy field, it is not uncommon for experts to move between private, public and non-profit sectors.

The application of the interview analysis to the results from the initial security assessment illustrated that there are big challenges for the development of a generalisable set of indicators for assessing the security of multiple potential electricity systems. These challenges are caused by three main factors: a lack of consensus regarding the inclusion of affordability and sustainability dimensions; a lack of consensus regarding the inclusion of 'traditional' indicators of energy security such as diversity and import dependence; and the importance of spatial and technological context on the choice of indicators. The thesis has shown that the security of an energy pathway or system is highly influenced by whether affordability and sustainability are viewed as integral to energy security: if affordability is *not* viewed as integral, all three pathways have fewer areas of high risk, whereas the opposite is true for sustainability. This is an important finding because it suggests that energy security assessments should be explicit about which view of security they follow, and should acknowledge the impact that opposing views could have on the results. The process of applying the interview analysis to the results from the initial security assessment also strengthened the conclusion that all three pathways exhibit a reduction in flexible and responsive supply capacity, and reiterated the importance of demand reduction and demand flexibility.

8.3 Contributions to knowledge

This thesis assesses the future security of the UK electricity system in a low-carbon context, in order to identify the main risks, trade-offs and synergies which may emerge between different objectives in a transition to a low-carbon electricity system. This thesis therefore makes a methodological contribution to knowledge by proposing and testing a set of indicators to measure the security of electricity systems in long-term scenarios of national energy transitions. To do this, this thesis has developed existing frameworks from the energy security literature, as follows: firstly, a set of four energy security 'dimensions' has been proposed as being suitable for assessing the security of low-carbon electricity systems (*acceptability, affordability, sustainability,* and *reliability)*: these four dimensions were first proposed by Elkind (2010), and have been applied here in a novel way to a set of pathways for a low-carbon transition. Secondly, a set of indicators has been proposed as being suitable for assessing a broad range of different aspects of energy security; this builds on existing assessment frameworks such as that developed by Jewell *et al* (2013; 2014), but with particular focus on assessing the security of national electricity pathways. The set of indicators is tested by using them to assess the security of three pre-existing low-carbon transition pathways for the UK electricity system.

This thesis operationalises the idea of a 'dashboard' of indicators, utilising a manageable number of quantitative and qualitative indicators without aggregation in order to identify trade-offs. It is the first time that such a comprehensive security dashboard has been used to assess a set of future electricity system scenarios. In doing so, this thesis takes an interdisciplinary approach which explicitly recognises the importance of actors and policies as well as technologies, systems and markets. A further novel aspect of the indicator dashboard is that it includes both reliability and cost parameters alongside other important aspects of energy security such as diversity, trade and acceptability; this thesis thereby extends the empirical work of existing frameworks to explore the potential implications of a low-carbon transition on electricity system reliability and costs, and the potential trade-offs between objectives.

This thesis makes a further empirical contribution by identifying the diversity of perspectives on energy security amongst UK energy stakeholders; this is a novel contribution to the energy security literature, which contains few empirical studies on experts' perspectives on energy security, and no previously-existing work of this kind in the UK context. The results from the interviews showed that there is a need to accept the existence of multiple perspectives and to at least attempt to take them into account when discussing energy security; for example, energy security assessments should be explicit about whether to include affordability and sustainability indicators, and should acknowledge the impact that opposing perspectives could have on the results. In keeping with this recommendation, this thesis has analysed the impacts of the experts' perspectives on the results of the security assessment; this is the first study of this kind to actively incorporate multiple perspectives on energy security into an indicator assessment. The results from this process have shown that all three analysed pathways experience security risk through maximising certain aspects of environmental sustainability whilst neglecting important reliability issues such as flexibility and shock resilience.

8.4 Limitations and areas for further research

8.4.1 Data gaps that the research has identified

As shown in chapter 5, there are considerable uncertainties in some of the projections of UK electricity security through to 2050, several of which arise from limitations in data availability. One highly useful outcome of this uncertainty is in highlighting areas in which further research could be beneficial in order to improve the robustness of the assessment. In particular, the analysis has illustrated several areas in which increased availability of information in transition pathways or scenarios would make it more feasible to conduct a full analysis of their security. To some extent, this could be achieved by increasing the scope of model inputs (or outputs); however, some aspects might be highly challenging to model, and therefore may be more suitable for alternative quantitative or qualitative approaches. This sub-section briefly identifies some of the key areas in which increased data availability would be beneficial:

- **Patterns of electricity demand:** In addition to data on the volume of electricity consumption, it would be useful to have more detailed information on the way in which consumers use electricity in the pathways in the future. This could include information on changes in consumer behaviour, 'smart' appliances, and rebound effects.
- **Spatial data**: It is highly challenging to make an assessment of security without locational detail regarding generation sites, networks and import terminals. Improved spatial data, including network maps and locations of major generation sites, would increase the robustness of estimates for multiple security indicators.
- **Imports**: The uncertainties in the assessment of future supply diversity and stability are enormous. Transition pathways would benefit from the inclusion of data on major exporting nations (and the likely resource availability in these nations), and the routes taken by major fuels and materials in transit. For gas, it is also vital to have information on proportions of piped gas and LNG, and the locations of import terminals.
- **Biomass:** Biomass is becoming an increasingly important fuel input, and its importance may increase in a low-carbon context as biomass is both renewable and flexible. It is extremely difficult to assess the future security of biomass generation without detailed information on types of feedstock (e.g. wood, residues, waste etc.), types of process (e.g. co-firing, anaerobic digestion etc.), major exporting nations, and import transit routes.
- **Fuel stockpiles:** To some extent, fuel security depends on the amount of storage available, therefore security assessments would benefit from data showing the proportion of fuel inputs which are sourced from domestic stockpiles.
- **Income data:** Data on people's incomes is needed to assess the future impact of electricity prices on levels of fuel poverty; disaggregated income data would assist in the identification of vulnerable groups. It would also be useful to have locational income data in order to identify the potential impact of electricity price increases on deprived areas. This could be especially useful for assessing in more detail the impact of a decentralised pathway on fuel poverty and inequality, because concerns have been raised that rapid decentralisation could result in fragmentation whereby deprived areas fail to reap the benefits.

8.4.2 Limitations and areas for further research

At the core of most of the biggest uncertainties in the analysis lies the fact that there are enormous challenges in attempting to actually assess empirically how people might act in the future. This is probably one of the reasons why many existing energy security assessments focus on a small number of quantifiable metrics such as diversity and import dependence; however, this thesis has shown that such an approach is not sufficient. Connected to this issue, uncertainties arise from the lack of ability to assess whether enough investment will be available to build the infrastructure required for a low-carbon transition: the results from both the security assessment and the interviews highlighted the fact that a major risk could be the political and economic feasibility of actually *realising* ambitious transition pathways, rather than the (technical) security of the pathways themselves. In order to address these issues in future research, there is a real need for *ongoing* work into maintaining a broader approach to assessing energy security, and focusing on actors and policies as well as technologies, whilst simultaneously working to find ways of reducing some of the inherent uncertainties.

The choice of transition pathways for any kind of assessment is always subject to multiple limitations. The justification for the choice of pathways was described in detail in section 4.2; however, the choice of pathways also created some limitations of the research, which are as follows:

- Unlike some other pathways options, the Transition Pathways do not include a BAU. Later reflections on the research suggested that comparing a BAU or high-carbon pathway would have been highly beneficial, because it would allow better identification of trade-offs between low-carbon objectives and the other indicators. However, creating and comparing a BAU or high-carbon pathway was outside the scope of this thesis, and would therefore potentially be an interesting area for further research.
- The pathways focus on the electricity system only, although heating and transport are included in their modelling. The thesis as a whole also focused on the electricity system, as a necessary means of bounding the study. Limiting the energy system to one carrier such as electricity is challenging and fraught with complications, and a whole-systems analysis would be desirable.
- The raw data used for the Transition Pathways, which begin from a baseline of 2008, is now completely out of date. Since 2008 there have been enormous changes to the energy system, including an oil price crash, significant advances in some technologies such as solar and storage, and severe setbacks to the UK’s nuclear and CCS ambitions.

> This illustrates the challenges of conducting research over long timeframes in a fast-moving field such as energy.

It is worth briefly mentioning the ‘oversupply/capacity factors’ indicator, which was found to be of somewhat limited utility in the analysis. This indicator was initially included on the basis that a key issue for the pathways could be the high amounts of spare capacity required to back up the high penetrations of intermittent RES in the pathways, potentially leading to investment risk. However, high amounts of spare capacity do not necessarily translate into high investment risk; investment risk is complex and difficult to assess (as discussed in section 7.3.1.2), and cannot therefore be easily reduced down into an indicator such as this one. It is therefore worth critically reflecting on the utility of this indicator for future energy security assessments.

Finally, it is worth highlighting a rather specific limitation of the interviews conducted as part of this thesis. Stakeholders were interviewed using a pre-defined set of indicators, in an attempt to tease out perspectives on energy security from concrete underpinnings; however, this leaves the responses vulnerable to framing effects whereby some of the pre-defined indicators may have sparked interest from the respondents which would not have been apparent if the questions had been framed in a more open-ended manner. Therefore it could be beneficial for further research to elicit stakeholder opinions using more open-ended questions, for instance by asking similar sets of stakeholders to define ‘energy security’ in their own words, and triangulating this with the responses regarding specific indicators.

8.5 Policy recommendations

Policy decisions are frequently justified on the basis of ‘improving energy security and reducing carbon emissions’, without detailed empirical assessment of whether the measures proposed will actually improve energy security in the context of a low-carbon transition. Therefore the findings in this thesis are highly policy relevant.

The UK Energy Security Strategy (DECC 2012a; see section 2.1.1) defines energy security primarily as access to energy supplies and avoidance of price volatility. As shown in section 1.2.3, current UK policies for ensuring electricity security are focused on centralised supply-side measures (for instance, incentives for large power stations) and are also keen to maximise indigenous fuel resources (for instance, by supporting shale gas exploration and North Sea fuel recovery). It is interesting to note that current UK energy security policy, with its focus on increasing generation capacity and reducing imports, may potentially be failing to capitalise on some of the key measures which this thesis has highlighted as beneficial for future electricity security. In particular, the results from the interviews showed that flexibility of supply and demand and public acceptability are felt by stakeholders to be important in improving energy security, whereas reducing reliance on imports is not. Therefore it could be argued that by focusing on a narrower concept of energy security which does not incorporate broader issues such as societal and environmental concerns, important risks and measures to mitigate those risks may be being underplayed.

This thesis has found that policies to improve electricity security should focus on measures which can improve the capability of the electricity system to *respond to* insecurity, in order to redress the imbalance which currently exists in which energy security is usually conceptualised as referring to measures which are thought to reduce *causes of* insecurity. For example, an emphasis on flexibility and responsiveness of both supply and demand is imperative, especially in the context of a low-carbon transition because of the increasing penetration of intermittent generation such as wind and solar and inflexible generation such as nuclear. This thesis has shown that high penetrations of wind generation plus high penetrations of nuclear would potentially compromise the resilience of the electricity system, as would high penetrations of intermittent generation plus high electricity demand; policy could mitigate these by maximising flexibility on the demand-side, or by increased use of measures such as electricity storage and interconnection.

The results show that reducing overall energy demand and increasing flexibility on the demand-side may be highly beneficial in terms of generating benefits in multiple dimensions. However, it should be emphasised that in this analysis, demand reduction was assumed to be cost and risk free, which may not be the case in reality. Moreover, there are concerns over how much demand flexibility can be realised, especially from the residential sector; government therefore needs to work to improve the evidence base in order to provide better estimates of how much flexibility is realistic from the residential and commercial sectors, and it needs to work to ensure that this important resource for security is realised as fully as possible. Current UK energy policy displays a very prevalent focus on supply-side measures such as support for large new power stations; the results from this thesis suggest that important opportunities on the demand-side may be being missed.

The results from this thesis suggest that biomass can provide a valuable source of flexible yet renewable electricity supply; however, there are multiple concerns over the sustainability and future availability of biomass feedstocks, and high uncertainty regarding sources and trade flows, meaning that maximising more sustainable resources such as energy-from-waste could be highly valuable for security. Closing down gaps in knowledge regarding the security of biomass feedstock may require more than just research; real-world experience of emerging supply chains for large-scale biomass power generation (e.g. the large conversion project at Drax) could also be highly useful.

Finally, this thesis has reinforced the point that realising any transition pathway will be dependent on ensuring sufficient investment in infrastructure, and has shown that whichever route to transition is taken there may be security problems caused by high levels of uncertainty regarding capital flows and investment. This is often an 'elephant in the room' when transition pathways are discussed; a number of transition pathways take a fairly technocratic approach which assumes that the investment is 'waiting out there' somewhere. This thesis argues that in order to incentivise the investment needed to realise a secure, low-carbon electricity system, there is an urgent requirement for policy stability and to reduce policy uncertainty. This requires long-term planning and continuity of policies, often on longer timescales than the 5-year election cycle.

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Appendix A: Indicators 'long list'

This appendix details the process for long-listing and short-listing potential indicators of the security of electricity system transition pathways.

Initially, indicators were identified from the list provided in Sovacool and Mukherjee (2011: 5347-5352). These were then narrowed down considerably by removing duplicates of indicators which are highly similar (for example, their article lists 'reserve-to-production' for each fuel individually). Potential indicators were then assessed for their suitability for the purposes of this thesis, following the advice of Axon *et al* (2013) that indicator sets should be derived 'for a set purpose', and following as much as possible the guidelines set out in the 'methodology' chapter (section 4.3). Indicators were rejected for a number of reasons:

a. They do not show a clear link to a plausible risk or vulnerability[29] to the electricity system
b. They are not relevant to the UK, or they are more suited to multiple-country comparative studies[30]
c. They cannot be used to assess multiple pathways or scenarios
d. Immediately apparent problems with accessing the data or information required for the indicator
e. Complex or aggregated indicators, or indicators which require dedicated modelling, were judged to be outside of the scope of this thesis.

The 'suitability' of each indicator was graded on a simple low/medium/high scale; table A.0.1 shows the notes from this initial selection process. Following this, the final set of indicators was selected using the methodology explained in section 4.3.

[29] Jewell *et al* (2014) define 'vulnerability' as a combination of exposure to risk, and resilience (i.e. the capacity of the system to respond).
[30] Indicators in the 'long list' are not necessarily specific to the UK. The indicators chosen to assess the pathways are chosen on the basis of being relevant for assessing the security of UK electricity systems, as per the explicit purposes of this thesis; however, many of these could potentially be applicable to other countries, and are indicated as such in the table.

Table A-0-1: Initial long-list of potential indicators for assessing the security of electricity system transition pathways

Dimension	Indicator	Relevant risk / vulnerability	Suitability [31]	Non-UK[32]	Notes
Availability	Supply/demand index	Supply does not meet demand	Medium	Yes	Complex composite index; out of scope
Availability	Import dependence	Supplies disrupted due to problems with imports	High	Yes	
Availability	Diversity of fuels / suppliers / routes	Alternative options not available in event of disruption	High	Yes	
Availability	Stability / corruption of exporting countries / historical relationship	Supply disruption due to instability in supplier country	High	Yes	
Availability	Popularity	Public opposition / disruption to new infrastructure	High	Yes	
Reliability	Willingness-to-pay	?	Medium	Yes	Data availability problems: challenging to measure or forecast
Availability	REES index (designed to quantify risk arising from geopolitical threats)	Disruption to imports	Medium	Yes	Complex composite index; out of scope
Availability	Reserve-to-production ratios	Fossil fuel depletion	Low	Variable	Only relevant for fossil fuels; less applicable to electricity systems, especially when integrating RES
Availability / reliability	Electricity demand / peak electricity demand	?	Medium	Yes	Unclear link to risk/vulnerability: doesn't tell you about the ability to meet that peak or that demand
Affordability	Price of imports	Economic risk: cost of fuel too expensive, or disruption to imports	Medium	Yes	Data availability problems
Reliability	Installed electricity	?	Medium	Yes	Unclear link to risk/vulnerability; doesn't

[31] Suitability key: "Low" = not relevant (for example, the indicator doesn't relate to electricity or doesn't relate to the UK). "Medium" = could be a useful indicator but possible problems with data availability or is out of scope. "High" = potentially useful indicator.

[32] The 'non-UK' column signifies the potential applicability of the indictor to countries other than the UK. "Yes" = applicable to other countries outside of the UK, particularly other industrialised countries. "Limited" = limited applicability; indicator may only be relevant for the UK context, or may only be relevant for a small selection of other countries, or not relevant for industrialised countries. "Variable" = applicability of indicator varies; may be applicable to a large number of other country contexts but this could be highly dependent on the country.

	generation capacity				tell us about the ability of supply to meet demand
Availability	Refining capacity	Not enough domestic oil refining capacity? Dependence on oil?	Low	Limited / variable	Relates to oil supply therefore less relevant for electricity security
Availability	Percent served by microgeneration / CHP / alternative transport fuels	?	Low	Variable	Unclear link to risk/vulnerability: doesn't tell us about the security of these options
Affordability	Balance of payments (imports)	Economic risk	Low	Yes	Challenging to measure and forecast
Reliability	Interconnection	Lack of options for system balancing	High	Variable	
Reliability / sustainability	Share of nuclear energy	?	Low	Variable	Is nuclear more or less secure? Unclear link to risk/vulnerability
Sustainability	Share of non-carbon energy sources	?	Low	Variable	Are non-carbon energy sources more or less secure? Unclear link to risk/vulnerability
Reliability	Flexible demand	Lack of options for system balancing	High	Yes	
Affordability	End-use energy prices (by fuel?)	Energy becomes unaffordable / economic risk	High	Yes	Needs to be a whole-system assessment
Affordability	Price volatility	Economic risk	Medium	Yes	Data availability problems: challenging to forecast
Affordability	Price of macroeconomic shocks caused by volatility	Economic risk	Medium	Yes	Extremely challenging to forecast
Reliability	Customer minutes lost	Supply not meeting demand; loss of welfare	Medium	Yes	Important but challenging to forecast
Reliability	Short-term balancing services (FR, STOR etc.)	Lack of options for system balancing	High	Yes	
Reliability	% / rate of households with grid connection	Energy access vulnerability	Low	Limited	Not relevant for highly industrialised nations
Sustainability	Reliance on biomass for cooking	Energy access vulnerability	Low	Limited	Not relevant for highly industrialised nations
Affordability	Household expenditure on energy	Households unable to afford electricity supply; fuel poverty	High	Yes	
Sustainability	Ownership levels of various specific appliances	?	Low	Limited	Less relevant for highly industrialised nations; not relevant for low-carbon context
Reliability	Level of decentralisation	?	Low	Variable	Unclear link to risk/vulnerability: is decentralisation good or bad for security?

Affordability	Market prices for fuels	Economic risk	Medium	Yes	More useful as system-wide costs than for individual fuels
Affordability	Transmission and distribution costs	Economic risk	High	Yes	Also could be used as a proxy for network adequacy / amount of network upgrades required?
Affordability	Energy prices	Economic risk; households unable to afford supply	High	Yes	
?	Innovation and research	Lack of development of more secure / efficient / clean / affordable energy options	Medium	Yes	Limited data availability
Availability	Number of terrorist attacks	Deliberate attack on electricity infrastructure	Medium	Yes	Lack of data availability to forecast; might be worth discussing as a side-note
Reliability	SAIDI / SAIFI / CAIDI (measures of system reliability)	System not reliable enough; electricity shortfalls	Medium	Yes	Complex aggregated indices; possibly out of scope
Reliability	VoLL (damage of an electricity shortfall per unit of lost load)	?	Medium	Yes	Huge uncertainty even in present-day calculations; link to specific risk/vulnerability is somewhat unclear
Reliability	Capacity margins	Lack of spare margin to ensure supply can meet demand	High	Yes	
Reliability	LOLE / generation adequacy	Lack of generation capacity to ensure that supply meets demand	High	Yes	
Reliability	Spare capacity / oversupply	Risks making investments in infrastructure economically unattractive	Medium	Variable	Can inform information about attractiveness of investment?
Sustainability	Energy intensity	Inefficiency (see below)	Medium	Yes	GDP data not available in the pathways; also see ‘efficiency’ notes below
Sustainability	Energy efficiency	?	Medium	Yes	Unclear link to risk/vulnerability: is an efficient system more or less secure?
Availability / reliability	Storage / stockpiles of fuels	Lack of spare fuel supply in case of a disruption	Medium	Variable	Less relevant in a system with lots of non-fuel-based supply (e.g. RES). Possibly worth mentioning in relation to availability indicators
Reliability	Electricity storage	Lack of options for system balancing	High	Variable	

Sustainability	Average thermal efficiency of power plants	Possible economic / fuel depletion risk?	Medium	Variable	Only relevant for conventional generation; less relevant for low-carbon system
Sustainability	Fuel economy of vehicles	Possible economic / fuel depletion risk?	Low	Yes	Not electricity
Reliability	Transmission and distribution losses	Network is inefficient; more network infrastructure needed to meet demand	Medium	Yes	Low data availability
Reliability	Investment in transmission / distribution	Faults on the network due to lack of investment	Low	Yes	Repetition of transmission / distribution costs
Reliability	Planned new energy projects	?	Medium	Yes	Low data availability; unclear link to risk
?	Employment in the energy sector	Low employment leads to lower levels of public support	Medium	Yes	Low data availability
Affordability	Investment in energy infrastructure	Lack of investment leads to lack of capacity or faults on ageing capacity	Medium	Yes	Comes in under affordability indicators? Possible problems with data availability
Sustainability	Deforestation	Deforestation leads to flooding which puts energy systems at risk	Low	Limited	Less relevant for the UK
?	Research intensity	Lack of development of more secure / efficient / clean / affordable energy options	Medium	Yes	Low data availability
?	Equity of access to Grid	Energy access vulnerabilities	Low	Limited	Low data availability; less relevant for the UK
Sustainability	Greenhouse gas emissions	Climate change impacts on energy infrastructure	High	Yes	
Sustainability	Carbon intensity	Climate change impacts on energy infrastructure	High	Yes	
Sustainability	Air pollution	?	Medium	Yes	Unclear link to risks to energy systems
Sustainability	Waste produced from electricity generation	?	Medium	Yes	Challenging to forecast with available data; unclear link to risks to energy systems
Sustainability	Oil spills	?	Low	Variable	Less relevant for electricity
?	Number of regulators	System is poorly regulated and managed	Low	Yes	More suitable for multiple-country comparative studies
?	Corruption / transparency index	System is poorly regulated and managed	Low	Yes	More suitable for multiple-country comparative studies
Availability	Satisfaction with policy and	Public opposition to infrastructure or investments	High	Yes	

	planning mechanisms				
Availability	Participation in decisions	Public opposition to infrastructure or investments	High	Yes	
?	Country credit ranking	Inability to access affordable credit for new infrastructure	Low	Yes	More suitable for multiple-country comparative studies
Availability	Trade (number of pipelines / import routes / interconnectors)	Supplies disrupted due to lack of import diversity	Low	Variable	Repetition of import stability/diversity and interconnection indicators
?	Foreign Direct Investment in the energy sector	?	Medium	Yes	Low data availability. Is foreign involvement good for security?
?	Competition / market share	Lack of diversity in the energy market = lack of alternative options in the event of a problem?	Medium	Yes	Low data availability
Affordability	Total amount of subsidies	?	Low	Limited	Are subsidies good or bad for security? This indicator is more relevant for developing country contexts
Availability	Public resistance / disruptive opposition	Disruption to operational or planned infrastructure	High	Yes	
?	Energy literacy	Low energy literacy = higher opposition to a transition?	Low	Yes	Low data availability; link to risk/vulnerability somewhat unclear
Availability	Number of customers served by net metering	Low levels of participation and energy literacy?	Medium	Variable	Low data availability; link to risk/vulnerability somewhat unclear
Availability	Industrial disputes	Disruption to infrastructure or supplies	Medium	Yes	Low data availability
Availability	Deliberate attack	Disruptive attack on electricity system infrastructure	Low	Yes	Repetition of 'terrorism' and 'public resistance'

Appendix B: Availability Methods

B.1 Likelihood of domestic disruption to electricity availability: Methods

B.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). The article goes 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 and pathways. This indicator therefore takes public levels of approval of various forms of energy generation as one possible indicator of acceptability in general, and therefore as a constituent indicator of levels of risk incurred due to opposition from the general public. This sub-dimension of the security assessment views the mitigation of domestic disruption to supplies as potentially a three-way strategy – improving overall support, increasing participation, and reducing opposition to specific aspects of the energy system or specific new additions. As such, this ‘public approval’ indicator should be viewed in parallel with the other two indicators from this sub-dimension.

The core data for this indicator is provided by a nationally representative survey, which was carried out by Demski *et al* in 2013 (n=2441). The data from this survey is supported by literature review of academic and grey literature into public opinions on various forms of energy, carried out by Whitmarsh *et al* (2011). The data regarding survey responses is given in terms of support (“very / mainly favourable”), opposition (“very / mainly unfavourable”) and neither in support or opposition (“neither favourable nor unfavourable”). Full methodology for the survey is available in Demski *et al* (2013).

The proportion of capacity of each type of fuel in the pathways (in GW) is weighted according to a ‘support’ parameter. The support parameter is given as a proportion (taken from the percentage results reported in the survey). Those in support are given a positive parameter, whereas those in opposition are given a negative parameter. This is then multiplied by the capacity of each generation technology in the pathways, for 2010, 2030 and 2050, for both support and opposition. The minus figures given to the 'opposition' parameters mean that for some fuel types, the end figure is a minus number. The results are then summed to give the total level of support for generation for the pathway (in GW). The total level of support is then divided by the total amount of generation in the pathway (in GW) to give a percentage of total capacity in the pathway which is 'approved of'.

B.1.2 Land requirements (proxy for disruptive opposition)

In addition to the public approval scores from the national survey, it is important to note that high levels of general public acceptance don't always translate into public support for specific projects (Devine-Wright 2005). In some cases, a lack of support for a project can result in highly disruptive opposition and even the cancellation of planned infrastructure. According to Bell *et al* (2005), in the UK around 80% of people claim to support onshore wind power, but only 25% of contracted wind power is actually commissioned; meanwhile Pidgeon and Demski (2012) suggest that much of the local opposition which arose in response to nuclear power in the 1970s may well be resurrected with the advent of large-scale onshore renewable installations, suggesting that many of the concerns are similar regardless of the technology in question. Therefore this indicator comprises 3 sub-metrics which measure the amount of land required by new infrastructure; these are used as proxies for likely levels of disruptive opposition: the amount of new generating infrastructure required, the amount of new transmission infrastructure required, and the amount of domestic extraction of resources.

Generation infrastructure

People are far more likely to protest against new installations, and communities which live close to older or existing sites are shown to be more supportive than national polls report (Greenberg and Truelove 2011). Therefore the amount of land required by new generation capacity in the pathways can act as one proxy for opposition to generation infrastructure.

The capacity at one point in time (e.g. 2030) is subtracted from the capacity at another point in time (e.g. 2050). It is then important to calculate the amount of land actually required to build this additional capacity; therefore the power output per area of each generation type is calculated using data from existing power stations (for coal, gas, oil, biomass and CHP) and from MacKay 2009 (for renewables). The power output per area is calculated in W/m2; this is then used to calculate the total land area which would be required to build the additional capacity required by the pathways. Finally, the results are weighted 70-30 to reflect the difference between onshore and offshore capacity, as offshore will usually be subject to lower levels of opposition because of reduced local impacts such as noise and environmental degradation, and a lower visual impact (Centre for Sustainable Energy 2011; Gardiner 2012).

It is important to note that this capacity measure is less a function of overall capacity (which is driven by levels of demand and the incorporation of intermittent RES) as it is a function of the level of change required from the current system. Larger changes will require more new capacity to be built as older or existing capacity is scaled back; as such, this indicator also provides a useful measure of the overall level of change from the current system.

Biomass assumptions

It should be noted that biomass is given a power output per unit of just 0.5W/m2 by David Mackay. However, this also includes the land required for growing the crops; this introduces some complexity, because much of the biomass required in the pathways will be imported (see section 5.2.2.1). Moreover, domestic production of biomass feedstock is covered in the 'extraction of resources' indicator below. Therefore the biomass output figures are taken simply using the power station itself (along with any stores onsite), using data from existing power stations in the same manner as for coal and gas.

Changing efficiencies over time

Assumptions must be made about the pace of technological advancement. In the future, improvements in technologies will potentially mean that less land is required to generate the same amount of power. Addressing this uncertainty would require detailed projections of learning rates over the next 40 years, which is outside the scope of this project. However, for the purposes of this analysis, this uncertainty is not a major drawback for comparisons of the pathways, because the difference in output per m^2 between RES and thermal plant is so huge that thermal generation doesn't really factor into the overall results, and all three pathways are actually relatively similar in terms of dependence on thermal plant.

Transmission infrastructure

People often protest against new transmission lines, especially when they feel that their community is receiving all the disruption of upgrades but none of the benefits (Cohen *et al* 2014; Pidgeon and Demski 2012). Therefore the level of transmission upgrades required is an aspect of risk from disruptive opposition. The cost of required transmission upgrades (identified as part of the 'affordability' indicator) is used as a proxy for total capacity required. Because offshore transmission is seldom subject to protests, the only figure for transmission will be the onshore transmission costs.

Extraction of resources

Another common cause of disruption is the domestic extraction of fuel resources, as illustrated by the recent delays and disruption caused by opposition to fracking for shale gas in the UK. Levels of domestic extraction of resources are identified in the 'import dependence' indicator (in TWh/y). Higher levels of domestic extraction (of coal, gas and biomass) are judged to be more insecure. For uranium, the import dependence indicator identifies a proportion of UK reserves as 'domestic'; however, these are from stockpiles rather than domestic extraction, and therefore are not considered here.

<u>Biomass assumptions</u>

Assumptions must be made about the importance of biomass in this indicator. Some forms of biomass are more subject to opposition than others – for instance, corn ethanol has been the subject of many environmental protests, and biomethane from waste (e.g. Anaerobic Digestion (AD) plants) are often opposed by local residents. On the other hand, biomass residues from forestry and agriculture are seldom unpopular. To avoid confusion, domestic biomass will be given equal weighting as for gas and coal; this introduces some uncertainty to the calculations, but this is mitigated somewhat by the low levels of domestic production of biomass projected in the pathways.

B.1.3 Public participation

People tend to protest less if they feel empowered in the decisions being made. Bell *et al* (2005) point out that a democratic deficit in the planning of generation sites could be to blame for much so-called NIMBYism. Therefore engagement with the public is crucial. As such, pathways which incorporate higher levels of public participation in energy provision will be assumed to militate against some of the acceptability issues outlined above.

This indicator is carried out using a qualitative assessment of the pathway 'storylines', using the narrative information provided in Foxon (2013). Interestingly, people currently perceive the government as having the core responsibility for undertaking the transition to a low-carbon energy system (Butler *et al* 2013). There are very low levels of trust in energy companies, and people don't perceive that the private sector is capable of delivering transition aims in an equitable or effective manner. Therefore market-led solutions rank the lowest in terms of public participation.

B.2 Likelihood of Non-domestic disruption to Electricity Availability: Methods

External disruption to fuel supplies can occur from a wide variety of sources, including natural events such as storms and tsunamis, terrorism, political instability, theft, and civil unrest, blockades or strikes in the exporting country. In order to accurately gauge the likelihood of external disruption in the exporting country, an unfeasible amount of knowledge about the future development of both exporting nations and regional and global supply chains would be required, along with considerable levels of disaggregation regarding the sources of the fuels and their supply routes. Even equipped with this level of knowledge, as pointed out by Stirling, an empirical risk-based assessment would only succeed in capturing the likelihood of events about which we have a good understanding of both the probability and impacts (Stirling 2008b; 2010). The potential sources of external unrest listed above do not fall into this category.

Nonetheless, there are proxies which are often used to show risk from external disruption. The 'external disruption' indicators consist of three core elements:

- Diversity
- Diversity and Stability of exporting nations
- Level of import dependence

B.2.1 Diversity of fuel types

Diversity can act as a hedge against multiple unpredictable and unknowable risks, and is therefore useful as a proxy by which to measure the risk of non-domestic disruption. The diversity of fuel sources in the pathways is calculated using the Shannon-Wiener diversity index (H') for 2010, 2030 and 2050:

$H' = -\sum p_i \ln(p_i)$, where p*i* is the proportion of fuel sources in the overall mix *i*.

Since by definition the proportions will all be between zero and one, the natural log makes all of the terms of the summation negative, which is why we take the inverse of the sum.

The Shannon index increases as both the richness and the evenness of the fuel mix increases. In a mix with just one fuel, H' will be 0, because P*i* would equal 1 and be multiplied by ln P*i* which would equal 0. It is important to note that absolute values for H' are insufficient on their own, and that the index is best when used for comparison.

Generation capacity (in GW) for each fuel is converted into proportions of the total generation mix. Calculations are then run for each proportion of the formula Pi*(Ln(Pi))
The inverse sum of the row is then calculated to give the Shannon Wiener Diversity Index result.

Assumptions

One of the main challenges with the calculation of a diversity index lies in the subjective choices which must be made regarding aggregation. In this instance, each fuel type is grouped together; so for example, 'coal', 'coal CCS' and 'coal CHP' are all simply shown as 'coal'. Renewables are disaggregated according to type, although the two types of wind energy (onshore and offshore) are grouped together.[33] The choices made here will substantially impact upon the diversity index; therefore the greatest value in a diversity index is in making comparisons between pathways using the same index.

B.2.2 Diversity and stability of fuel imports

B.2.2.1 Import diversity

For import diversity in 2010, the origins of existing imports of major fuels (gas, coal, uranium, biomass and electricity imports) are researched using publicly available data (see below). These are then used to create the diversity measure for 2010, for each of these fuels, in order to illustrate those which currently experience higher diversity (and therefore higher security of

[33] It is important to note that proponents of wind energy could argue that offshore and onshore should be grouped separately, as they make use of a spatially disaggregated resource; this is a point for discussion, but they have been grouped together here for simplicity.

supply). The import diversity calculation uses the Shannon-Wiener diversity index outlined above.

Diversity data sources

Coal:
Data from DECC (2013g). It should be noted that the DECC data groups EU supply as homogenous. The EU supplies a very small proportion of UK coal (2%), so this shouldn't have a particularly significant effect on the diversity index.

Gas:
Data from DECC (2013h).

Uranium:
Rather unsurprisingly, it is not possible to obtain data showing where the UK imports its uranium from. However, Good Energy published a report which reaches a rough approximation (Good Energy 2012); their method can be used here. They used data from the World Nuclear Association (2014), which shows the levels of production of uranium according to country, for each year from 2002 onwards. Of these countries, according to the World Nuclear Association the UK only has supply contracts with three nations: Australia, Canada and South Africa. Using production volumes from each of these countries, an approximation of supply to the UK has been extrapolated.

Biomass:
Data for imports of biomass is more complicated than for gas or coal, because the UK doesn't have such a strong history of accountability for imports to the biomass industry. Moreover, types of biomass supplies are very diverse, and most products are used for other processes as well as energy (for instance, wood chips are also used in construction). Therefore data for biomass is limited. Ofgem issued a directive which required all biomass electricity generators to publish their import sources for the year 2009-10; this dataset provides the necessary data for this accounting period (Ofgem 2010).

The Ofgem data only includes dedicated biomass or AD plants; it does not include data for co-fired plants. Data for the proportion of total power from co-firing is highly fragmented.

However, for 2010, DUKES estimates that imported biomass made up 8% of the total biomass used in the UK. This is fairly consistent with the other estimates; the imported biomass is mainly used for co-firing, which makes up a small yet not insignificant proportion of total generation from biomass. Information regarding the likely sources of imported fuel for biomass co-firing is also fragmented and highly incomplete. Information for 2007 imports is available in the UK biomass strategy (DTI/DEFRA 2007). This data shows that the majority of imported solid fuel for co-firing comes from the UK and from Indonesia and Malaysia (from palm residues). Although the data only permits estimates to be made, as it is highly incomplete, the proportion of total power from imported biomass for co-firing is small enough that it doesn't impact too greatly on the overall results.

Oil:

Oil represents a tiny fraction of the UK's electricity mix, and in all the pathways the oil-fired share of the mix is projected to drop to zero very early on (at the latest, by 2015 in the Central Coordination pathway). Therefore a diversity analysis was deemed irrelevant for oil supply. However, it should be noted that oil can still provide a useful backup supply for gas-fired generators. To this end, it should be noted that the UK's imports of oil are in general extremely diverse (more so than for any of the other fuels), therefore oil doesn't represent a concern for supply diversity.

Electricity imports:

We actually have more information about where electricity imports may come from in the future than we do for fuels, because of the many interconnectors which are already operational or which are in the planning stages. Assuming that the planned interconnectors get built, we will source electricity from Ireland (up to 1200MW); France (up to 3500MW); Netherlands (up to 1000MW), Belgium (up to 2000MW) and Norway (up to 1400MW) (National Grid 2013a; 2013d).

B.2.2.2 Import stability

For stability in 2010, this indicator uses existing data on the origins of major fuels. The import diversity data is augmented with information regarding the political stability of the exporting countries. This is done by including a parameter 'b' representing stability into the SW index outlined above, using the Neumann Shannon-Wiener Index (NSW1):

NSW1= -∑ Pi*(Ln(pi))*b

The stability parameter is taken from the Fragile States Index 2014 (Foreign Policy 2014). These are converted to a stability parameter by dividing by 178 (the total number of states in the list), giving a stability score from 0 to 1 (1=highest stability).

For 2030 and 2050, the lack of data in the pathways about the source of imports in the future means that a stability calculation is impossible. Therefore, qualitative statements are all that can be made regarding the situation in 2030 and 2050, based on the calculations for each fuel for 2010.

B.2.2.3 Import dependence

Gas and coal

The total amount of domestic extraction for gas and coal is given in the pathways data. From this, it is possible to calculate the proportion of coal and gas coming from domestic extraction in 2030 and 2050. Unfortunately, the pathways data doesn't give any units for the domestic extraction figures. Therefore the domestic proportions need to be worked out using percentages. This is done by calculating the percentage decrease in domestic extraction relative to 2010 (for 2030 and 2050), and then using this combined with the data on gas and coal output (in TWh/y) to show the output which comes from domestic sources. This is then shown as a percentage of total gas and coal output.

Uranium

As noted above, it is difficult to find out where the UK gets its uranium from. The UK doesn't produce any of its uranium domestically. However, the UK does hold significant stockpiles of uranium; these stockpiles are estimated as being enough to fuel three 1GW reactors for their entire 60-year lifespans (Nuclear Decommissioning Authority 2007). Because of this, stockpile data has been used instead of domestic production data. Data on UK stockpiles is only available for the year 2007. From this, the year 2010 is assumed to show very little change from 2007.

Assumptions must be made regarding the proportion of imports to stockpiles for 2030 and 2050; in absence of any data, the assumption is that levels remain the same.

Biomass

The UK currently imports around 50% of its solid fuel requirements. For the most part, it is solid fuel which is used in electricity production, while liquid fuels are mostly used in transport and heating. The pathways data uses an estimate of the indigenous UK biomass resource as an input for the model of 19TWh/y. Therefore this same input will be used here. In 2030, biomass requirements for the Market Rules pathway were 20.599TWh for electricity alone. This indicator assumes that 50% of biomass is used for electricity, with the other 50% used for heating and transport.

Appendix C: Affordability methods

C.1 Cost of electricity generation

The Levelised Cost of Electricity generation (LCOE) is calculated for the pathways, using a widely recognised calculation which includes CAPEX (pre-development and construction), fixed OPEX (fixed operation and maintenance, insurance and connection charges) and variable OPEX (variable operation and maintenance and fuel). This is then used to calculate the total annual costs of generation in the pathway (in £bn), using the method shown below. Unless otherwise stated, all data is from DECC (2013d) and Mott MacDonald (2010).

C.1.1 Mathematical method

CAPEX

1. Capital costs of building the plant (in £/MW) = pre-development + construction costs
2. Discount rate of 10% (the standard rate used by DECC)
3. CAPEX LCOE (£/MWh): This is the yearly financial payment to cover a loan taken out at a rate of the discount rate, over a period of the lifetime to cover the total capital costs. It is 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

1. Fixed costs (in £/MW/y) = Fixed Operation and Maintenance (O&M) + Insurance + Connection and Use of System (UoS) charges
2. Variable costs (in £/MWh) = Fuel + Variable O&M + Decommissioning
3. OPEX LCOE: This is the fixed cost (in £/MW/Year) divided by full load hours and added to the variable OPEX (in £/MWh) to give OPEX LCOE in £/MWh

Total costs

Total LCOE (in £/MWh) = CAPEX LCOE + OPEX LCOE

Cost per unit output (in £/MW) = Total LCOE/MWh*Load hours

Total annual generation costs for the capacity in the pathway = Total/MW * Capacity

C.1.2 Generation costs assumptions

Learning cost curves

CAPEX reductions are assumed for newer technologies: in 2030 and 2050, the pre-development and construction costs take the low estimate from the DECC core data (DECC 2013d) for wind, solar, biomass, marine, CHP, and CCS. Sensitivity analyses are also run; see sections C.1.3 and C.1.4.

Discount rate

DECC and Mott Macdonald both quote their discount rate at 10%. However, real-world discount rates vary and tend to be commercially sensitive, therefore data was not possible to obtain. The base case of 10% doesn't reflect the fact that different types of power generation will incorporate different levels of risk. Therefore sensitivity tests are also carried out; details are given in sections C.1.3 and C.1.4.

Fuel costs

Projected fuel costs are based on DECC central scenario projections out to 2030 (DECC 2011b), and sensitivity tests carried out (see sections C.1.3 and C.1.4). There is no data available on projections of fuel costs past this point, therefore due to absence of data the fuel cost trajectory is extended in a linear fashion past this point. This means that there is greater uncertainty in the results for 2050 than for 2030 for generating types which have high fuel costs (gas, coal and biomass).

For biomass, data is given in E4Tech (2010). The report recommends that a typical supply chain for future price projections could not be constructed, because of high variety of feedstock types, the prevalence of long-term contracts and bilateral agreements, and uncertainty over how the sector will develop in the future. Therefore they recommend instead that 2009 prices are used as indicative. The report gives prices for indigenous and imported biomass, which allows us to work out price projections using the proportion of indigenous biomass. Price increases can be calculated using the proportional increase from one year to another.

Load factors

The load factors given in the Transition Pathways data are low for all types of generation. This is for two main reasons:

- The FESA model used to calculate the Transition Pathways data does not model unexpected outages or system failures. This makes the capacity factor look a bit low; however, it also makes the ability of the system to meet peak demand look slightly optimistic (see sections 5.8.1 and 5.8.2 for more on this).
- The data from 2007 and 2008 upon which the model is based showed high installed capacity and margins. In fact, even in 2010, the nameplate installed capacity was over 80GW (Ofgem 2012), resulting in low capacity factors.

Scale of hydropower, solar and onshore wind

The DECC cost assumptions differentiate between different scales of generation for hydro, solar and onshore wind. These are assumed to be pathway specific. Therefore, for the Market Rules and Central Coordination pathways, the largest scales given in the DECC report are used. For the Thousand Flowers pathway, it is assumed that there will be a high enough proportion of small-scale power generation in the mix to alter the cost of the generation. However, there will also still be some large-scale generation technology in the mix, especially as the mix will still include some power generation options which are being commissioned in the near future. Therefore for the TF pathway, for each technology where both large-scale and small-scale costs are given (onshore wind, solar PV, hydro and dedicated biomass), the mean of these is used.

Type of biomass

Because the pathways don't specify the type of biomass used, the cost data uses the figures for large-scale dedicated biomass for the Market Rules and Central Coordination pathways, and for small-scale dedicated biomass for the Thousand Flowers pathway.

Tidal

The DECC figures give cost estimates for 3 types of tidal technology – shallow tidal stream, deep tidal stream, and tidal range. There is no data in the pathways to identify which of these three technologies is used, and it is not really possible to predict. Therefore in absence of data, the mean of these three is used.

Coal

The DECC report does not give figures for unabated coal. Therefore these figures are taken from Mott MacDonald (2010). Mott MacDonald gives different price estimates for Advanced Supercritical (ASC) and Integrated Gasification Combined Cycle (IGCC); therefore the coal capacity is split according to the IGCC proportion figures given in the Transition Pathways model inputs. The coal prices are all for 'nth of a kind' coal plants, as it is assumed that in a low-carbon pathway no new unabated coal will be built.

CHP

No cost estimates for CCGT CHP are given in the DECC report; therefore cost assumptions are taken from Mott MacDonald (2010) (which informed most of the DECC fuel assumptions).

The Transition Pathways include some CHP from 'other fuels'; this is partly coal and partly oil. This represents a very small part of capacity in the pathways. Figures are not given for non-gas fossil CHP in either DECC or Mott MacDonald. Therefore it is only possible to give a very rough assumption for this technology. To do this, the uplift on a CCGT CHP plant as compared with a regular CCGT plant (without CCS) is applied in order to uplift the coal cost to a coal CHP cost.

C.1.3 Generation costs sensitivity tests: methods

Sensitivity tests are carried out to show the impact of changing assumptions regarding discount rates, CAPEX figures, fuel costs, and carbon price. Sensitivity analyses are carried out based on both flat changes to assumptions across all pathways, and assumptions which are specific to the pathway storylines.

Discount rates (DR)

In order to reflect the impact of discount rates, it is possible to conduct sensitivity analyses of the generation cost data, based on the logic of the pathways. The key story here is the confidence of investors. If risks are perceived to be low, investors can make big investment decisions with low cost of capital (i.e. low discount rate).

DR1. Doubling of the discount rate (for all pathways)

DR2. Discount rate impacted by choice of pathway, but same for all fuels:

a. Market Rules = medium confidence = DR 10%

b. Central coordination = high confidence = DR 5%

c. Thousand Flowers = low confidence = DR 20%

DR3. Discount rate differs for different fuels:

d. Market Rules = higher discount rate for high CAPEX power generation (see notes below)

e. Central Coordination = government soaks up the risk, therefore 10% DR for all powergen

f. Thousand Flowers = very little assurance, therefore very high DR for high CAPEX powergen

V. high CAPEX = >£3m/MW = MR 18% discount rate, TF 25%

High CAPEX = £2-3m/MW = MR 15%; TF 20%

Medium CAPEX = £1m-2m/MW = MR 10%, TF 12%

Low CAPEX = <£1m/MW = MR 5%; TF 5%

CAPEX reductions (LC)

As outlined above, several technologies are assumed to benefit from decreasing CAPEX (i.e. pre-development and construction costs) due to learning and economies of scale by 2030. However, this is an assumption which will benefit from sensitivity analysis. This can illustrate how sensitive the calculations are to various assumptions regarding CAPEX reductions over time. All other assumptions remain equal, including a flat discount rate of 10%.

In order to show the sensitivity of the calculations to proportional decreases in pre-development and construction costs, this sensitivity test assumes a flat percentage decrease:

LC1: All technologies CAPEX decrease by 10%

LC2: CAPEX decrease of 50% for newer technologies (wind, solar, biomass, gas/renewable CHP, CCS, marine)

These percentage decreases are not intended as a reflection of the actual learning rates to be expected (which are complex, contested and outside the scope of this thesis). Rather, they are intended to show the sensitivity of the calculations to assumptions such as a 50% reduction in CAPEX.

Change in CAPEX based on DECC estimates (CAP)

A further sensitivity test for pre-development and construction costs is based on the actual data in DECC 2013d. It takes higher and lower estimates from the report (according to the technology assumptions outlined earlier):

CAP1: CAPEX low estimate for wind, solar, biomass, gas and renewable CHP, CCS and marine

CAP2: CAPEX high estimate for all technologies

CAP3: CAPEX low estimate for all technologies

For hydro and storage, no high or low estimates are given in the DECC report. Therefore estimates are based on the proportional differences between high and low CAPEX for other established technologies.

Fuel costs (FC)

Projecting fuel costs into the future is highly challenging and notoriously inaccurate. Therefore, the best approach is to show the sensitivity of the calculations to fuel price assumptions in 2050.

- FC1: Low fuel price: no change in fuel price from 2010
- FC 2: DECC central scenario costs (DECC 2011b) are increased by 50% for all fuel inputs (gas, coal, biomass, uranium)
- FC 3: High gas: gas increases 50% on DECC central scenario costs, the rest stay the same

Carbon price (CC)

Carbon pricing depends on carbon policy, which is more unpredictable and isn't given explicitly in the pathways. For this reason, carbon prices are added separately to the main cost analysis, as a sensitivity test.

Originally, DECC planned a carbon price floor rising to £76/t CO_2 in 2030 (DECC 2012b). However, this was originally supposed to be a top-up to the carbon price in the EU Emissions Trading Scheme (ETS). Recently, the carbon price in the ETS has been so low that the trajectory rising to £76/t in 2030 has been deemed unsustainable, and a cap of £18/t until 2020 has been implemented. This cap will be revised under successive carbon budgets (HM Revenue and Customs 2014).

There is therefore considerable uncertainty over the level of the carbon price in the future. As such, the analysis has adopted a 'high, medium and low' sensitivity approach:

CC1: flat carbon price of £6/tonne (reflecting the current level in 2014)

CC2: low: carbon price is capped at £18/tonne in 2030, and remains here in 2050

CC3: high: carbon price is capped at £18/tonne in 2030, and rises to £76/tonne in 2050

The cost of carbon is calculated using the following indicative values for carbon intensity (assuming a small amount of carbon reduction in 2030 and 2050 from today's levels due to efficiency improvements):

Coal 0.85g/MWh

CCGT 0.4g/MWh

Coal CCS 0.1g/MWh

Gas CCS 0.05g/MWh

Open-Cycle Gas Turbine (OCGT) 0.5g/MWh

For simplicity of calculation, non-thermal generation is assumed to be 0g/MWh

C.1.4 Generation costs sensitivity tests: results

Figure C-0-1: Results of generation costs sensitivity tests 2030

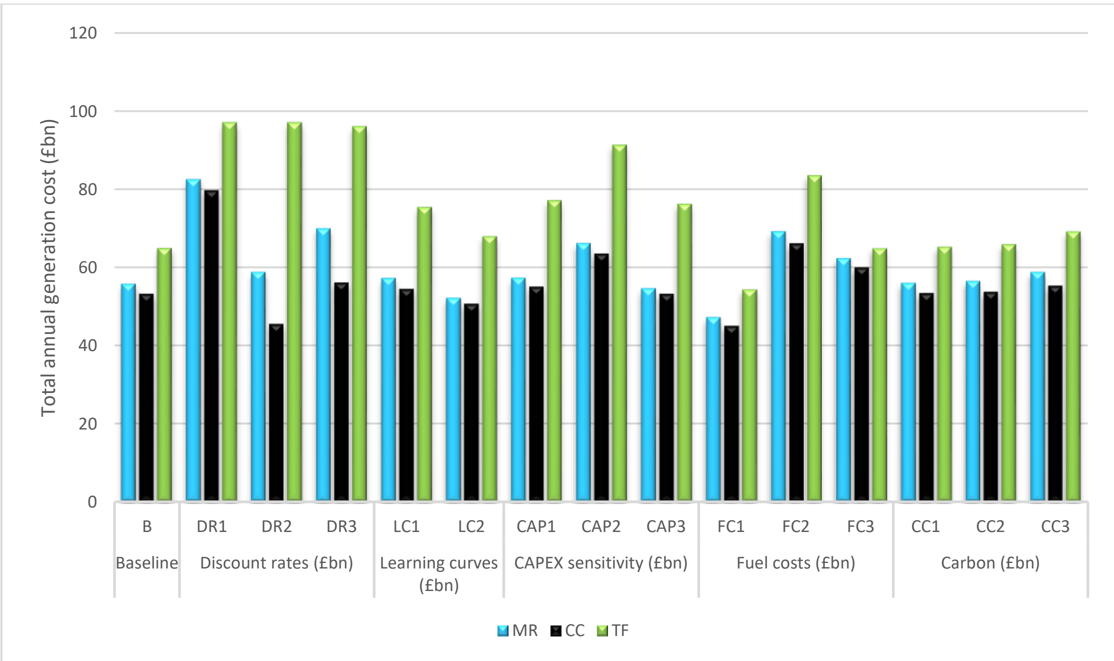
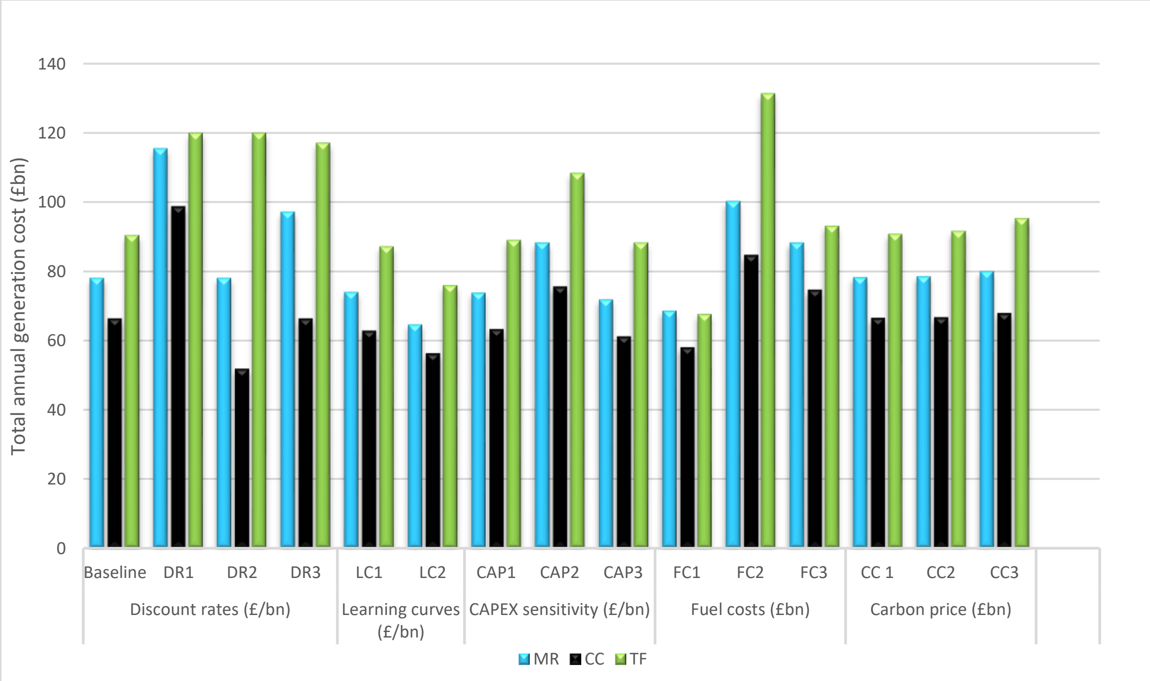


Figure C-0-2: Results of generation costs sensitivity tests 2050



As shown in figures C.0.1 and C.0.2, the range of results returned by the sensitivity calculations is considerable. Despite the range of sensitivities tested, it is clear that the TF pathway is still by far the most expensive in terms of total annual generation costs in 2050. There is actually fairly little overlap between the pathways; the CC pathway consistently has the lowest total annual generation costs.

The greatest impact is felt from the sensitivities around discount rates; this is unsurprising, but problematic, as it is extremely difficult to get hold of reliable data on discount rates. Discount rates are essentially a measure of how risky a project is to undertake, and the extent to which the government is underwriting the risks; as such, commercial sensitivity leads to low data availability.

A further significant sensitivity test result is for fuel costs, specifically the impact of a doubling of fuel costs across the board. This has an enormous impact on the TF pathway, because of the dependence on biomass in this pathway; biomass fuel costs are high already, and therefore any increase to biomass prices could have a big impact on the generation cost of the TF pathway. This is very important because there is still considerable uncertainty about biomass fuel prices.

C.2 Wholesale prices

Step 1: Define Load Duration Curve

The net demand data for the pathways is used to create Load Duration Curves (LDC). The LDC curves need to include inflexible generation, but not intermittent generation.

Step 2: Vertical points on the graphs

The LDC curves are split into time periods along the x axis, representing four illustrative demand periods for the year: winter peak, winter off-peak, summer peak, summer off-peak
Winter = 50% of the time
Peak = 25% of the time
Therefore winter and summer peak = 12.5% of the time; winter and summer off-peak = 37.5% of the time

These demand periods are placed in order of amount of electricity usage, beginning with winter peak and ending with summer off-peak:
Winter peak = 12.5% = 0 to 1095 hours
Summer peak = 12.5% = 1096 to 2190 hours
Winter off-peak = 37.5% = 2191 to 5475 hours
Summer off-peak = 37.5% = 5476 to 8760 hours

These demand periods are plotted vertically on the LDC graphs. The exact demand for the boundary point of each time period is identified. For each of these time periods, the hour is plotted on the LDC graph to find out the load at that point in time.

Step 3: Horizontal stacks

The LDC graphs are split horizontally into ‘stacks’. Each stack represents a fuel generation technology. The technology is ordered in terms of merit order of generation. The merit order of generation through to 2050 is slightly uncertain, as it depends on the market, prices and subsidies involved. However, some assumptions can be made, leading to the merit order as listed below:

- Nuclear as baseload: nuclear comes first in the merit order, because it is inflexible.
- Hydro: hydro runs all year, and is a renewable power source with zero fuel costs.

Therefore it can be assumed to come just after nuclear in the merit order

- Biomass: although there is some uncertainty as to the role of biomass in the merit order in the future, currently biomass is being used mainly as a direct substitute for coal, and many plants are either converting directly or are switching to co-firing of coal and biomass. Therefore biomass is assumed to come alongside coal in the merit order.
- Coal (abated and unabated)
- CCGT (abated and unabated): CCGT is very flexible, and capable of quick ramping up and down in response to changes in demand.
- Pumped storage: storage is best used when most needed, and is therefore considered a peaking provision, to be used only when capacity is required to meet big peaks in demand
- Imports: Imports flow into the electricity system in the UK when the UK price is higher than that in neighbouring jurisdictions. Therefore it is assumed that imports will be flowing into the UK to meet peaks in demand, when electricity will be at its most expensive (Ofgem 2014).

The generation capacity of each fuel is adjusted according to availability factors. The availability factors are given in the Transition Pathways data; the availability of CCGT, coal and biomass is 90%, and of nuclear is 75% up to 2025 and 80% thereafter.

It should be noted that such generation stack models using LDCs are always to some extent an inaccurate reflection of how the electricity merit order works. The merit order is decided by the market, and as such it is impossible to assess with any kind of accuracy the exact merit order into the future. However, stack models are widely used in both markets and engineering fields, and are an accepted method for establishing the likely price-setting fuel [Staffell and Green 2012]; therefore they are used here with the caveat that they are sensitive to market forces. It can be assumed that certain characteristics of the merit order (such as the use of inflexible nuclear as a baseload) are likely to continue into the future.

Step 4: Defining price-setting fuel

The number of hours at which each fuel type is setting the price is calculated. For example:
MR 2010 winter peak: Demand peak for coal = 34.03GW
Time period for winter off-peak = 2190 to 5475 hours
Demand curve drops below 34.03GW at 4565 hours

Therefore gas is setting the price from 2190 to 4565 hours. Coal is setting the price from 4565 to 5475 hours (910 hours).
Total winter off-peak time period = 3285 hours
910 = 27.7% of 3285. Therefore gas is setting the price for 27.7% of the winter off-peak.

Step 5: Calculating average wholesale price for the time period

'Total variable costs' from the LCOE calculations are used to estimate the wholesale price of the price-setting fuel. The total variable costs include fuel costs, variable operation and maintenance, and decommissioning and waste, and carbon prices (see below). The variable costs for each fuel are given in £/MWh. A weighted average is obtained by multiplying the cost of each (in £/MWh) by the number of hours it is setting the price for. These are then added together and divided by 8760 to give the weighted average wholesale price, in £/MWh.

For 2010, the variable cost estimates used here include a carbon price of £6/tonne. For 2030 and 2050, there is too much uncertainty over future carbon prices; therefore the baseline is run with no carbon price, and sensitivity analyses are carried out (see section C.1.3).

For coal and gas, a weighted average price for the different types of gas and coal generation is obtained from the load hours.

Step 6: Weighted demand

As shown in the steps above, the generation is weighted according to winter peak, winter off-peak, summer peak, and summer off-peak. Therefore, the wholesale price estimates will be more accurate if demand is weighted in the same way. Mean average demand is calculated for each time period. For example, for winter peak, the hourly demand for each hour between 0 and 1095 are added together, and divided by 1095.

C.4 Distribution upgrade costs

The cost of upgrades to the distribution system in the pathways has been carried out by Pudjianto *et al* (2013). They modelled the potential cost to the system of the electrification of UK heating and transport under the Transition Pathways. They first modelled peak electricity demand, taking into account hourly demand profiles, shown in figure C.4. The peak demand profiles are also given in the Transition Pathways data.

It is important to note that Pudjianto et al only modelled demand which is connected to the distribution network, therefore some demand centres (especially of large industrial consumers which are connected straight into the transmission network) are ignored. For this reason, it can clearly be seen that the peak demand data in the Pudjianto paper is significantly lower than in the Transition Pathways data. For the purposes of this indicator, the data in figure C.0.3 is more suitable, because this indicator is only interested in demand which connects to the distribution network.

Figure C-0-3: Projected peak demand

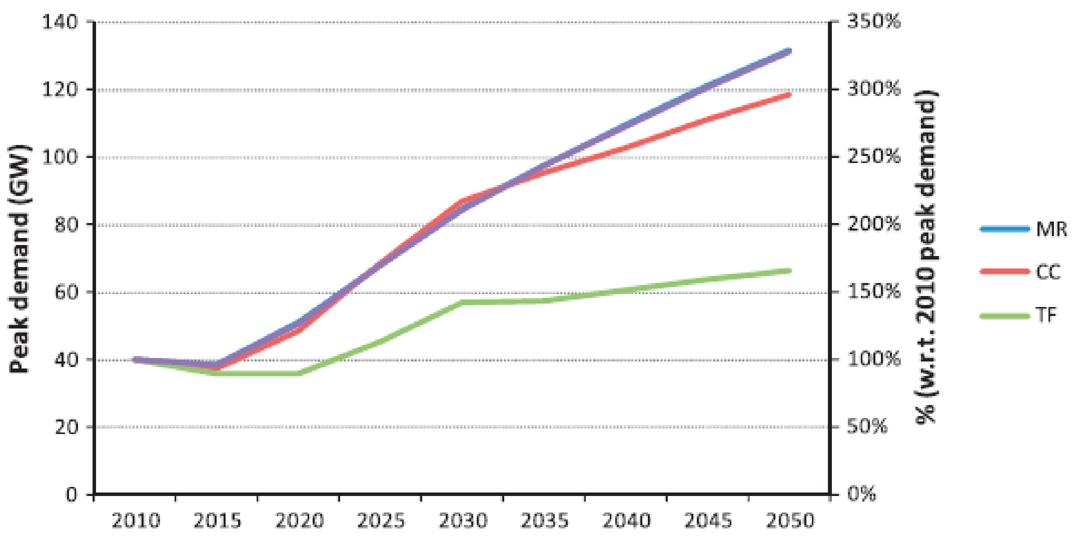


Fig. 10. Projected demand in three Pathways' scenarios.

Pudjianto *et al* (2013) then modelled the cost of distribution network reinforcements and upgrades necessary to meet the peak demand profiles shown above. The method is described in more detail there, but the basic steps are as follows:

1. Create network topology at the Low Voltage (0.4kV) level. Different consumer settlements (urban, rural etc.) are created on the basis of fractal theory. Locations of distribution transformers are optimised to minimise cost, loss and voltage drops.
2. Two representative low voltage (LV) networks are developed, one for rural and one for urban.

3. From this network topology, year-round Alternating Current (AC) load flow calculations are performed. These are then used to design the network circuits, based on minimising life-cycle cost.
4. An interconnection High Voltage (11kV) matrix is created, also using fractal theory. This creates a High-Voltage (HV) distribution network, using the LV networks created in step 1.
5. Steps 2 and 3 are carried out for HV network.
6. An Extra-High-Voltage (≥33kV) network is created using a simplified model which connects the different HV networks created in step 4.

C.2.1 Wholesale price assumptions

Gas price assumptions

The gas price tends to be higher in winter due to colder weather and demand for gas for heating, especially so during peak periods when gas is in high demand. As such, gas wholesale prices are assumed to be 20% higher for winter off-peak, and 30% higher for winter peak (estimates based on a general comparison of UK summer and winter gas spot prices for 2010 and 2011, EIA 2011).

Interconnector assumptions

Interconnector prices are the wholesale price for that country. It is impractical to attempt to project wholesale prices for all of the potential import nations (especially as imports set the price for very few hours per year). Therefore estimates must be made of the import price. These are appended with sensitivity analyses, because of the inherent uncertainty. It is to be expected that the import price will make very little difference to the average wholesale price, because of the limited number of hours per year (typically less than 50) for which imports are setting the price.

It is assumed that the interconnectors will only import when we need it, i.e. at peak times when the UK price exceeds that of neighbouring countries in Europe. Therefore we can assume that the interconnector price will be higher than the UK wholesale price. For 2030 and 2050, a baseline import price is assumed which is £5 higher than the average wholesale price for that pathway. A sensitivity analysis is then run for imports valued at 50% higher than this baseline estimate, to show that even with such a high mark-up, the price of imports has very little impact on the average wholesale price.

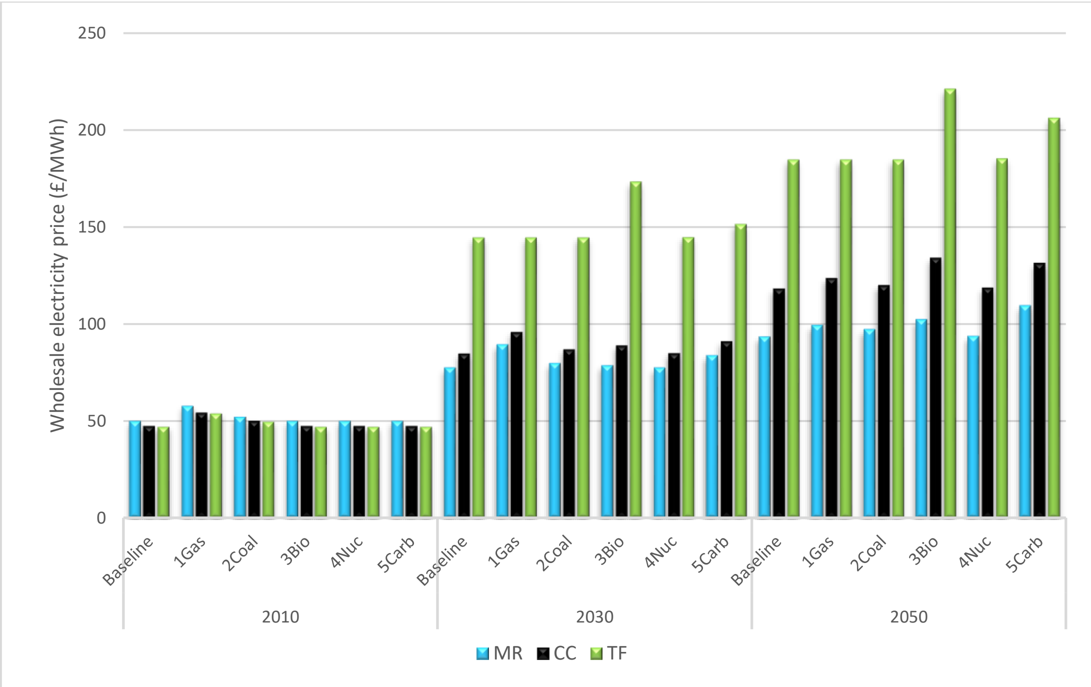
C.2.2 Wholesale electricity prices sensitivity tests

In order to keep things simple, wholesale prices sensitivities were carried out for the key price-setting fuels (gas, coal, nuclear and biomass). For each fuel, the total variable cost was increased by 20% to show the impact of this upon the average wholesale price. A further test was carried out to show the impact of carbon pricing.

- 1Gas = Gas price of generation increases by 20%
- 2Coal = Coal price of generation increases by 20%
- 3Bio = Biomass price of generation increases by 20%
- 4Nuc = Nuclear price of generation increases by 20%
- 5Carb = Wholesale price includes a carbon price at £18/tonne for 2030 and £76/tonne for 2050.

The results in figure C.0.3 show that the pathways are not overly sensitive to wholesale price assumptions for the individual price-setting fuels; the results are fairly consistent across the various sensitivity tests. The biggest impact is on biomass in the TF pathway, especially in 2050; an increase in biomass generation costs results in a significant increase in the wholesale price for this pathway. Finally, including a carbon price has a fairly significant impact on the wholesale price in 2050. Surprisingly, the biggest impact of a carbon price is felt in the TF pathway; this is probably due to the overall prices rather than the fuel mix, as the higher prices for the TF pathway lead to a higher differential.

Figure C-0-4: Wholesale price sensitivity results



C.3 Transmission upgrade costs

C.3.1 Offshore costs

Offshore wind

The analysis first develops an understanding of the likely future sites for offshore wind energy. This can be done using the most recent licensing round for offshore wind, as well as National Grid information about future siting of onshore wind. Much of the information regarding siting and capacity comes from the National Grid Electricity 10-Year Statement (National Grid 2012), which looks at likely transmission upgrades for the UK until 2030 for all of their pathways. Their 'Accelerated Growth' pathway is very aggressive for large-scale wind and nuclear power, meaning that the National Grid projections of necessary upgrades for this pathway are sufficient to carry the Transition Pathways out to 2050.

The order in which the wind farms are built is important, as this dictates to some extent which are included in the pathway and which are not (which will affect overall cost). This is impossible to assess with any certainty, as the building of wind farms is subject to a wide array of political and market pressures. Therefore offshore wind farms are divided into Round 2 and

Round 3, with the assumption that the Round 3 arrays will be built last. They are then ordered according to distance from shore (assuming that closer to shore is cheaper, and thus more likely to get built; this creates a conservative cost estimate).

The costs for connecting the offshore farms are calculated using the unit costs of the transmission infrastructure. All unit cost data is from the National Grid 10-year statement technology appendix (National Grid 2013c). The unit costs used are given in Appendix F.

Interconnection

The interconnector costs are calculated using the same method as for wind farms, using the cost/km of undersea cable (in this case, all HVDC; see Appendix F), and the distances for each cable (mostly obtained from information from the individual projects, available online). The ordering of the projects is fairly important, because the pathways don't use all the potential interconnector capacity which is planned or proposed for the UK. Therefore the projects were ordered in terms of their projected completion date (with some projects having already been completed). This method is clearly a big estimation, as costs of installation are probably much higher in the deep water required by interconnectors. However, the amount of interconnection in the pathways is very similar, so the estimates don't affect the results too much.

C.3.2 Onshore costs

The Electricity Strategy Networks Group (ESNG) has provided some cost estimates for upgrades and reinforcements to the onshore transmission network, based on certain amounts of installed capacity in various areas of the UK (ENSG 2012: 36). From the information given by the report, it is possible to estimate the necessary costs of reinforcement of the onshore wind in the pathways. The cost per MW is calculated from the information in the report; from this, the cost of additional generation is calculated according to the capacity of the pathway: Total cost = (cost/MW)*capacity.

Onshore wind

Today's proportions for wind power in Scotland, England and Wales are carried forward to estimate regional onshore wind generation in the pathways. As for all onshore transmission cost estimations, it is only the *additional* capacity required for 2030 and 2050 which is taken into account.

Nuclear power

The nuclear capacity in several of the pathways is very high. Uncertainties around the Hinkley C project indicate that it is very challenging at present to estimate the potential sites of new nuclear upgrades. Therefore in order to estimate the siting of new nuclear capacity, the existing nuclear capacity of the UK is used. This is split into proportions according to the regions in ENSG 2012, in the same way as for onshore wind.

Other onshore

Using the same figures, it is also possible to calculate additional onshore costs for all other types of onshore generation. Other types of generation are assumed to be much more distributed; therefore for ease of calculations, other onshore costs are assumed to be spread equally across the country.

Centralised vs decentralised

It is important to note that considerable amounts of decentralisation in a pathway could have an impact on the transmission costs, as in general, decentralised installations will be connected directly to the distribution network. Therefore this must be taken into account, by reducing the onshore costs accordingly.

The pathways data shows figures for 'maximum total electricity demand' and 'maximum centrally-generated demand'. This provides an indication of the amount of decentralised generation (in GW).

The transmission method splits onshore costs into wind, nuclear and 'other'; nuclear can be assumed to all be centralised. The proportion of the pathway which is decentralised is subtracted from the onshore generation requirements of the wind and 'other onshore' components of the pathway.

C.5 Annual household electricity bills

Annual electricity bills can be calculated using estimates of the breakdown of the various components which make up a household electricity bill, from DECC (2013e). For this indicator, it is estimated that the wholesale price of generation makes up around 40% of an average electricity bill. Energy and climate policies are estimated to add 9% to the annual bill. Supplier profits and costs are currently estimated at around 19%. Network costs are around 20%. VAT is 5%.

The baseline estimate for annual bills is taken from the wholesale price of electricity, the method for which was covered in section C.2, added to a proportion for supplier costs, a proportion for social and environmental programmes, and a proportion for network charges. For the baseline, these are taken straight from the DECC figures. The 5% VAT is not included: this is standard methodology for calculating electricity bills, because it makes it easier to compare between countries. It should also be noted that this calculation does not include any discounts consumers may receive for buying their gas and electricity from the same supplier.

We then need to calculate average household usage, in MWh. Total UK demand figures are given in the pathways.
Average household demand = Total UK demand / number of households
Household demand (in MWh) * full cost (in £/MWh) = annual bill (in £)

Population growth forecasts are taken from the Office for National Statistics 'principle' case (ONS 2015). The interactive website offers a number of alternative forecasts, some of which will be used later in the sensitivity tests. The household demographic is assumed to stay roughly the same; that is, the ratio of people to households is assumed to stay constant in order to work out the number of households:
2010: 63.7 million = 26.4 million households
2030: 71 million = 29.4 million households
2050: 77 million = 31.9 million households

C.5.1 Annual bills sensitivity tests: methods

Sensitivity tests were carried out to show the impact of assumptions regarding the various components of the 'uplift' on the bill (i.e. the proportion which is added to the bill on top of the wholesale price). These included changes to social and environmental programmes, network charges, and carbon price. Tests were also carried out to show the impact of population growth and changes to the wholesale price of electricity.

Additionally, a further three tests were carried out based on the narratives of the pathways themselves, thus involving different assumptions for each of the pathways. This involved testing the impact of changes in costs due to learning and economies of scale, changing costs due to policies for incentivising low-carbon generation, and the profit margins of the generators. All tests and baseline are shown without VAT.

Social and environmental programmes:

- Env1. Assumes that the percentage represented by social and environmental costs remains the same, but are shifted to general taxation. This results in a 9% decrease in the retail uplift.
- Env2. Assumes that the impact of increasing pressure to mitigate climate change leads to increasing costs, and the cost of EMR impacts increases electricity prices significantly. The cost of social and environmental programmes is doubled, meaning an 18% increase in the retail uplift.

Wholesale price

There is lots of uncertainty regarding wholesale price. Therefore high and low estimates, from the wholesale price tests, are used. For each, the percentage increase is on the wholesale price:

- Wh1. High estimate
- Wh2. Low estimate

Use of System (UoS) charges

The baseline UoS charge is 20% of the total bill.

Total system costs = Baseline UoS charge + upgrade costs

A percentage uplift is calculated using the results from the ‘transmission costs’ indicator, and added to the 20% UoS charge on the total bill.

Population growth

Household demand is calculated using total annual demand figures from the pathways data, and population estimates of the number of households. Therefore the higher the assumption regarding population growth, the lower the cost per household will be. Population data is from Office for National Statistics (ONS) 2015.

- Pop1. ONS low case: 2030: 68.3 million people, 28.3 million households. 2050: 68.8 million people, 28.5 million households
- Pop.2 ONS high case: 2030: 73.8 million people, 30.5 million households. 2050: 85.4 million people, 35.3 million households

Carbon price

A carbon price is introduced of £18/tonne in 2030 and £76/tonne in 2050. These are the same indicative carbon prices as used in the 'generation cost' indicator; the rationale behind these assumptions is explained in more detail in Section C.1.3.

Economies of scale

This test assumes that the small-scale generation in the TF pathway fails to capitalise on economies of scale, and thus wholesale prices are assumed to be 20% higher. For the MR pathway, the test assumes that cheaper components and technologies are purchased from overseas, and wholesale prices are 20% lower.

Incentivising low-carbon generation

This test assumes that capacity payments and subsidies for low-carbon sources rise considerably. The social and environmental programmes component of the bill is varied according to individual pathways storylines. The MR pathway stays the same; CC pathway sees government programme costs triple; TF pathway sees costs double due to pressure on local councils to incentivise low-carbon sources.

Profit margins

This sensitivity test assumes that the MR pathway is left vulnerable to rent-seeking by large utilities. As such, the profit margin in this pathway increases from 5% of the total to 15% of the total. The CC pathway is assumed to be less vulnerable to rent-seeking, and central control reduces profit margins to 2.5%. TF pathway is controlled by small companies, who are less capable of rent-seeking but also encounter higher risk; profit margins increase to 7.5%

C.5.2 Annual bills sensitivity tests: results

Figure C-0-5: Results from annual bills sensitivity tests, 2030

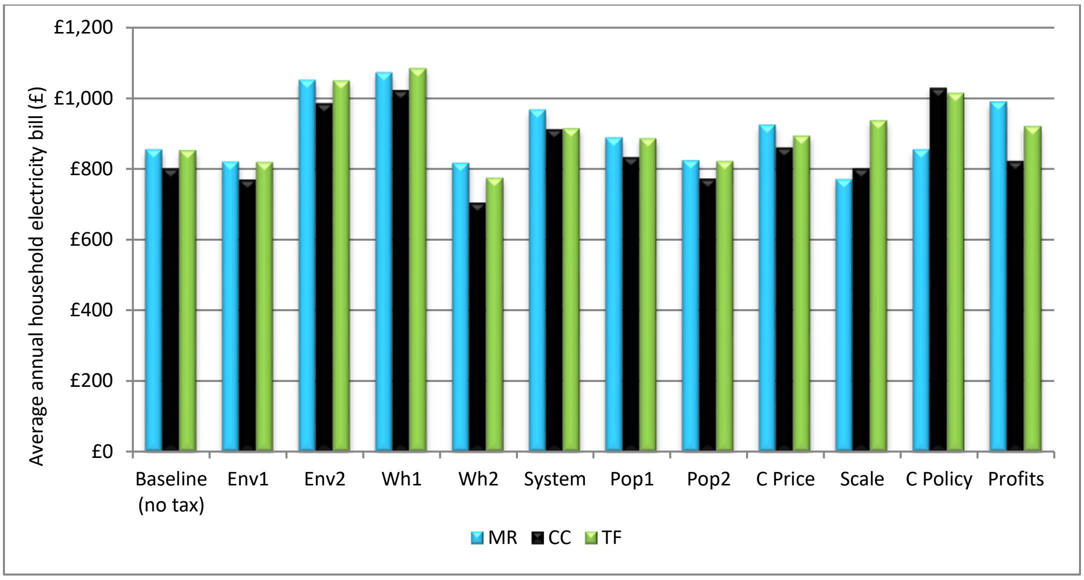
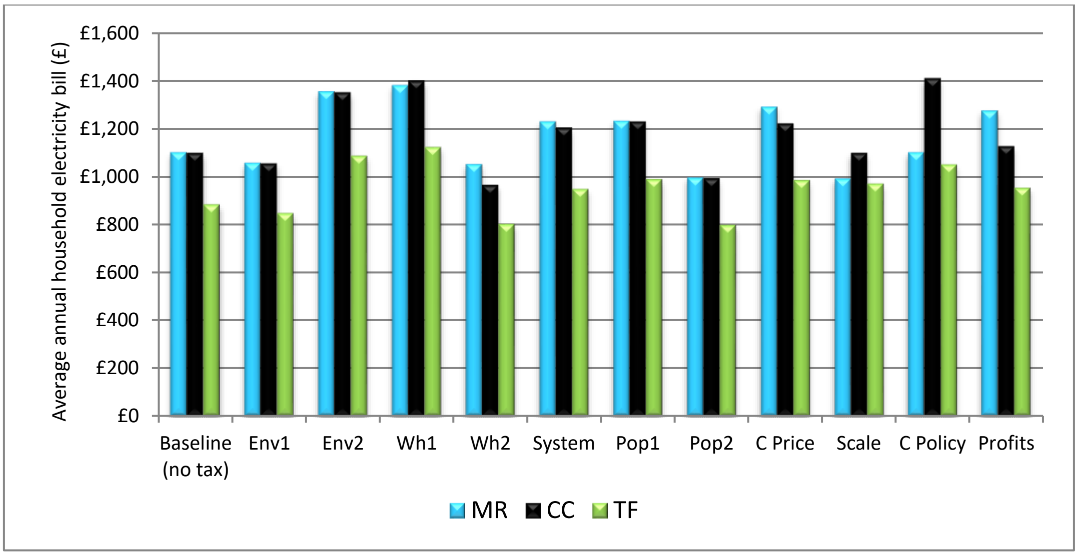


Figure C-0-6: Results from annual bills sensitivity tests, 2050



As shown in figures C.0.5 and C.0.6, the biggest impact on annual bills is in changes to the wholesale price. This is important, because there is considerable uncertainty over wholesale prices in the future. Increases in wholesale prices – especially in the gas price – have led to significant increases in fuel bills in the UK in the past (UK Committee on Climate Change 2012), and therefore this could represent considerable risk for all the pathways. Changes to environmental and social programmes also have a big impact; again, this affects all the pathways in a similar manner. This is important because it shows that the price of achieving a low-carbon transition could impact consumers even more than the baseline price originally shown for this indicator, depending on government policy regarding subsidising low-carbon generation. Interestingly, changes to system costs don't have a huge impact on annual bills. Finally, the graphs show that a lower population would result in higher bills, because the demand figures assumed for the pathways would be split between more people and therefore would result in lower bills per household. However, this sensitivity test should be regarded as illustrative only, because the electricity demand figures assumed in the pathways are based upon mid-way population assumptions, as used in the baseline estimate above.

The last three sensitivity tests (scale, carbon pricing, and profits) are conducted on the basis of the pathways storylines, and therefore make different assumptions for each pathway. As shown, the biggest impact is felt through changes to social and environmental programmes – the CC pathway experiences price risk if the government is expected to pay for incentivising low-carbon generation. This could result in a public backlash in this pathway, and could result in a trade-off between incentivising low-carbon generation and keeping bills at a manageable level, although this depends somewhat on whether these costs are paid for out of energy bills or general taxation (see section 5.4.4). The results for economies of scale show a big differentiation for the TF pathway in 2030, making this pathway the most expensive; however, by 2050, this difference has evened out and the TF pathway is once again the least expensive.

C.6 Fuel poverty

A key aspect of affordability is equity, and because of this it is desirable to examine the possible impact of the pathways on levels of fuel poverty. Broadly defined, a household in fuel poverty will spend 10% or more of their disposable income on fuel for lighting, heating, cooking, transport etc. However, moving on from this basic definition, the Hills Review – a major piece of work commissioned by the Secretary of State for Energy and Climate Change in 2011 – recommended that this definition fails to fully illustrate important underlying trends of fuel poverty, and that by including fuel as a relative proportion of income it incorporates households who are clearly not poor. Therefore, the Hills Review argues that fuel poverty should refer to “individuals living on a lower income in a home that cannot be kept warm at reasonable cost” (Hills 2012:7).

It isn’t possible to accurately project levels of fuel poverty without income data. The Hills review only manages to project incomes out to 2016; and even then, the review notes that the projections are based on non-linear trends, and are therefore highly likely to be severely inaccurate. Moreover, levels of fuel poverty are highly dependent on income inequality: higher median incomes don’t necessarily mean higher incomes for those most likely to be affected by fuel poverty. Because of these limitations, the analysis will be limited to a review of rising bills, and the importance of government policies in limiting fuel poverty.

The method for this indicator uses the high, median and low estimates of annual bills from the annual bills indicator. These are then assessed qualitatively in conjunction with narrative information about the ‘storylines’ of the pathways, from Foxon (2013).

Appendix D: Sustainability methods

D.1 GHG emissions and intensity

The IPCC has collated data on the life-cycle GHG emissions intensity of electricity generation, measured in CO2e/kWh, as shown in table D.0.1 (Moomaw *et al* 2011). It is important to take into account the possible range of estimates, because of the inherent uncertainty in calculating life-cycle emissions intensity. This information can be particularly important for biomass, because biomass emissions can be high if poor land-use practices take place (for instance, the replacement of tropical rainforest for palm); on the other hand, they can also be very low, because in theory it is possible to generate negative emissions from biomass by capturing the embodied carbon which the plants have absorbed over their lifetimes.

Pathway carbon intensity = Fuel-type intensity * (fuel-type generation / Total generation)

Table D-0-1: Carbon intensity of various generation types. Source: Moomaw et al (2011)

Table A.II.4 | Aggregated results of literature review of LCAs of GHG emissions from electricity generation technologies as displayed in Figure 9.8 (g CO_2eq/kWh).

Values	Bio-power	Solar		Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
		PV	CSP								
Minimum	-633	5	7	6	0	2	2	1	290	510	675
25th percentile	360	29	14	20	3	6	8	8	422	722	877
50th percentile	18	46	22	45	4	8	12	16	469	840	1001
75th percentile	37	80	32	57	7	9	20	45	548	907	1130
Maximum	75	217	89	79	43	23	81	220	930	1170	1689
CCS min	-1368								65		98
CCS max	-594								245		396

Note: CCS = Carbon capture and storage, PV = Photovoltaic, CSP = Concentrating solar power.

D.1.1 Carbon intensity assumptions

Bioenergy

For bioenergy, it appears that there is a misprint on the original version of Table D.0.1 – it seems highly unlikely that the 25th percentile for bioenergy is 360g/kwh when the 50th percentile is only 18g/kwh. Therefore, a mid-estimate of 5g/kwh is used. This is consistent with the assertion in the IPCC report that the carbon intensity of bioenergy is between the emissions intensity of nuclear and of gas.

CCS

For CCS, only minimum and maximum values are given by the IPCC. Therefore a mid-point was arrived at by selecting the mid-point between these estimates.

CHP

Woods and Zdaniuk (2011) estimate CHP carbon intensity at around 400g/kwh (assuming that CHP heat is replacing electrical heat from gas power stations, and assuming a CHP electrical efficiency of 35%). This roughly equates to the mid-estimate for gas. Thus the carbon intensity is assumed to be the same as for the non-CHP fuel.

D.2 Resource depletion

'Resource depletion' can cover a wide range of issues, including scarcity of cheap-to-extract primary fuels such as oil, potential scarcity of non-fossil fuel sources (e.g. lack of biomass due to land shortages), and depletion of important materials used in the production of power. Some of the potential issues with the supply of fuels are covered in the 'availability' dimension. As such, the following two indicators focus on physical depletion:

1. Depletion of primary fuels (gas, coal, biomass, uranium etc.)
2. Depletion of secondary materials (metals, minerals and elements used in power production)

There are high levels of uncertainty around future resource availability. Much of the impact of resource depletion will probably be felt through prices, rather than actual scarcity; Helm (2011) argues that 'peak fuel' is unlikely to happen, as increasing fuel prices due to scarcity simply mean that it becomes more possibly to extract previously uneconomic fossil resources. Moreover, many of the security risks associated with resource depletion can be overcome through better practices – for instance, increased use of residues for biomass, or increased recycling of metals. As such, it is difficult to make quantitative projections. Therefore the best means of tackling this indicator is via qualitative methods. Information from the existing literature is used to explore the extent to which primary fuels and secondary materials may be at risk of depletion through to 2050. The pathways are then assessed for their level of reliance on these fuels and materials.

D.3 Water usage for cooling and for biomass production

Water usage estimates for each type of power generation are shown in Table D.0.2. The table shows both water withdrawals and water consumption – an important distinction, especially when considering water-based generation such as hydropower, which has virtually no water withdrawals but high water consumption (mainly due to evaporation from the lakes created by dams) (Mekonnen and Hoekstra 2011). Because of this, this indicator carries out analysis for both water withdrawals and water consumption.

Table D-0-2: Water withdrawal and consumption intensities. Source: Kyle et al (2013)

Table 1

Assumed water withdrawal and consumption intensities, by electric generation technology and cooling system type. 1-thru: once-through flow. Evp: evaporative cooling tower. Pond: cooling pond. Hybrid/dry: hybrid or dry. Data sources detailed in Davies et al. (2012).

Technology	Cooling system	Water withdrawals	Water consumption
Coal	1-thru	158	0.95
	Evp	3.8	2.6
	Pond	53.2	2.06
	1-thru w/CCS	241	1.25
	Evp w/CCS	4.83	3.57
Oil/natural gas	1-thru	152	0.91
	Evp	4.55	3.13
	Pond	4.55	3.13
Other steam	1-thru	152	1.14
	Evp	3.32	2.09
	Pond	1.7	1.48
Nuclear	1-thru	193	1.02
	Evp	4.17	2.54
	Pond	30.7	2.31
Natural gas combined cycle	1-thru	49.5	0.38
	Evp	0.96	0.75
	Pond	25.9	0.91
	1-thru w/CCS	62.5	0.66
	Evp w/CCS	1.88	1.43
	Dry w/CCS	0.41	0.41
IGCC	1-thru	147	0.13
	Evp	1.48	1.41
	1-thru w/CCS	186	0.41
	Evp w/CCS	2.22	2.04
	Dry w/CCS	0.41	0.41
Geothermal (conventional)	Evp	6.82	6.82
	Hybrid/Dry	0.67	0.67
EGS	Evp	18.1	18.1
	Hybrid/Dry	3.2	3.2
CSP	Evp	3.35	3.35
	Hybrid/Dry	0.3	0.3
PV	n/a	0.02	0.02
Wind	n/a	0	0
Hydro	n/a	0	17

For each type of power generation, water intensity estimates (in m^3/MWh) from Kyle *et al* (2013) are multiplied by the power output in the pathways (in MWh). The results are shown in m^3/year for overall water usage (consumption and withdrawals).

D.3.1 Type of cooling

Table D-0-3: Assumed cooling system shares in % (Kyle et al 2013)

Table 2
Assumed thermoelectric power plant cooling system shares (%), by generation technology and GCAM region, in the base year (2005) and assumed in future periods. 1-thru: once-through flow cooling systems. Evp: evaporative cooling systems. Dry: dry cooling systems.

Region	Time	Seawater[a]	Coal			Other fossil/bio			Combined cycle			Nuclear	
			1-thru	Evp	Dry	1-thru	Evp	Dry	1-thru	Evp	Dry	1-thru	Evp
USA[b]	Base year	30	39	48	0	59	24	0	12	77	10	38	44
	Future	99	5	80	5	5	80	5	5	33	60	5	85
Canada	Base year	10	71	29	0	71	29	0	71	29	0	71	29
	Future	10	10	90	0	10	90	0	10	90	0	10	90
Western Europe	Base year	20	28	70	3	28	70	3	28	70	3	28	72
	Future	95	28	70	3	28	70	3	28	70	3	28	72
Japan	Base year	97	90	7	4	90	7	4	90	7	4	100	0
	Future	99	90	6	4	90	6	4	90	6	4	100	0
Australia & NZ	Base year	66	37	56	7	100	0	0	50	50	0	0	100
	Future	99	50	20	30	50	20	30	50	20	30	100	0
Former Soviet Union	Base year	10	37	63	0	37	63	0	37	63	0	37	63
	Future	10	10	90	0	10	90	0	10	90	0	10	90
China[b]	Base year	13	20	65	8	20	65	8	20	65	8	20	73
	Future	95	20	72	8	20	72	8	20	72	8	20	80
Middle East	Base year	96	60	38	2	60	38	2	60	38	2	60	40
	Future	99	50	20	30	50	20	30	50	20	30	100	0
Africa	Base year	30	12	76	12	12	76	12	12	76	12	12	88
	Future	30	10	78	12	10	78	12	10	78	12	10	90
Latin America	Base year	30	18	78	4	18	78	4	18	78	4	18	82
	Future	10	10	86	4	10	86	4	10	86	4	10	90
Southeast Asia	Base year	87	75	21	4	50	46	4	50	46	4	95	5
	Future	87	75	21	4	50	46	4	50	46	4	95	5
Eastern Europe	Base year	10	35	66	0	35	66	0	35	66	0	35	66
	Future	95	10	90	0	10	90	0	10	90	0	10	90
Korea	Base year	97	20	77	4	20	77	4	20	77	4	100	0
	Future	99	20	76	4	20	76	4	20	76	4	100	0
India	Base year	30	47	50	4	47	50	4	47	50	4	47	53
	Future	95	10	86	4	10	86	4	10	86	4	10	90

[a] Portion of water inputs to once-through power plants that are assumed to be saline (seawater or saline groundwater), applied to all time periods in this study.
[b] For the United States and China only, cooling pond percentages are not listed but can be derived from the difference between the sum of values provided and 100%.

As can be seen in table D.0.2, the type of cooling which is used in the power station has a significant impact on the water use. Table D.0.3 shows assumed proportions of different cooling systems for the base year of 2005, and projections for future years. For Western Europe, there is no difference between current and future proportions of cooling systems used; therefore the same cooling system proportions can be assumed for all projections.

For each type of power generation, the type of cooling which is used is estimated using the data above. This data is used to give a weighted average of the water use for each type of power generation. So for example, for coal with 80% evaporative and 20% 1-thru, and an estimate of 1000L/MWh for evaporative and 500L/MWh for 1-thru, and a power output of 5,000MWh, the calculation would be: ((1000*5000)*0.8)+((500*5000)*0.2)

D.3.2 Weighting

Further to the calculations above, it is suggested for this indicator that it is more damaging from an environmental perspective if the power station uses fresh water as opposed to salt water, because sea water is more plentiful. Therefore, the results are weighted 70-30 to reflect this. Sensitivity tests are carried out to show the impact of different weightings on the results; see section D.3.4.

For each fuel type, National Grid data (National Grid 2012) on current power station placement is used to count the proportion of power stations on land, and the proportion by the sea, of each type (coal, gas, biomass, nuclear). All hydro, solar and pumped storage is assumed to be on land. For renewables, the water use is minimal, therefore RES are not included in the weighting. For each result for water use, withdrawals and consumption, the consumption is first split into land and sea using the existing proportions for each. Then a 70-30 weighting is applied.

D.3.3 Assumptions

Biomass

Biomass uses around the same amount of water for cooling as coal plants. Kyle *et al* (2013) assume that water requirements for biomass post-2025 are roughly the same as for IGCC. Water is also required for biomass production; however there are big differences in the water requirements depending on what type of feedstock is used and where it is grown. In the absence of such information, it is not possible to accurately measure the water requirements of biomass feedstock. As with other issues of biomass, it is likely that feedstocks produced in the UK (which rarely suffers from drought) may be less vulnerable than those produced in some overseas regions.

CCS

Table D.0.2 shows the water intensities for CCS, which is about 30-40% more water intense than unabated generation.

Coal: ASC and IGCC

Different types of coal generation have different water requirements. Therefore the 'coal' generation in the Transition Pathways must be split between ASC and IGCC coal. This is done for years 2030 and 2050, as the UK did not have any IGCC in 2010. The coal generation is split according to the same proportions used in the 'generation cost' indicator, following from the proportions shown in the Transition Pathways data.

Climate change

It should be noted that one major impact on water usage could be decreasing availability of water due to climate change. However, Van Vliet *et al* (2013) carried out modelling of hydro and thermal power production potential for European countries (based on the IPCC SRES A2 [medium/high] climate scenario, for the years 2031 to 2060), and found that for the UK, climate change has a minimal impact on power production and on wholesale power prices. Although this doesn't directly correlate to the issue of water temperatures, it does illustrate that for the UK under a low-carbon transition pathway, the impact of climate change on water resources is probably not significant enough to be a major issue.

D.3.4 Water sensitivity tests

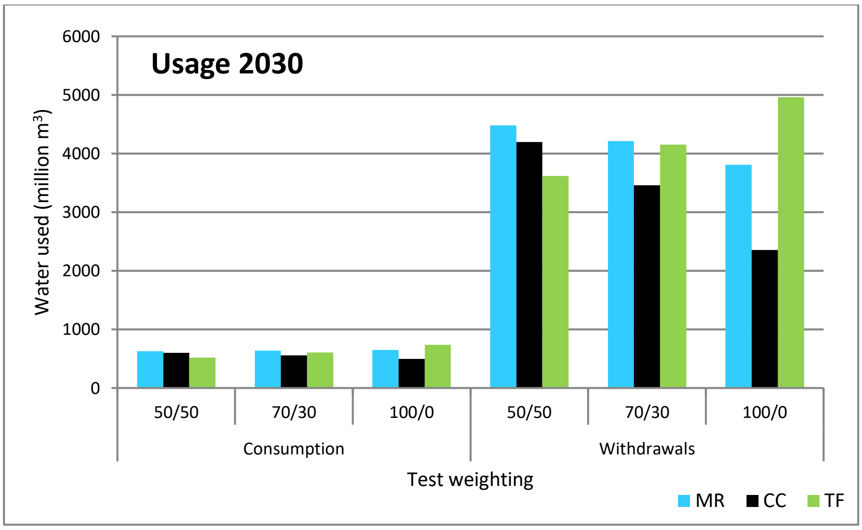
Depending on the location of an electricity generator, it may use either freshwater or seawater. When assessing the sustainability of water withdrawals and water consumption, it is important to take both into account. For instance, water use for cooling from either freshwater or seawater will impact the temperature of the water being replaced, thus impacting ecosystems and potentially human activities which rely on that water. However, freshwater use is probably more damaging from a security perspective, because of the implications of using a potentially depletable resource and on drinking water and food systems. Because of this, the baseline estimates for water usage use a weighting of 70-30 to show the greater impacts of freshwater requirements.

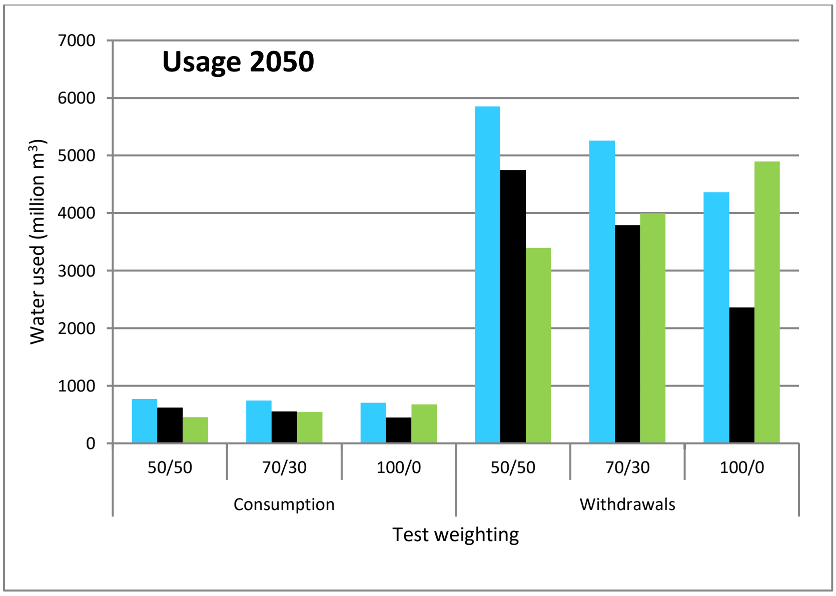
However, this weighting is somewhat arbitrary, because of the significant challenges in developing a non-arbitrary weighting. To do this would require detailed data on plant locations, water temperatures and ecosystem services, and would be highly location-specific. Because of this, it is useful to carry out a sensitivity test which shows the impact of different assumptions regarding freshwater/seawater weightings on the results. Figure D.0.1 below shows the results for sensitivity tests using weightings of 50/50, 70-30, and 100/0.

These results show that the weighting of freshwater vs seawater has a significant impact on the results, including altering the results of the pathways relative to each other. Weighting freshwater and seawater equally means that the TF pathway uses less water than the other two pathways, whereas weighting freshwater use at 100% (i.e. completely ignoring seawater use) means that the TF pathway uses most water. The CC pathway shows the opposite pattern, driven by the large amount of nuclear power in the CC pathway (which in the UK is mostly located on the coast), and the large amount of biomass and CHP plant in the TF pathway (which due to the decentralised nature of the pathway will mostly be located near to population centres, many of which will be inland). The MR pathway appears to have relatively high water use regardless of the weighting, although similarly to the CC pathway the MR pathway benefits from a 100/0 weighting due to the prevalence of nuclear in this pathway.

These results indicate that it is important to specify what the main concern is when looking at water requirements for power generation. If the main concern is an environmental or ecological one, it makes sense to use a more equal weighting. It is important to note that these ecosystem impacts may also have societal and economic impacts, due to the effects on ecosystem services such as fish stocks. On the other hand, if the main concern is related to natural resource depletion or the 'nexus' of food, water and energy, it makes sense to place emphasis on freshwater use, because saltwater is not at risk of depletion. The patterns are the same regardless of whether focusing on consumption or withdrawals. This is probably due to the fact that the main difference between consumption and withdrawals is in the use of hydro power, which withdraws lots of water but does not consume it; all three pathways have similarly low levels of hydro.

Figure D-0-1: Results of sensitivity tests using different weightings for freshwater vs seawater





Appendix E: Reliability methods

E.1 De-rated capacity margin

In a context of increased renewable and intermittent generation, it is becoming common to measure capacity margins using a 'de-rated' measure (DRCM), which reduces the maximum capacity for all generation types to give an assumed level of generation capacity availability at the time of peak demand. Therefore, even non-intermittent sources such as coal and nuclear are given a rating of less than 100%, to account for planned maintenance and faults at the plant. DRCM for the pathways is calculated using the assumed percentage of operating capacity for each fuel, weighted according to the generation mix in the pathways.

Assumed de-rated capacity margins for each fuel are referred to as 'capacity credit'. The capacity credit of each generation type is estimated by the National Grid 10-year statement, as shown in Table E.0.1 (National Grid 2012: 30).

Table E-0-1: Capacity Credit of generation types (National Grid 2012: 30)

Biomass	87%
CCGT	89%
CHP	89%
Coal	89%
Geothermal	90%
Hydro	92%
Nuclear	86%
OCGT	77%
Offshore wind	8%
Oil	81%
Onshore wind	8%
Pumped storage	95%
Tidal	35%
Wave	35%

DRCM is calculated as follows (RAEng 2013):

$$DRCM\ (\%) = \frac{total\ available\ capacity - peak\ demand}{peak\ demand}\ x100$$

Where total available capacity = (nameplate capacity * capacity credit)/100.

E.1.1 DRCM Assumptions

Imports

Imports have been rated at 50%, to take into account the potential that supply through the interconnector will be unavailable at the time of peak demand, either due to a fault or due to high demand in the interconnected country. Sensitivity analyses are also run to show the impact of changing assumptions on import capacity credit; these are explained in section E.1.2.

CCS

Defining the capacity credit of CCS is complex, because it depends on assumptions regarding whether the CCS has been built flexibly. CCS reduces plant efficiency, therefore in theory it could reduce the capacity credit. However, there are several ways of building a CCS plant, some of which could incorporate flexible CCS. Therefore for instance, during a demand peak, the CCS part of the plant could be switched off temporarily, which would allow the plant to generate more power to deal with the peak. Another possibility would be to configure the CCS plant to delay the most energy intensive processes of CCS, so that the carbon is captured but the processing is carried out during the night when system demand is low, thus increasing the peak time capacity credit. However, building plant to incorporate this kind of flexibility is more expensive.

The Transition Pathways data does not express whether the CCS plant has been built flexibly. Therefore as a starting assumption, coal CCS is given the same capacity credit as unabated coal, and gas CCS the same as unabated gas. Sensitivity analyses are then run for different assumptions (see sections E.1.2, E.1.3 and E.1.4).

Solar

National Grid does not give a capacity credit for solar. This is probably because the credit for solar is effectively 0%, because peak demand generally occurs on winter evenings, when no solar is available at all.

Changing capacity margins over time?

It could be argued that generation technologies will improve over time, and that therefore their generation availability may increase. However, this has not been assumed in the initial calculations. This is because the availability of a new generation technology generally follows more of a bell-curve pattern: when the new technology or plant is introduced, its availability is generally small, increases over time, and then drops again towards the end of its lifetime. Therefore capacity margins are held constant to 2050.

E.1.2 DRCM sensitivity tests: methods

Imports

Imp 1: baseline

For the baseline, imports are assumed to have a capacity credit of 50%, to take into account the possibility that power will be unavailable through the interconnector at the time of the request.

Imp 2: Imports low

As noted above, the capacity availability of imports is dependent on assumptions regarding the likelihood of a fault occurring on the other end of the interconnector at the same time as the system peak. Therefore a sensitivity analysis is carried out for imports at 0% capacity credit.

Imp 3: Imports varied according to pathway logic

It could be argued that the market and governance structure of the European electricity system will have an effect on the likelihood of these events occurring. Therefore a sensitivity analysis is carried out which differentiates between the centralised and decentralised pathways in terms of the likeliness of an Integrated European Market for electricity (IEM). It is assumed that the MR and CC pathways would be more likely to have an IEM; therefore in these pathways, imports are rated at 80%. For the TF pathway, an IEM is assumed to be less likely, therefore imports are rated at 20%.

Wind

National Grid (2012) points out the importance of assumptions regarding the capacity availability of wind power, and the large difference that this can make to conclusions regarding overall system DRCM. Therefore sensitivity analyses are carried out which rate wind at 5%, 20% and 40% capacity credit, to show the effects this has on the overall DRCM.

Baseline: wind at 8% capacity credit (from National Grid 2012: 30)
Wind 1: wind at 5%
Wind 2: wind at 20%
Wind 3: wind at 40%

CCS

CCS 1: Baseline
For the baseline, CCS is rated the same as unabated coal and gas generation (89%).

CCS 2: CCS high
In theory a flexible CCS plant would offer an extra energy boost at times of system peak (see section E.1.1, and therefore would be rated at above 100%. Therefore a sensitivity analysis is carried out for CCS at 110% (to take into account the 89% of unabated coal and gas, plus 21% extra).

CCS 3: CCS low
However, this only happens if the plant is built flexibly to begin with. If not, the reduced efficiency of the plant caused by CCS (which can reduce efficiency by up to 30%) will reduce the capacity credit; therefore a further calculation is carried out which subtracts the same amount as above, and assumes a capacity credit of 68%.

E.1.3 DRCM sensitivity tests: results

Figures E.0.1 and E.0.2 show that the DRCM results are not overly sensitive to assumptions regarding the capacity credit of electricity imports. Reducing imports to a 0% capacity credit reduces the DRCM of the MR and CC pathways to below zero in both 2030 and 2050, suggesting very poor system reliability. In these pathways, were power to be unavailable through the UK's interconnectors at the time of peak demand, the system may not be able to meet this peak. Even increasing the capacity credit of imports to 80% – a very high assumed capacity credit for imports – is not enough to increase the DRCM of the MR and CC pathways to above zero in 2050. The DRCM of the TF pathway remains high throughout; even reducing the imports credit to 0% only reduces the overall margin to 39% in 2050. Electricity surplus remains an issue in the Thousand Flowers pathway (see sections 5.8.2 and 5.8.3).

These results show that despite low DRCM in general, the MR and CC pathways both achieve a positive DRCM when wind is rated at 20% capacity credit. However, the DRCM for the CC pathway is still only just above zero for a 20% wind capacity credit. Despite the potential for aggregation of wind generating capacity over a large area (which, assuming no transmission bottlenecks, should improve the wind capacity credit), it should be noted that large anticyclones do occur occasionally, meaning that 20% for wind could be an optimistic assumption. If the pathways were to include large amounts of electricity storage, it could be argued that higher capacity credit for wind would be plausible, because of the ability of storage to make intermittent power available when required; however, the economics of electricity storage are unfavourable, and as such the pathways do not include the level of electricity storage which would be required to achieve this (see section 5.8.4).

Assumptions regarding CCS are shown to be fairly important for the DRCM of the MR and CC pathways, with inflexible CCS resulting in very low DRCM for both. Inflexible CCS is a fairly realistic assumption to make and would thus signal that the MR and CC pathways may struggle to meet peak demand in 2050. The TF pathway, as in the sensitivity analyses for the other fuels, shows a high DRCM throughout.

Figure E-0-1: Results from DRCM sensitivity analyses 2030

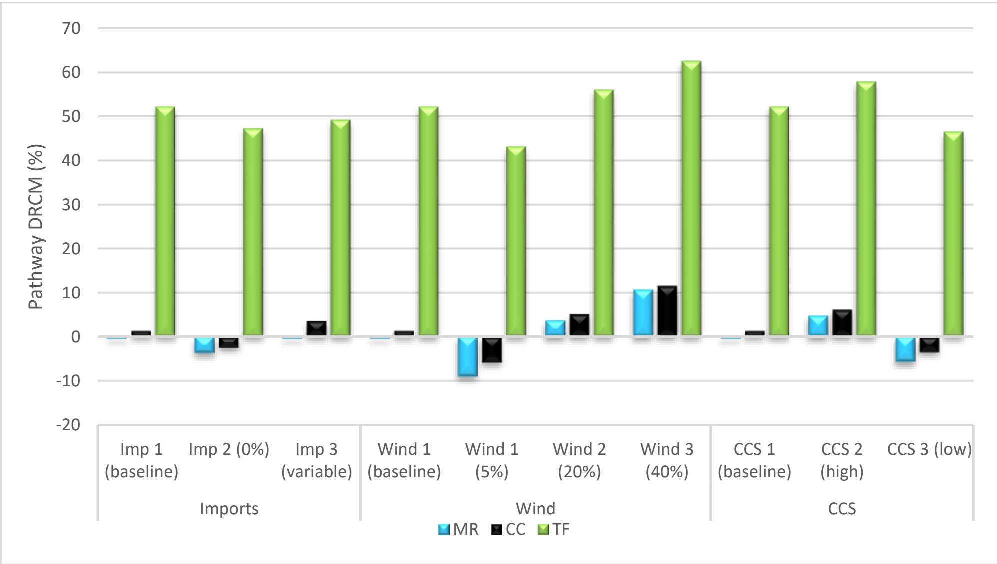
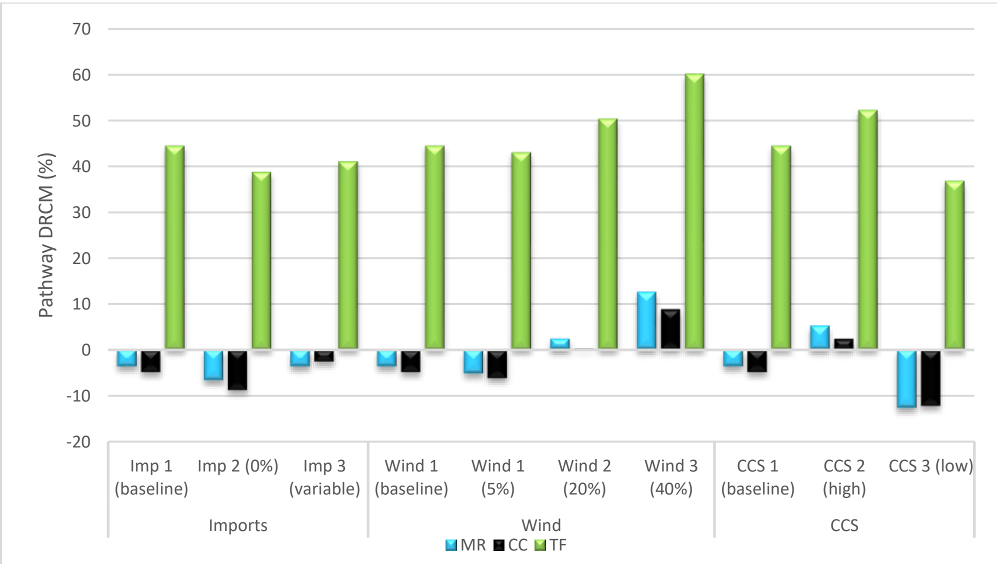


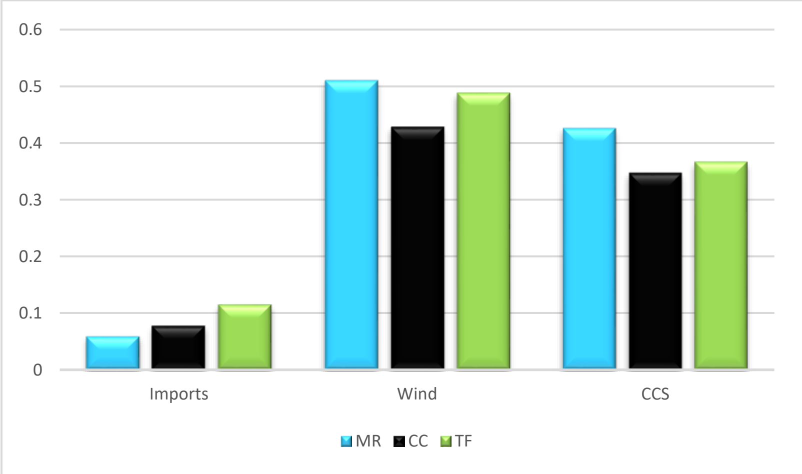
Figure E-0-2: Results from DRCM sensitivity analyses 2050



E.1.4 DRCM sensitivity tests: marginal increases

Figure E.0.3 shows the percentage change which could be expected in the overall DRCM of the pathways, in response to a 1% change in the estimated capacity credit of imports, wind power, and CCS. The graph shows that the pathways are most sensitive to assumptions regarding wind power; this is especially important for the MR and TF pathways. This result is somewhat surprising as the TF pathway includes less wind power than the CC pathway; however, the demand in the TF pathway is also lower, which means that wind makes up a greater proportion of overall demand and therefore has a bigger impact on the DRCM.

Figure E-0-3: Impact of sensitivity assumptions on marginal (per unit) changes in DRCM



E.2 Capacity factors and oversupply

The FESA model which was used to create the Transition Pathways adjusts the capacity factors of each type of generation. In order to accommodate increased penetration of intermittent power generation, the remaining dispatchable generation must accommodate this variability. This causes an increase in the range of dispatchable generation output, which results in a decrease in average capacity factors. A reduction in capacity factors could be a cause for concern for operators or investors, as it risks making the initial investment in this type of generation capacity economically unviable. As such, the main security impact would be on cost; it would be a concern that the flexible generation needed to balance the pathways (in the form of low-carbon thermal generation) would not be realised, because of the economic unattractiveness to generators of operating their plants at such low capacity factors.

E.3 Shock resilience: methods overview

Even in a system which has been carefully designed to ensure that supply is adequate to meet demand at all times, and that the network is capable of delivering this supply, there is still a possibility that unexpected deviations will occur in the supply-demand balance. These can occur for a wide variety of reasons – for instance, a fault at a large generating unit, a trip somewhere on the transmission network, or errors in weather forecasting causing a much larger or smaller output from renewables. Such shocks are felt through deviations in the frequency of the load (in Hz); when supply is greater than demand the frequency will increase, and when demand is greater than supply the frequency will decrease.

Whilst steps should be taken to ensure that such 'shocks' are avoided, a resilient system will also have the ability to quickly restore the system to an acceptable frequency level. National Grid acts to ensure that the system responds quickly and effectively; this is important, because a trip in one part of the system can occasionally lead to a knock-on effect of further trips, which could eventually lead to large-scale blackouts (RAEng 2014). Therefore an important aspect of energy security is not just how likely it is that faults and deviations may occur, but also how well the system is capable of mitigating the effects of such deviations. These deviations are referred to in this section as 'shocks', meaning an unexpected change in the supply-demand balance, occurring over a short time-period of less than 4 hours.

There are several different means of ensuring that the system can respond to a shock:

1. Flexible generation
    - Frequency Response
    - Short-term Operating Reserve (STOR)
    - Black start plant
    - System Inertia
2. Flexible demand
3. Electricity storage and interconnection

E.4 Frequency response capability

Frequency Response (FR) is the first response of the system when it encounters a shock. When there is an unexpected imbalance between supply and demand, the frequency will deviate away from 50Hz. FR manages this by quickly bringing more or less generation onto the system. FR is an extremely short-term measure; it is provided on 2 timescales: Primary (6-30 seconds) and Secondary (30 seconds to 30 minutes).

FR is mandated by National Grid – generation units need to provide a certain FR capacity within a certain timeframe, for a certain duration, depending on their contract with National Grid. National Grid publishes data which shows the FR capabilities of all the different units on the system (including pumped storage) (raw data available from the author on request). From this, it is possible to work out historical data and averages on the FR capability of different generation types.

The different plants are grouped in terms of type, and an average and a maximum FR capability is obtained for each type from the National Grid data. This data shows FR capabilities for 0.2Hz, 0.5Hz and 0.8Hz for primary FR, and for 0.2Hz and 0.5Hz for secondary FR: this is the capability of the unit (in MWh) to respond to a 0.2, 0.5 or 0.8Hz deviation in frequency. For simplicity, the results for the shock resilience indicator are calculated just for 0.8Hz for primary FR and 0.5Hz secondary FR. thus representing the capability of the unit to respond to a significant deviation, following a large shock to the system.

From this, the FR capability of each unit of generating power is calculated per MW capacity. So for a 500MW unit, the FR capability (in MWh) is divided by the unit capacity (in MW), to show the FR capability for each MW of that unit. An average FR capability per MW and a maximum FR capability per MW is calculated for each generation type. Finally, the capacity of each fuel type in the pathways is multiplied by the FR capability per MW to show the average and the maximum potential FR capability of the pathway (in MWh).

It should be noted that this method paints a very broad representation of the potential FR capability of the system. It should only be used for comparative purposes between the pathways.

E.4.1 Frequency response assumptions

It is assumed that all plants which are capable of providing FR are fitted with this capability. Therefore for a 10GW coal capacity, it is assumed that 10GW of the pathway is capable of providing the average FR capability for coal power.

However, because FR is a very short-term measure, plants cannot provide it if they are switched off at the time of the request. The pathways do not contain data on whether specific plants will be on or off, but it is possible to estimate this using the load factors (which in many cases are fairly low, and which therefore provide an important representation of short-term STOR capability). It is more cost effective to have some plants off and some operating at near-full capacity, rather than all plants operating at reduced load factor. Therefore for example, if the load factor of coal is '60%', it will be assumed that 30% of plants are off. The remaining 10% comes from the fact that most plants will be operating at near-full, rather than total full capacity. The load factors are calculated to give a weighted average for each type of generation (e.g. 'coal', 'coal CCS' and 'coal CHP' are combined into a weighted average for coal load factor). The load factor then has 10% added to it (to reflect the fact that most plants won't be running at quite full capacity) to show an estimated percentage of plants which are switched on at the time of the FR request.

Recent plant changes

It should also be noted that the data from National Grid is from 2011; as such, some of the power stations shown have since closed or converted to biomass. However, as this is to give an indication of the FR capabilities of different types of power station, the 2011 data is used in full and is not updated for more recent station closures.

Biomass and co-firing

For biomass, because of the early stage of the technology at the time of publication of the National Grid data, only one dedicated biomass plant is shown as offering FR (Tilbury). It can be expected that the FR capability of biomass will be similar to coal or gas, especially if co-firing takes place. The average results for Tilbury are similar to the results for coal and gas; however, it should be noted that the maximum is rather low, as it is simply the same as the average for Tilbury. Therefore, the maximum FR is given as the same as coal.

E.5 Short-term operating reserve and black-start capability

Frequency Response covers the system if generating power is suddenly lost (for instance, due to a fault at a large generating unit). However, for the system to return to normal, reserve power then needs to come online, to cover the system until it returns back to 'normal' status. For this, the system uses Short-term Operating Reserve (STOR). STOR acts over slightly longer timescales than FR; it is delivered within 4 hours or less. However, National Grid is mostly interested in the ability of power generation to deliver reserve capacity within about 30 minutes. STOR then needs to be maintained for a minimum duration of 2 hours.

In theory, all conventional generation can provide STOR. All such plants (gas, coal, biomass, nuclear) can usually provide STOR within about an hour, regardless of the status of the plant at the time of the National Grid request. However, providing STOR over shorter timescales (e.g. under 45 minutes) depends on the status of the plant:

- OCGT can ramp up very quickly, regardless of whether it's switched on at the time of the request
- Coal, CCGT and biomass struggle to ramp up quickly if the station is off at the time of the request. For these stations, STOR for a switched-off station is unlikely within 1 hour
- Oil can ramp up quickly if it's warm; however, most of the UK's oil stations are old and most are being retired; therefore for the small amount of oil-fired generation in 2010 in the pathways, it is assumed that oil suffers the same constraints as coal etc.
- Nuclear cannot provide STOR if the station is off

Because of the differences in STOR capability, there will be two indicators of STOR capability for the pathways – 'short-term' (under around 45 mins) and 'long-term' (45 mins to 4 hours).

E.5.1 Long-term STOR

The capacity of each STOR-capable generation is divided by the total capacity of the pathway, and these are summed to give a percentage of the total pathway which is capable of providing long-term STOR. Nuclear cannot provide STOR if it is switched off; therefore the nuclear capacity is adjusted to take into account load factors (see below). Nor can nuclear provide black-start capability.

E.5.2 Short-term STOR

Like for FR, plants cannot provide short-term STOR if they are switched off at the time of the request. Because the pathways do not contain data on whether specific plants will be on or off, this must be estimated using the same method as for the FR indicator (section E.4.1). The percentage of each type of plant which is estimated to be running using this method is then multiplied by the capacity of each type of fuel (coal, gas, biomass and oil) and summed to give the percentage of the pathway which would be capable of providing short-term STOR in <45 minutes.

E.5.3 Black-start capability

Some power plants have black-start capability. This is the ability to start the plant without the use of electricity from the grid. This is normally done using a small generator (usually using liquid fuel), which is used to 'jump start' a larger generator; generators of increasing size are then daisy-chained to start the main turbine. This is important in the event of a blackout over a large spatial area.

Because of the spatial aspect of black-start power, calculating an accurate representation of system black-start capability requires highly granular data on the locations of power plants. This data is not available in the pathways; therefore black-start capability is calculated using the same method as STOR, because the two functions are very similar. Any thermal plant which can provide STOR can in theory provide black-start power provided it is fitted with the capability, with the exception of nuclear. Because black-start power usually takes longer than STOR, the difference between short-term and long-term ramp rates is not important.

E.5.4 Fast start capability

Historically, certain plants were also contracted to offer 'fast-start' capability, i.e. the ability to ramp up quickly from a standing start. However, this requirement has been phased out by National Grid, possibly because it is preferred that capacity payments come through the new Capacity Mechanism, rather than through the ancillary services market. Therefore fast start capability is not factored into the analysis.

E.6 Response and reserve requirements

E.6.1 Calculating the response (FR) requirement

In the future, the electricity system may require more Frequency Response capability, for two reasons:

- Loss of system inertia (from increasing RES and reducing conventional thermal generation)
- Increasing size of largest generation unit (for instance, due to large nuclear power plants).

E.6.1.1 Inertia

When a turbine is spinning, it has built-up kinetic energy; when the turbine stops (due to a fault or trip), it slows down gradually. Therefore making use of this kinetic energy provides natural inertia. Inertia is therefore a by-product of any generation which involves a turbine (coal, gas, biomass, CCS, nuclear and hydro).

Wind generation doesn't currently provide inertia. Therefore in a system with high penetration of wind, more FR from the rest of the generation mix would be required to cover the same amount of losses. Wind therefore creates a double problem – it creates the need for more FR via lack of inertia, yet can't provide any FR. There has been some discussion in the UK about requiring new generators – including wind – to provide inertia. Some overseas manufacturers and power companies require renewable generation to provide inertia, and it is technically feasible. However, the UK does not currently mandate synthetic inertia control in wind farms.

There is little existing modelling work into the impact of increasing wind generation on levels of inertia and the resulting increases in FR requirements, therefore there is little quantitative basis upon which to build an analysis. Therefore inertia is assessed using a simple proxy for this thesis, using a representation of the proportion of the generation mix is capable of providing inertia, and the resulting percentage increase in FR requirements. The proportion of the generation mix which would be capable of providing inertia (GW capacity of all generation minus wind, marine, solar and imports) is turned into a percentage increase/decrease in inertia capability, from 2010 to 2030 and from 2030 to 2050. This is then translated directly into percentage change in FR requirement; so a 20% decrease in system inertia corresponds to a 20% increase in FR requirement.

E.6.1.2 Size of generation units

National Grid (2011) states that the FR requirement is expected to increase with the anticipated connection of larger generation assets. Their projections show a marked step change in reserve requirements in 2014-15, due to the increase in the largest credible in-feed loss risk from 1320MW to 1800MW; this is based on an expectation that the first 1800MW unit (probably at Hinkley C) will connect to the grid. This is clearly out of date now due to project overruns at Hinkley C; however, Hinkley C is still predicted to connect sometime in the 2020s, therefore these projections can still be used to calculate the FR requirement for the pathways in 2030 and 2050. National Grid projects FR requirements out to 2025 in MW, as shown in figures E.0.4 and E.0.5.

As shown, the primary FR requirement is projected to increase from 600 to 1050/MW at the time of connection of the 1800MW units: an increase of 75%. The secondary FR requirement is projected to increase from 1050/MW to 1600/MW in 2014/15: an increase of 52%.

Figure E-0-4: Primary Frequency Response Requriement (sic.), 2010 to 2026 (National Grid 2011)

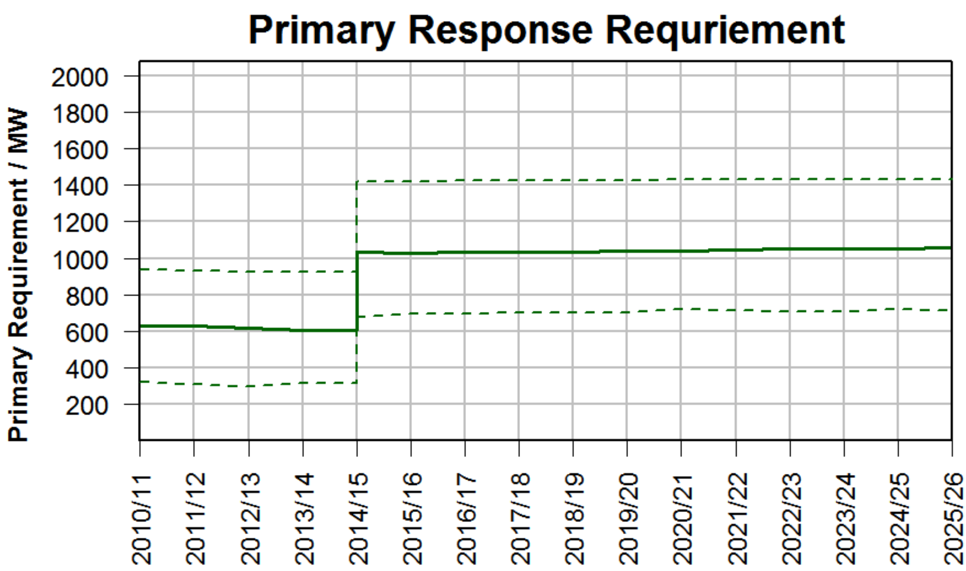
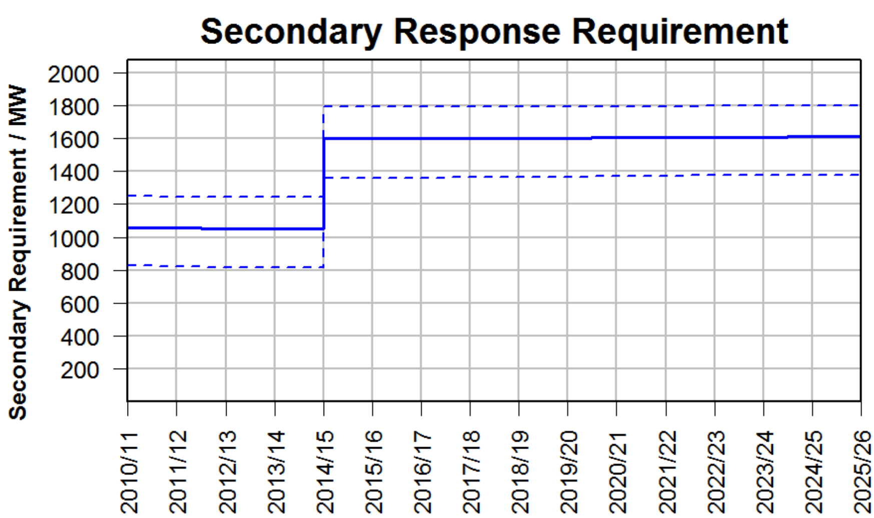


Figure E-0-5: Secondary Frequency Response Requirement, 2010 to 2026 (National Grid 2011)



This step change is accounted for in the FR calculations. However, it would also be necessary to estimate from the pathways whether the largest generation asset could be expected to increase any more than 1800MW. It seems plausible that the Thousand Flowers pathway will not undergo any more increases in the size of the largest generator. However, as noted in the 'transmission costs' indicator, the Hinkley C nuclear plant is expected to still be operational out to 2050, and as there is still some nuclear capacity in 2050 in the Thousand Flowers pathway, it seems likely that this 1800MW unit size will remain.

For the Market Rules and Central Coordination pathways, the centralised nature of the generation mix makes it seem plausible that there will be an increase in the largest credible in-feed loss (it is worth noting that although the National Grid projections calculate this based on the connection of a large generating unit, this could also in theory be caused by the connection of a large interconnector, or even a group of large wind arrays connecting directly to the transmission system). However, this is not possible to calculate from the information given in the pathways. Therefore a sensitivity test is carried out which assumes another unit size increase from 1800MW to 2280MW, sometime between 2030 and 2050. Therefore the sensitivity test illustrates a further 75% increase in primary FR requirement and a further 52% increase in secondary FR requirement in 2050. The increases in FR requirements due to inertia and unit size are then combined to give percentage change estimates for the FR requirements in 2030 and 2050. For the low estimate, only the change due to decreases in system inertia is taken into account.

E.6.2 Calculating the reserve (STOR) requirement

There are two factors which could lead to increasing reserve requirements:

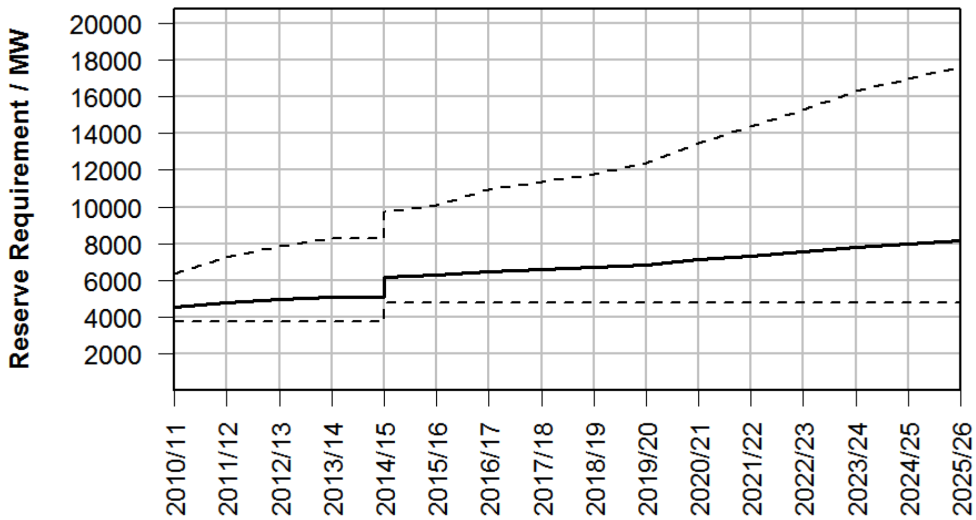
- An increase in wind generation
- An increase in the largest unit size on the grid.

E.6.2.1 Increase in wind generation

In a pathway with much more wind, the reserve requirement will be much greater. This is mainly to allow for inevitable errors in wind forecasting. In theory, this could be mitigated from 2020 onwards by improvements in forecasting accuracy; however, National Grid does not indicate a slow in the rate of reserve requirement growth up to 2025, therefore there is no data with which to calculate the impact of this. It is also worth noting that it is still unlikely that it will become possible to accurately predict wind speeds on the short timescales required for system balancing. Importantly, even if forecasting errors become less common, the *impact* of such forecasting errors will increase as more wind generation comes onto the system.

Indicative reserve requirements are given by National Grid (2011). They estimate that for their 'Gone Green' pathway, which projects an installed capacity of 29GW of wind in 2020, for an average 30% load factor the reserve requirement increases by around 50% from 2010 to 2020, in a generally linear fashion (see figure E.0.6). The average load factor of wind in the Transition Pathways is close to 30%, therefore this trend can be applied to the pathways. For an additional 23.8GW of wind, the reserve requirement increases by 50%. Therefore for every extra GW of wind, the reserve requirement increases by approximately 2.1%.

Figure E-0-6: Operating reserve requirement Gone Green (0%, 30% and 100% wind load factor)



E.6.2.2 Increase in largest grid-connected unit size

National Grid (2011) also notes that the reserve requirement is expected to increase with the anticipated connection of larger generation assets. Their projections show a marked step change in reserve requirements in 2018, in line with the expectation that the first 1800MW generator will connect during this period. This is due to the increase in normal in-feed loss risk from 1000MW to 1320MW, and the largest credible in-feed loss risk from 1320MW to 1800MW. This step change is reflected in the calculations described above. However, it would also be necessary to estimate from the pathways whether the largest generation asset could be expected to increase any more than 1800MW. This is carried out using the same method as for increases in FR requirement due to unit size, described in section E.6.1.2.

E.7 Flexible demand

Historically, most system resilience has come from generation flexibility, as described in the preceding sections. However, the demand side could also offer shock resilience services. Demand-side response (DSR) involves altering demand at a signal from the System Operator or the distribution network operator, in response to a change in the supply-demand balance. There is potential for flexible demand to allow peak-shaving and load-shifting, which would flatten the peaks in electricity demand. Flattening the peak means that less generation is required to meet peak demand, resulting in potentially fewer requirements for the types of shock resilience measures described in sections E.4 and E.5 above. It is therefore likely that increased flexibility of demand could mitigate many of the risks described previously in this section.

However, unfortunately, the demand data in the pathways is fairly limited, and therefore it is very difficult to estimate the proportion of flexible demand. It is noted in the pathway narratives (Foxon 2013) that all three pathways will require smarter networks (i.e. which can automatically shift and alter demand in response to signals from National Grid or the DNOs) in order to balance supply and demand. However, more detailed information than this is absent. Therefore rough estimates and proxies are all that can be used to estimate the potential for flexible demand in the pathways.

There have been a number of other useful studies into load-shifting potential in the present-day UK electricity system:

- Dudeney *et al* (2014) found that the *technical* shiftable potential across all sectors (present-day) may be up to ~18GW on a January weekday winter evening, and up to ~10 GW on an August weekend evening. However, the amount that is *realistically* shiftable is unclear, but is almost certainly much less.
- Element Energy and De Montfort University (commissioned by Ofgem) found peak load-shifting potential in non-domestic buildings of 8 to 30% (Element Energy 2012)

- Smart meter trials have indicated that 7 to 10% of residential load could be shifted without any automation (AECOM 2011)
- Palmer *et al* (2013) found that there is some potential to shift peak household loads using controls on washing machines, tumble dryers and dishwashers. However, replacing appliances with more efficient ones would do more to reduce the peak than DSR at present (Dudeney *et al* 2014).

From this, it is possible to suggest that 10% total load represents a very conservative estimate for total shiftable potential in the future, whilst 20% represents a more ambitious estimate. Importantly, this must then be compared with peak demand in the pathways, because the main purpose of flexible demand is to reduce peak load. This indicator amends peak demand in the pathways for 2030 and 2050 (in GW) according to the conservative and ambitious shiftable potential estimates.

Secondly, electric vehicles (EVs) and heat pumps can be used as a rough proxy for flexible demand in the pathways in 2030 and 2050. EVs and heat pumps both provide potential mechanisms for flexible demand, because both can be used to shift electrical load to the time that it's needed most. For example, if the owner of an EV comes homes from work at 6pm and puts the car on to charge overnight, it won't take all night to charge; therefore if there's a spike in demand at 8.30pm at the end of a particularly riveting episode of EastEnders, a 'smart' demand system could automatically stop the car charging for a short period of time, thus reducing demand at the crucial moment. EVs and heat pumps both represent relatively large electrical loads, especially compared to other appliances which could be used to load-shift such as fridges, therefore their use as a proxy for flexible demand as a whole is justified. This is also necessary in the absence of further data in the pathways about the composition of demand (i.e. how much demand comes from certain services or appliances). The numbers of EVs and heat pumps in the pathways are added together to show an indicative level of flexible demand in the pathways. This is presented in % of the total generation mix, and also in TWh/y in order to show the impact of reducing overall demand.

Appendix F: Offshore wind technology costs

All the data in this appendix is from National Grid 10-year statement technology appendix (National Grid 2013c). For all technologies, National Grid gives a low and a high estimate. The mean of both / all estimates is used here. For each technology, the notes below denote that technology's relevance to the types of array and connections used in the Transition Pathways, and if necessary the multiplication methods used for application to the pathways.

High-Voltage Direct Current (HVDC) subsea cable

The options for HVDC cables come in Extruded and Mass Impregnated, which have similar costs. Mass Impregnated Insulated Subsea (MIIS) cables are a mature technology with high reliability and performance. Therefore cost estimates will all be for MIIS.
The maximum contracted rating is 500kV and 800MW on a single cable.
This component is relevant for all HVDC. The number of cables is multiplied according to the maximum contracted rating.
Cost of an 1800mm 400kV cable with a maximum rating of 800MW = £497/m

High-Voltage Alternating Current (HVAC) three-core subsea cable

These have been the preferred technology for connecting offshore farms which are located relatively close to shore and with relatively low power transfer requirements. They have maximum capacity abilities; therefore sometimes more than one cable will be needed.
Multipliers are given in the 10-yr statement (National Grid 2013c: 11) as follows:

Power capacity (MW)	Number of cables	Cable Voltage	Cost of each cable
100-250	1	132kV	£602/m
251-450	2	132kV	£602/m
451-700	2	220kV	£655/m
701-900	3	220kV	£655/m
901-1200	4	220kV	£655/m
1201-1500	5	220kV	£655/m
1501-1800	6	220kV	£655/m
1801-2100	7	220kV	£655/m
> 2101	8	220kV	£655/m

HVDC and HVAC onshore cables

Onshore cables are used to transfer the electricity from the onshore substation to the rest of the grid.

Overhead cables are less expensive than underground cables, because the underground cables cannot use the air as insulation and therefore require extra insulation. Underground cables therefore only tend to be the preferred option in built-up areas where overhead lines are impractical.

However, the only cost data for onshore cabling is for HVAC overhead lines. The actual choice of cable is likely to be project-specific. Including onshore cabling costs would require data on the length of the cable required to connect from the onshore substation to the grid. Because of lack of data availability, this cannot be done easily. However, the National Grid Round 3 Connection Study (National Grid n.d.) gives an assumption of an additional 10% of total cost to be added for onshore costs. Therefore this can be used as a rough estimate for all.

Voltage source converter (VSC)

VSCs are used to convert from HVAC to HVDC (or vice versa). They are used when an offshore wind farm requires an HVDC connection.

These are a new technology (building on the more conventional Current Source Converter [CSC], see below); they are currently only used for relatively low capacity installations, but there have been significant advances. Current costs mean that these are cheaper than CSC for anything up to 1000MW.

One VSC is used for each HVDC array at or below 1000MW. Costs are dependent on the nameplate capacity of the array, as follows:

1-500MW = £76m. 501-850MW = £100m. 851-1000MW = £122m.

Current source converter (CSC)

CSCs are essentially the same as VSC; however, these have been around for longer and can deal with a higher capacity at lower cost.

One CSC is used for all HVDC farms above 1000MW. Costs are dependent on the nameplate capacity of the array, as follows:

1000MW = £84m. 1001-2000MW = £152m. 2001-3000MW = £194m.

Transformer

Transformers are used to step up the voltage from a turbine to the high voltage required for efficient long-distance transmission.

One transformer is required for all arrays, according to substation details as follows:

MegaVolt Amp rating (MVA)	Voltage rating (kV)	Transformer cost
90	132/11/11	£1.065m
180	132/33/33 or 132/11/11	£1.475m
240	132/33/33	£1.675m
120	275/33	£1.47m
240	275/132	£1.83m
240	400/132	£2.09m

Switchgear

Switchgear is used to allow switching to be performed to control power flows on the network. The switchgear includes a variety of technology, including circuit breakers, disconnectors, earthing switches and instrument transformers.

One switchgear set is used for all arrays, at a cost of £1310 (132kV).

Shunt reactor

Shunt reactors are used to compensate for the capacitive reactive power present in HVAC systems, and to provide a means of regulating the network voltage. They are used at the onshore interface point and possibly at the offshore platform.

Two shunt reactors are used for each array, at an average cost of £3818.

Static VAR compensator / Shunt capacitor bank / STATCOM

These are all options at the onshore substation, to provide capacitive reactive power. The three options have fairly similar costs, and the cost depends very much on how much reactive power is required; this level of detail isn’t available in the pathways, therefore VAR compensator is used throughout.

One 200 MVAR compensator is used for each onshore substation, at a cost of £13 million.

Offshore platforms

Offshore platforms are used to house the electrical equipment required for generation collection and transmission to shore. Depending on the capacity of the project, multiple platforms may be required.

AC platforms have an option of 200-400MW or 500-700MW types; it is assumed that the biggest possible is used. So for an AC array of 350MW, a 400MW platform is used. For a big array of 2000MW, 3x700MW is used.

For HVDC arrays, a separate Direct Current (DC) platform is also required. DC platforms are also available in various sizes, the top rating being 2500MW. Again, it is assumed that the biggest is used.

Each array requires one AC platform.

Each HVDC array requires one DC platform.

Costs are as follows:

Type	Array nameplate capacity (MW)	Cost
AC	200-400	£43m
	500-700	£88m
DC	1000	£295m
	1250	£333m
	1500	£424m
	1750	£472m
	2000	£477m
	2250	£534m
	2500	£572m

Subsea cable installation

Costs of cable installation vary according to the type of installation, whether single cable, twin cable, or two single cables. The cost for two single cables is higher; therefore it is assumed that where multiple cables are required, they are laid as a twin cable. Costs of installation are as follows:

Single cable = £0.52m/km

Twin cable = £0.73 m/km

Appendix G: Copy of briefing note sent to all stakeholders in advance

Expert Stakeholders: Briefing Note

"Assessing the future security of the UK electricity system in a low-carbon context"

Many thanks for agreeing to participate in this research; your views are highly valuable and greatly appreciated. This brief introductory document will set out the aims and background of the study.

During the interview, we will be discussing a framework for the assessment of the security of electricity systems in the context of a low-carbon transition. The indicators which make up this framework are presented overleaf. Please feel free to think about the indicators in advance of the interview; however, this isn't vital as there will be time for discussion in the interview.

Participants have been selected from diverse sectors including policy, academia, suppliers and civil society. Participants will be kept anonymous.
With permission, interviews will be recorded for ease of note-taking.

Background

In order to meet legislative targets for mitigating climate change, future energy systems will need to become secure, affordable and low-carbon – the so-called 'trilemma' of sustainable energy policy (Boston 2013). In the UK, the trilemma has received growing attention as energy security concerns rise up the political and public agenda, driven by declining indigenous fossil fuel reserves and increasing concerns over anthropogenic climate change (DECC 2012; MacKerron 2009). As part of a growing body of research into energy security and low-carbon energy transitions, this project focuses on the security of electricity systems in the UK in the context of a low-carbon transition.

Previous research has noted that 'energy security' means different things to different people (Chester 2010). This situation is unlikely to change; however, it creates challenges for energy security policy, because it makes it difficult to reach agreement on how best to maximise overall system security. This study will use the indicator framework overleaf as a starting point for a discussion about this diversity of views, including question such as:

- What are the most important dimensions of low-carbon electricity security?
- What metrics and indicators are most useful, and why?
- What impact do different timescales have on which dimensions are most relevant?
- Are there important dimensions and indicators missing from the framework?

During the interview, respondents will be asked to rate the indicators on a scale of 1 to 5, to reflect their importance as part of an overall assessment of the security of a low-carbon electricity system (with 5 as 'crucially important' and 1 as 'not important').

The indicator list is presented overleaf. Please feel free to think about how you would rate the indicators in advance; however, this isn't vital as we will be discussing them in the interview.

Indicators for assessing the security of low-carbon transition pathways for the UK electricity system

- Public approval
- Levels of public participation and engagement
- Likelihood of disruption due to direct opposition
- Diversity of fuel types in the energy mix

- Import dependence
- Import diversity (diversity of imports of both fuels and materials)
- Import stability (stability of major supply nations and supply routes to the UK)
- Annual electricity bills to consumers
- Cost of electricity generation
- Cost of upgrades to the distribution networks
- Cost of upgrades to the transmission networks
- Impact on levels of fuel poverty
- Carbon emissions
- Depletion of major fuels (gas, coal etc.)
- Depletion of secondary materials (metals, rare earth elements etc.)
- Water consumption and water withdrawals
- De-rated capacity margins
- Oversupply / spare generation capacity
- Response and Reserve for Grid balancing
- Flexible demand
- Storage
- Interconnection

References

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

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

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

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

Appendix H: Application of individual stakeholder perspectives to security assessment results

Table H-0-1: Application of individual stakeholder perspectives to security assessment results, 2030

Stake holder	Most important indicators	Least important indicators	This stakeholder would find major security risks in…	This stakeholder would find moderate security risks in…
A	Fuel depletion; DRCM; Response and Reserve (R&R)	Annual bills; Generation cost; Fuel poverty; Carbon; Water	MR pathway x1; CC pathway x1	MR pathway x1; CC pathway x1; TF pathway x1
B	R&R; Flexible demand; Storage	Import dependence; Import stability; Import diversity	CC x1	MR x1; TF x1
C	Public approval; DRCM; Interconnection	Generation cost; Fuel poverty; Fuel depletion; Oversupply	MR x1	CC x1
D	Import dependence	Generation cost; Fuel poverty; Materials depletion; Fuel depletion		MR x1; TF x1
E	Emissions; Interconnection	Opposition; Import dependence; Import diversity		
F	Annual bills; Generation cost; Fuel poverty	Fuel diversity; Import stability; Import diversity; Materials depletion; Water	MR x1; TF x1	MR x1; CC x1; TF x2
G	Public approval; Participation; Opposition; Fuel diversity; Import diversity; Flexible demand; Storage	Import dependence; Generation cost; Annual bills; Fuel poverty; Fuel depletion; Water; Oversupply	MR x1	CC x1
H	Public approval; Annual bills; R&R; Flexible demand; Storage; Interconnection	Emissions; Fuel depletion	CC x1	MR x2; CC x2; TF x2
I	Public approval; Import stability; Fuel poverty; Emissions; Interconnection	Fuel depletion; Oversupply	MR x1	TF x1
J	Public approval; Annual bills; Distribution costs; Fuel poverty	Emissions	MR x1	MR x2; CC x2; TF x3
K	DRCM	Fuel poverty; Emissions; Oversupply	MR x1	CC x1
L	Annual bills; Emissions	Materials depletion; Storage		MR x1; CC x1; TF x1
M	Import diversity; Fuel depletion	Emissions; Oversupply		
N	Annual bills; Network costs; Fuel poverty; R&R; Flexible demand; Storage; Interconnection	Import dependence	MR x1; CC x1	MR x4; CC x4; TF x4

O	Public approval; Participation; Opposition; Imports x3; Annual bills; Generation; Fuel poverty; Emissions; DRCM; Oversupply; R&R	Fuel depletion	MR x3; CC x1; TF x1	MR x3; CC x4; TF x5
P	Imports x3; Emissions; R&R; Flexible demand; Storage; Interconnection	Public approval; Opposition; Fuel poverty; Fuel depletion	CC x1	MR x2; CC x1; TF x2
Q	Annual bills; Generation cost; Fuel poverty; Emissions; DRCM; Flexible demand; Interconnection	Import dependence	MR x2; TF x1	MR x1; CC x2; TF x2
R	Participation; Fuel diversity; Fuel poverty; Emissions; Water; DRCM; R&R; Flexible demand; Storage; Interconnection	Import dependence	MR x3; CC x1	MR x1; CC x2; TF x2
S	Public approval; Participation; Opposition; Import stability; Generation cost; Fuel poverty; Emissions; DRCM; Oversupply; R&R	Fuel depletion; Water	MR x3; CC x1; TF x1	MR x1; CC x3; TF x3
T	Opposition; Generation cost; Flexible demand	Distribution costs; Fuel poverty; Materials depletion; Water	TF x1	CC x1
U	DRCM; Oversupply; R&R; Flexible demand; Storage; Interconnection	Fuel poverty; Fuel depletion	MR x1; CC x1	MR x1; CC x2; TF x2
V	Fuel diversity	Transmission costs; Emissions; Materials depletion		
W	DRCM; R&R	Opposition; Fuel diversity; Generation cost; Annual bills; Transmission costs; Fuel poverty; Materials depletion; Water	MR x1; CC x1	MR x1; CC x1; TF x1
X	Public approval; Participation; Opposition	DRCM	MR x1	CC x1
Totals			**MR 22; CC 10; TF 5**	**MR 23; CC 31; TF 33**

Table H-0-2: Application of individual stakeholder perspectives to security assessment results, 2050

Stake holder	Most important indicators	Least important indicators	This stakeholder would find major security risks in…	This stakeholder would find moderate security risks in…
A	R&R; DRCM	Annual bills; Generation cost; Fuel poverty; Water; Carbon	MR pathway x1; CC pathway x2	MR pathway x1; CC pathway x1; TF pathway x1
B	R&R; Flexible demand; Storage	Import dependence; Import stability; Import diversity; Distribution costs	CC x1	MR x1; CC x1; TF x1
C	Public approval; DRCM; Interconnection	Generation cost; Fuel poverty; Fuel depletion; Oversupply	MR x1; CC x1	
D	Import dependence	Generation cost; Fuel poverty		MR x1; TF x1
E	Network costs; Emissions; Interconnection	Opposition; Import dependence; Import diversity	MR x2; CC x2	TF x2
F	Annual bills; Generation cost; Fuel poverty	Fuel diversity; Import stability; Import diversity; Materials depletion; Water	MR x2; TF x1	MR x1; CC x1; TF x1
G	Flexible demand	Import dependence; Generation cost; Annual bills; Fuel poverty; Fuel depletion; Water; Oversupply		
H	Public approval; Annual bills; R&R; Flexible demand; Storage	Import stability; Emissions; Fuel depletion; Oversupply; Interconnection	MR x1; CC x2	MR x1; CC x1; TF x2
I	Public approval; Import stability; Fuel poverty; Emissions; Storage; Interconnection	Fuel depletion; Oversupply	MR x1	CC x1
J	Public approval; Annual bills; Distribution costs; Fuel poverty	Emissions	MR x3; CC x2	CC x1; TF x2
K	Participation; Opposition; Fuel diversity; DRCM; R&R; Flexible demand	Fuel poverty; Emissions; Oversupply	MR x2; CC x2	MR x2; CC x1; TF x1
L	Annual bills; Emissions	Materials depletion	MR x1; CC x1	TF x1
M	Import diversity; Materials depletion	Emissions; Oversupply		
N	Fuel diversity; Annual bills; Network costs; Fuel poverty; R&R; Flexible demand; Storage; Interconnection	Import dependence	MR x4; CC x4	MR x1; CC x2; TF x4

O	Public approval; Participation; Opposition; Annual bills; Fuel poverty; Emissions; DRCM; Flexible demand	Fuel depletion	MR x4; CC x2	MR x1; CC x1; TF x1
P	Imports x3; Emissions; R&R; Flexible demand; Storage; Interconnection	Public approval; Opposition; Fuel poverty; Fuel depletion	CC x1	MR x2; CC x1; TF x2
Q	Fuel diversity; Annual bills; Generation cost; Fuel poverty; Emissions; DRCM; Flexible demand; Interconnection	Import dependence; Fuel depletion	MR x3; CC x2; TF x1	MR x1; CC x1; TF x1
R	Participation; Fuel diversity; Fuel poverty; Carbon; Water; DRCM; R&R; Flexible demand; Storage; Interconnection	Import dependence	MR x3; CC x2	MR x2; CC x2; TF x1
S	Public approval; Participation; Opposition; Import stability; Generation cost; Network costs; Fuel poverty; Emissions; DRCM; Oversupply; R&R; Flexible demand; Storage; Interconnection	Water	MR x5; CC x4; TF x2	MR x3; CC x3; TF x3
T	Opposition; Generation cost; Flexible demand	Distribution costs; Fuel poverty; Materials depletion; Water	TF x1	MR x2
U	Emissions	Fuel poverty; Fuel depletion		
V	Fuel diversity; R&R	Transmission costs; Emissions; Materials depletion	CC x1	MR x1; CC x1; TF x1
W	Import dependence; Import diversity; DRCM; R&R	Opposition; Generation cost; Transmission costs; Fuel poverty; Water	MR x1; CC x2	MR x2; CC x1; TF x2
X	Public approval; Participation; Opposition	Water; DRCM	MR x1	MR x1
Totals			**MR 35; CC 31; TF 5**	**MR 23; CC 19; TF 27**