UKERC
UK Energy Research Centre

The Security of UK Energy Futures

UKERC Research Report

Jim Watson, Ioanna Ketsopoulou, Paul Dodds, Modassar Chaudry,
Simon Tindemans, Matt Woolf and Goran Strbac

March 2018

Preface

Authors

Jim Watson
Ioanna Ketsopoulou
Paul Dodds
Modassar Chaudry,
Simon Tindemans
Matt Woolf
Goran Strbac

About UKERC

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

www.ukerc.ac.uk
Follow us @UKERCHQ

This report should be cited as: Watson, J., Ketsopoulou, I., Dodds, P., Chaudry, M., Tindemans, S., Woolf, M., and Strbac, G. (2018) *The Security of UK Energy Futures*. London, UK Energy Research Centre.

Acknowledgements

The authors would like to thank Gareth Harrison, Jess Britton and Mike Bradshaw for their very helpful comments on a draft of this report; to Emily Cox for help and advice on the application of her indicator framework; and the participants in a workshop that was held in April 2016 to discuss an early draft of our new scenarios. The content of the report, and errors or omissions, remain the responsibility of the authors.

UKERC/EP/2018/RR/02

Contents

Executive Summary

Ensuring energy security is a central goal of energy policy in most countries. The UK is no exception. Throughout the increasingly rapid changes in the energy sector over the past few years, energy security has remained high on the policy agenda. This winter has been a good example. Whilst gas demand has fallen significantly in the last decade, recent cold weather and infrastructure problems have tested the resilience of the UK gas system.

This report explores how the security of the UK energy system could change in the future. UK energy security will be shaped by a range of factors including action to reduce emissions, technological change and shifting geopolitics – including the UK's changing relationship with the EU due to Brexit.

The report is particularly concerned with the synergies and trade-offs that could arise between emissions reduction and energy security. It is often argued that there will be energy security benefits from the transition to a low carbon energy system. Whilst benefits are likely to emerge, so too will new risks. Low carbon electricity systems are likely to require new approaches to balancing supply and demand. Our energy system will need to be increasingly resilient to cyber-attacks.

The report assesses a new set of UK energy scenarios using a dashboard of energy security indicators. It examines scenarios that comply with statutory carbon budgets and targets, and futures where climate action becomes a low priority. The scenarios include qualitative storylines about national political, economic and social developments. The direction of international policies and technological innovation are also included. Our quantitative analysis of these futures has used the UK TIMES energy systems model, alongside two other models to carry out the security assessment.

The indicator dashboard covers a range of energy system features that are important for security. These include diversity of technologies and fuels, the extent and nature of energy imports, the potential risks of public opposition, and measures of energy system resilience and flexibility. The final dashboard of energy security indicators is summarised in Figure 1, which shows how each indicator has changed between 2016 and 2050. Indicators where there is an increased risk are highlighted in red. Indicators where there is a significant increase in risk are dark red.

This assessment leads to three main conclusions. First, the results suggest that there is an important role for energy efficiency and energy demand reduction in energy security strategies. The two scenarios with the fewest red indicators, *Technology Optimism* and *Energy Island*, have the lowest primary energy demand. *Technology Optimism* also has much lower final energy demand than the other five scenarios.

Second, it highlights how the relationship between decarbonisation and energy security is not straightforward. *Technology Optimism* meets climate change targets via significant technical change, decentralisation and demand reduction. By contrast, *Energy Island* is a scenario in which action on climate change mitigation stalls, and there is a radical shift in favour of domestic energy resources – including a renewed role for coal. The *Low Carbon* and *Slow Decarbonisation* scenarios deliver a more mixed performance, with a significant number of indicators showing higher risks to security. These results imply that energy security risks will not automatically reduce as the energy system decarbonises.

Third, our analysis shows that significant risks to security can be mitigated. Electricity and gas system reliability can be improved significantly by investing in system flexibility. This report has focused on a sub-set of the options available to achieve this: demand side response and gas storage. Increasing demand side response has a particularly positive impact on electricity and gas system reliability.

Taken together, these conclusions suggest priorities for government and other actors that are responsible for UK energy security. As the energy system changes, it will be particularly important to prioritise actions that improve energy system resilience. This includes more emphasis on energy efficiency and measures to improve diversity and flexibility such as storage, demand side response and international interconnections.

There are some important caveats that should be borne in mind when interpreting these results. Some of the indicators are only partial proxies for the energy security risks they are seeking to measure. This applies in particular to indicators of public opposition risks and electricity demand flexibility. Public support for, or opposition to, energy resources or technologies is highly likely to change over time. These changes will depend to some extent on other economic, political and societal changes, many of which are described in the scenario narratives.

The use of energy imports as an energy security indicator is also controversial. Whilst imports are often cited as being insecure, such claims need to be examined closely. Imports can help to enhance security; providing access to additional sources of energy, lowering the cost of energy, and increasing fuel diversity. Whilst Brexit may affect the UK's relationships with international energy markets, it is not possible to draw a simple correlation between increasing imports and decreasing security.

Whilst the report explores the role of energy storage in energy security, this analysis is limited. As the transition to low carbon energy systems progresses, the role and nature of energy storage is also changing. Our assessment has included the role of gas storage in helping to improve gas system security. However, model limitations mean that we have not been able to examine electricity storage in detail. Significant growth in electricity storage is expected under a wide range of future scenarios. This could complement demand side response, interconnection and other sources of flexibility.

Due to the uncertainties involved, it is not possible to provide a comprehensive analysis of the costs of these scenarios or the implications for household energy bills. This is an important limitation as price is an important dimension of energy security. For example, some low income consumers struggle to pay for sufficient energy to provide the services they need, particularly keeping warm in cold weather.

Two further risks to energy security deserve scrutiny in future research: cyber security and risks due to climate change. Cyber security is receiving an increasing amount of attention, as the energy sector and many others become more dependent on the use of digital technologies. Cyber-attacks have negatively impacted the energy sector in some countries, either by targeting companies or specific infrastructures.

Climate change is likely to lead to changes in energy demand patterns, and to increased risks due to flooding and other adverse weather events. These risks are particularly acute for the *Energy Island* scenario where action to mitigate climate change is weak.

1. Introduction

1.1 UK energy policy and energy security

Ensuring energy security is a central goal of energy policy in most countries. The UK is no exception. Throughout the increasingly rapid changes in the energy sector over the past few years, energy security has remained high on the policy agenda.

The government's recent Clean Growth Strategy is primarily focused on how further reductions in greenhouse gas emissions will be achieved to comply with the Climate Change Act. The Strategy also places a lot of emphasis on ensuring that the costs of meeting statutory targets are minimised and the industrial opportunities that this could bring. It also argues that there will be potential benefits for energy security:

> *"… crucially, many of the actions in the Clean Growth Strategy will enhance the UK's energy security by delivering a more diverse and reliable energy mix."*
>
> **HM Government, 2017: 11**

Whilst there could be energy security benefits from reducing emissions, this does not necessarily mean that the transition to a low carbon energy system will automatically deliver a more secure system. Some risks to energy security are likely to reduce in importance during this transition. Fossil fuel use is likely to decline if the energy system continues to decarbonise, thereby reducing the UK's exposure to price shocks. However, other risks could emerge (e.g. Mansson, 2015). Low carbon energy systems are likely to mean more complex electricity systems that require new approaches to balancing supply and demand, or increasing risks of cyber attacks due to the widespread use of digital technologies. There may also be fossil fuel 'demand destruction' due to decarbonisation, which could pose risks for countries that are heavily dependent on fossil fuel exports.

This report explores how the security of the UK energy system could change in the decades ahead. It assesses a new set of energy scenarios using a 'dashboard' of energy security indicators. These scenarios include some which comply with statutory climate change targets, and some which do not. They also include scenarios that allow significant fossil fuel use to continue through the extensive use of carbon capture and storage (CCS) as well as scenarios in which efforts to commercialise CCS fail. The main aim of the report is to examine how security risks might change over time, and what synergies and trade-offs there could be between emissions reduction and energy security.

1.2 Defining energy security

Whilst energy security is a widely used term in policy and public discourse, there is significant debate over scope and definitions (e.g. Mitchell and Watson, 2013a; Chester, 2010). An important starting point for this report is that security is a property of the energy system. Whilst there are many debates about how particular resources or technologies could affect energy security, it is seldom possible to make definitive statements about their impact without knowing the context. This depends, for example, on where resources come from, what other resources and technologies are also being used, and what roles they play.

There is also an important distinction between narrower definitions of energy security which focus on reliability and affordability of energy, and those that also include environmental sustainability – particularly climate change (Cox, 2016). In this report, we have taken a narrower approach to the definition of energy security. We explore the interaction with climate change mitigation through the comparison of different scenarios.

A useful overview of the history of energy security debates, and some of the differences in perspective, has been provided by Cherp and Jewell (2011). They distinguish three approaches to energy security that come from different academic disciplines, and focus on different sets of risks and strategies:

- A *sovereignty* perspective that has its roots in geopolitical events such as the 1970s oil price shocks, and focuses on threats from external actors. It emphasises the need for control over energy systems and actions to prevent specific threats.
- A *robustness* perspective that focuses on predictable natural and technical risks to energy security such as technical failure or resource scarcity. It focuses on infrastructure upgrades and switching away from scarce resources.
- A *resilience* perspective that acknowledges the diversity of risks to security, some of which are not predictable. It therefore emphasises a need for energy systems withstand and recover from such diverse risks.

This report is influenced in particular by the resilience perspective due to its emphasis on both known and unknown risks. In the Clean Growth Strategy, the government also offers a definition of energy security that relies heavily on this perspective.

> *"Energy security is about ensuring secure, reliable, uninterrupted supplies to consumers, and having a system that can effectively and efficiently respond and adapt to changes and shocks. It is made up of three characteristics: flexibility, adequacy and resilience."*
>
> **HM Government, 2017: 154**

This emphasis on flexibility and resilience is not surprising given that the UK was one of the first countries to liberalise its energy sector, and that the sector is undergoing major changes. Whilst the state has had an increasing role in shaping the energy sector in recent years, the Clean Growth Strategy continues to emphasise the role of markets and uncertainty about how emissions reductions will be achieved. In this context, energy security is not the sole responsibility of a single decision maker. It is the outcome of decisions by a wide range of public and private actors.

1.3 Assessing energy security

A central challenge for any assessment of energy security is the choice of indicators. How should energy security be measured? Some assessments use specific indicators to explore particular dimensions of energy security such as the interaction between import dependency and emissions reduction (e.g. Jewell el at, 2016). Others attempt to combine multiple indicators of energy security to provide an overall index for comparison between countries (e.g. World Energy Council, 2017).

Whilst such examples provide results that are relatively easy to track, they have significant drawbacks. Single indicators are not suitable for assessing the security of the energy system as a whole, whilst composite indicators can be opaque. Understanding how energy system change will affect security often requires a broader approach, with multiple indicators (e.g. Kruyt et al, 2009).

With this in mind, this report takes a dashboard approach to energy security indicators. It builds on conceptual work within a UK research network on energy security (Mitchell and Watson, 2013b), and adapts and applies a framework of indicators that has previously been developed and tested on scenarios of the UK electricity system (Cox 2018).

1.4 Report structure

This report comprises four further sections, followed by appendices that provide further detail about the models and tools that were used. Section 2 discusses a new set of six UK energy scenarios that were developed for this research. The scenarios include qualitative storylines and quantitative analysis using the UK TIMES energy systems model. Section 3 sets out the indicators that have been used to assess the energy security of scenarios in 2030 and 2050. These indicators focus on two main dimensions of energy security: availability and reliability.

Section 4 presents the results of the energy security assessment of all six scenarios. It discusses these results for each indicator separately, and highlights some important caveats to our analysis. Finally, section 5 brings the results together in an overall indicator dashboard and draws some conclusions. The indicator dashboard compares the six scenarios in 2050 to the current situation, and highlights areas where risks to energy security could increase. This concluding section also notes some important limitations of the report, including potentially important risks to security that have not been assessed in any detail.

2. The 2018 UKERC energy scenarios

2.1 Scenario development

In order to systematically assess the energy security implications of different energy futures a set of six UK energy scenarios has been developed:

- Energy Island;
- Slow Decarbonisation;
- Low Carbon;
- Low Carbon without CCS;
- Low Carbon without negative emissions; and
- Technology Optimism.

The scenarios consist of qualitative narratives and quantitative analysis using an energy system model: UK TIMES (See Appendix 1 for more details). UK TIMES is a bottom-up, cost optimisation energy system model that is often used to explore the implications of different energy futures and identify pathways that achieve carbon reduction targets. UK TIMES, and its predecessor UK MARKAL, have contributed numerous insights to the development of UK energy policy since the 1990s, and most recently to the Clean Growth Strategy (HM Government, 2017).

Not all the parameters used to develop the qualitative narratives could be modelled in UK TIMES. Therefore some components of the narratives, such as governance or environmental awareness, are not reflected directly. The scenarios presented here have been renamed in order to avoid confusion with their earlier versions, published in McGlade et al., (2016).

The narratives were generated through a morphological analysis. This is a method for developing scenarios that include a number of components and their interrelationships. It has been used in various sectors, ranging from astronomy to national defence studies, as well as energy (Kosow & Gassner, 2008; Ritchey, 2006). Each scenario narrative includes a variant of each component, whilst ensuring that it is internally consistent.

The components cover national political, economic and societal policy developments, as well as the direction of international policies, and technological innovation. In terms of national context, this included the UK's economic and climate policies, the distribution of governance at different scales, as well as the role of civil society. In terms of the international context, the key parameters include the level of commitment to climate change mitigation and the degree of commitment to international rules-based trading arrangements.

The referendum on the UK's membership of the EU took place part way through the project. Due to the outcome, substantial modifications were undertaken to the narratives to reflect uncertainties about the UK's future relationship with the EU. Finally, technological progress, and particularly the availability of carbon capture and storage (CCS), was explored as a critical parameter that could affect the future direction of the energy system.

The variants of those key components and the combinations within each scenario narrative are summarised in Figure 1.

2.1.1 Energy Island scenario

In Energy Island the UK has taken an inward-looking turn. The economy has been very slow to recover from the 2008 recession and the vote to leave the EU. There is a minimal appetite for public investment, except where this is regarded as necessary for national security. The UK leaves the European single market and customs union, which results in a new trade deal that provides the UK with partial access to European markets on unfavourable terms. Scotland holds a second referendum and votes to leave the UK, partly driven by a desire to remain within the EU[1].

Climate change policy in the UK is downgraded in importance during the late 2010s. There is a drive towards 'energy independence', with an emphasis on the use of limited domestic resources, which leads to a revival of coal consumption. Previous commitments under the Paris Agreement are abandoned and the Climate Change Act is repealed in 2021. This means that further limits on emissions beyond the third carbon budget are not implemented. While at the global level the commitment to climate change mitigation continues to be backed up by international agreements, in practice there are significant delays.

---

[1] To ensure that this scenario is comparable with the others, the quantitative data for Energy Island covers the whole of the UK – including Scotland.

Figure 1: Summary of 2017 UKERC scenarios

Governance level	Government decision-making remains centralised at UK level 🔵 🟡	The UK government shares power with devolved and local administrations ⚫ 🟢 🟠	Government decision-making remains centralised but Scotland leaves the UK 🟣	Scotland leaves the UK and power is devolved to remaining countries of the UK	
Economic policy	Dominance of 'small state' philosophy, with weak appetite for policy action to change infrastructure sectors or invest in them 🟣	Some state intervention to shape markets and selective public investment in infrastructure sectors 🔵 🟢	Strongly interventionist state: actively shapes markets and co-invests in infrastructure with the private sector ⚫ 🟡 🟠		
National climate policy	Strong long-term commitment to the environment & climate change mitigation, complemented by sustained action. The UK is seen as a global leader ⚫ 🟡 🟢 🟠	long-term commitment to decarbonisation remains central for UK policy. However action to meet targets is delayed. Different levels of progress are observed across the UK	While there is limited interest in decarbonisation, policy commitment is faltering. There is no incentive to achieve & maintain a global leadership position. The forth carbon budget is achieved, but the fifth budget is not 🔵	Policy commitment is significantly scaled back in the mid to late 2010s. The UK aims to fulfil a minimum level of commitment due to international agreements. The third carbon budget is achieved but further targets are abandoned 🟣	
International climate policy	There is a high level of commitment to climate change mitigation at a global level. Climate policies are implemented in a successful and timely manner ⚫ 🟡 🟠	There is a high level of commitment to climate change mitigation at a global level. However obstacles and delays impede policy implementation 🔵 🟢	There is a fair level of global commitment. However there are significant delays in taking concrete steps and policies are poorly implemented 🟣		
International trade	Continuing commitment to liberalisation of global trade ⚫ 🟡 🟢 🟠	Decreased emphasis on global trade; trade barriers increase 🟣 🔵			
Relationship with the EU	The UK stays in the EU	The UK leaves the EU but agrees compromises to ensure full access to the Single European Market ⚫ 🟡 🟠	The UK leaves the EU. Access to Single European Market on unfavourable terms due to 'red lines' 🟣 🔵 🟢		
Fossil Fuel Prices	High 🟣	Medium 🔵	Low ⚫ 🟡 🟢 🟠		
Environmental awareness	High levels of disposable income have led to continued increases in consumption. There is little interest in sustainability. Environmental awareness and action is low.	Due to economic difficulties, the public is preoccupied with immediate affordability concerns. Environmental awareness is moderate but action is low. 🟣	There is some public interest in sustainability, but it is a secondary concern. Environmental awareness and action by citizens is moderate. 🔵	Sustainability issues gain traction. The emphasis is on demand side reduction, social innovation and the adoption of more sustainable lifestyles as well as decentralised low carbon technologies. Environmental awareness and action is high. 🟠	Sustainability is high on the agenda. The emphasis is on green technology products & 'buying solutions' for climate change, which are seen as a sign of social status. Environmental awareness and action is high. ⚫ 🟡 🟢
Technological progress, particularly for carbon capture and storage	CCS commercialised successfully in the 2020s 🟡	CCS commercialised successfully in the 2020s, but biomass energy with CCS (BECCS) is not permitted ⚫	Delays in commercialisation of CCS offset by faster than expected progress in renewables 🟠 🔵	CCS fails to commercialise 🟣 🟢	

Key to Scenarios:
🟣 Energy Island
🟡 Low Carbon
🔵 Slow decarbonisation
🟢 Low Carbon (no CCS)
⚫ Low Carbon (no BECCS)
🟠 Technology Optimism

Despite the lack of central direction, there is some environmental awareness among the public. However action is minimal. The effects of climate change are becoming increasingly visible in everyday life, particularly in terms of flooding and increased temperatures, though their severity varies across the UK (CCC, 2017a). The demand for energy services continues to decrease, partly due to persistently high fossil fuel prices. Domestic fossil fuel extraction continues throughout the period to 2050. Domestic coal continues to be produced and domestic shale gas is pursued. While there is very little further investment in renewables, the state makes a strategic decision to invest in nuclear power from the mid-2020s.

2.1.2 Slow Decarbonisation scenario

In the world of Slow Decarbonisation, there is a primary focus on economic growth. The UK economy continues to recover from the recession that followed the 2008 financial crisis and the effects of Brexit. A decision is made to leave the single European market. A new trade deal is concluded that offers access to EU markets, albeit on less favourable terms. In parallel the government has successfully concluded other bilateral and multilateral trade deals that provide some benefits to the UK.

Decarbonisation falls down the policy agenda. Commitment to climate change mitigation starts to weaken from the early 2020s. Policies that support the deployment of renewables continue for a time, but are progressively scaled back in the 2030s. While the fifth carbon budget has been agreed, there are constant delays and failures in policy implementation. This means that the fourth carbon budget is still met, but the fifth carbon budget is not. At the international level legally binding agreements are set in place, however their implementation proves to be challenging. The public is mainly concerned with improving their levels of income and is only moderately interested in environmental issues.

The commercialisation of CCS is delayed. Following technical breakthroughs in the 2030s in China, low cost CCS is available in the UK. There is some investment in biomass CCS in the 2030s and 2040s as climate change impacts become more apparent. This is favoured because it allows a lack of progress with the decarbonisation of heat and transport in previous decades to be partly offset. As a result in 2050, heat and transport energy continues to be dominated by fossil fuels.

2.1.3 Low Carbon scenario

In the Low Carbon scenario, the UK continues to meet current statutory carbon budgets and targets. Despite the fact that the UK has left the EU, the economy recovers from the recession of the late 2000s and the immediate effects of Brexit. Compromises during negotiations with the European Commission have allowed UK firms to have full access to the single European market. There have also been further global moves to liberalise trade. The government's economic policy is interventionist, and includes policies to ensure a shift to sustainability and resource efficiency. Government investment in key infrastructures is increasingly common, often in partnership with the private sector.

Climate change mitigation is seen an opportunity to take up a leadership position in the green technology market, both nationally and at an international level. Internationally, ambitious international agreements are set in place, which are ratified by national governments and backed up by policy action in a timely manner. Environmental awareness is relatively high among the public. There is some demand for cleaner technologies which are seen as status symbols.

Fossil fuels production declines in the UK. A continued role for natural gas is facilitated by CCS technologies which are successfully commercialized from 2025 for both electricity and hydrogen production. Biomass CCS (BECCS) also plays an increasingly significant role in electricity generation from 2030 onwards, thereby enabling other sectors to decarbonise more slowly.

2.1.4 Low Carbon scenario without CCS

This is another scenario in which the UK continues to meet its climate change targets. However a failure to successfully commercialise CCS technologies critically affects the way in which decarbonisation is achieved and means that fossil fuels only play a minor role by 2050.

The government's economic policy includes some willingness to intervene to shape markets and invest. Negotiations to leave the EU are difficult and result in a series of sectoral trade deals that provide some access to the single European market, albeit on less favourable terms. Globally, trade liberalisation remains firmly on the agenda for many countries, which helps to offset the impacts of leaving the EU. The UK maintains its current commitment to climate change mitigation and retains its position as a leader in sustained environmental action. Climate policy also maintains momentum at the international level, despite delays in policy implementation. Environmental awareness is high among the public. The main focus is on the adoption of cleaner technologies rather than making fundamental changes in lifestyles.

Fossil fuel prices remain low, therefore there are fewer incentives for production in the UK. The failure of CCS is partly offset by the faster development and cost reductions for some renewables, particularly wind power. Wind and biomass generation increase significantly in the 2020s. This is followed by a rapid expansion of nuclear power after 2030, aided by more favourable economics due to a global revival of investment and technological standardisation. Smarter technologies fail to live up to their initial promise, meaning that electricity system balancing is achieved through interconnectors, biomass and hydrogen power plants.

2.1.5 Low Carbon scenario no negative emissions

This scenario also meets current carbon budgets and targets, but does so without the deployment of negative emissions technologies. Whilst CCS technologies are successfully commercialised from the mid-2020s, public opposition to negative emissions technologies leads to a ban on the deployment of biomass with CCS.

In common with the Low Carbon scenario, the government takes an interventionist approach to economic policy, including a willingness to co-invest in the infrastructure sector. However a key difference is that decision-making responsibilities are shared between central government, devolved administrations and local authorities. Also in common with Low Carbon, this is a scenario in which both UK and international climate change policies are strong and effective. The public is also committed to sustainability; environmental awareness and the levels of individual and community action are high.

In this scenario, electricity generation comes from a diverse range of sources, including gas with CCS, nuclear, wind and hydrogen. Solar and biomass play minor roles. Due to the relatively rapid commercialisation of CCS technologies, there is an important ongoing role for natural gas– particularly for the production of hydrogen through steam methane reforming. However, domestic shale gas production is not pursued. By 2050, most homes have switched away from gas heating systems to other sources such as heat pumps and district heating. Hybrid electric and hydrogen cars and vans are also in widespread use.

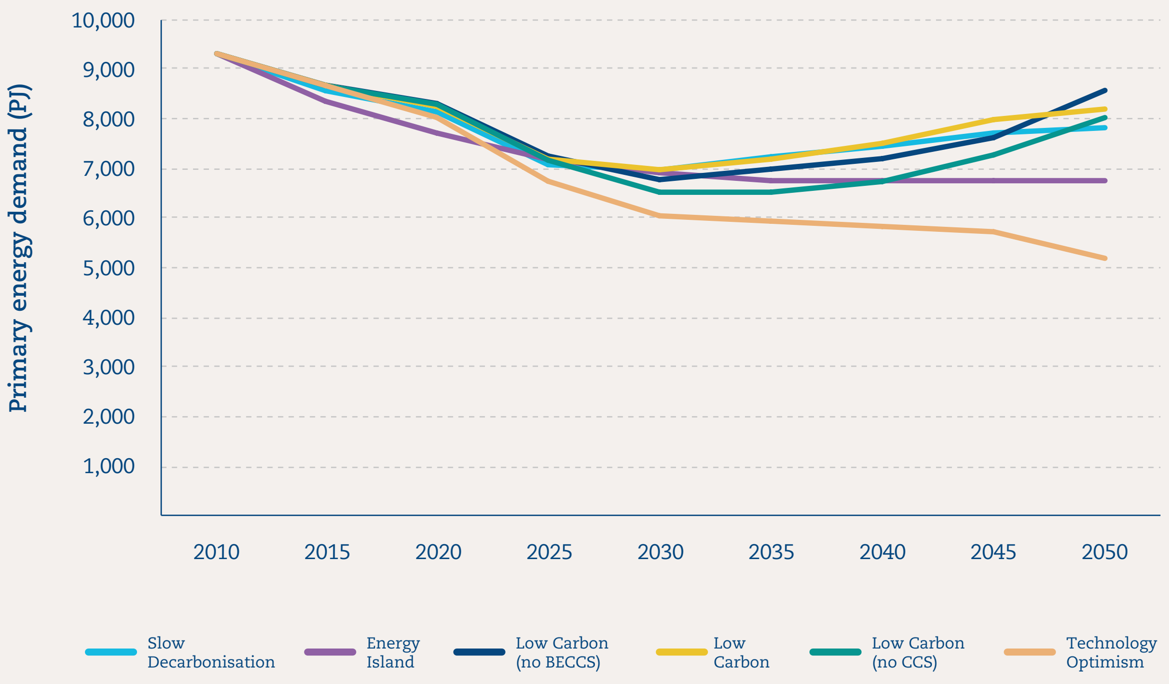
This scenario will be hereafter referred to as 'Low Carbon (no BECCS)'.

2.1.6 Technology Optimism scenario

Technology Optimism is a more decentralised scenario characterised by rapid reductions in the costs of renewable technologies, especially solar PV. The economy returns to long-run average levels of growth following the difficult conditions of the 2010s. However, the pattern of growth and the role of the state change significantly. Decision making is decentralised, with more powers for devolved administrations and local government. Government at all levels is more proactive in shaping markets and investment, and shifting the economy to a more environmentally sustainable trajectory. This radical programme of devolution of power creates political space for a new deal with the European Union that provides full access to the single European market.

The UK maintains its commitment to climate change mitigation. Existing carbon budgets and targets are met, and there is a new commitment to go fully zero carbon in the second half of the century. Similar climate policies are successfully set up and implemented across the globe. This leads to sustained government support for the development and deployment of low carbon technologies. Markets for cleaner technologies grow dramatically. Consequently, the cost of many renewables falls and offsets frustrating delays with the commercialisation of carbon capture and storage. Environmental awareness is high among citizens who are keen to invest in the latest green technologies. In parallel equal emphasis is placed on demand reduction and sustainable living.

Figure 2: Primary energy demand (2010-2050)



In this scenario the energy system is more decentralised, and in 2050 final energy demand falls to less than half of the 2010 level. Petrol and diesel cars are phased out by 2035 in favour of hybrid, pure electric and some hydrogen vehicles. Heavy goods vehicles switch to hydrogen, whilst the use of biofuels for aviation starts to grow from 2025 onwards. By 2050, the UK's electricity needs are met by solar, hydrogen fuel cells, bioenergy and a small contribution from gas with carbon capture and storage. Nuclear power is abandoned because of high costs. To help balance the system, the deployment of storage technologies increases rapidly. The housing stock is overhauled through an ambitious programme of energy efficiency.

2.2 Scenario comparison

This section provides a brief comparison of the scenarios. Figure 2 shows primary energy demand for the period to 2050. From the early 2020s onwards Technology Optimism has the lowest demand levels. In Energy Island, primary energy demand remains at relatively stable levels from 2030 onwards. These two scenarios have lower energy demand than the others because they were assumed to have lower energy service demands in line with their respective storylines.

In the Low Carbon and Slow Decarbonisation scenarios there is an initial decline in primary energy demand. However, there is a visible increase from 2030 onwards. In all cases demand in 2050 is lower than 2010 levels.

Figure 3 shows net greenhouse gas (GHG) emissions from 2010 to 2050. In all cases emissions are on a downward trajectory. However the UK's statutory emissions reductions targets are only met in the Low Carbon variants and Technology Optimism. There are some differences in annual emissions levels over time in these four scenarios because an overall carbon budget is implemented between the 5th carbon budget period and 2050.

In Energy Island there is a reduction to 2030, but progress slows after that date. Emissions in 2050 are only 50% lower than 1990 levels rather than the 80% required by the Climate Change Act. In Slow Decarbonisation emissions decline throughout the period to 2050, but at a slower rate from 2025 onwards. 2050 emissions for Slow Decarbonisation are 60% lower than in 1990.

Figure 3: Net GHG emissions (2010-2050)

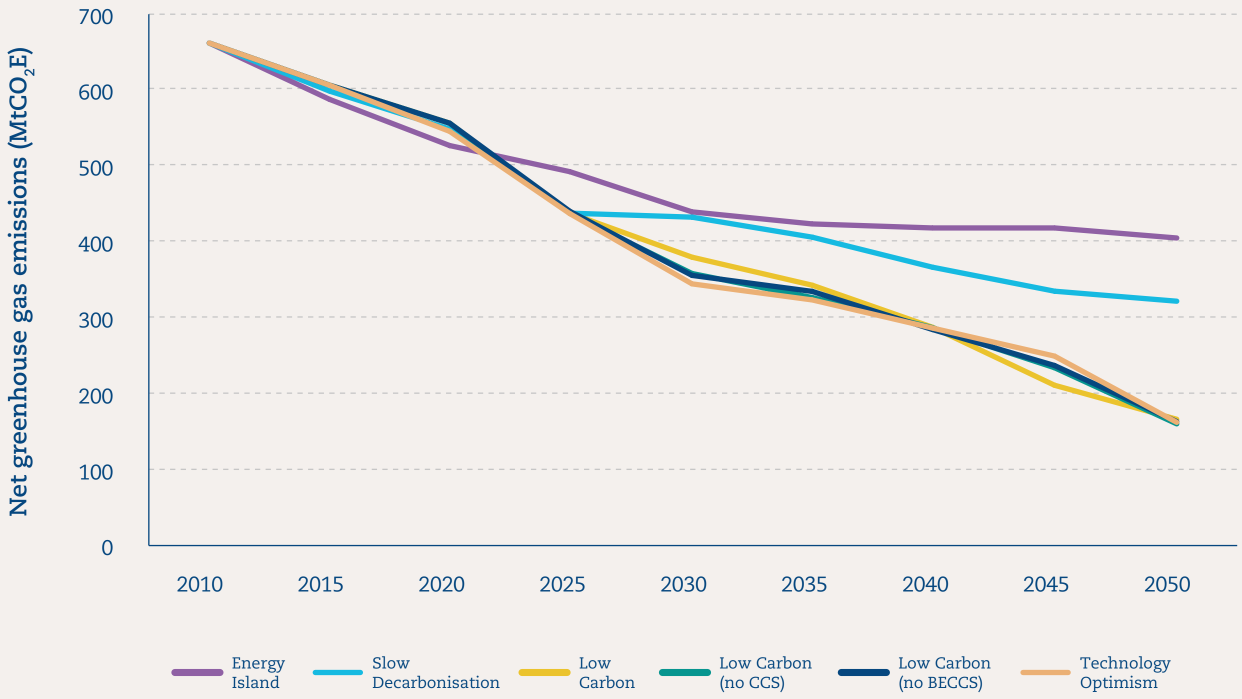


Figure 4: Electricity generation in 2050

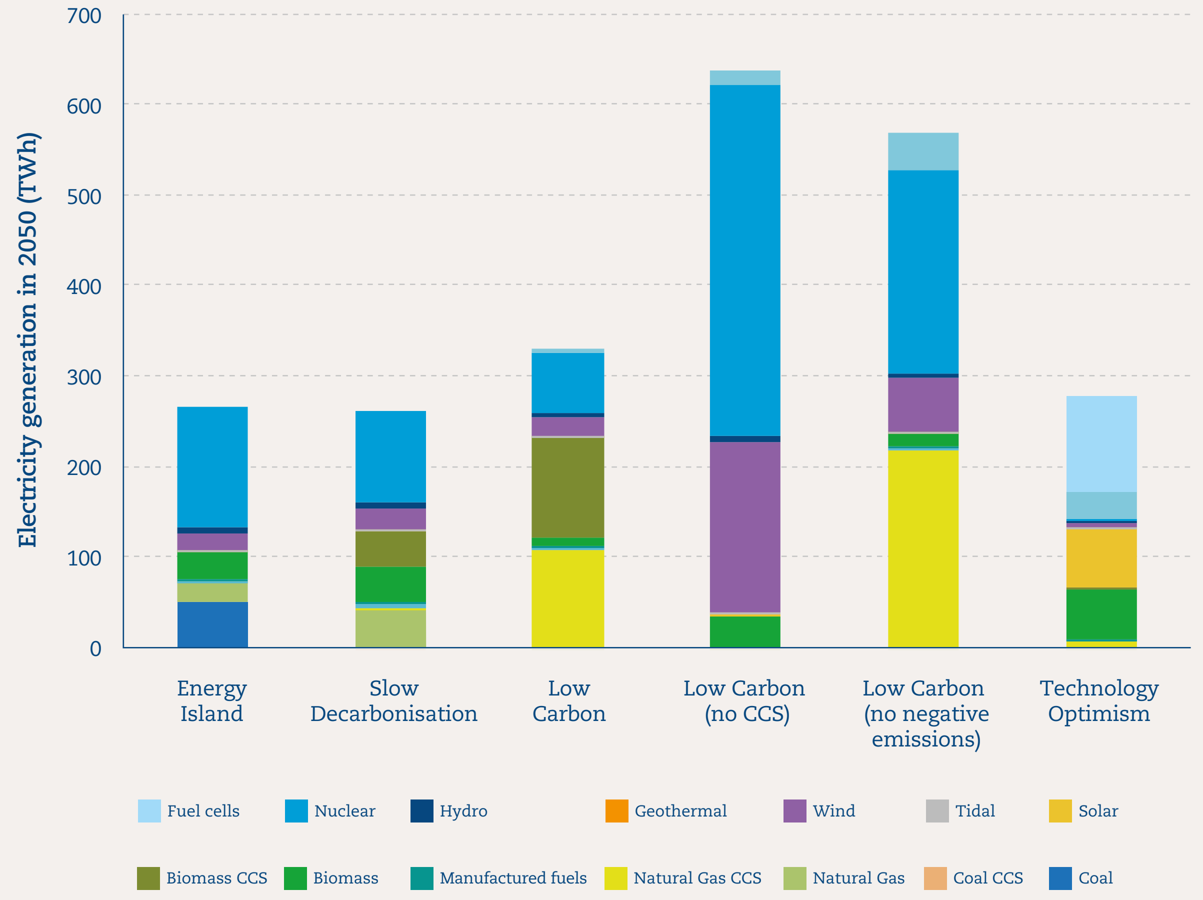


Figure 4 summarises the electricity generation mix in 2050. The level of electricity generation in 2050 tends to be higher in the scenarios that meet the 2050 targets, indicating a higher degree of electrification. The exception is Technology Optimism, in which there is a significant deployment of hydrogen-fuelled technologies and there is more radical action to reduce energy demand. In the two Low Carbon variants where CCS and BECCS are not available, nuclear plays a particularly important role. In the no CCS variant, wind power becomes significant by 2050, while in the no BECCS variant, natural gas CCS is prominent both in 2030 and 2050. As might be expected, coal is only present in the Energy Island scenario. Technology Optimism presents a unique mix, particularly in 2050 where electricity generation is dominated by fuel cells, solar and biomass.

Figure 5: Transport fuel demand in 2050

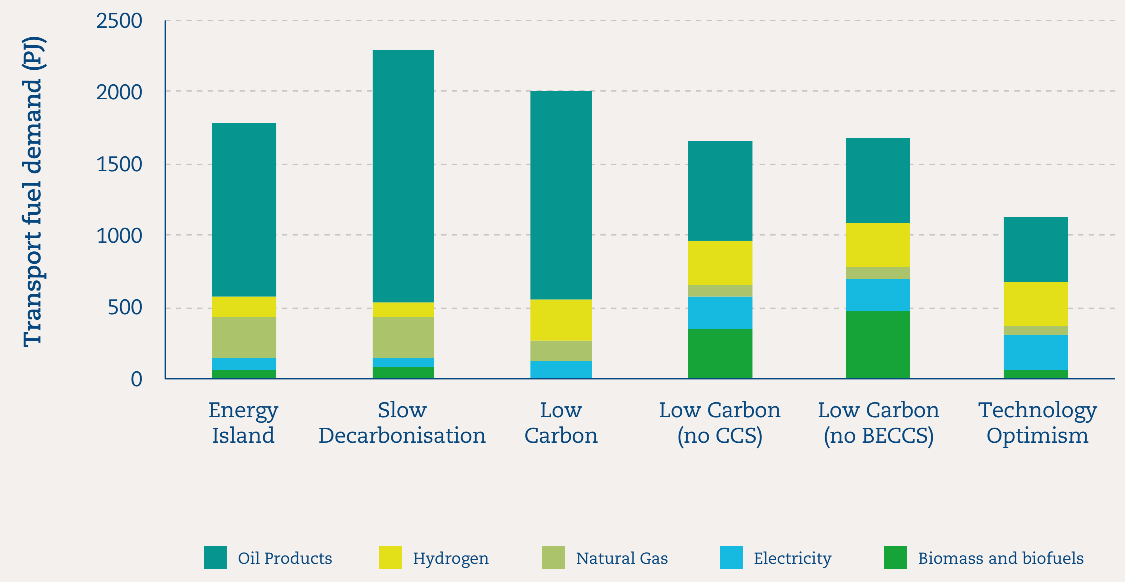
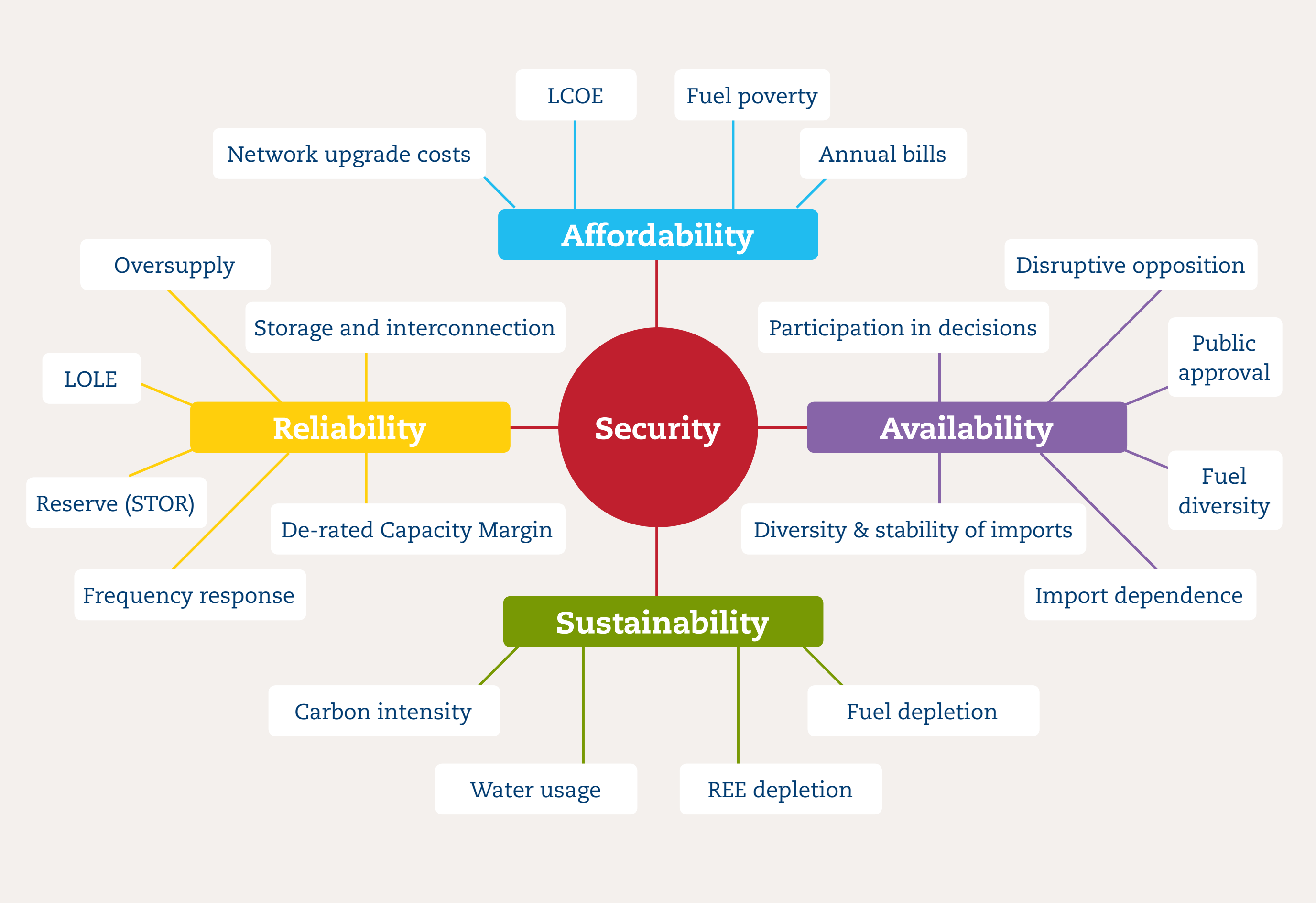


Figure 5 shows transport fuel demand in 2050. In all scenarios, petroleum fuels (or bio-derived versions) continue to dominate aviation and shipping throughout the period to 2050. However, their contribution to road transport is very low in 2050 in Low Carbon (no CCS and no BECCS variants) and Technology Optimism. Hydrogen is present mainly in the Low Carbon variants and Technology Optimism in 2050. Biomass and biofuels make a significant contribution mainly in Low Carbon (no CCS) and Low Carbon (no BECCS) in 2050. Those scenarios, as well as Technology Optimism, are also characterised by a higher degree of transport electrification.

3. Energy security indicators

This section discusses the dashboard of indicators that have been used to assess UK energy security. Our indicator dashboard is based on a framework that was developed by Emily Cox (2018). This framework built on an extensive literature review, and includes four main dimensions of energy security: *affordability*, *sustainability*, *reliability* and *availability*. It includes both short-term shocks and long-term stresses that could affect energy security, and include both quantitative and qualitative indicators (see Figure 6).

Figure 6: Energy security framework, adapted from Cox (2018)



Short term operating reserve (STOR); loss of load expectation (LOLE); resting energy expenditure (REE); levelized cost of electricity (LCOE)

As discussed in the introduction to this report, our research uses a relatively narrow definition of energy security that excludes environmental sustainability. We therefore focus mainly on the horizontal axis of the framework shown in Figure 6: i.e. on the reliability and availability dimensions of energy security. A full list of indicators is provided in Table 1.

Whilst affordability is also an important dimension of energy security, this report excludes most affordability indicators. This is because it is inherently difficult to estimate energy costs or consumer bills several decades into the future. Instead, the relative costs and greenhouse gas emissions from UK TIMES for each scenario will be discussed in the concluding section. This will include potential synergies and/or trade-offs with reliability and affordability.

Table 1: List of indicators used to analyse energy security in the scenarios

Category	Indicator
Availability	Public opposition: electricity and resource extraction
	Diversity of energy and electricity
	Imports and consumption: biomass, oil and gas
Reliability	Electricity system reliability (plus sensitivities)
	Gas system reliability (plus sensitivities)
	Electricity interconnector capacity
	Demand side flexibility (proxies)

3.1 Availability indicators

According to the framework, availability indicators mainly deal with longer term risks to energy security. They include the risk of disruption due to public opposition, the diversity of the energy system and electricity system; and the extent to which the UK is dependent on imported fuels (including, where possible, the diversity of these imports).

Two indicators relating to the risk of public opposition have been calculated based on the methodology developed by Emily Cox. The first indicator assesses the proportion of the electricity generation mix in each scenario that could be vulnerable to public opposition. This is calculated using the results of a national opinion survey from a previous UKERC project on public attitudes to energy system change (Demski et al, 2013). This has important limitations, including the likelihood that public attitudes will change over time and will be partly scenario-dependent. The second indicator of public opposition risk is based on the level of domestic resources used in each scenario (including fossil fuels and biomass). The reasoning is that higher levels of domestic resources could potentially lead to opposition. However, it is also possible that in some scenarios (particularly Energy Island), the use of domestic resources could face much lower risks of opposition.

These two indicators relating to public opposition risk should be considered together to provide a well-rounded assessment. In her original framework, Cox also included the level of public participation in decision making. Whilst this is not explicitly discussed as part of the dashboard of indicators in this project, is considered in the scenario narratives.

The availability indicators also include indicators of energy and electricity diversity, and import dependence. Diversity is calculated using the Shannon-Wiener Index (SWI). This index has been used in energy studies and other disciplines, and combines both variety (the number of options in the mix) and balance (their relative proportions) (Stirling, 1994; Jansen et al, 2004). A higher index indicates a more diverse mix, which consequently is less vulnerable to unexpected disruptions. It has been noted that a value greater than 2 denotes a 'high' level of diversity (Grubb et al, 2006). However, the index is dependent on the extent of disaggregation of the energy mix. A comparison between scenarios that apply the same disaggregation can be more meaningful than considering absolute index values (Cox, 2018). The SWI can be modified so that it also includes disparity: the extent to which different options are different to each other (Stirling, 2010). However, this requires more data, and has not been used here.

The final availability indicator is import dependency, which has been calculated for biomass, oil and gas. It is one of the most widely discussed issues in energy security assessments (McCollum et al, 2013; Spanjer, 2007). However, it is also controversial. Whilst reducing imports is often a policy goal, imports can also help to strengthen energy security – for example by adding to diversity, providing access to low cost resources or by compensating for a lack of indigenous resources (Mansson et al, 2014). The UK TIMES model does not explicitly consider how European and global energy systems are evolving, and so does not provide enough information for a full assessment of the sources, diversity and supply routes of imports. However, some context is provided for this indicator by comparing net import data with demand data for each resource.

3.2 Reliability indicators

In contrast to the availability indicators, the reliability indicators mainly deal with shorter-term energy security challenges and issues relating to the system's ability to respond to sudden changes. Most of these indicators are derived directly from the energy models used in the project.

Indices such as Loss of Load Expectation (LOLE) and Expected Energy Unserved (EEU) are commonly used to assess the reliability of energy systems. The LOLE is a probabilistic weighted average value that measures the likelihood that supply will fail to meet demand and is typically represented by number of hours per year. The UK's electricity security standard is that LOLE should be less than 3 hours per year, which is lower than in some other EU countries. The EEU for any particular period (day, week, year etc) gives the probability weighted magnitude of interruption to energy supplies (size of loss of load).

In this project, these indicators have been calculated for each scenario using a modified form of the CGEN+ (Combined gas and electricity network) model (Chaudry et al, 2008; 2014). This is an optimisation tool for gas and electricity infrastructure. It minimises total operational costs (with optimal values for pressures, gas flow, power generation and load shedding) whilst meeting gas and electricity demand. The model consists of load flow analysis of the electricity network and detailed modelling of the gas network including facilities such as gas storage and compressor stations. The interaction between the two networks is through gas turbine generators connected to both networks (Chaudry et al, 2008). The CGEN+ model has been upgraded to enable time sequential Monte Carlo simulation that is used to analyse reliability (Chaudry et al, 2013).

The UK TIMES model provides all the base data for CGEN+, including the generation capacity mix, energy supply sources and demand data (including peak demand) for both gas and electricity. Given that the UK TIMES model includes no locational information, an additional step is required to distribute the UK TIMES model outputs across geographic locations (especially in relation to generation capacity). The CGEN+ model was used in planning mode[2] to determine the cost optimal location of power plants and associated network investments for both gas and electricity.

Using historical data for energy demand fluctuations on the system and failure rates for network and generation plants, probability density function (Pdf) inputs for the Monte Carlo model were created (see Appendix 2 for more details). The Monte Carlo model is run using an intelligent quasi random sampling technique[3]. This reduces the amount of simulations substantially from thousands of individual runs to hundreds.

The LOLE and EEU indicators are complemented by several other reliability indicators. Due to the contribution of electricity interconnectors to electricity system flexibility and reliability, an indicator of electricity interconnection capacity is taken directly from the UK TIMES model. The representation of interconnectors in UK TIMES has been modified for this project to account for saturation effects. As more interconnector capacity is added to the UK electricity system, the incremental contribution to electricity system security falls.

A separate probablistic model was used to quantify this effect (see Appendix 3 for more details). It models the UK electricity system coupled via interconnectors with a second system, based on France. A series of runs of the probabilistic model were used to understand the impact of a range of factors on the 'capacity value' of interconnection: i.e. the contribution to system security (see Figure 7). These factors include variations in electricity demand, changes in demand profile, variations in wind capacity and the correlation of wind output in different areas, and variations in generator availability. The results show how the marginal capacity value falls as interconnector capacity increases for different model runs.

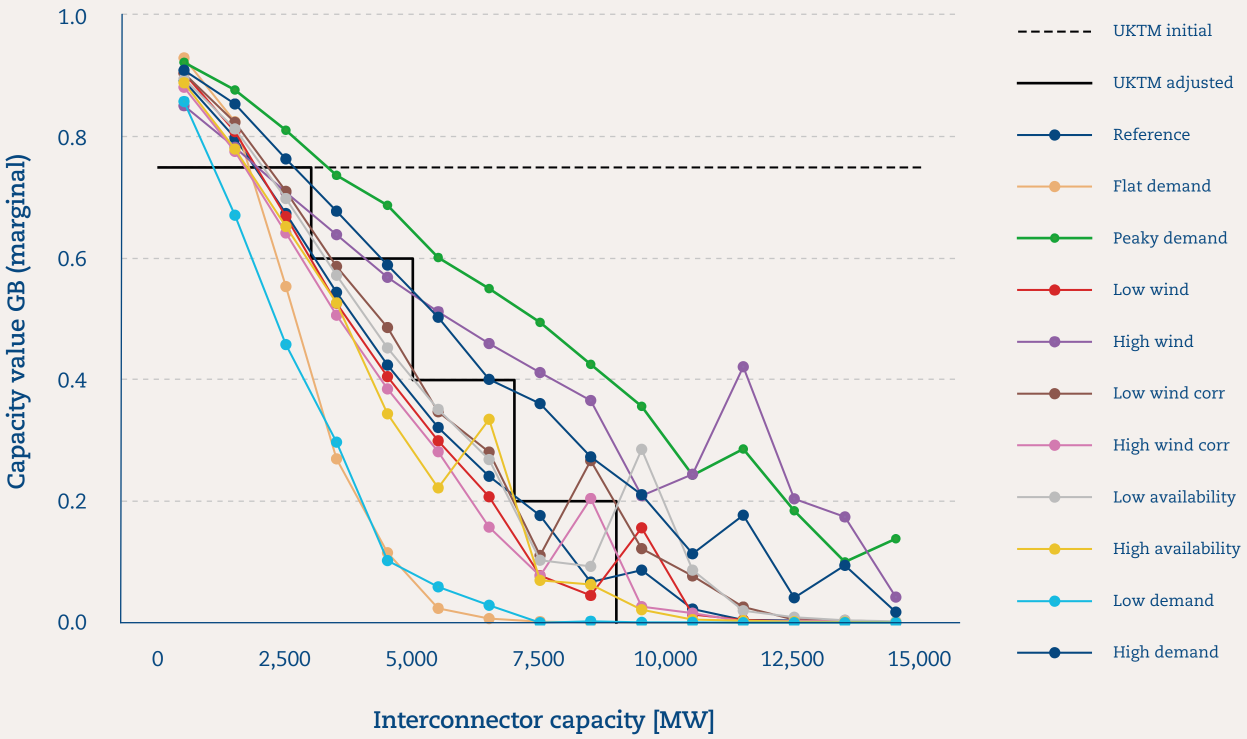
On the basis of this analysis, the UK TIMES model was updated to include this saturation effect. Figure 7 shows that the marginal capacity value starts from approximately 95% (the assumed technical availability of the interconnectors) and reduces steadily to 0% as saturation sets in. The default marginal capacity value for the UK TIMES model is shown as a dashed line, and the adjusted value is shown as a solid black line. The first 3GW has a 75% contribution (unchanged from the default position), and the next 2GW blocks have marginal capacity values of 60%, 40%, 20% and 0%, respectively. Above 9GW, the marginal capacity value is zero. The addition of interconnection capacity beyond 9GW by the model is therefore solely driven by cost or emissions reduction objectives.

---

[2] The CGEN+ model in planning mode was run with a rolling time horizon approach. So instead of simulating the model for 40-50 years it was run every 10 years. This reduces perfect foresight from 40-50 to 10 years. This captures uncertainties reflecting the reality of how decisions are made (without perfect information).

[3] A quasi random sampling – SOBOL sequence was used. These types of sequences are sub-random. The advantage they have over pure random numbers is in that they cover the domain of interest quickly and evenly therefore applications such as Monte Carlo simulations would need far less iterations to reach a similar level of confidence.

Figure 7: Marginal capacity contributions as a function of installed interconnector capacity



The final reliability indicators are focused on factors that could contribute to electricity system flexibility and reliability. Two proxy indicators for demand side flexibility have been included, building on Emily Cox's original framework: the numbers of electric vehicles (EVs) and the numbers of heat pumps. In UK TIMES, EVs are already assumed to contribute to flexibility, through "smart" overnight charging of part of the fleet to avoid increasing peak evening electricity demand.

Clearly, these are only partial proxies for demand side flexibility, and they do not cover other important areas of flexible demand. The broader impact of demand side flexibility on electricity and gas system reliability is explored in this report through sensitivity analysis using the CGEN+ model. As other research has shown, demand side flexibility has significant potential to help balance supply and demand (e.g. Poyry, 2017).

These indicators also leave out the role of electricity and gas storage, which is another option for improving flexibility and reliability. Whilst gas storage capacity is not assessed in a separate indicator, it is explored through sensitivity analysis using the CGEN+ model. Electricity storage is not reported as a separate indicator because of the way the UK TIMES model works. As part of the least cost optimisation, the model tends to flatten electricity demand profiles in most scenarios – with the partial exception of Technology Optimism. Moreover, the temporal resolution of UK TIMES is very limited compared with CGEN+, and so demands for storage are not resolved. As a result, UK TIMES invests in very little new electricity storage capacity. In reality, significant growth in electricity storage would be expected in most of our scenarios.

The role of electricity storage has been analysed in more detail in other recent studies. For example, a report for the Committee on Climate Change on the role of flexibility in decarbonised electricity systems investigated a range of flexibility options, including an additional 6-35GW of electricity storage by 2030 (Poyry, 2017). This additional storage was modelled alongside other flexibility strategies including flexible generation, interconnection and demand side response.

4. UK energy security assessment

This section of the report presents the results of the security assessment for each of the scenarios. Where possible, the indicators for 2030 and 2050 for each scenario are compared to the current situation, using 2016 data from the Digest of UK Energy Statistics.

4.1 Availability indicators

4.1.1 Public opposition and domestic disruption

This section examines the risks of public opposition to energy system change, focusing on the electricity generation mix and the use of indigenous fossil fuel and biomass resources.

Figure 8 shows the risk of public opposition to the electricity mix in each scenario up to 2050. In 2016, 24% of the electricity mix comprised technologies that have relatively low levels of public support (and are therefore at risk of public opposition). In all scenarios except for Energy Island, the risk of public opposition falls by 2030, since the electricity mix changes to incorporate a larger proportion of technologies with higher levels of public support. However in Energy Island, Slow Decarbonisation, Low Carbon (no CCS) and Low Carbon (no negative emissions) there is an increase in the risk of opposition from 2030 to 2050. In three of these scenarios, the risk is higher in 2050 than it was in 2016. In 2050 significant differences between scenarios can be observed, with 2% to 33% of the electricity mix at risk of opposition. It is worth noting that Energy Island consistently has a higher risk score than the other scenarios. The rise in opposition ratings in the scenario from 2030 to 2050 can be attributed to a significant decrease in wind and an increase in nuclear power.

Figure 9 shows the production of domestic fossil fuel and biomass resources in the scenarios. In all cases except Energy Island, we see the levels of indigenous resource production falling in the period to 2050. The relatively consistent level of domestic production in Energy Island is in line with the narrative of that scenario, and the constraints on imports that have been imposed on the UK TIMES model. UK coal mining experiences a revival, and there is significant development of UK shale gas in this scenario. Domestic resource production is also high in Slow Decarbonisation in 2030, followed by a significant drop in the period to 2050, when gas production (including shale gas) is gradually abandoned. Production in the Low Carbon scenario variants remain relatively constant at just below 2000PJ/year. Technology Optimism is characterised by the lowest level of domestic resource production due to a policy decision to phase out fossil fuel production. This suggests that the risk of active opposition is likely to be lower in the Low Carbon and Technology Optimism scenarios. However, this opposition could be tempered in the Energy Island scenario if there are perceived to be economic and social benefits from the use of indigenous resources.

Figure 8: Risk of public opposition to the electricity mix

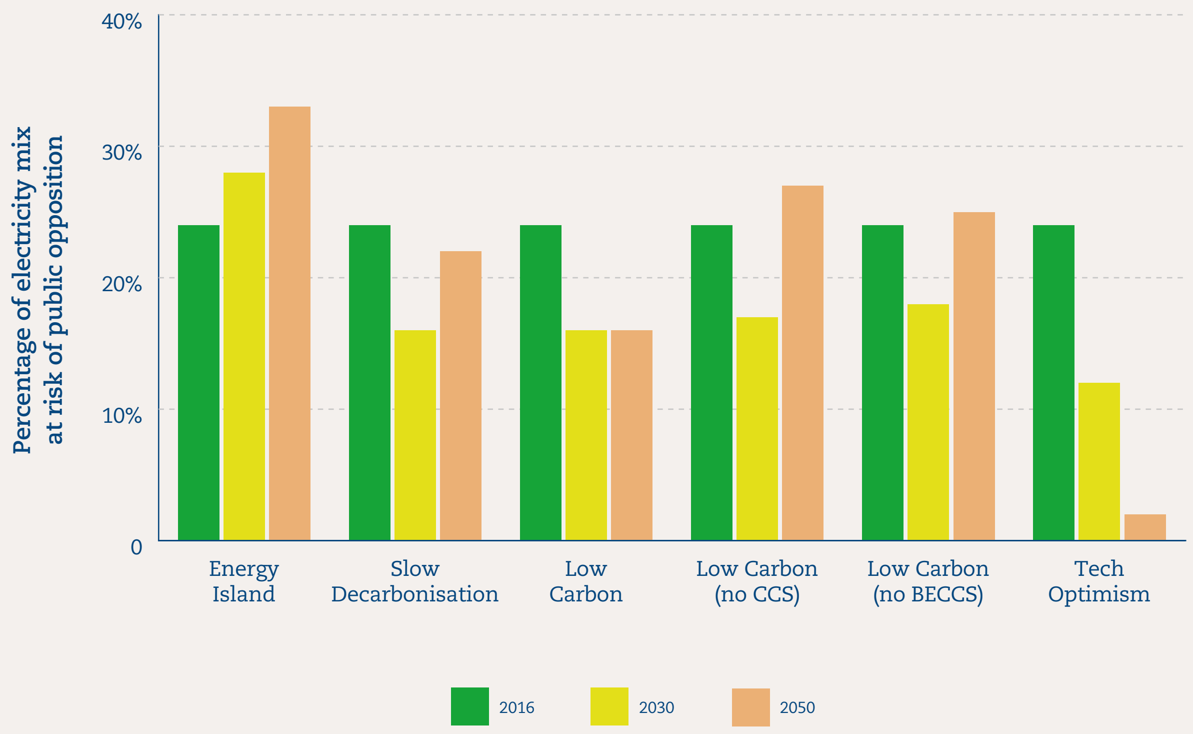
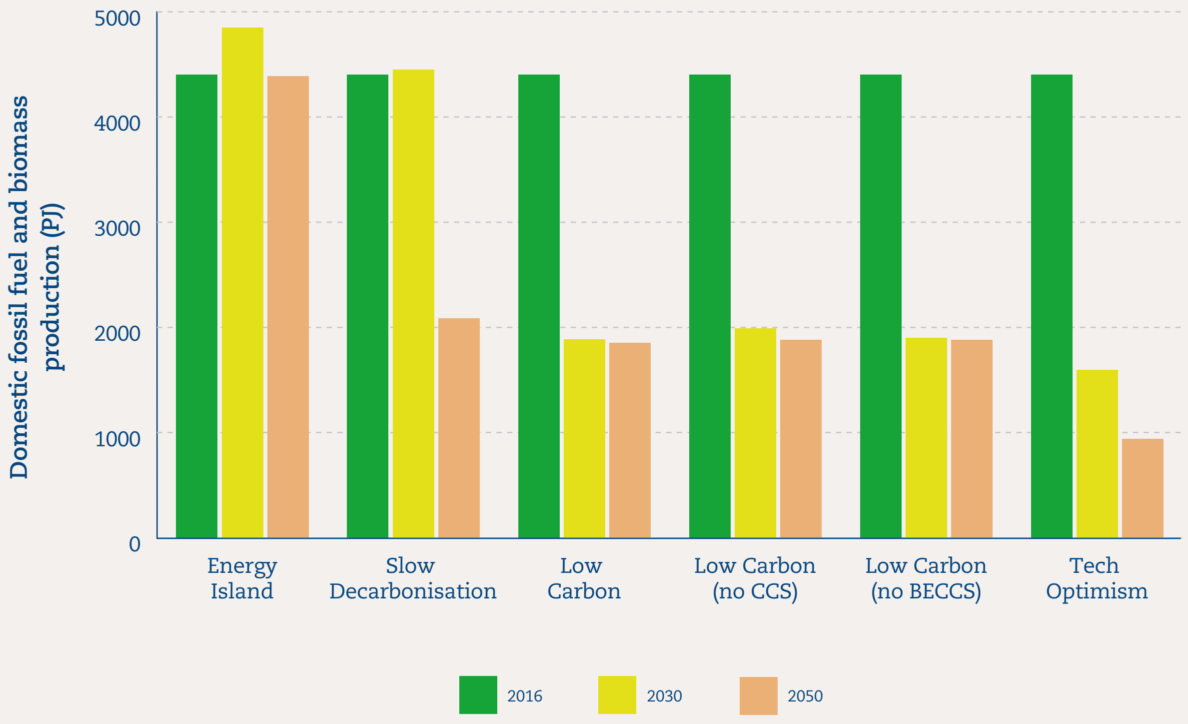


Figure 9: Production of domestic fossil and biomass resources in the scenarios



4.1.2 Diversity

The Shannon-Weiner index for primary energy in 2016 and 2050 is displayed in Figure 10. In line with the trend in many other OECD countries, this index has increased significantly over the past decade due to an increase in the share of renewable energy. This improvement builds on an earlier increase in diversity during the 1980s and early 1990s due to the increasing role for gas (and corresponding decline of coal) in the UK energy system.

Small changes in diversity are observed for most scenarios in 2030. Energy Island and Low Carbon (no CCS) scenarios show larger increases in diversity from the 2016 level of 1.39 – to reach 1.62 and 1.57 respectively by 2030. In 2050 Energy Island and Low Carbon (no CCS) continue to be the highest scoring scenarios at 1.66 and 1.61 respectively. Technology Optimism in 2050 scores slightly lower than the current level, at 1.30. This is because biomass and natural gas make up approximately two thirds of the energy mix in 2050, while in other scenarios there is a better balance between different energy sources.

Figure 11 shows the diversity index for electricity generation. In most scenarios the index is higher or similar in 2030 to the current level. Diversity then decreases in all scenarios between 2030 and 2050, except Slow Decarbonisation. In 2050, the most diverse scenarios are Slow Decarbonisation, Low Carbon and Technology Optimism. The least diverse scenario in 2050 is Low Carbon (no CCS). This is largely due to the dominance of nuclear (at 58% of electricity generation) and wind (at 28%) in 2050.

Figure 10: Shannon-Wiener Index for primary energy

Figure 11: Shannon Weiner index for electricity

4.1.3 Import dependence

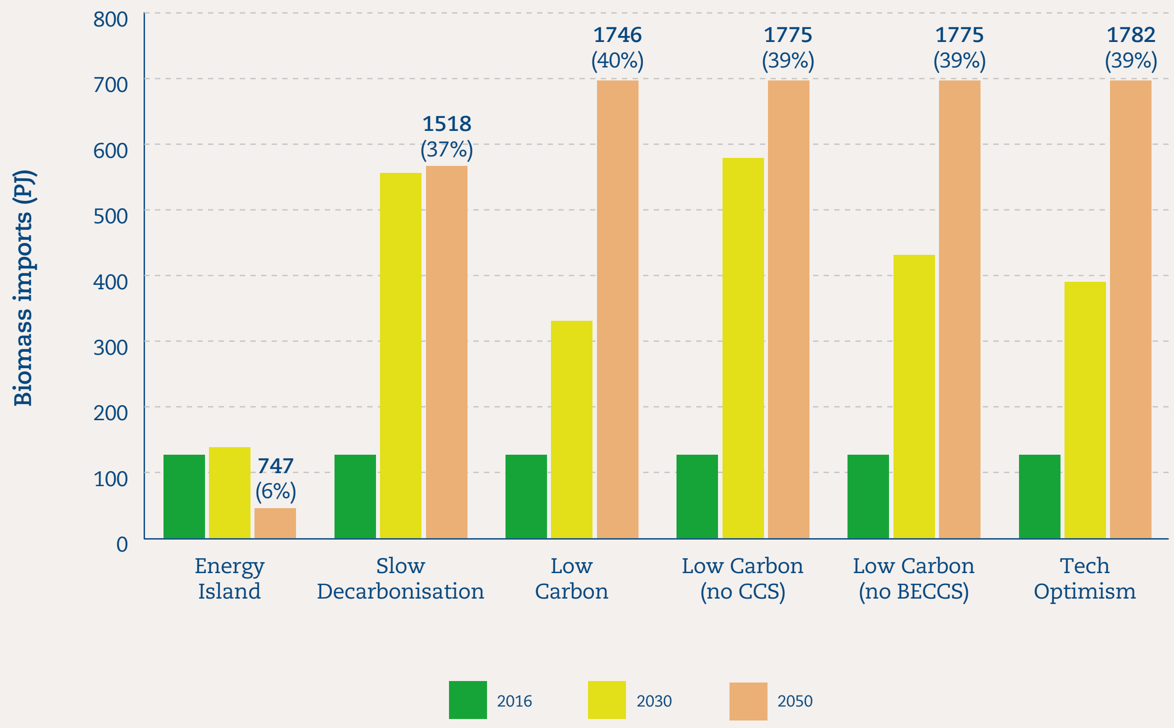
4.1.3.1 Biomass

The level of biomass imports across the scenarios is shown in Figure 12. In all scenarios solid biomass, i.e. wood crops, is the main type of import, except in Energy Island where ethanol is the key import. There is a large rise in biomass consumption between 2016 and 2050. In all except Energy Island there is also a rise in biomass imports. In 2050 a higher level of imports is observed in the Low Carbon scenario variants and Technology Optimism, illustrating the higher level of biomass consumption in these scenarios to help meet climate targets. The levels of biomass consumption and imports are similar in these four scenarios because there is a limit imposed in the UK TIMES model to reflect constraints on resource availability and/or concerns about sustainability. Biomass imports and consumption are lower in Slow Decarbonisation. The low level of imports in Energy Island reflects the importance of self-sufficiency in this scenario.

4.1.3.2 Oil

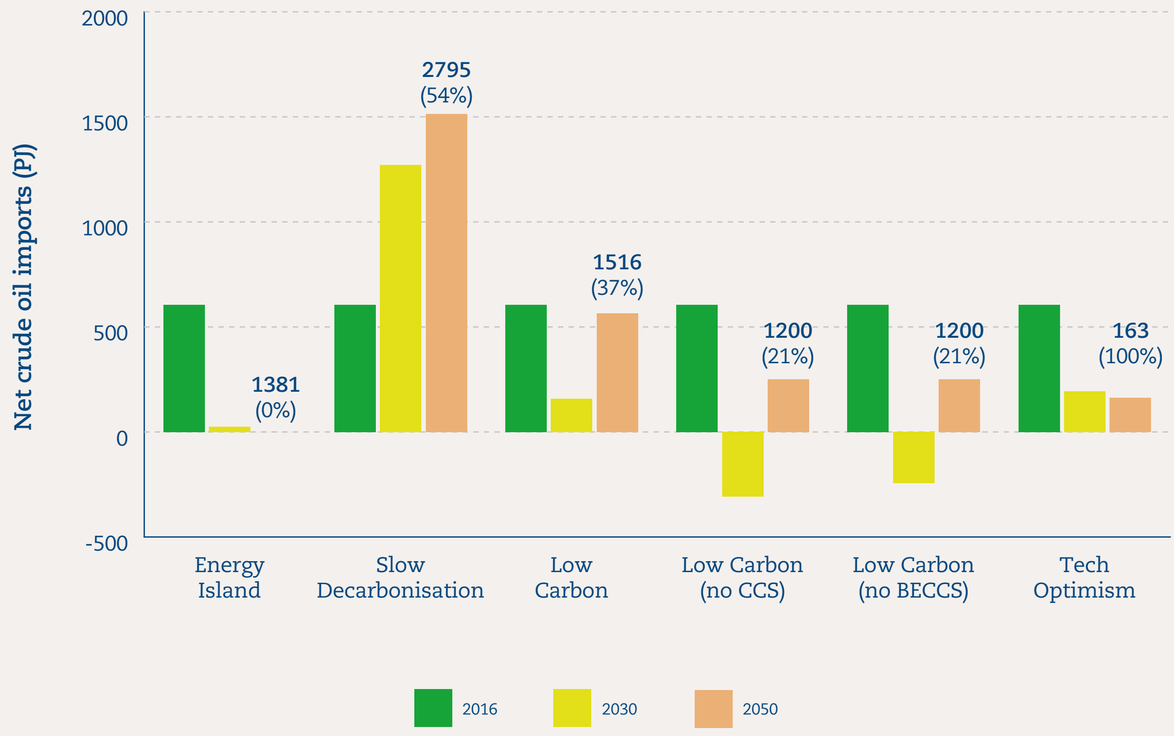
The level of UK crude oil imports in the scenarios is shown in Figure 13. Note that these figures do not include oil products, which have different trade patterns to crude oil. In most scenarios imports fall from their current levels by 2050, with the exception of Slow Decarbonisation which includes a significant increase. In all scenarios, crude oil demand falls from 2016 levels – though the extent of demand reduction varies significantly. Demand in Slow Decarbonisation falls to 76% of 2016 levels by 2050, whilst demand in Technology Optimism is less than 5% of the 2016 level by the same date.

Figure 12: Biomass imports and consumption



Data labels show consumption and % of imports. 2016: 127PJ, 61%

Figure 13: Net crude oil imports and consumption



Data labels show consumption and % of imports in 2050. 2016: 3658PJ (17%)

4.1.3.3 Gas

Data on gas consumption and imports in 2030 and 2050 are shown in Figure 14. In 2050 imports in Slow Decarbonisation, Low Carbon, Low Carbon (no BECCS) and Tech Optimism are higher than 2016, with the highest level of gas imports observed in Low Carbon. In Low Carbon (no CCS) there is an increase in gas imports in 2030, followed by a steep drop in 2050. This reflects the fall in gas consumption required to meet climate change targets without the availability of CCS. Gas imports also drop significantly in Energy Island due to the emphasis on self-sufficiency in this scenario.

The figure also shows the composition of gas consumption in more detail for each scenario, including whether imported gas is by pipeline or ship (as LNG) and the extent of any shale gas production. These detailed figures should be treated with caution since they depend on estimates of relative costs a long way into the future. In the case of UK shale gas, there is not yet sufficient evidence to estimate costs with any precision. Therefore, UK shale gas production was only introduced in those scenarios where this could be compatible with the scenario narrative – i.e. in Energy Island and, to a lesser extent, in Slow Decarbonisation.

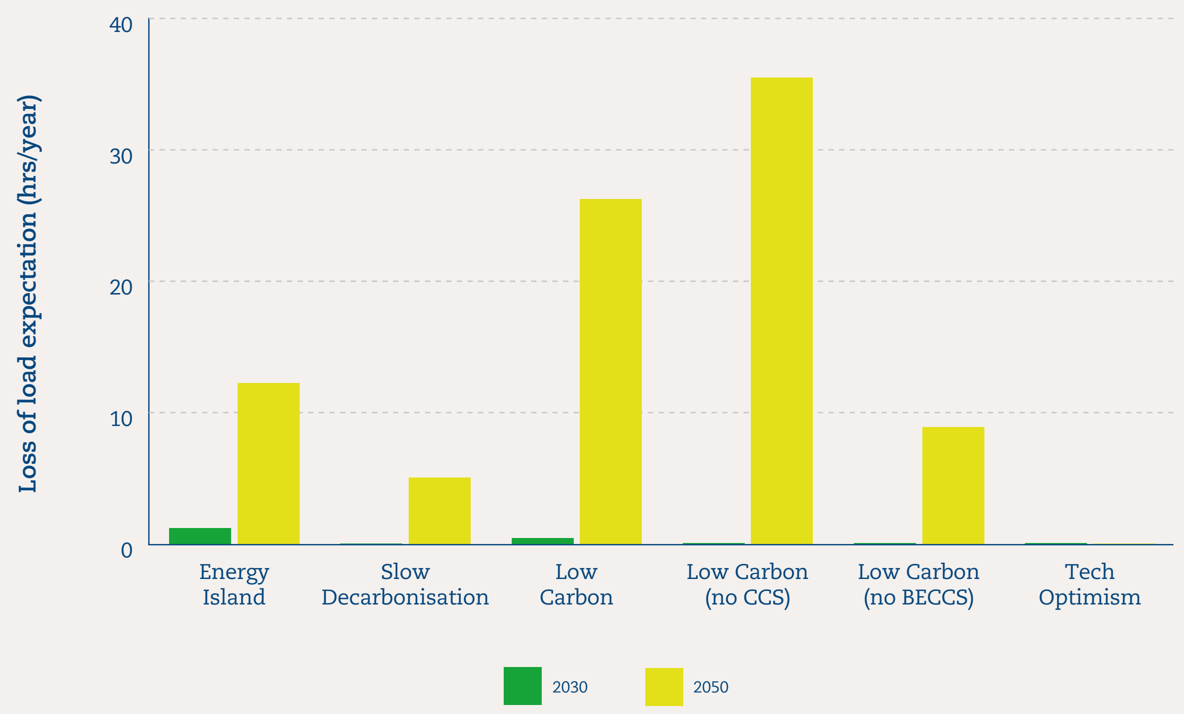
Figure 14: Gas consumption and imports in 2030 and 2050

4.2 Reliability indicators

4.2.1 Electricity system reliability

The electricity system Loss of Load Expectation (LOLE) in each scenario is shown in Figure 15. All scenarios meet the current security standard of 3 hours or less per year in 2030, but in 2050 five of the six scenarios breach this standard by a significant margin. For comparison, LOLE for winter 2016/17 was assessed by National Grid to be 0.5 hours per year (or 8.8 hours per year if contingency balancing services are excluded) (National Grid, 2016).

Figure 15: Electricity system LOLE in 2030 and 2050

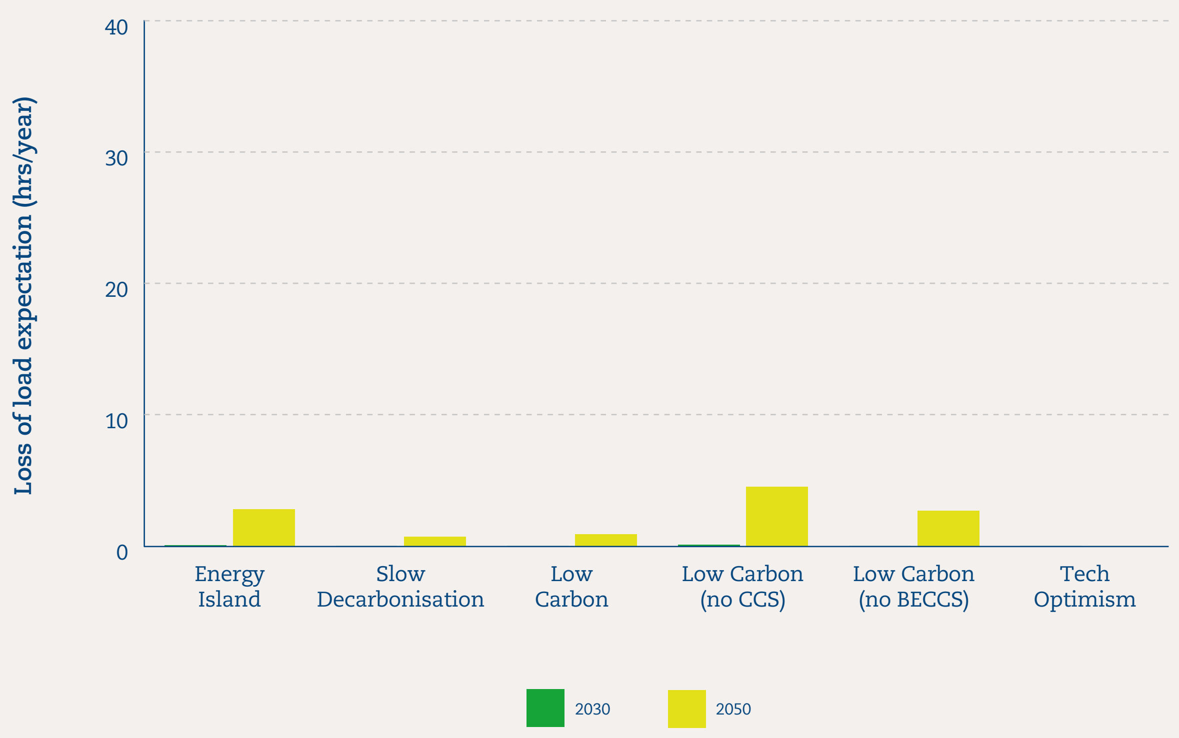


A more detailed analysis of the results highlights the following features in 2050:

- Energy Island has approximately 64GW of installed capacity and an average peak demand of 45GW. The LOLE is 12 hours per year. Although it does not meet the security standard, this system would still have a reliability of greater than 99%. The Expected Energy Unserved (EEU) is 105GWh.
- Slow Decarbonisation has a larger capacity than Energy Island scenario, with similar average peak demand. Unlike Energy Island, coal generation has been phased out – and there is also double the capacity of gas-fired plants. This results in a LOLE of around 5 hours per year and EEU of 26GWh.
- Low Carbon has a mix of low carbon generation technologies installed such as wind, nuclear, hydrogen and fuel cells plus >10GW of import capacity. This scenario has the highest gas demand in 2050, leading to constraints on gas supplies. The average peak demand is approximately 50GW resulting in a moderately high LOLE of 26 hr/year and EEU of 44GWh.
- Low Carbon (no CCS) has the largest average peak demand (104GW), and a total installed capacity of 193GW. A combination of high average peak demand and low contribution of wind during peak periods contributes to the highest LOLE of 35.5 hours per year and EEU of 205GWh.
- Low Carbon (no BECCS) also has a high peak demand (94GW) and generation capacity (145GW). The LOLE is 8.9 hours per year, which is higher than the current security standard. EEU is 19GWh.
- Technology Optimism has the highest installed capacity (~200GW) and a low average peak demand (47GW). The net capacity margin is therefore very high at 72%. Despite the lack of contribution to peak demand from solar PV, the combination with other generation technologies and flexibility results in a very low LOLE and EEU.

Figure 16 shows the impact of adding 3GW of demand side management (DSM) to the CGEN+ model (Ofgem, 2016). In the current system, this could be implemented through mechanisms available to National Grid to balance short term supply and demand. In the model, this DSM is assumed to be equally available around the electricity network, thus freeing up capacity bottlenecks and substituting for generation. This leads to a dramatic reduction in LOLE in 2030 and 2050. In all scenarios except Low Carbon (no CCS) in 2050, the LOLE figures are less than the current security standard. The figures for Expected Energy Unserved also reduce when this sensitivity test is performed, for example from 205GWh to 12GWh in Low Carbon (no CCS). This highlights the impact that DSM with the equivalent capacity of a large nuclear power plant could have on reliability.

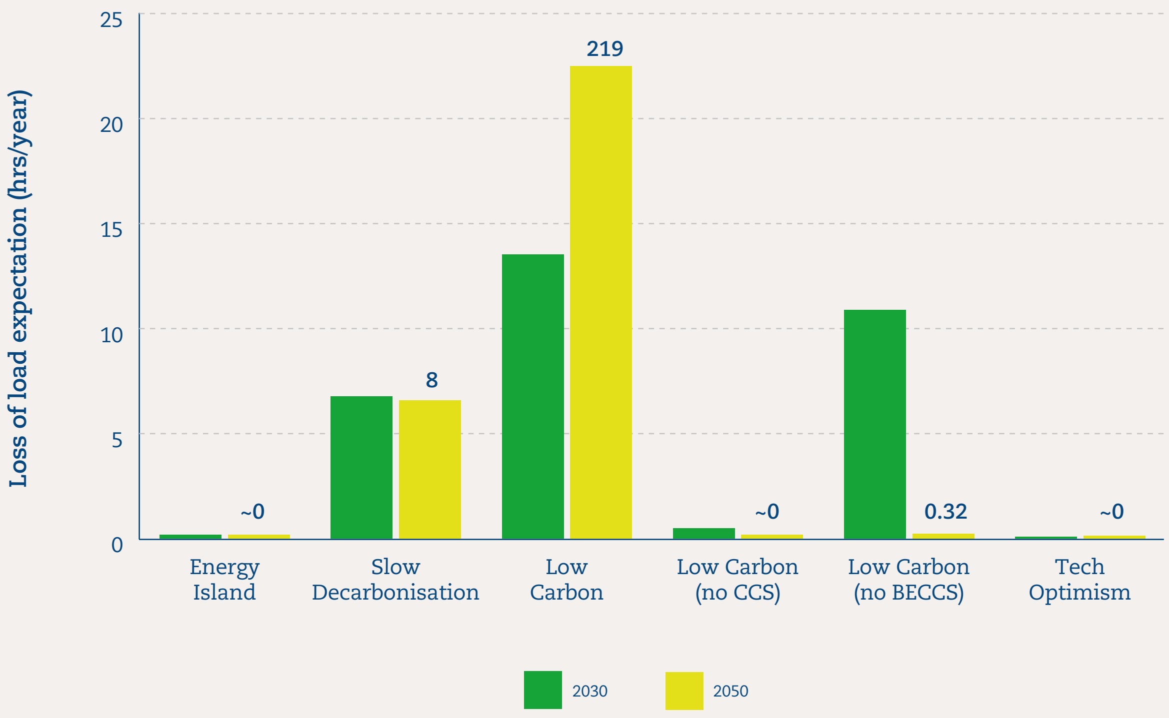
Figure 16: Impact of additional Demand Side Management (DSM) on LOLE



4.2.2 Gas system reliability

The LOLE of the gas system for each scenario is shown in Figure 17. Current assessments of gas system reliability do not use this metric, so it isn't possible to provide a direct comparison with the 2016 level of LOLE. However, it is clear from the analysis that three scenarios have low LOLE values in 2030, and four of them have an LOLE of less than 1 hour in 2050. The Low Carbon and Low Carbon (no BECCS) scenarios have the highest gas demand in 2030, with LOLE of 11-14 hours per year and EEU of 25-45 mcm. Slow Decarbonisation also has a significant LOLE value of 7 hours per year in 2030. Whilst significant, these levels could be mitigated by demand side management via interruptible contracts and industrial and commercial demand flexibility (see Figure 18). In 2050 the Low Carbon scenario has the highest gas demand, LOLE and EEU. LOLE is 22 hours per year and EEU is 219 mcm. For comparison, peak daily gas demand in the UK reached 370mcm in winter 2015/16.

Figure 17: Gas system LOLE in 2030 and 2050

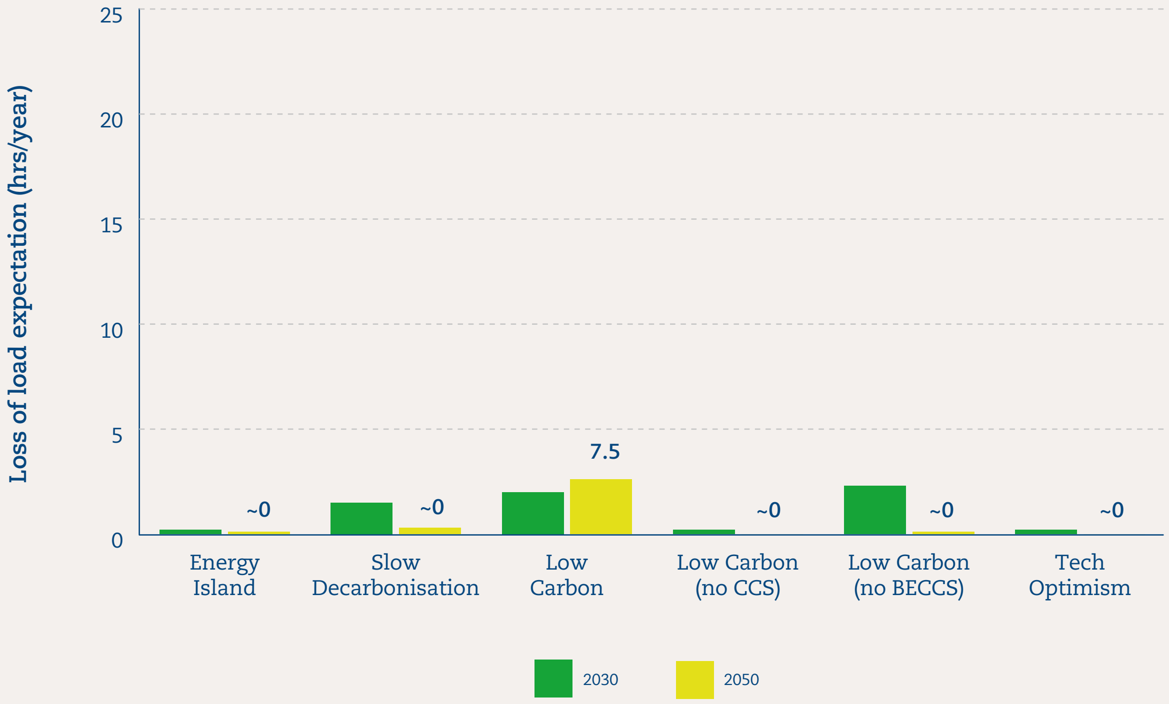


Data labels show EEU in 2050 (mcm). Peak daily demand in 2016 is 370mcm

Figure 18 illustrates the impact of including demand side response in the model. Demand side response was applied to the industrial and commercial sectors of 10 mcm/d (from Poyry, 2010). As was the case for the electricity system, DSM has a large impact on LOLE and EEU. In the least secure Low Carbon scenario, LOLE for 2050 falls from 22.5 to 2.7 hours per year and EEU falls from 219 to 7.5 mcm. The gas system and gas flows are highly non-linear. Therefore, moderate amounts of DSM are likely to have a large impact on loss of load.

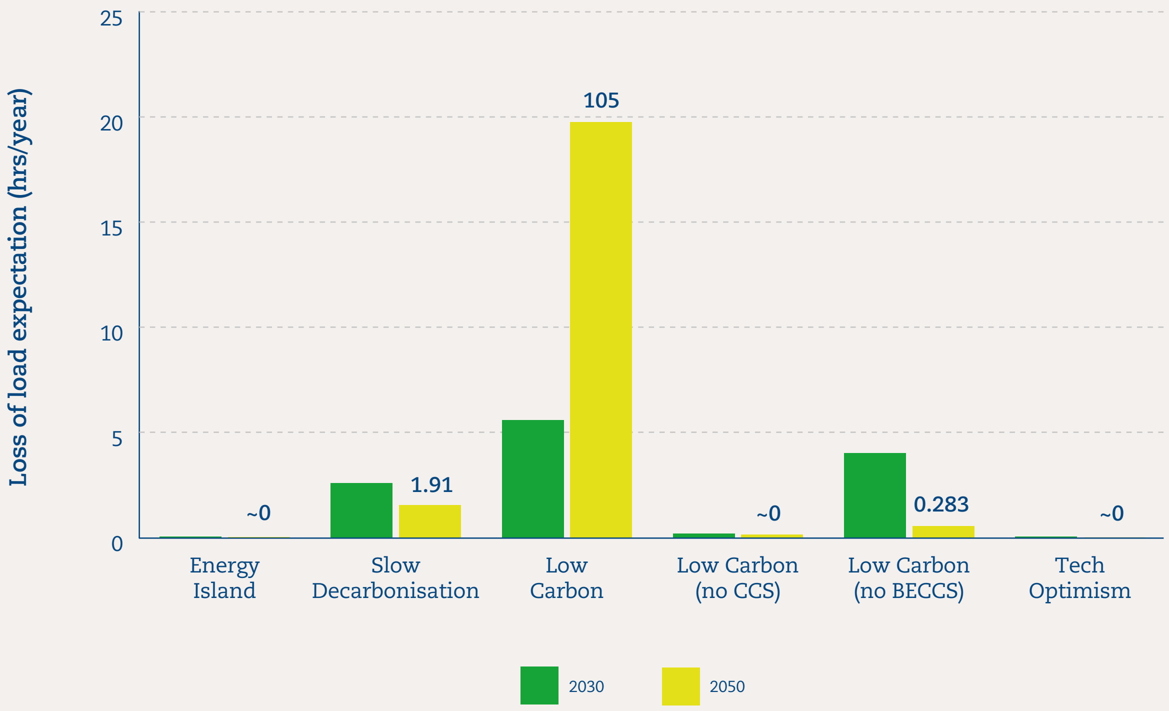
Figure 19 shows a further sensitivity that was explored for gas. It shows the impact of adding gas storage with a similar capacity to the recently decommissioned Rough facility. There is a significant reduction of LOLE and EEU for all scenarios, though these reductions are not as large as for the DSM sensitivity. In the least secure Low Carbon scenario we see a reduction of LOLE, and a significant reduction in EEU in 2050 from 219 to 105 mcm. This particular sensitivity only leads to small reductions in electricity system LOLE and EEU. This is partially because gas fired generation plants are running at near maximum capacity. Therefore, any increase in gas availability will tend only to alleviate losses in the gas system.

Figure 18: Impact of DSM on gas system LOLE



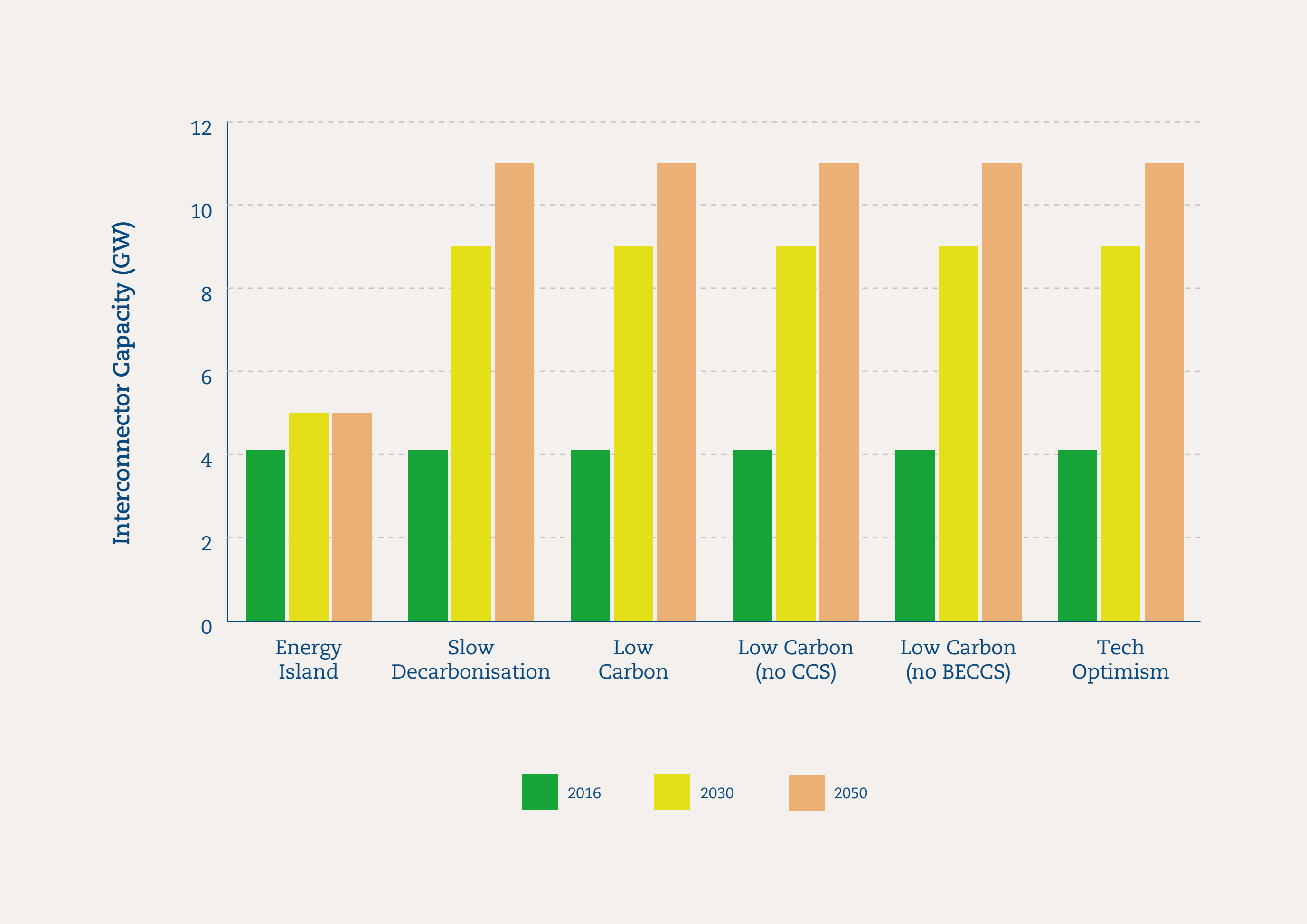
Data labels show EEU in 2050 (mcm). Peak daily demand in 2016 is 370mcm

Figure 19: Impact of additional gas storage capacity on gas system LOLE



Data labels show EEU in 2050 (mcm). Peak daily demand in 2016 is 370mcm

Figure 20: Interconnector capacity



4.2.3 Electricity interconnectors

The capacity of electricity interconnectors in each scenario is shown in Figure 20. Apart from Energy Island, where constraints are imposed on the extent of energy imports, interconnection capacity increases uniformly in all scenarios. Capacity grows from the current level of 4GW to 11GW in 2050, and net imports during 2050 reach 33TWh.

Whilst increasing the level of interconnection from current levels will tend to improve security, it is important to take into account saturation effects. As discussed in section 3, this means that as more interconnection capacity is added, the incremental improvement in the security of the electricity system (the ‘capacity value') will steadily fall. As discussed in section 3, the UK TIMES model assumptions have been modified to reflect this.

4.2.4 Demand side flexibility

Demand side response has already been discussed in this section of the report in relation to electricity and gas system reliability. In addition to this, we are using two indicators that could be seen as partial proxies for demand side flexibility – the number of electric vehicles and the capacity of heat pumps. In principle, both could be used to help balance the electricity system.

Whilst there is a lot of interest in EVs and the market is growing rapidly, there were only approximately 90,000 electric vehicles[4] in the UK in 2016. As Figure 21 shows, there is a steep increase in the adoption of electric vehicles (EVs) in some scenarios between 2030 and 2050. The figure includes battery and plug-in hybrid cars and vans, as they can all potentially contribute to system flexibility. Plug-in hybrid vehicles are adopted much earlier across all scenarios except Technology Optimism. Electric and plug-in hybrid vans are also characterised by increasing adoption – especially in the Low Carbon scenarios. The highest level of adoption of pure EVs is seen in Technology Optimism, where they account for more than 60% of road transport demand in 2050.

---

[4] Data on cumulative EV registrations from www.nextgreencar.com/electric-cars/statistics/

Figure 21: Number of electric vehicles

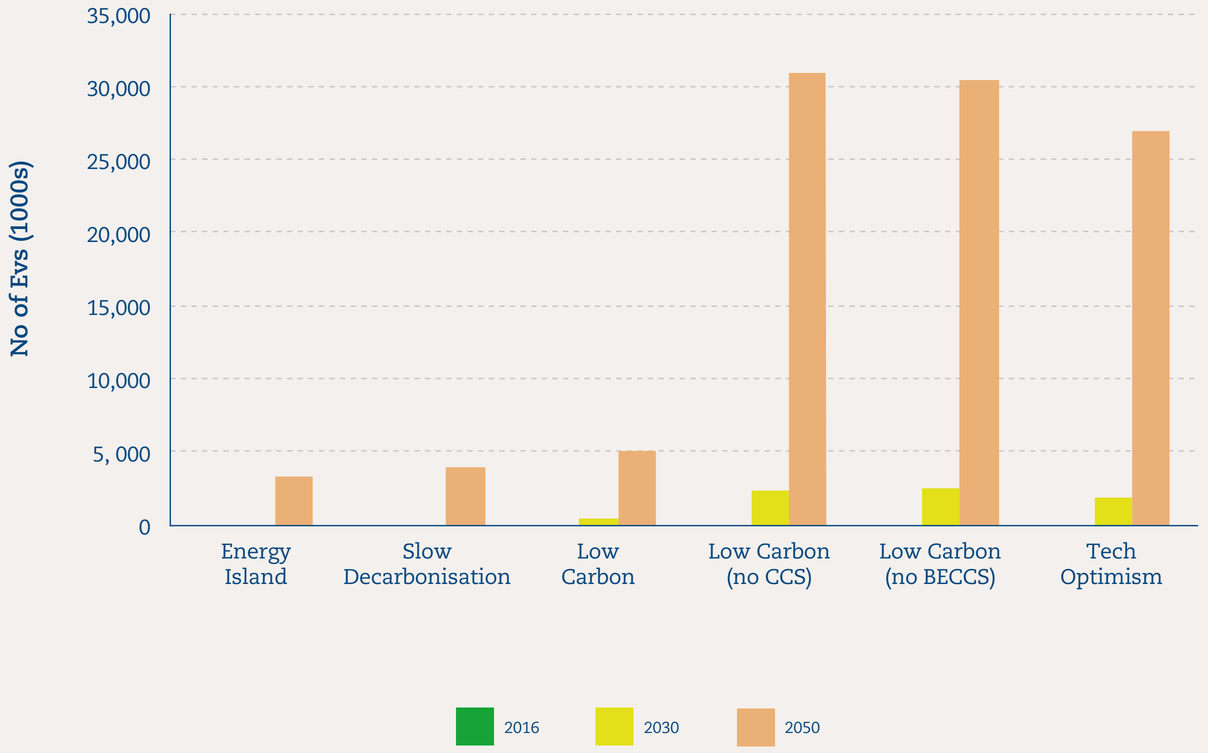
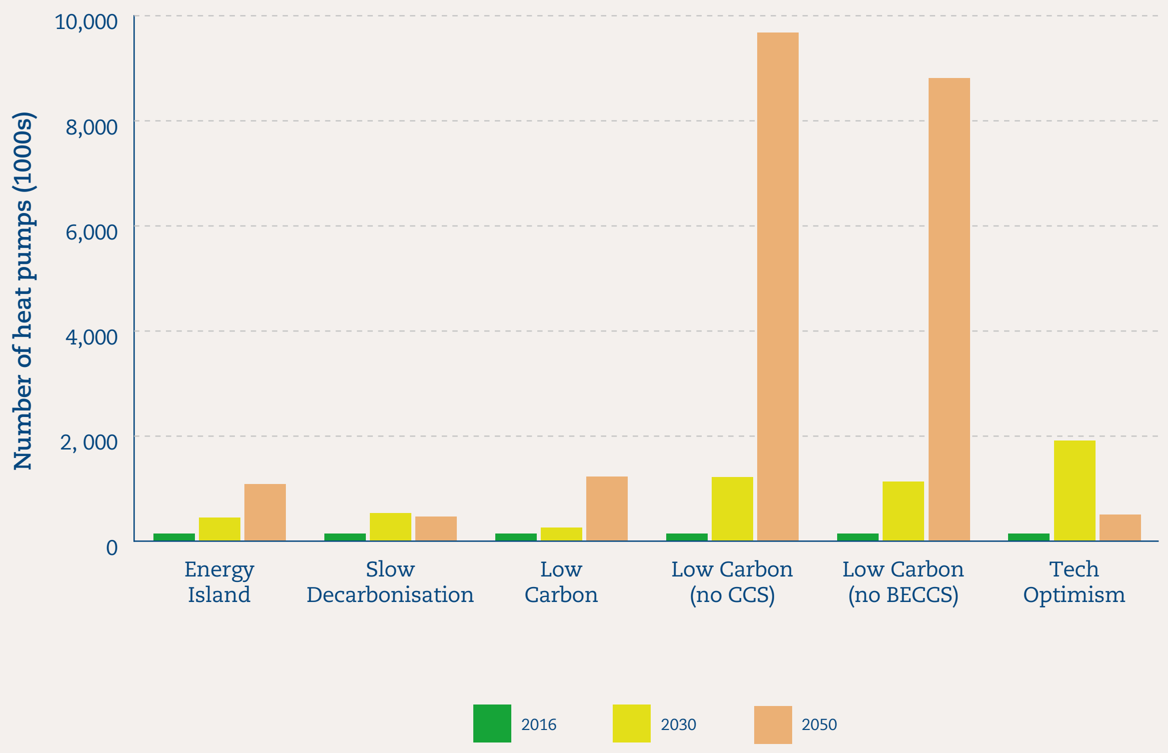


Figure 22: Number of heat pumps in the residential sector



In principle, heat pumps can also be used to help balance electricity supply and demand – though to a lesser extent than electric vehicles. The level of heat provision by heat pumps in the residential sector is shown in Figure 22. For comparison, there were approximately 150,000 heat pumps installed in the UK in 2016 (CCC, 2017b).

In most scenarios there is a continuous increase in heat provided by heat pumps in the period to 2050. The highest level is observed in the Low Carbon (no CCS) and the Low Carbon (no BECCS) scenarios, where there is a steep increase post 2030. The adoption of heat pumps in the Low Carbon scenario is much lower because of the deployment of bioenergy with CCS on a large scale. This creates 'emissions space' that allows 60% of residential heat to be provided by gas boilers in 2050. In Technology Optimism, an initial phase of rapid diffusion gives way to a fall in the use of heat pumps between 2030 and 2050. This is because other low carbon technologies such as hydrogen fuel cells and solar heating become more important during this period. The Slow Decarbonisation scenario has the lowest uptake of heat pumps.

4.3 Energy security dashboard for 2050

The full dashboard of energy security indicators for 2050 is shown in Figure 23. It shows how each indicator has changed between 2016 and 2050. A double arrow is used to denote a large change, whilst a single arrow is used to show a more modest change. A horizontal line shows that the value of a particular indicator is similar in 2016 and 2050. In cases where there is an increased risk to energy security, red shading is used.

Technology Optimism has the fewest red indicators on the dashboard, followed by Energy Island. These two scenarios characterise very different futures. Technology Optimism meets climate change targets via significant technical change, decentralisation and demand reduction. This scenario has much lower final energy demand in 2050 than the other five scenarios. By contrast, Energy Island is a scenario in which action to climate change mitigation stalls, and there is a radical shift in favour of domestic energy resources – including a renewed role for coal.

Figure 23: Energy security indicators for 2050, compared to 2016

	Energy Island	Slow Decarbonisation	Low Carbon	Low Carbon (no CCS)	Low Carbon (no BECCS)	Technology Optimism
Risk of public opposition to electricity mix	↑	↓	↓	↑	–	↓↓
Domestic fossil fuel and biomass production	–	↓	↓	↓	↓	↓↓
Energy diversity	↑	↑	–	↑	↑	–
Electricity diversity	↓	–	–	↓	↓	–
Biomass imports	↓	↑	↑	↑	↑	↑
Oil imports	↓↓	↑	–	↓	↓	↓
Gas imports	↓	↑	↑	↓↓	↑	–
Electricity LOLE	↑	↑	↑↑	↑↑	↑	↓↓
Gas LOLE	–	↑	↑↑	–	–	–
Electricity interconnector capacity	–	↑	↑	↑	↑	↑
Demand side flexibility: electric vehicles	–	–	–	↑	↑↑	↑↑
Demand side flexibility: heat pumps	↑	↑	↑	↑↑	↑↑	↑

Slow Decarbonisation and the three Low Carbon scenarios have higher risks. This is particularly the case for Low Carbon and Low Carbon (no CCS), which have particularly poor levels of electricity system reliability, and gas system reliability in the case of Low Carbon. Slow Decarbonisation performs worse than 2016 in five indicators, including increased imports of oil, gas and biomass and poorer electricity and gas system reliability.

5. Conclusions

This report explores how the security of the UK energy system could change in the next three decades. It has assessed the security of six future scenarios using a dashboard of indicators. The assessment leads to a number of important conclusions.

First, the results suggest that there is an important role for energy efficiency and energy demand reduction in energy security strategies. As others have argued, there is a tendency for such strategies to be dominated by supply side measures, and to neglect the important roles the demand side could play (e.g. Hoggett, Eyre and Keay, 2013). The two scenarios with fewest red indicators; Technology Optimism and Energy Island, have the lowest primary energy demand. Technology Optimism also has much lower final energy demand than the other five scenarios.

Second, there is not a straightforward relationship between decarbonisation and energy security. Technology Optimism meets climate change targets whilst Energy Island includes a decisive shift away from climate change action. The Low Carbon and Slow Decarbonisation scenarios have a more mixed performance, with a significant number of indicators showing higher risks to security. The implication is that risks to energy security will not automatically reduce as the energy system decarbonises.

Third, significant risks to security can be mitigated. The sensitivity tests show that electricity and gas system reliability can be improved significantly by investing in system flexibility. This report has focused on a sub-set of the options available to achieve this: demand side response and gas storage. Increasing demand side response has a particularly positive impact on electricity and gas system reliability. As a recent UKERC evidence review has shown, increasing flexibility in the electricity system is also likely to reduce the costs of integrating higher shares of intermittent renewables (Heptonstall et al, 2017).

Due to the uncertainties involved, it is not possible to provide a comprehensive analysis of the costs of these scenarios or the implications for household energy bills. At an aggregate level, the annual costs of all scenarios from the UK TIMES model are similar in 2030. Whilst Energy Island comes out marginally cheaper than the others, the highest cost scenario (Low carbon no CCS) is only 10% more expensive in that year. In 2050, there are a wider range of costs. In that year, the annual costs of Energy Island are also the lowest, followed by Slow Decarbonisation. The annual costs in 2050 of the four scenarios that comply with carbon targets are 16-44% higher than Energy Island.

There are some important caveats that should be borne in mind when interpreting these results. Some of the indicators are only partial proxies for the energy security risks they are seeking to measure. This applies in particular to indicators of public opposition risks and electricity demand flexibility. Public support for, or opposition to, energy resources or technologies is highly likely to change over time. They also depend to some extent on other economic, political and social changes, some of which are described in the scenario narratives.

The use of energy imports as an energy security indicator is also controversial. Whilst imports are often cited as being insecure in public policy discourse, such claims need to be examined closely. Imports can also help to enhance security – e.g. by providing access to additional sources of energy, by lowering the cost of energy, or by increasing diversity. Therefore, it is not possible to make a simple equation between increasing imports and decreasing security. What matters is whether imports are dominated by particularly risky sources or supply routes – and what the macroeconomic costs and benefits could be. Answering such questions is beyond the scope of the models that were used for this report.

Another caveat concerns the role of storage in this report's scenarios. As the transition to low carbon energy systems progresses in the UK, the nature and role of storage is changing. Fossil fuel storage (e.g. coal at power stations) is declining rapidly, whilst newer forms of storage (e.g. batteries) are increasing. The security assessment in this report has included the role of gas storage in helping to improve gas system security. The role of electricity storage is more difficult to assess due to the way the UK TIMES model works. As part of the least cost optimisation, the model tends to flatten electricity demand profiles in most of our scenarios – with the partial exception of Technology Optimism. As a result, the model invests in very little new electricity storage capacity. In reality, significant growth in electricity storage would be expected in several of our scenarios. This could add significantly to electricity system flexibility and lead to reductions in indicators such as LOLE.

This report has not covered two risks to energy security that are likely to become increasingly important: cyber security and risks due to climate change. Cyber security has received an increasing amount of attention as energy and other sectors become more dependent on the use of digital technologies. There have already been some cyber-attacks on electricity networks and energy companies (e.g. WEC, 2016). Whilst it is not possible to carry out a detailed assessment of cyber security risks for our scenarios, it is important for companies and governments to ensure that the increasing digitalisation of energy systems does not lead to major new security risks.

The impact of climate change on UK energy systems has also received some attention in official risk assessments and the academic literature (e.g. CCC, 2017a; Blake et al, 2015). These impacts could include changes to patterns of energy demand (e.g. though increases in the demand for cooling in summer) and impacts on infrastructure due to extreme weather (e.g. through flooding of electricity sub-stations). A detailed analysis of these impacts and the extent to which they increase risks to energy security is beyond the scope of this project. The latest assessment by the Committee on Climate Change (CCC, 2017a) concludes that increased flood risks 'appear inevitable' in some areas – especially if mean global temperatures increase by 4 degrees or more. Energy systems could also be affected by shortages of water. Within the Energy Island scenario, both UK and global action to mitigate climate change is relatively weak. This means that this scenario is more likely than the others to include a higher increase in global temperatures – and an increased risk to energy security from climate change impacts.

6. References

Aas, K. et al (2009) Pair-copula constructions of multiple dependence. Insurance: Mathematics and Economics 44(2): 182–198.

BEIS (2016) UK Risk Assessment on Security of Gas Supply, Report completed for EU Regulation 994/2010, 2016.

BEIS and OFGEM (2016) Statutory Security of Supply Report 2016.

BEIS (2017) Digest of UK Energy Statistics 2017. London: BEIS.

Blake, S., Davison, P., Greenwood, D. and Wade, N. (2015) Climate change risks in electricity networks. Infrastructure Asset Management 2(2): 42-51.

CCC (2017a) UK Climate Change Risk Assessment. Synthesis report: priorities for the next five years. London: Committee on Climate Change.

CCC (2017b) Meeting the carbon budgets: closing the policy gap. 2017 progress report to Parliament. London: Committee on Climate Change.

Chaudry, M., Jenkins, N., and Strbac, G. (2008) Multi-time period combined gas and electricity network optimisation, Power Systems Research, 2008, 78, 1265-1279

Chaudry, M., Jenkins, N., Qadrdan, M., Wu, J. (2014) Combined gas and electricity network expansion planning. *Applied Energy* 113 , pp. 1171-1187.10.1016/j.apenergy.2013.08.071

Chaudry, M., Wu, J., Jenkins, N. (2013) A sequential Monte Carlo model of the combined GB gas and electricity network. *Energy Policy* 62 , pp. 473-483. 10.1016/j.enpol.2013.08.011

Cherp and Jewell (2011) The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. Current Opinion in Environmental Sustainability 3(4) 202-212.

Chester, L. (2010) Conceptualising energy security and making explicit its polysemic nature. Energy Policy 38(2) 887-895.

CLUES (2012) *Energy: Looking to the future. A tool for strategic planning*. UCL.

Cox, E. (2016) Opening the black box of energy security: a study of conceptions of electricity security in the United Kingdom. Energy Research and Social Science 21: 1-11

Cox, E. (2018) Assessing long-term energy security: The case of electricity in the United Kingdom. Renewable and Sustainable Energy Reviews. 82(3): 2287-2299

DECC (2014) Delivering UK Energy Investment 2014.

Demski, C., Spence, A., Pidgeon, N. (2013) Transforming the UK Energy System: Public Values, Attitudes and Acceptability – Summary findings from a survey conducted August 2012. UKERC, London

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

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

Heptonstall, P., Gross, R. and Steiner, F. (2017) The costs and impacts of intermittency: 2016 update. London: UK Energy Research Centre.

HM Government (2017) The Clean Growth Strategy. London.

Hoggett, R., Eyre, N. and Keay, M. (2013) Demand and Energy Security. in Mitchell, C., Watson, J. and Britton, J. New challenges in energy security: the UK in a multipolar world. Basingstoke: Palgrave Macmillan.

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

Jansen, JC, van Arkel, WG, Boots, MG. (2004) Designing indicators of long-term energy supply security. Energy Research Centre of the Netherlands. Available at : http://www.ecn.nl/docs/library/report/2004/c04007.pdf [accessed 23rd August 2017]

Jewell, J. et al (2016) Comparison and interactions between the long-term pursuit of energy independence and climate policies. Nature Energy 1: 1-9.

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

Kosow, H., Gassner, R. (2008) *Methods of Future and Scenario Analysis: Overview, Assessment and Selection Criteria*. German Development Institute

Kruyt, B., van Vuuren, D.P., de Vries, H.J.M. and Groenenberg, H. (2009) Indicators for energy security. Energy Policy 37(6) 2166-2181

London Economics (2011) Estimating Value of Lost Load (VOLL) for Electricity in Great Britain: Final report to OFGEM 2011.

London Economics (2013) The Value of Lost Load(VOLL) for Electricity in Great Britain: Final report for OFGEM and DECC 2013.

Mansson, A, Johansson, B. and Nilsson, L. (2014) Assessing energy security: An overview of commonly used methodologies. Energy 73: 1-14.

Mansson, A. (2015) A resource curse for renewables? Conflict and cooperation in the renewable energy sector. Energy Research & Social Science 10: 1-9

McCollum, D., Krey, V., Riahi, K., Kolp, P., Grubler, A., Makowski, M., Nakicenovic, N. (2013) Climate policies can help resolve energy security and air pollution challenges, Climatic Change, 119 (2), 479-494

McGlade, C., Pye, S., Watson, J., Bradshaw, M., Ekins, P. (2016) The future role of natural gas in the UK. UKERC research report. London: UKERC.

Mitchell, C. and Watson, J. (2013a) Introduction: conceptualising energy security. in Mitchell, C., Watson, J. and Britton, J. New challenges in energy security: the UK in a multipolar world. Basingstoke: Palgrave Macmillan.

Mitchell, C. and Watson, J. (2013b) Conclusions and recommendations. in Mitchell, C., Watson, J. and Britton, J. New challenges in energy security: the UK in a multipolar world. Basingstoke: Palgrave Macmillan.

National Grid (2016) Winter Outlook Report 2016/17. Warwick: National Grid.

NERC (2017) Probabilistic Assessment: Methods and Assumptions, 2017

OFGEM (2015) Electricity Security of Supply 2015

OFGEM (2016) Industrial & Commercial demand-side response in GB: Barriers and potential 2016

Oxera (2007) An assessment of the potential measures to improve gas security of supply, 2007.

Poyry (2010) GB Gas Security of Supply and Options for Improvement, A report to DECC, 2010.

Poyry (2017) Roadmap for flexibility services to 2030. Report to the Committee on Climate Change. London: Poyry and Imperial College.

Ritchey, T. (2006) Problem structuring using computer-aided morphological analysis. *Journal of the Operational Research Society* **57**, 792–801.

Spanjer, A. (2007) Russian gas price reform and the EU-Russia gas relationship: incentives, consequences and European security of supply. Energy Policy, 35, 2889-2898

Staffell, I. (2017) Measuring the progress and impacts of decarbonising British electricity. Energy Policy 102: 463-475.

Staffell, I. and Pfenninger, S. (2016) Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114: 1224-1239.

Steinberger-Wilckens, R., Dodds, PE, Kurban, Z., Velazquez Abad, A. and Radcliffe, J. (Eds.) (2017) *The role of hydrogen and fuel cells in delivering energy security for the UK*. H2FC Supergen, London, UK

Stirling, A. (1994) Diversity and ignorance in electricity supply investment: addressing the solution rather than the problem. Energy Policy, 22 (3): 195-216

Stirling, A. (2010) Multicriteria diversity analysis: a novel heuristic framework for appraising energy portfolios. Energy Policy, 38, 1622-1634

UK Foresight (2008) *Powering our lives: sustainable energy management and the built environment, Final report*. Government Office for Science

Van der Welle, A.J., Van der Zwaan, B.C.C. (2007) An Overview of Selected Studies on the Value of Lost Load (VOLL). in National and EU level estimates of energy securities, CASES EU FP-VI project, Work Package 5 report D5.1, December 2007

World Energy Council (2016) The Road to Resilience: Managing cyber risks. London: WEC.

World Energy Council (2017) World Energy Trilemma Index 2017. London: WEC.

Zachary, S. & Dent, C.J. (2011) Probability theory of capacity value of additional generation. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability 226(1): 33–43.

Appendix 1: Further details on UK TIMES model and assumptions

UK TIMES represents the UK as a single region. Temporally, it includes four seasons of equal duration, which are each represented by an average day. Each average day consists of four contiguous time periods with different lengths: night, day, evening peak, and late evening. The model includes three supply-side sectors (resources and trade, processing and infrastructure, and electricity) and five demand-side sectors (residential, services, industry, transport and agriculture and land use). It represents all greenhouse gas emissions (as CO2, CH4, N2O and HFCs) and many air quality pollutants. The model assumes perfect foresight, i.e. that decisions are made in a rational manner by a single decision-maker that has perfect knowledge of the future in terms of economic and technical developments, as well as future demand.

UK TIMES is calibrated to the year 2010 using data from the UK Government's Digest of Energy Statistics (DUKES, 2011). Technology costs are updated periodically and deployments of technologies such as wind and solar PV generation since 2010 are forced into the model. Recent cost decreases in wind and solar were not represented in the model version used for these scenarios. The low temporal resolution of UK TIMES leads to the model underestimating the need for energy storage. It also enables the model to minimise costs by flattening the electricity load curve in the future, thereby minimising the need for investment in spare electricity generation capacity. Other research at higher temporal resolutions has shown that electricity storage can potentially play a significant role in decarbonisation (Poyry, 2017).

An iterative process was used to ensure consistency between the scenario narratives and UK TIMES model outputs. The quantitative scenarios in this report were based on an earlier set of UKERC scenarios that were used to examine the future role of natural gas (McGlade et al, 2016). The new scenarios include more extensive narratives and a significant number of changes to modelling assumptions. These include:

- Constraints on energy service demand for the Energy Island and Technology Optimism scenarios.
- Mandatory energy conservation measures in all the Low Carbon scenario variants and Technology Optimism.
- UK shale gas production is only included in Energy Island and Slow Decarbonisation. In Energy Island, shale gas production takes place from the early 2020s to the late 2040s. Production is at much lower levels in Slow Decarbonisation, starting in the mid-2020s and running up to the mid-2030s.
- Electricity interconnector capacity was also varied to fit with the scenario narratives. In Energy Island future interconnections were capped at 5GW. In all other scenarios a total of 11GW capacity is included – which is in line with current investment plans[5].
- In Energy Island, the UK is required to be 90% self-sufficient in energy resources (except uranium) from 2030 onwards.
- Technology Optimism includes delayed CCS deployment for power and hydrogen production to 2035. New nuclear is restricted to 6.4GW in 2035 and a reduction takes place in renewable technology capital costs.
- CCS was also delayed in Slow Decarbonisation to the late 2020s due to high investment costs.

Assumptions about economic growth rates in each scenario were taken from UK government projections. The three Low Carbon scenarios and Slow Decarbonisation has a growth rate of 2.2-2.3% per year; whilst Energy Island and Technology Optimism have a slightly slower growth rate of around 2% per year.

---

[5] https://www.ofgem.gov.uk/electricity/transmission-networks/electricity-interconnectors

Appendix 2: Additional background on CGEN+ modelling

This appendix includes further information about two aspects of the CGEN+ model that was used to generate the electricity and gas reliability indicators: network capacity additions and the Monte Carlo data uncertainty modelling.

Network capacity additions

Additional electricity transmission capacity was included in the CGEN+ model to reflect the 'Delivering UK energy investment' report by the former Department of Energy and Climate Change (DECC, 2014). The majority of these investments will take place in Scotland with projects such as the Western HVDC link. These investments are added as projects that occur at specific years for all the scenarios. It was also assumed current or future capacity is fully maintained and replaced like for like. So, the cumulative electricity transmission capacity additions shown in Figure A1 illustrate the capacities above and beyond of that assumed in the base CGEN+ data.

For the gas network, additional supply capacity can be added within the model at entry terminals either for interconnectors, LNG or domestic gas. In addition to this, inland pipes can be reinforced alongside further gas storage capacity. Figure A2 shows the cumulative LNG capacity in the model for the scenarios, from 2020 to 2050.Apart from capacity added to inland pipelines (mainly around terminals to alleviate constraints and allow greater gas flow), virtually all new additional capacity was added at existing LNG entry terminals. No new gas storage or interconnectors were added in any of the scenarios modelled. It was also assumed that gas would still be withdrawn from the recently decommissioned Rough storage facility until the early 2020s. This will allow recovery of the estimated 183 bcm of cushion gas in the field. Beyond the mid 2020s, no gas is assumed to flow from the facility.

Figure A1: Additional electricity transmission capacity 2020-2050

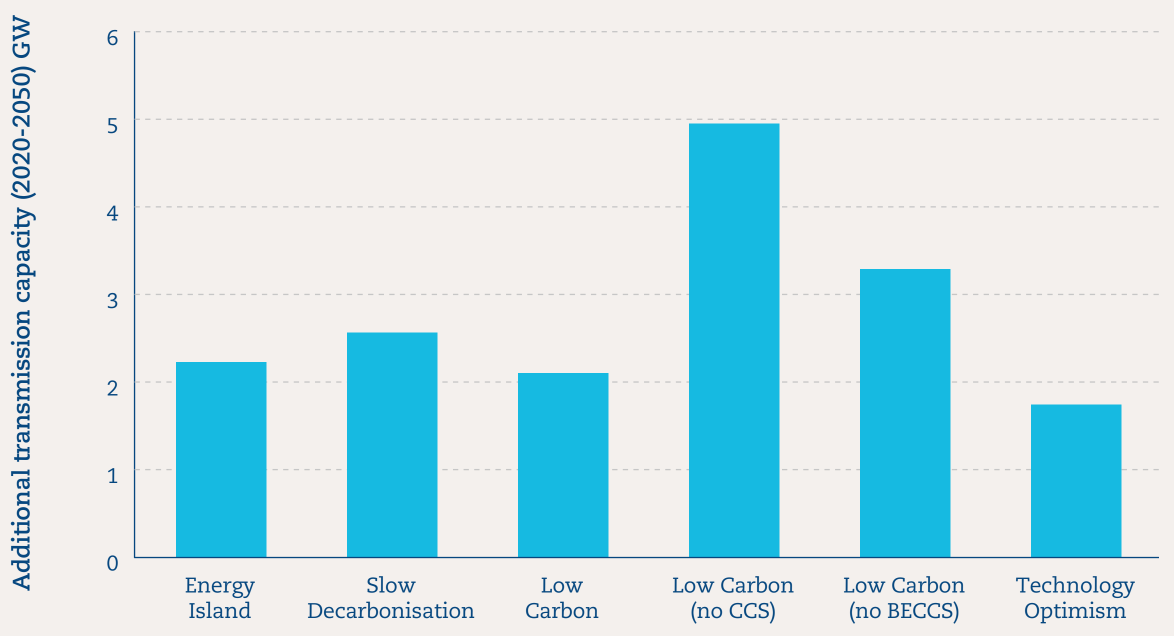
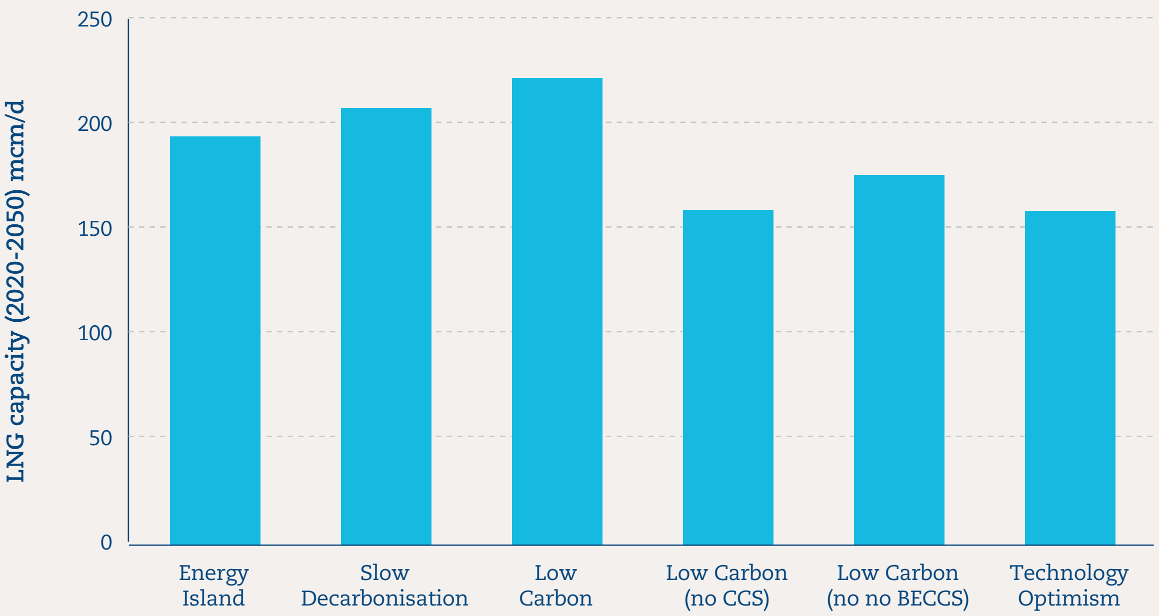


Figure A2: LNG capacity additions in the scenarios, 2020-2050



Monte Carlo data uncertainty modelling

Gas supplies to the UK within the model are split into three main sources: indigenous (UKCS or shale gas), LNG (e.g. from Qatar/Algeria) and pipeline imports (e.g. from Norway or continental Europe). Each gas source is represented by separate probability density functions and normal distribution is assumed.

Both gas and electricity demand can fluctuate from forecasted values due to events such as colder/milder weather and unexpected incidents. These fluctuations are modelled via normal distribution probability density functions.

For both supply and demand, the mean is determined by UK TIMES model outputs for a particular scenario. For gas supply, standard deviations are determined by comparing forecasted supplies with real supply data alongside data taken from previous studies (Oxera, 2007; Poyry, 2010). Similarly, energy demand (gas and electricity) standard deviations where calculated by comparing forecast data from National Grid with actual data to determine the probable variations.

The electricity network uncertainties modelled include conventional generation plant, transmission line and interconnector availabilities. The modelling is identical for the gas network. For all components an exponential distribution is used to determine the time to failure and a Weibull distribution is used for calculating the time to repair. The power generation failure (Forced Outage Rates-FOR) and repair rate data is taken from the comprehensive plant data available from the North American Electric Reliability Council (NERC, 2017). No cross correlations between any of the supply/demand probabilities or failure rates are assumed.

Several references provide typical values for the Value of Lost Load or VOLL in the model (London Economics, 2011; 2013; Van der Welle and Van der Zwaan, 2007). The following values for VOLL in the gas sector were used: residential (2300 p/therm), industrial (1,600 p/therm) and commercial (100 p/therm). In the electricity system a VOLL of between £9000 to 30,000 MWh was used for residential and commercial sectors.

Appendix 3: The impact of interconnection on system adequacy

This appendix describes the probabilistic model and analysis used to quantify the contribution of electrical interconnection to electricity system security. The analysis is based on a two-area model; the two areas are connected electrically by four interconnectors that each have an availability of 95%. The properties of the two areas are derived from the Great Britain and French systems, with modifiers to analyse a large range of scenarios. The French system is scaled to 150% of its nominal size to represent the collective interconnection of Great Britain with France as well as other continental European countries. Those countries are effectively treated as a single system, under the assumption of strong interconnections between them. Internal transmission constraints within the GB and FR systems are not taken into account. The analysis has been performed using a convolution model, which allows for an explicit enumeration of system margins and their availabilities without the uncertainties that are inherent in a Monte Carlo approach.

Demand and wind model

Historical electricity demand data from GB and France (5 years: 2010-2014) was used to specify a joint probability model for demand in both systems. The data was kindly provided by Iain Staffell (Staffell, 2017). Net demand measurements were used, which exclude exports and recharging of storage units, and correct for (estimated) output from embedded renewable generation. Two parameters were introduced to probe qualitative changes to the load profile:

1. An overall scaling of the energy consumption (from -50% to +50%)
2. A parameter that linearly scales the fluctuations of the load (at a constant overall energy consumption) from flat to twice the nominal amount.

Demand and wind power output were assumed to be statistically independent for this analysis. GB wind power output for the period 2010-2014 was synthesised on the basis of an assumed installed capacity (13GW in the reference case) and a capacity factor time series. The capacity factor data was derived from MERRA reanalysis data for wind speeds and an assumed constant distribution of wind generation sites (Staffell and Pfenninger, 2016). The resulting distribution of GB wind power outputs was used to generate a dependent distribution for wind power in the French system by assuming that both have the same marginal distribution (up to a scaling factor that is determined by the installed capacity), and the joint distribution is represented by a Gaussian copula (Aas, 2009). This provides distribution of wind power with an adjustable correlation parameter ρ, that varies from 0 (no correlation) to 1 (full correlation). Actual wind power output from the GB and French grid (2014 calendar year) was used to determine a best fit parameter of ρ=0.5376, which was used unless otherwise stated.

Dispatchable generation model

Both Great Britain and France operate capacity markets to maintain the security of their electricity systems, governed by a standard of 3 hours LOLE (loss-of-load expectation) per year. This statistical measure implies that each network should face a shortfall of generating capacity of not more than 3 hours a year, when averaged over realisations of a probabilistic model of the generation-demand balance. We assume that a capacity market guarantees that sufficient generators are built to ensure that the standard is met.

In line with typical generation adequacy calculations, dispatchable generators are modelled as independent two-state units that are characterised by their (maximum) capacity and their average availability. Generic unit capacities are used to capture the range of available units: 1200MW for nuclear units, 600MW for large coal/CCGT units, 300MW for smaller units and large hydro units, 150MW for peaking plant, and 80/20/10MW for various smaller units. To maintain a balanced portfolio, units are added in sets that are characteristic of each system:

- GB: set of 1200, 2x600, 2x300, 150, 80, 2x20, 3x10.
- FR: set of 2x1200, 600, 300, 150, 80, 2x20, 3x10.

The difference in unit sizes reflects the greater reliance on nuclear units in the French system (resulting in correspondingly larger fluctuations in available capacity). A typical unit availability of 90% was assumed for the reference case. For each system, the number of generator sets was incremented until the LOLE is reduced below the 3 hours/year standard. Then, load offsets were computed to achieve LOLE=3hours/year (in the absence of interconnection). For the reference case, the following values resulted:

- GB system: 19 generator sets, 649 MW load offset
- FR system (scaled): 45 generator sets, 2188 MW load offset

Computation of capacity values

In this report, the capacity value of interconnection is defined as the *equivalent load carrying capacity* (ELCC) (Zachary and Dent, 2011). In the context of interconnection, this is the maximum amount of additional (constant) load that can be supported by the *interconnected system*, such that its security meets or exceeds that of the *unconnected system*. Equivalently, it can be interpreted as the amount of 'firm generating capacity' (i.e. the product traded in capacity markets) that is provided by the interconnector(s). The implication is that other sources of capacity can be reduced by the same amount.

For a two-area system, the problem of computing a capacity value does not have a single solution. Instead, the solution consists of a one-dimensional set of load combinations (LGB, LFR) that, when added to each area, result in LOLE ≤3 hours, in both systems. The largest total capacity value is found at the point ($LGB*, LFR*$) where LOLE=3 hours in both systems. Unless otherwise stated, the GB load addition $LGB*$ is used for further analysis of total capacity values and marginal capacity values.

Two-dimensional capacity values were computed using a convolution procedure. A convolution-based approach was used to determine a discrete distribution (50MW resolution) of generation margins of both systems simultaneously. It is computed on the basis of the bivariate load series, the bivariate wind model with parametrised correlation coefficient, and the two (independent) distributions for dispatchable generating capacity (10MW resolution). Contributions from solar power were ignored, given the winter-evening peaking nature of the GB system.

UKERC
UK Energy Research Centre

11 Princes Gardens
London SW7 1NA
tel: +44 (0)20 7594 1573
email: ukercpressoffice@ukerc.ac.uk

www.ukerc.ac.uk