The Economics of Climate Resilience Buildings and Infrastructure Theme: UK Power Generation and Transmission CA0401

A REPORT PREPARED FOR DEFRA AND THE DEVOLVED ADMINISTRATIONS

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Context of this report

The Economics of Climate Resilience (ECR) has been commissioned by Defra and the Devolved Administrations (DAs) to develop evidence to inform the National Adaptation Programme and the adaptation plans of the DAs. The report should be read in the context of other programmes of work on adaptation being taken forward separately.

The scope of the ECR

The ECR follows the publication of the UK Climate Change Risk Assessment (CCRA) in January 2012 and differs in scope from work envisaged prior to that date. While its original aim was to consider individual climate change risk metrics from the CCRA and specific adaptation options, this evolved as the project was considered across government departments. The current ECR therefore focuses on broader policy questions, with each report covering multiple climate risks and CCRA risk metrics. In this context, the economic assessment is broader than a quantitative assessment of costs and benefits – it concerns identifying and assessing market failures and other barriers to effective adaptation action, seeking to understand drivers of behaviour which hinder or promote the adoption of adaptation actions. The framework for assessing the costs and benefits of adaptation actions is considered in a separate phase of the ECR.

Questions addressed

The questions addressed by the ECR were chosen following cross-government engagement by Defra. They ask whether there is a case for further intervention to deliver effective adaptation given the current context – i.e. the current adaptive capacity of those involved and the policy framework. Criteria for the choice of questions by policy officials include: the current and projected degree of the climate change risk; priorities for additional evidence gathering beyond that already being considered in other work-streams, and the data and evidence currently available. Questions were deliberately broad to allow the wider context to be considered, rather than just individual climate metrics. However, this approach prevents a detailed evaluation of individual risks or localised issues being made. Detailed assessments of climate thresholds and the limits of specific adaptation options have also not been possible.

Analysis undertaken

The analysis has sought to build on existing assessments of current and projected climate change risks (such as the CCRA). The context in which sectors operate has been assessed, including the current adaptive capacity of relevant actors and the policy framework in which those actors function. Categories of actions currently being taken to adapt to climate change have been explored, including those which build adaptive capacity where it is currently low, and those which limit the adverse impacts or maximise opportunities, allowing identification of barriers to effective adaptation. The case for intervention is then presented.

The degree to which an adaptation action is likely to be cost-effective requires more detailed assessment, reflecting the particular context in which adaptation is being considered.

This report is underpinned by stakeholder engagement, comprising a series of semi-structured interviews with sector experts and a range of other stakeholders. This has enabled the experiences of those who undertake adaptation actions on the ground to be better understood. We are grateful to all those who have given their time.

Tables & Figures

1 Executive summary

Climate change to the 2050s and beyond poses a number of threats and challenges for the energy sector. Although subject to uncertainty, mean winter precipitation is projected to increase overall and is expected to fall increasingly frequently as intense downpour events; mean summer temperature is projected to increase and extreme weather events could increase in their intensity and frequency, potentially resulting in flooding and heat waves[1].

In response to these risks, Defra identified the following question as the focus of this report:

"What is the case for further intervention in relation to climate change adaptation for key energy supply infrastructure?

Analysis should focus on: (i) change in capacity and output of electricity (including gas) and nuclear power stations in the UK (i.e. MW and MWh); (ii) impacts of heat on the transmission grid, and (iii) change in seasonal demand for energy due to cooling/heating".

The potential implications of climate change on energy distribution are also important but they are beyond the scope of this report.

The projected increase in temperature is expected to have a negative effect on performance, particularly of gas-fuelled power stations. A reduction in power plant efficiency, also known as 'heat rate degradation' would lead to lower generating output for any given level of installed capacity.

The impact of heat on transmission capacity varies depending on the particular piece of equipment. However, it is not generally considered to be greater than 1% loss per 1°C rise[2]. Flooding can affect power generation infrastructure, rendering it temporarily inoperative.

The policy context

Security of energy supply is of national importance given the wider economic and social costs associated with any interruption (beyond those experienced by the energy suppliers). The regulatory framework and broader government policy therefore play a key role in the sector.

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[1] Storms are also considered to be a threat but are not addressed in detail in this report given the challenges in projecting them.

[2] These estimates use a baseline period of 1961-1990, and assume that equipment is maintained to EU and international design standards and not susceptible to faults. The estimates also assume a constant average wind speed.

The regulator influences the extent to which climate change is accounted for in decision-making through the incentives it provides to operators of energy infrastructure.

Broader government policy has recently been reshaped through the Electricity Market Reform (EMR). EMR introduces measures to attract investment, reduce impacts on consumer bills, and create a secure mix of electricity sources including gas, new nuclear, renewables, and carbon capture and storage (DECC, 2012). Of particular relevance for adaptation is the introduction of a Capacity Market Mechanism.

The purpose of the market-wide Capacity Market is to "…*ensure sufficient reliable capacity is available to ensure security of electricity supply in times of system stress, for example during a cold, windless period. It puts in place contracts to incentivise providers of reliable capacity to be available when needed. This could include both generation and non-generation forms of capacity, such as demand side response and storage.*" (DECC, 2011b).

It will therefore be important that the Capacity Market continually accounts for emerging information on the threat of extreme weather events and long-term climate change. This may be achieved through the design of the process for translating the reliability standard into the amount of capacity to be contracted[3], and by the Capacity Market providing appropriate rewards for providing reliable capacity and penalties for failing to do so.

In terms of the sector itself, it will undergo fundamental changes over the coming decades. Around a fifth (some 19GW) of capacity available in 2011 has to close by the end of this decade (DECC, 2012). In addition, much of the aging assets in the transmission network are due for renewal. Both of these aspects offer the **opportunity for decision-makers to take account of potential climate threats and hence reflect adaptation requirements when investing in new-build and replacement assets.**

Investments in the transmission grid will also be influenced by the increasing importance of distributed and renewable energy generation. Specifically:

the location of new generation capacity with respect to the bulk of demand will push the network to adapt its transmission capacity to support the new electricity flows; and,

the intermittent nature of distributed and renewable energy generation will also require investments in system operation capabilities.

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[3] At the time of writing the Government's thinking is for the Minister to set the amount of capacity to be contracted under the Capacity Mechanism with reference to an enduring reliability standard.

Adaptive capacity

The adaptive capacity of the sector is considered to be generally high, largely owing to the relatively small number of actors. In addition, stakeholders from the power sector interviewed for this study stressed that climate change is not likely to introduce any new types of risk to operations, but rather to change the likelihood or severity of risks which are currently managed (AEP, 2011; Centrica Energy, 2011; InterGen UK, 2011; International Power, 2011, and RWE Npower, 2011).

Significant interdependencies between the energy sector and other sectors could exacerbate inherent consequences of climate change risks, the management of which could be external to the control of the energy sector itself. For example, climate change resilience of another sector, such as communications, could affect the resilience of the energy sector. Such impacts on resilience are not generally well-understood owing to a lack of transparency and information and hence the ability to assess them. This lowers adaptive capacity and highlights the importance of adaptation being considered from a cross-sectoral perspective.

On the demand-side, the adaptive capacity of consumers is extremely variable owing to the differing ability of consumers to make energy efficiency savings, capture the benefits of distributed generation and undertake demand-side measures. However, while there is an increasing awareness of energy usage, there is generally a prominence of short-term price-sensitive decision-making, albeit that the knowledge and skill to make long-term decisions exists for major energy-intensive users.

A range of adaptation measures are already being implemented to both build adaptive capacity and limit the potential adverse effects of climate change.

Adaptation actions currently being implemented to address climate risk

Adaptation actions can be either incremental modifications to current processes or guidelines or transformative in nature. The key categories of measures currently being implemented include: engineering and design measures (e.g. flood defences); investment decisions to ensure resilient capacity margins, and demand-side measures. The generally high level of adaptive capacity implies effort is already invested in maintaining that level (which is a form of adaptation action in itself).

The analysis finds relatively high current levels of adoption of adaptation actions such as flood defences, network expansion or upgrade and capacity expansion. These are influenced by climate change but are largely driven by other factors, such as market pressures, commercial gain or business case. However, they are often likely to result in an effective response to the threats posed by climate change to key power supply infrastructure.

Looking forward, there are several infrastructure investment decisions that need to be made before the 2020s. Strong incentives are in place for operators to be resilient to climate change - this is particularly important given the long design lifetime. While many of the adaptation actions identified in the analysis will be on-going, for effective adaptation, i.e. that which allows the sector to account for information on the potential impacts of climate change over time, and to learn from actions taken by themselves and others, **there will need to be regular reviews of the resilience of the sector**. This should incorporate (i) the resilience of assets; (ii) the adaptive capacity of key players, and (iii) the degree to which projected climate change is incorporated into specific investment decisions.

The policy and regulatory framework is evolving but there is a need for this to occur in a way which ensures suitable incentives are in place to help the sector adapt effectively. In particular, it is important that the Capacity Market accounts for the influence of climate change on resilience. The Capacity Market, if operating effectively, would be expected to ensure the system-wide capacity margin helped make the power sector resilient to the effects of climate change.

As part of the policy development process, it will be important to include a wide range of stakeholders to ensure that all emerging issues receive adequate visibility.

The **replacement of capital assets expected in terms of generation and transmission investment provide opportunities for adaptation to be duly accounted for in the longer term**.

Non-climate drivers (such as increasing demand) also may provide the additional incentive to take action which would be complementary to the need to address climate change risks.

It should be noted that when locating new generation capacity as some power stations are de-commissioned, it may not be possible to avoid flood plains entirely. It will therefore be important for flood risk to be fully accounted for in their planning and design.

Barriers to effective adaptation and recommended interventions to address them

Although there is generally a high level of adoption of adaptation actions, and this is expected to continue, there are some important barriers to consider for the action to be appropriate and effective. These include:

Barriers

As part of the Energy Act that is expected to be passed in 2013, the Government will implement a Capacity Market that will be initiated if necessary. However, the details of the Capacity Market have not been

finalised at the time of writing. The Energy Act (2011) is expected to create an investment environment that can support the deployment of a sustainable generation mix.

External costs and **information failures**[4] **arising from interdependencies** may impede adaptation actions. Examples of interdependency of the power sector with others include: distributed generation and demand-side management (which relies on information technology); network expansion and upgrades; generating capacity expansion; flood defences or operational responses to flooding (which interact with wider infrastructure requirements), and generation and transmission (which is dependent on real-time information and communication technologies (ICT)). In many cases, these linkages work effectively - National Grid's management of the transmission network, which relies on real-time information and communication, is a primary example of this. However, interdependencies increase the risk that the effects of climate change are felt more widely.

In addition, from the consumer's perspective, **the time taken to realise a private return from investing in energy efficiency measures could mean they may not have compelling economic incentives to make investments, despite a social return being likely.** This may, for example, occur if a residential efficiency investment has a payback period which exceeds the investment horizon that individual investors are willing to consider, such as if they are moving house or renting.

The analysis identifies a series of recommendations.

Recommended interventions[5]

Build adaptive capacity of the sector by enhancing knowledge and understanding of interdependencies of the energy sector and adjacent sectors. In particular:

- Undertake system-wide modelling, or case study assessments, as appropriate, to explore different climate risk and adaptation scenarios to understand both how the resilience of one sector is affected by actions in another, and how adaptation actions can affect the system more widely.

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[4] In this sense, the information failure relates to asymmetric information as one party will know more about the level of climate change risk they face than another, even though both parties could be affected by the outcome.

[5] This analysis has focused on power generation and transmission. Evidence reviewed as part of this work and engagement with stakeholders suggests that the distribution network could be more significantly affected, for example in terms of the impact of flooding on distribution sub-stations. As distribution was beyond the scope of this report, these issues should be explored in more detail.

- Ensure climate change is appropriately factored into assessments of potential future interdependencies across infrastructure sectors, particularly in terms of technology, operations and actions taken in other sectors.

Require the assessment of potential climate threats – including extreme weather events – as a core component of the decision on how much capacity to contract through the Capacity Market. Government's current thinking is that the decision on capacity will be taken with reference to a reliability standard.

Ensure that the policy and regulatory framework is kept under review in order for it to be able to provide the sector with the right incentives for climate change adaptation in a timely fashion.

Review and identify appropriate opportunities to embed consideration of climate change threats into the location, design and construction of new generation capacity. Key decisions will be taken over coming years as generation capacity is de-commissioned and replaced, and as the transmission grid is updated – these offer important opportunities for the sector to develop solutions which deliver a higher level of resilience.

2 Power generation and transmission

2.1 The focus of this report

The analysis addresses the following question set by government policy officials:

Given projected climate change and expected adaptation, what is the case for further intervention in relation to adaptation for key energy supply infrastructure?

Analysis should focus on:

- **Change in capacity and output of electricity (including gas) and nuclear power stations in the UK (i.e. MW and MWh);**
- **Impacts of heat on the transmission grid; and,**
- **Change in seasonal demand for energy due to cooling/heating.**

In accordance with the scope of the question set, the following have not been considered in this analysis:

- Projected impacts of climate change on the distribution network; and,
- Flooding risks to power sub-stations.

Analysis has been carried out and presented for the UK as a whole, providing commentary on how this may vary across English regions and the Devolved Administrations (DAs).

2.2 Approach

The analysis was undertaken over a period of two months and has drawn upon a wide published evidence-base alongside stakeholder engagement and expert advice. The work was advised and reviewed by Paul O'Rourke, a sector expert with over 40 years' of power industry expertise.

Stakeholder engagement

A series of semi-structured interviews were conducted with stakeholders (as detailed in **Annex 1**) from a range of organisations including: energy supply generators, Ofgem, other representatives of the power industry and the Devolved Administrations.

Analysis

The framework for analysis to address the question involves a series of steps.

- Understand the scale of the challenge: this involves exploring the evidence on the current scale of risks posed by climate change (including extreme weather events) and understanding the potential magnitude of impacts these give rise to.

- Understand the context in which adaptation is considered: this includes identifying the relevant actors and their adaptive capacity as well as identifying relevant policies that are likely to facilitate or hinder effective adaptation.

- Identify and assess adaptation actions currently being implemented by some in the sector, considering their adoption and relative effectiveness. These actions include building adaptive capacity and implementing action to limit damage or make the most of an opportunity. Barriers are then identified in terms of where uptake or effectiveness (or both) is constrained. Barriers are explored in the following categories:
  - Market failures: the degree to which there are market failures relating to pricing signals; externalities[6]; public goods; and where information may not be timely, accurate, relevant or is incomplete;
  - Policy: the framework of regulation and policy incentives;
  - Governance: institutional decision-making processes; and,
  - Behavioural: for example, short-sightedness and willingness to act.

Recommendations to address barriers are highlighted.

The quantitative and qualitative analysis presented differs to that of the UK Climate Change Risk Assessment (CCRA) in recognition of the particular question asked of this report. To reflect uncertainty, illustrative worked examples and 'what if?' scenarios are presented to demonstrate the scale of the potential impacts of climate change, and how a particular outcome from a recent or plausible climate event could have improved through effective adaptation action. Within the time and scope of this analysis, and given available data, it has not been possible to model the wide range of impacts of projected climate change on specific sectors under a full range of projected future climate scenarios, nor to rely on dispatch modelling.

Where possible, the ranges for climate projections cited cover the UK Climate Projections 2009 (UKCP09) from a low emissions scenario, 10% probability (10th percentile), meaning that the value is very likely to be exceeded, to a high

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[6] Where there are costs or benefits imposed on others that are not accounted for in individual decision making.

emissions scenario, 90% probability (90th percentile), meaning that the value is very likely not to be exceeded. In some cases, the medium emissions scenario, 50% (50th percentile) probability is cited, meaning that the value is as likely as not to occur.

2.2.1 Structure of the report

This report is structured as follows:

- Section 3 presents the scale of the challenge posed by climate change for power generation and transmission.

- Section 4 provides an overview of the context for adaptation in terms of the structure of the sector, nature of energy demand, the current policy framework and adaptive capacity;

- Section 5 presents the range of adaptation actions that are already being taken and would be expected in the future under current incentives. This Section also highlights the barriers to taking effective adaptation action; and,

- Section 6 presents the case for intervention incorporating illustrative adaptation roadmaps, consistent with the concept of adaptive management, and 'what if?' scenarios to illustrate the potential effectiveness of particular actions within those roadmaps.

3 Scale of the challenge

Key messages

Climate change poses a number of threats and challenges to the sector including both long-term average change in climatic variables, and extreme weather events that could increase in intensity and frequency (e.g. flooding and heat-waves). Several examples illustrate the magnitude of potential effects to the 2050s, and although the impacts of climate change may be uncertain, these examples suggest:

- The risk of flooding could in some circumstances leave power stations inoperative for unspecified, potentially extended, periods. This would create a cost to the system owing to the need to call on back-up generation and potentially the need to build additional generation capacity;
- Projected temperature increases and extremes would be likely to lead to heat rate degradation, implying a loss of output in CCGT plant in particular; and,
- Higher (and extreme) summer temperatures would be expected to lead to a reduction in capacity of overhead transmission lines and underground cables and transformers (ENA, 2011).

3.1 Introduction

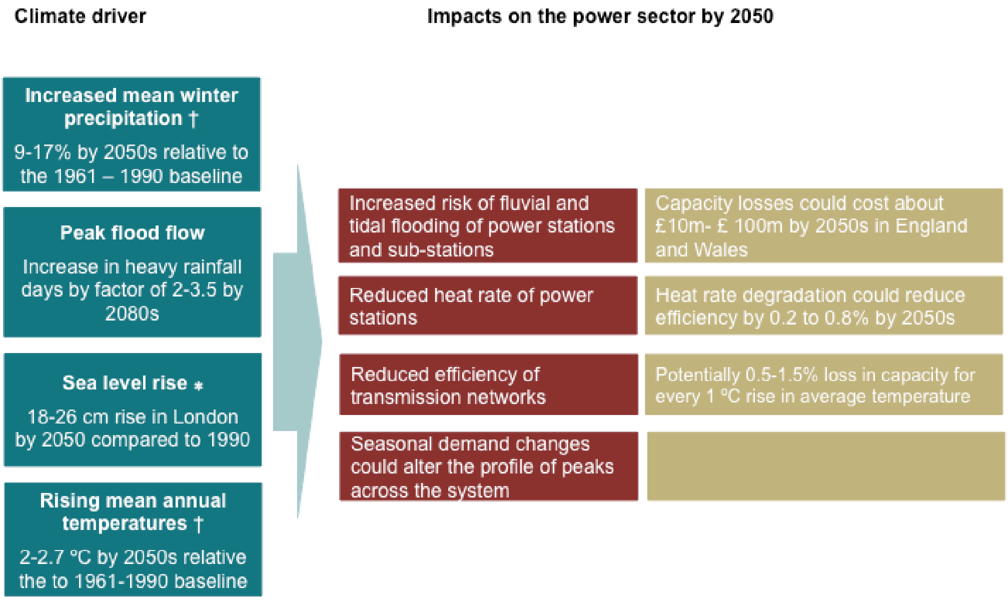
This section sets out the potential scale of impact from climate change both in terms of the long-term average change in climatic variables, and the impacts of extreme weather events.

The scale is illustrated through the use of worked examples with estimates presented in ranges to reflect uncertainty.

3.2 The potential climate change effects

Figure 1 summarises the key climate change threats that are projected to affect the sector to the 2050s.

Figure 1. Climate risks for energy supply infrastructure to the 2050s



Source: Based on McColl *et al.*, 2012. † In the UKCP09 medium emissions p50 scenario.

* In the UKCP09 low to high emissions p50 scenarios.

3.2.1 Risks of flooding to power stations

Climate projections indicate that precipitation is expected to fall increasingly frequently as intense, downpour events. Moreover, mean winter precipitation is projected to increase overall - by 9-17% by the 2050s relative to the 1961-1990 baseline (central estimate in the medium emissions scenario). The spread in projections is wide and varies by location: from -2% for the lower bound of the UKCP09 low emissions scenario in Scotland East to +41% for the upper bound, high emissions scenario in South West England (UKCP09, 2009).

Heavy rain days (>25 mm) are likely to be more frequent over most of the lowland UK; central estimates show an increase by a factor of 2 – 3.5 in winter and 1 – 2 in summer by the 2080s under the medium emissions scenario (UKCP09, 2009).

The north is projected to be less affected by sea level rise compared to the south (Lowe *et al.,* 2009). By 2050, the rise could be between 18 and 26 cm under the p50 low and high emissions scenarios in London and between 10 and 18 cm in Edinburgh, both relative to 1990 (Lowe *et al.,* 2009).

DECC (DUKES 2012b) reports that UK generation capacity was 89 GW at the end of 2011. This measure includes small power stations and de-rates some renewable generation to reflect its intermittent output. By the 2050s, capacity could be 50-80% higher than today (DECC, 2011a).

Due to their need for cooling water, many power stations are currently located near the coast, so the risk of flooding from rising sea level is likely to increase. The CCRA report on the Energy Sector (McColl *et al.,* 2012) has estimated the number of ***existing*** power stations in England and Wales at significant (1:75 years) fluvial or tidal flood risk – baseline levels and projected levels - is 19; this amounts to a combined capacity of 10.2 GW. This is projected to rise to 21-27 power stations with a combined capacity of 11.0-16.3 GW by the 2020s (**Table 1**).

However, it should be noted that these estimates assume no actions are taken to mitigate flooding risks, so they do not represent the true level of risk. Secondly, they consider current power stations only (not any new capacity that is likely to be built over coming years). In practice, many power stations will have been replaced by the 2050s. This will provide an opportunity to adapt to climate change risks by choosing less vulnerable locations or by building according to more stringent standards to ensure flood resilience.

Table 1. Number of power stations at significant risk (1:75 years) of fluvial or tidal flooding by the 2020s in England and Wales)

	Baseline	2020s medium emssions scenario			% of current installed capacity in England and Wales at risk in the 2020s
		p10	p50	p90	
Fluvial flooding	6 (2.2 GW)	6 (2.2 GW)	9 (3.6 GW)	10 (4.3 GW)	2.2% to 4.3%
Tidal flooding	13 (8.0 GW)	15 (8.8 GW)	17 (12.0 GW)	17 (12.0 GW)	8.2% to 12.2%
Total	19 (10.2 GW)	21 (11.0 GW)	26 (15.3 GW)	27 (16.3 GW)	10.4% to 16.5%

Source: CCRA: McColl *et al.*, 2012

3.2.2 Risks of rising temperatures to power stations and the transmission grid

Mean summer temperature is projected to increase significantly due to climate change. By the 2050s, for the central estimate of the medium emissions scenario, there could be increased temperatures of approximately 2.3-2.7 °C in England, 2.5 °C in Wales, 2-2.3 °C in Scotland and 2.2 °C in Northern Ireland, all relative to a 1961-1990 baseline.

There is, however, a large range around these projections. For example, the projected temperature increase for South East England – the region with the highest predicted increase – is between 1.1°C (2050s p10 low emissions scenario) and 5.2°C (2050s p90 high emissions scenario) (UKCP09, 2009).

For power stations, the increase in temperatures would be expected to have a negative effect on performance, especially gas-fuelled power stations. A reduction in power plant efficiency, also known as 'heat rate degradation' would lead to lower generating output for any given level of installed capacity.

For transmission lines, as the temperature increases, capacity declines. This is known as "de-rating."

The impact of heat on transmission capacity varies depending on the particular piece of equipment. However, it is not generally considered to be greater than 1% loss per 1°C rise.[7] The loss is a little higher for overhead line conductors (CCRA: McColl *et al.,* 2012). This is summarised in **Figure 2**. Capacity losses are estimated relative to the current ratings for each of the types of equipment. It is worth noting that for underground cables, the CCRA (McColl *et al.,* 2012) included only the equipment with the highest de-rating per voltage type from the sixteen types of underground cable considered in the ENA report (2011), so the de-rating estimates for underground cables should be viewed as a an upper bound potential scenario. The capacity loss results are for distribution *and* transmission equipment[8].

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[7] These estimates use a baseline period of 1961-1990, and assume that equipment is maintained to EU and international design standards and not susceptible to faults. The estimates also assume a constant average wind speed.

[8] This is specified for the overhead cables in **Figure 2**, and the relevant underground cables for transmission are those at 132 kV or higher.

Figure 2. The effects of increased heat on transmission capacity

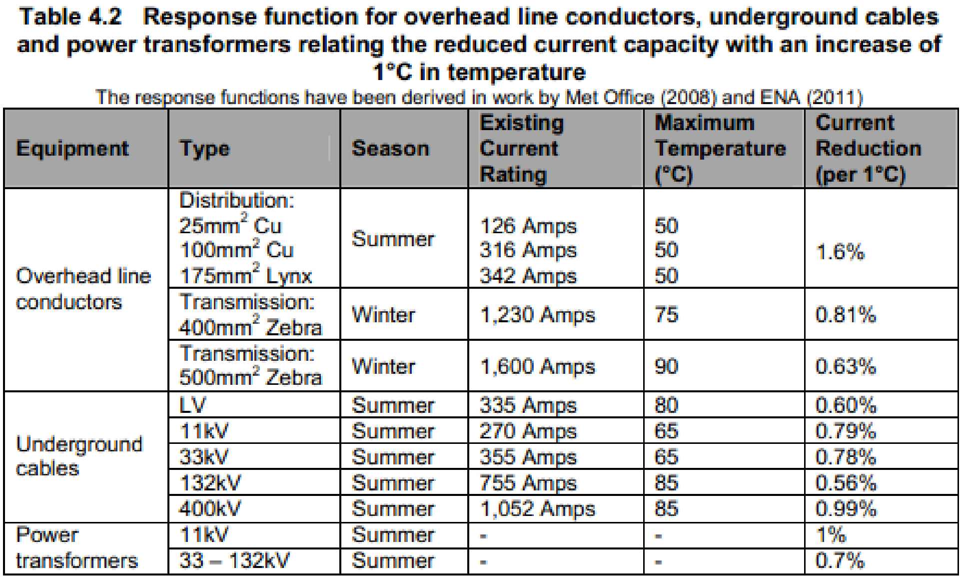

Table 4.2 Response function for overhead line conductors, underground cables and power transformers relating the reduced current capacity with an increase of 1°C in temperature

The response functions have been derived in work by Met Office (2008) and ENA (2011)

Equipment	Type	Season	Existing Current Rating	Maximum Temperature (°C)	Current Reduction (per 1°C)
Overhead line conductors	Distribution: 25mm^2 Cu 100mm^2 Cu 175mm^2 Lynx	Summer	126 Amps 316 Amps 342 Amps	50 50 50	1.6%
	Transmission: 400mm^2 Zebra	Winter	1,230 Amps	75	0.81%
	Transmission: 500mm^2 Zebra	Winter	1,600 Amps	90	0.63%
Underground cables	LV	Summer	335 Amps	80	0.60%
	11kV	Summer	270 Amps	65	0.79%
	33kV	Summer	355 Amps	65	0.78%
	132kV	Summer	755 Amps	85	0.56%
	400kV	Summer	1,052 Amps	85	0.99%
Power transformers	11kV	Summer	-	-	1%
	33 – 132kV	Summer	-	-	0.7%

Source: CCRA: McColl *et al.*, 2012.

In addition, National Grid (2010a) estimated the potential reduction in transmission capacity under an 8°C rise in summer mean temperatures for the 2080s (using the UKCP09 high emissions p90 scenario). **Table 2** presents results for London and South East England. The CCRA estimated similar magnitudes of effects on two types of overhead line conductors (part of the transmission network) by noting the effects are "unlikely to be greater than 2% in the 2020s and 2050s" (McColl *et al.*, 2012).

Table 2. Effect on transmission capacity of increased mean summer temperature of up to 8 degrees (2080s, high emissions scenario, p90) in London and the South East of England

Equipment	Typical reduction in asset capacity
Overhead lines	3%
Underground cables	5%
Transformers	5%

Source: National Grid (2010a)

The conclusion reached by the ENA in its analysis of this issue is that

"Projected capacity reductions due to increased future temperatures were small relative to recent load growth. In addition, the investment required in order to upgrade the transmission network to accommodate future changes to the energy mix is expected to be larger than that required to accommodate de-ratings due to higher temperatures. As a result, it appears that the risk posed by increased temperatures is already being addressed in response to other changes faced by the transmission network." (ENA, 2011)

This suggests that de-rating is part of a wider issue than just climate change; the network experiences approximately 1.5-2% load growth per year and this may increase if the transport system or heating becomes more dependent on electricity.

3.2.3 Risks to water availability for power stations

The importance of water availability for power stations is evident from looking at the water demand figures for new and existing nuclear sites in the UK, provided by the Nuclear Decommissioning Authority (NDA). The total water use for all existing sites in the financial year 2009-10 was just over 8,682 Ml and water demands vary widely by site. Water requirements in Ml/d for NDA sites by river basin region range from almost 19 Ml/d in North West England to 0.05 Ml/d for the Thames river basin region. In addition, there are two proposed sites which would add to the overall water requirements (CCRA: McColl *et al.,* 2012)

Water is not explored significantly in this report because the Government announced in the Water White Paper that it intended to reform the water abstraction regime. In order to do this, Defra, the Welsh Government and the Environment Agency are funding a major programme of research to develop the evidence-base to assess the impacts of different options for reform of the regime. Key areas of work include improving knowledge of:

- Future availability of water, particularly the effects of future demands for water by the power agricultural sectors;
- The relationships between water levels and water ecological status;
- Regulatory design options and their technical feasibility; and,
- Abstracter response strategies to changes in water availability under different regulatory options.

3.3 Estimated impacts of climate change

For illustrative purposes, this section seeks to indicate the potential scale of impact of projected climate change on the sector, under particular assumptions. The analysis shows the estimated costs if generation of transmission capacity is affected by flooding or extreme heat – adaptation actions that would mitigate these effects are discussed in Section 5.

3.3.1 Generation capacity and supply

Two particular risks to generation and transmission highlighted above are the risks of flooding and rising temperatures. Below, the impact of each challenge is expressed through worked examples in terms of generation output that could be lost in the absence of particular adaptation actions that could mitigate the effects (including design or operational measures). The potential scale of monetary value of this impact is estimated.

The analysis is largely based on the findings of the CCRA (McColl *et al.,* 2012) – i.e. estimates of the power stations at risk of flooding. The limitations of this study (discussed below) must be noted.

Flooding

The amount of generating capacity at risk of flooding was estimated by the CCRA (McColl *et al.,* 2012). Estimates are not to be interpreted as a projection of what may occur but rather illustrate the scale of impact if a certain level of power generation was to be taken out of action. This allows the order of magnitude of effect to be explored.

CCRA (McColl *et al.,* 2012) estimates do not explicitly factor in the age of the current generation fleet nor do they account for existing measures to address flooding. As explained above, a significant amount of capacity will need to be rebuilt by the 2020s. By the 2030s, most of the capacity existing today will have been replaced. This suggests that the sector may be able to adapt to this risk by factoring adequate flood protections in the design or by changing the location of future power stations. Such actions are discussed in Section 5. The amount of installed capacity, the generation mix, and the location of power stations would be expected to change over time. However, in the absence of other available evidence, these data have been used for the following analysis to provide worked examples to illustrate the scale of the challenge.

The CCRA (McColl *et al.,* 2012) concludes that under a medium emissions scenario (p10 to p90) by the 2020s, an additional 1 GW to 6 GW of installed capacity could be exposed to an annual risk of flooding of at least 1.3% (1:75). By the 2050s, the CCRA (McColl *et al.,* 2012) projects that the incremental capacity exposed to the same risk of flooding, compared to today's baseline (using low p10 emissions scenario to high p90 emissions scenario) will have grown by between 5 GW and 12 GW.

Flood events can vary significantly, not least in terms of the return period. Surface water may flow away in a couple of hours, while flash floods from storms could last about 6-7 hours. However, tidal and fluvial flooding can last for days.

The first worked example explores the impact of power stations at risk of flooding with a 75 year return period being rendered inoperative for an illustrative period ranging between 30 days (720 hours) and 180 days (4,320 hours) while the damage is being repaired. It assumes, for illustration, that all of the increased capacity at risk of fluvial or tidal flooding identified by the CCRA (McColl *et al.*, 2012) is affected in this way. The probability of flooding is calculated as the expected annual value of such an event. We assume an average load factor of 62%, as shown in **Table 3**.

Table 3. Summary of assumptions for the estimate of the order of magnitude of impact of flooding

Assumption	2020s	2050s
Incremental capacity at risk of flooding (GW)	1 to 6	5 to 12
Probability of flooding (%)	1.3%	1.3%
Load factor (%)	62%	62%
Duration of each flooding event (hours)	720 to 4,320	720 to 4,320

Source: CCRA (McColl *et al.*, 2012), DECC (2012b) and DECC (2011)

The costs associated with the generating capacity that would be at risk from floods with a 75 year return period in the 2020s and the 2050s are illustrated in **Table 4**[9].

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[9] This is calculated as annual output lost (GWh) = incremental capacity at risk (GW) * probability of flooding (%) * length of outage (hrs).

Table 4. Potential magnitude of impact of flooding risk on generation output if CCRA estimates of incremental capacity at risk are used (not accounting for adaptation)

Period	Incremental capacity at risk (GW)	Lost output (GWh and as % of current total generation)
2020s		
Low - (medium emissions p10)	1 GW	6 GWh to 36 GWh (0.002% to 0.010%)
High (medium emissions p90)	6 GW	36 GWh to 214 GWh (0.010% to 0.061%)
2050s (for illustration, though note this does not account for expected changes in generation capacity to the 2050s)		
Low (low emissions p10)	5 GW	30 GWh to 179 GWh (0.008% to 0.051%)
High (high emissions p90)	12 GW	71 GWh to 429 GWh (0.020% to 0.122%)

Source: Analysis based on assessed capacity at risk from McColl *et al.*, (2012)

Table 4 shows that, using the illustrative assumptions above (i.e. no adaptation actions) by the 2020s, up to 214 GWh of annual generation output could be lost owing to flooding (75 year return period). This could rise to an annual output loss of between 30 GWh and 429 GWh per annum by the 2050s, depending on the duration of the outage period and the generation capacity at risk.

To estimate the associated costs of such lost output, the shortfall in generation is assumed to be met by using existing reserve. Specifically, OCGT plants are assumed to be used instead of the affected plants. Given that the marginal cost of this type of plant is about 2.8 p/kWh higher than the marginal cost of gas fired CCGT plant[10], the incremental (undiscounted) expected average annual cost of

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[10] This calculation is based on the efficiencies for new Nth of kind OCGT and CCGT plants sourced from Parsons Brinckerhoff (2012), Electricity Generation Cost Model - 2012 Update of Non Renewable Technologies, gas prices from DECC (2012a), DECC Fossil Fuel Price Projections, a CO2 price of €7.00/tCO2 and CO2 emissions factors from Carbon Emission Factors and Calorific Values from the UK Greenhouse Gas Inventory (AEA, 2012) to Support the EU ETS. A cost difference of 2.8p/kWh should

flooding is estimated to range between £0.2 million and £6.0 million per year in the 2020s, and between £0.8 million and £12.0 million per year by the 2050s. [11]

The impacts described above are based on assumptions about the *average* expected impacts of climate change accounting for the 1:75 level of risk of fluvial and tidal flooding. However, flooding occurrences can be disruptive and, if they affect a large power station, they could lead to a significant output loss at a particular point in time. By way of illustration, we estimate what the impact of a flooding event would be if it affected a large power plant.

To illustrate the impact of a one-off flood event (as opposed to an average or 'expected' impact, as above), this worked example explores the potential impacts if a flood affected a large CCGT plant with capacity 885 MW, rendering it unavailable for between one and six months[12] (30 - 180 days, equivalent to 739 - 4,380 hours). On the basis of a load factor of 62%[13], during the forced outage period, this power station would have produced electricity for between 458 and 2,716 hours. This is equivalent to an output loss of between 0.4 TWh to 2.4TWh. If OCGT balances this loss by using reserve plants whose marginal cost is currently about 2.8 p/kWh higher than the marginal cost of a standard CCGT plant, the incremental one-off cost of the lost output during this outage period would be approximately between £11.4 million and £67.3 million in 2012 prices – though this sits within a wide range of uncertainty.

We note that in the case of extreme weather events, with a much lower probability than those identified by the CCRA, there may be much wider economic and social costs, especially if flooding leads to widespread blackout (i.e. if several power stations were severely affected at the same time). However, due to the complexity of the interdependencies characterising the energy sector, and the uncertainty associated with the scale of the impact, a reliable quantification of

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be considered a lower bound since, in practice, OCGT plants may replace other plants that have a lower marginal cost than gas fired CCGT, in a situation with the loss of generation due to flooding, OCGT plants may be able to exploit their (temporary) market power and apply a higher mark-up on their cost, and over time gas and CO2 prices are expected to rise. This estimate has been used for the purpose of illustration. A more detailed analysis would be required for an accurate estimate of the associated costs.

[11] It should be noted that flooding events may have direct implications on customers, which may be suffer outages due to the transmission and, more significantly, the distribution network being damaged. The monetary loss in these specific cases would be significantly higher, given that estimates place the Value of Lost Load (VoLL) as high as £10,000/MWh. However, as this section looks at the specific impact of flooding on power stations, we do not include VoLL in the calculation. This is because forced outages of some power station would not immediately translate into customers suffering outages.

[12] This time-frame has been selected for the purposes of illustration – in reality, the duration of any effects would be entirely dependent on the nature of the flood and the extent to which the power station had taken action to ensure it is resilient.

[13] DECC (2012b) Dukes Table 5.10. The load factor indicates the number of hours during which a plant generates electricity out of the total number of hours available. This value has been calculated as an average of CCGT plant load factors during the period 2007-2011.

the cost of such an event was not possible within this report. This aspect would benefit from further research if probabilities could be assigned to such an event.

Heat rate degradation

The heat rate is a measure of the efficiency of power plants that convert a fuel into heat to generate electricity[14]. Specifically, the heat rate measures the amount of energy needed to generate a unit of electricity.

Among other factors, the heat rate of a plant would depend on ambient and cooling water temperature. The higher the temperature, the less efficient the plant would be. In other words, for a given amount of fuel, the plant would generate less electricity as ambient temperature increases. This phenomenon is known as 'heat rate degradation'.

The impact of climate change on heat rate degradation has been estimated using climate projections combined with an established relationship between ambient temperatures and heat rate degradation[15]. Several worked examples are explored to show the magnitude of potential effects for given assumptions.

UKCP09 projections suggest that by the 2050s in South East England – the region with the highest projected increase - temperature could increase by between 1.4 °C (p10 low emissions scenario by the 2050s) and 5.2 °C (p90 high emissions scenario by the 2050s) compared to the 1961-1990 baseline of 15 °C (UKCP09, 2009). Using the established relationship (Carnot's rule) the theoretical impact of these temperature increases on the efficiency of a thermal plant can be estimated. **Table 5** summarises the results of this calculation.

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[14] Heat is used to generate steam which in turn is used in turbines to generate electricity. This type of plant includes coal, gas and nuclear power stations.

[15] The so called 'Carnot's rule' can provide an illustration of how this works. Carnot's rule specifies the maximum efficiency that any heat engine can achieve. Such efficiency depends solely on the differential between the high temperature produced using combustion and the cold temperature where the heat is expended into the surrounding environment. Specifically: Efficiency = [1 – (Cold temperature / Hot temperature)] * 100. For example, if the ambient temperature (air and cooling water) were to increase from 15 degrees Celsius to 20 degrees Celsius, the plant's thermal efficiency would fall from 65% to 64.4%, a 0.93% decrease. Carnot's rule is a theoretical relationship. In practice, the efficiency of a power plant depends on a variety of other factors. This notwithstanding, it can be used to provide an illustration of the impact of rising temperatures on plants efficiency.

Table 5. Estimated impact of temperature change on plant efficiency by the 2050s in the South East of England (exploring projected temperature change from p10 low emissions scenario to p90 high emissions scenario)

Period	Temperature increase (Celsius)	Change in efficiency (%)
Low	1.4	-0.3%
High	5.2	-0.9%

By the 2050s, the **reduction in efficiency could range between 0.3% and 0.9%** (from p10 low emissions scenario to p90 high emissions scenario)**.**

Out of all heat-based plants (coal, gas and nuclear), combined-cycle gas turbines (CCGT) are potentially the most impacted by rising air temperatures. This is because an increase in ambient air temperature results in the warmed air becoming less dense which in turn reduces the mass flow of air being drawn into the turbine and so less gas can be burned. Nuclear and coal power stations are less affected in this way.

CCGT plants account for a large share of thermal generation. In 2010, CCGT plants in the UK generated about 170 TWh of electricity (about 45% of total electricity generated). This example explores what might happen if the operating pattern of these plants does not adapt such that the projected increase in temperatures could lead to a reduction in CCGT generating output.

As summarised in **Table 6**, in the absence of adaptation, **the estimated annual lost output by the 2050s could range between 523 GWh and 1,569 GWh**.

Table 6. Illustrative impact of temperature change on generation output for lost CCGT by the 2050s (from p10 low emissions scenario to p90 high emissions scenario)

Period	Temperature increase (Celsius)	Lost output (GWh, and as % of current generation)
Low	1.4	523 GWh (0.15%)
High	5.2	1,569 GWh (0.45%)

This impact is significantly greater than the impact of flooding analysed under the worked examples above. This is because the increase in average temperatures would be expected to affect all power plants rather than just those in specific locations. In addition, this is **likely to be an over-estimate** because it is expected that CCGT would form a decreasing share of generation capacity over time.

To provide an indication of the monetary value of this impact, it is necessary to consider the ways in which this generation shortfall could be met. The main options are:

- Use existing reserve capacity: as seen above, this solution is about 2.8p/kWh more expensive than standard CCGT.
- Build new CCGT capacity, at a cost of about £604 per kW (Parsons Brinckerhoff, 2012)[16] (obviously a longer-term action).

By the 2050s, without adaptation, if there is a generation shortfall equivalent to the lost output of 523GWh – 1569GWh per annum, then:

- If the shortfall was met using existing reserve capacity, the incremental cost of generating 523 GWh-1569GWh could be around £14.6 million -£43.9 million (in 2012 prices, undiscounted). Over thirty years (the life of a CCGT power station), the total (undiscounted) cost would be £439 million – £1,318 million.

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[16] The cost of CCGT capacity does not take account of financing during construction or fixed operating costs. If these addition costs were included and rolled up or discounted to the commissioning date, the cost of capacity could rise to as much as £912/kW.

- If new capacity were built, the total (undiscounted) cost could be around £58.2-174.5 million in 2012 prices. This is because around 96-289 MW of additional CCGT capacity could need to be built, assuming an average load factor of 62%.

The cost illustrated above is based on the expected average impact of climate change on average temperatures. However, climate change may also result in more extreme weather conditions, such as occasional, much hotter summer months. A further worked example addresses this.

Using an illustrative example of a two-week heat-wave[17] during the month of August that leads to the average temperature of 27 °C (6.5 degrees higher than the historic monthly average maximum temperature of 20.5 °C for August in England), this example does not rely on a specific climate change emissions scenario projection. The relationship discussed above suggests that the efficiency of CCGT plants could decrease by 1.2%. Given that the current average August output of CCGT plants is around 11.5 TWh (DECC, 2013)[18], the reduction in efficiency would imply an output loss of about 62 GWh. Replacing this shortfall with OCGT generation[19], for example, at an incremental cost of 2.8p/kWh would imply a total cost of about £1.75 million (2012 prices) per event.

Impacts on seasonal demand

The current typical average winter peak electricity demand in the UK is around 53 GW (National Grid, 2011). The peak occurs during the winter months as the demand for heating and lighting outstrips the demand for cooling. Typical summer load generally peaks at around 41 GW, 12 GW less than the winter peak.

The temperature rise associated with climate change is expected to have an impact on energy demand. Warmer temperatures could lead to a decline in winter energy demand, but also to an increase in cooling demand during the summer months. This would be expected to impact on the power sector in two ways:

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[17] A heat Health Watch System is operated by the Met. Office in the UK. This system comprises "four levels of response based upon threshold maximum daytime and minimum night-time temperatures. These thresholds vary by region, but an average threshold temperature is 30 °C by day and 15 °C overnight" (Met. Office website, accessed 2012). The duration of the heat-wave is based on the duration of extreme past weather events. For example, the Met. Office reports that "during the long hot summer of 1976, temperatures exceeded 32 °C (90 °F), somewhere in the UK, on 15 consecutive days starting on 23 June. During the summer of 1976, Heathrow had 16 consecutive days over 30 °C from 23 June to 8 July (its highest number of consecutive days above 30 °C) (Met. Office website, accessed 2012).

[18] DECC (2013) DUKES Monthly Table 5.4. Average calculated using 2008-2012 data.

[19] In practice, some of the lost CCGT generation may be replaced by other CCGT generation that was not otherwise running during summer.

- Winter demand would be likely to fall, although demand for cooling in summer is likely to increase: the net impact will determine whether more generation would be needed to accommodate additional demand; and,

- Although the winter peak could decrease, the summer peak would be expected to grow, increasing the demands on generation and transmission during the summer months.

For the first type of impact, there are various studies that consider the relationship between electricity demand and temperature. However, given the current low penetration of ambient cooling equipment in the UK, these studies tend to concentrate on the reduction in heating demand. For example, in their study of British homes, Summerfield *et al.,* (2010) modelled the impact of average winter air temperature on heating energy. Their results suggest that a 1 °C increase in air temperature leads to around 5% decrease in annual energy demand. The work of Firth *et al.,* (2010), using a bottom-up stock model, produced a figure of around 6.2% decrease per 1°C temperature rise.

For the residential sector, the actual impact on electricity demand would depend on the extent to which fuel is switching away from gas. Should space heating and heat pumps displace gas heating, then the demand for heating electricity could still increase despite the increase in temperatures lowering heating requirements. At present, however, it is difficult to predict what the net impact of rising temperature on electricity demand for heating would be.

Rising temperatures, however, are likely to increase the demand for cooling, which is entirely reliant on electricity. Some recent studies provide an indication of the extent to which demand could increase because of climate change. Day *et al.,* (2009) suggest the demand for cooling could grow by 5% every year with the growth of air-conditioning sales. As the cooling of buildings currently accounts for around 4% of the total electricity demand in the UK (about 15 TWh), the incremental demand for cooling could be about 7 TWh in 2020 and reach 80 TWh in 2050 (see the ECR report "Overheating in Residential Housing" for more details).

Depending on the relative magnitude of these two contrasting effects, net electricity demand could either increase or decrease. Unfortunately, the uncertainty surrounding these estimates does not make drawing firmer conclusions possible.[20]

As noted above, the second type of impact of climate change would be to increase the summer demand peak. Whether this is an issue for power generation

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[20] We note that a more comprehensive assessment of this effect would require determining whether climate change would have an impact on maximum peak load in winter and summer. In the absence of reliable information on this, consumption is used as a proxy.

largely depends on whether the summer peak would be expected to exceed the winter peak.

The change in the residential demand for cooling has been considered by the ECR in a separate report (ECR report "Overheating in Residential Housing").

Under a medium emissions (p50) scenario, energy demand for cooling could triple between 2010 and 2050 in both London and the West Midlands case study areas if uptake of air conditioning systems rises from the current 0.6% uptake to around 1% of households in 2050 ("low uptake" case).

If 50% of households install air conditioning systems by 2050, energy demand for cooling could be 37 times greater than in a low uptake case in 2050 (assuming the same p50 medium emissions scenario).

The most extreme case that was modelled considered 100% of households installing air conditioning systems by 2050. This could result in energy demand for cooling in 2050 of more than 84 times higher than in the low uptake case.

The results are very sensitive to the assumptions around the uptake of cooling systems and are for the case study areas only.

Any increases in energy demand for cooling and CO_2 emissions could be partially offset by improvements in the efficiency of air conditioning systems and de-carbonisation of the grid, and would be affected by the rate of climate change.

Required installed capacity could increase substantially under a range of uptake scenarios. The analysis undertaken for the ECR report "Overheating in Residential Housing" suggests that:

- For the low uptake case, the installed capacity in 2050 could be more than double 2010 levels. For illustration, the extra generation capacity that would be required to service this increase in demand would be around 25-40 MW in London and 9-15 MW in the West Midlands, assuming a coefficient of performance[21] of between 3 and 5. This is a very small requirement, considering that many power stations have a capacity of around 1 GW.

- Assuming a high uptake rate, the installed capacity in London could increase by 11,400 MW in London and 7,800 MW in the West Midlands between 2010 and 2050. These are significant increases and suggest that peak load electricity demand could be notably higher than it is today. Assuming a co-efficient of performance of between 3 and 5 by the 2050s, then the additional peak cooling load required in 2050 could be equivalent to 2.4-4

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[21] The Coefficient of Performance (COP) is the 'instantaneous' measure of efficiency of the refrigeration system. It is the ratio of the cooling output to the electricity input. It is used in this instance to determine the peak electrical demand of cooling system.

GW of extra generation capacity in London and 1.6-2.6 GW in the West Midlands. **The indicative installed capacity results illustrate that significant capacity could be required** in certain regions of the UK to serve demand in the event of high uptake of active cooling systems. More detailed modelling would be required to estimate the effects with greater accuracy.

These findings only apply to London and the West Midlands, covering around 7.1 million households, by the 2050s. Furthermore, this analysis covers the residential demand for cooling only – the commercial and industrial sectors should also be explored in more detail.

Based on current values, the increase shown under the extreme case would be larger than the existing differential between winter and summer peak. However, there are important caveats that should be considered when interpreting these results:

- The analysis presents an upper bound with an extreme scenario, assuming 100% uptake of air conditioning. Such a level of uptake is unlikely.
- Given the expected increase in electricity demand from other sources (e.g. electric vehicles, heat pumps, electrification of manufacturing), generation capacity is projected to increase by the 2050s. The DECC Carbon Plan suggested four possible scenarios which increase installed capacity by between 40% and 80% relative to 2010 (DECC, 2011a).
- The planned increase in generation capacity (both renewable and thermal back-up generation) would increase the level of redundancy on the system.

Therefore, provided opportunities to incorporate climate change considerations within planning and investment are taken (i.e. that market signals are channelled effectively and mechanisms such as the Capacity Mechanism work effectively), the system should be able to adapt to the increase in the demand for cooling over time. However, it would be important to undertake more detailed analysis to determine the impacts on peak loads with greater accuracy.

Impacts on the transmission grid

There is uncertainty over the impacts of increased temperatures on the transmission grid. The primary effect is likely to be the loss in capacity when temperatures rise.

This is projected to be not more than 1% for every 1°C rise in temperature for the majority of UK transmission and distribution assets (see **Figure 2**). The ENA's projections (see **Table 2**) of capacity losses for an 8 °C rise in mean summer temperatures by 2080 (high emissions scenario p90) project a capacity reduction of 3% for overhead lines, and 5% for underground cables and transformers.

The CCRA (McColl *et al.,* 2012) reported adaptation costs rather than welfare costs to illustrate the extent of the economic impact without adaptation. These figures, using Ofgem data and reported by the ENA (2011), suggest a total cost of adaptation of £2.6 billion over 60 years.[22] Indicatively, the cost is estimated by multiplying the quantity of the relevant asset, the indicative maximum de-rating, the unit cost, and the percentage affected length of the asset, using data reported by the Energy Network Association (ENA, 2011). This implies a £40 million investment per annum in adaptation[23]. Overhead lines make up the biggest part of the cost (£1.3 billion), and the remaining costs are for underlying cables (£0.75 billion) and transformers (£0.5 billion) (CCRA: McColl *et al.,* 2012). The high de-rating assumptions and the climate change scenario used for the analysis (p90 high emissions scenario to the 2080s) suggest that it may be a high estimate of the adaptation costs. In addition, the transition to a low-carbon economy means that adaptation costs in the transmission network are expected to "predominantly emerge as marginal costs incurred at the time of other works, rather than an outright adaptation only cost" (ENA, 2011).

For context, expected capital investment in energy networks is more than £14 billion between now and 2020/21 (ENA, 2011). Customer-driven and non-customer-driven capital expenditure by National Grid over the period 2013/14-2020/2021 is forecast to be £11,900 million[24] (National Grid, 2012). The estimated annual adaptation cost is small relative to these figures.

The **actual impacts on transmission capacity of climate change may vary across the overall network**, as increases in mean temperatures are expected to differ regionally. The CCRA (McColl et al., 2012) estimated capacity losses by administrative region for overhead line conductors in the distribution network under different UKCP09 climate scenarios. These estimates indicate that the greatest impacts of increased temperatures on capacity were expected in London, South West and South East England. The smallest impacts were expected in Northern Ireland and Northern Scotland. While regional projections of capacity losses were not made for transmission assets, these estimated effects for the distribution network could provide an indication of how impacts could differ across the UK for the transmission network.

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[22] This figure uses estimated costs of de-rating from Ofgem data. The estimate applies the "worst-case" de-rating as a result of climate change for 2080, using the high emissions scenario and 90% probability, and pessimistic cost and de-rating assumptions.

[23] The annual figure does not take the location and age of individual assets into account, and instead uses a "simple straight line approach." (p.71, ENA, 2011).

[24] This is in 2009/10 prices.

In light of these risks, the next section presents an assessment of the context in which adaptation is being considered including a description of the key characteristics of the sector and the policy framework.

4 The context for adaptation

Key messages

Key trends shaping the medium-term development of electricity generation in the UK are:

- Around a fifth (some 19GW) of capacity available in 2011 has to close by the end of this decade (DECC, 2012). In addition, much of the aging assets in the transmission network are due for renewal. A significant proportion of new generation is likely to be from renewables and therefore more intermittent and less flexible.
- The electricity transmission network is expected to undergo a significant change by the 2050s, due to changes to the generation mix and increased demand as a result of the electrification of heat and transport. New generation is likely to be dispersed, and offshore wind generation will require investment in offshore transmission (National Grid, 2012).
- In terms of policy, the most significant innovation that will affect the sector is Electricity Market Reform (EMR). The reforms would be expected to increase the potential for appropriate adaptation of the sector, as long as potential climate change threats (such as flood risk and increasing mean temperatures) are appropriately accounted for within regulatory frameworks, investment planning and operational resilience considerations.

Adaptive capacity of the power generation and transmission sector overall is assessed as high. While decision life-times are long, activity levels are high given the investment occurring, and planned, in the sector.

4.1 Introduction

This Section focuses on the context for adaptation in terms of the key characteristics of electricity generation and transmission in the UK, the policy framework in which actors operate, the future outlook for the sector and the adaptive capacity of relevant (non-government) actors.

Whether adaptation action is likely to be taken to address climate threats effectively requires two key factors to be considered:

- **Adaptive capacity (see below):** Adaptive capacity is a necessary condition for the design and implementation of effective adaptation strategies, so as to reduce the likelihood and magnitude of harmful outcomes resulting from climate change (Brooks and Adger, 2005).

- **Adaptation actions (Section 5)**: There is a suite of actions that could form part of an effective adaptation strategy. The choice of actions will depend on the capacity of both the organisation and the sector in which it operates, and the climate change risks under consideration – these factors should be considered systematically together with non-climate risks.

The structure of the sector is briefly outlined before exploring the policy context and adaptive capacity in this Section. The adaptation actions currently being taken, and those likely to be taken in the near-term, are discussed in Section 5.

4.2 The characteristics of the sector

The power sector supply chain is made up by five components, namely:

- **Generation:** production of electricity using power plants of various types (nuclear, gas, coal, renewables, etc.). Electricity generated in 2011 was 368 TWh, down 3.7% from 381 TWh in 2010 (DECC, 2012b);
- **Transmission:** electricity is transported over long distances from the generating power plant;
- **Distribution:** electricity is transported at low voltage to final users;
- **Supply:** electricity is sold to final users; and,
- **Hedging and trading activities** around fuel acquisition (i.e., buying fuel to run the generator), and energy sales.

In England and Wales, National Grid owns and operates the electricity transmission system. National Grid also operates the transmission system in Scotland, in its role as system operator, while Scottish Transmission Limited and Scottish Hydro-Electric Transmission Limited own the network and are responsible for its long-term maintenance and reinforcement. The current location of supply infrastructure in Great Britain is shown in **Annex 2.**

In Northern Ireland, there are currently three large fossil fuel power stations and 24 wind farms which generate approximately 8% of electricity consumed in Northern Ireland. The transmission and distribution networks are owned by Northern Ireland Electricity (NIE), and transmission is operated by the System Operator Northern Ireland (SONI). EirGrid plc, which owns SONI and its Republic of Ireland counterpart EirGrid, runs the single wholesale electricity market for the island, which was established by the Single Electricity Market (SEM) reform in 2007. The Distribution System Operator is ESB Networks Ltd.

4.2.1 Generation

Table 7 shows the breakdown of current generation by fuel type. Gas accounts for the largest share (40%) of production, coal (30%), nuclear (19%) and, renewables (both thermal, such as biomass, and non-thermal, such as solar, wind and wave), (8%). The remaining 4% is accounted for by hydro-power and other less-used thermal sources (oil, coke oven-gas, blast furnace gas and waste products from chemical processes).

Table 7. Electricity generation in 2011 by fuel type

Fuel type	Generation (TWh)	Share of total generation (%)
Gas	147	40%
Coal	109	30%
Nuclear	69	19%
Renewables	29	8%
Hydro	9	2%
Other (Oil and other thermal)	6	2%
Total	368	100%

Source: DECC (2012b) (DUKES Table 5.6)

Table 8 shows the winter (January) and summer (July) load factors for the three main thermal sources: gas, coal and nuclear. It also shows the annual average load factor.

Table 8. Average and seasonal load factors of main thermal sources (for 2011)

Source	Annual average	January	August
Gas (CCGT)	48%	56%	50%
Coal	41%	66%	34%
Nuclear	66%	75%	62%

Source: DECC (2012b) DUKES tables 5.7 and 5.10 and Monthly table 5.4[25]

The table shows that both on average and in specific months, the current installed capacity operates well below its maximum output. Load factors are lower in summer as there is less demand for electricity. As prices are therefore lower during the summer, annual maintenance and nuclear plant refuelling takes place in this period.

Looking to the future, various trends are shaping the medium-term development of electricity generation in the UK.

Firstly, around a fifth of existing generation capacity is closing over the next decade. Specifically, around 19 GW of installed capacity is expected to close by the 2020s as a result of EU environmental regulations on coal plants, and nuclear plants coming to the end of their regulated life (DECC, 2011a). This capacity will need to be replaced to ensure security of supply. By 2030, most current generating capacity will have reached the end of its economic life and will have been replaced.

Second, a significant proportion of new generation is likely to be more intermittent and less flexible. **Figure 3** shows the projected evolution of generating capacity by fuel type to 2030. Coal's share is expected to decrease significantly, while large quantities of renewables (mainly wind) are projected to be installed. As wind generation is intermittent and non-controllable, gas power stations will also be built to provide back-up capacity in periods of low wind.

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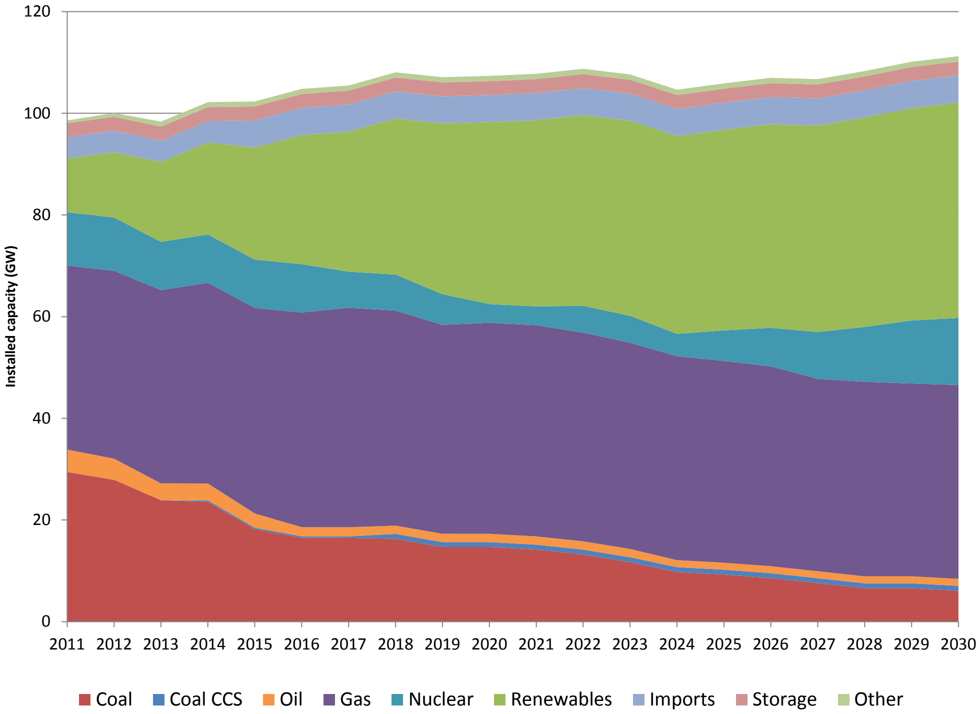
[25] *ibid*

Figure 3. Evolution of installed generating capacity by fuel type



Source: DECC (2011d) Updated Energy & Emissions Projections – October 2011 (Central scenario)[26]

Generating capacity is projected to increase by over 10% by 2030 under DECC's central scenario. To 2050, there is more uncertainty about the generation mix, with the DECC Carbon Plan suggesting four possible scenarios which increase installed capacity by between 40% and 80% relative to 2010 (DECC, 2011a). These scenarios are discussed in more detail below. There is likely to be an increase in low carbon energy sources.

Changes in generation capacity are driven by policy (renewables will be more prominent in the generation mix given climate change mitigation obligations). Others are driven by the need to replace an ageing fleet of generators with newer, more efficient plants.

4.2.2 Transmission

The National Electricity Transmission System (NETS) in Great Britain transports electricity from generators to the distribution networks. Electricity is

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[26] More recent projections than those used at the time of writing are available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65717/6660-updated-emissions-projections-october-2012.pdf

transported over long distances at high voltage, before being transformed to low voltage upon entering the distribution networks.

The Great Britain NETS is made up of three networks, one in England and Wales, owned by National Grid, and two in Scotland, owned by Scottish Power and Scottish and Southern Energy respectively. The total length of the NETS is about 25,000 km. The network transmits electricity between generation and distribution systems, and consists of overhead lines, underground cables, substations, power transformers and Quadrature Boosters, and grid supply points (National Grid, 2011). The transmission system typically operates at 400 kV or 275 kV, and at 132 kV in Scotland (ENA, 2011). This is illustrated in **Figure 4** below.

Figure 4. The electricity supply chain

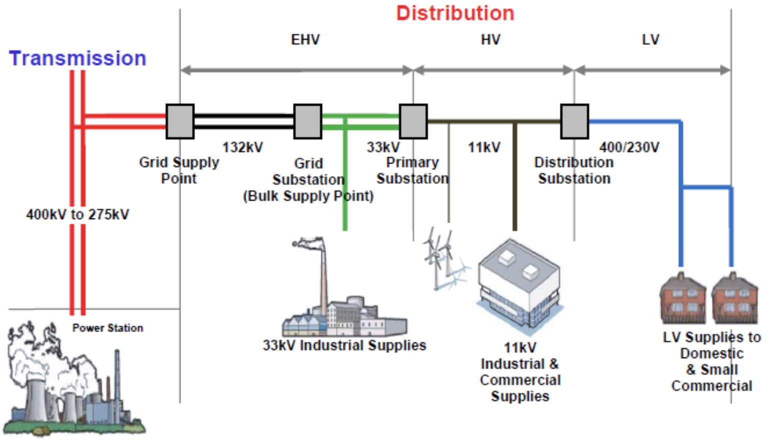

Figure 1 - Typical Electricity Supply Chain

Source: ENA (2011)

In Northern Ireland the transmission network consists of 400 km of 275 kV overhead line (developed between 1963 and 1978); 924 km of 110 kV overhead line, and 90 km of 110 kV cable (the majority of the 110 kV system was installed between 1944 and 1958). The network is interconnected with Scotland and the Republic of Ireland, and a new interconnector between Tyrone and Cavan is currently being planned (NIE, 2011).

As a natural monopoly, National Grid is subject to price controls which must be approved by Ofgem. These set targets for supply interruptions to customers, with financial penalties/incentives based on performance against these (ENA 2011). Under its Transmission Licence, National Grid's obligations include:

“National Grid shall at all times have in force and comply with, a Balancing and Settlement Code[27]

National Grid shall operate the transmission system in an efficient, economic and co-ordinated manner. Having taken into account the relevant price and technical differences, National Grid shall not discriminate between any persons or classes of persons in its procurement of Balancing Services. (National Grid, 2011)

The electricity transmission network is expected to undergo significant change by the 2050s, due to changes to the generation mix and increased demand as a result of the electrification of heat and transport. New generation is likely to be dispersed, and offshore wind generation will require investment in offshore transmission (National Grid, 2012).

The replacement rate of transmission infrastructure is expected to be high. The age profile of GB transmission and distribution in 2008, as assessed by the Energy Networks Association (ENA, 2011) shows a large proportion of transmission assets are more than thirty years old. Significant new investments are therefore required to replace the ageing infrastructure. For example, by 2020 the ENA estimates that over half of the poles will be close to their 60 year nominal life (ENA, 2011).

Investments to ensure that the energy assets are resilient are generally considered as non-load related expenditure. This means it is “driven primarily by the need to manage the on-going safety, reliability and environmental performance of our asset base” (National Grid, 2012). In its investment forecast, non-load-related investment represented 39% of National Grid’s RIIO-T1 business plan (2012). (The plan details investment for 2013-2021.)

In Northern Ireland, NIE is subject to five-year investment plans approved by the regulator (the Northern Ireland Authority for Utility Regulation). High levels of investment (NIE proposed a 72% increase in spending on asset replacement in the regulatory cycle starting in 2012 compared to the previous cycle) in the transmission network are expected due to ageing assets and increased renewable generation in the future.

National Grid is the sole System Operator as it is responsible for the operation of the NETS. As System Operator, National Grid must ensure that at any given

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[27] From Ofgem’s website: “The Balancing and Settlement Code (BSC) contains the governance arrangements for electricity balancing and settlement in Great Britain. The energy balancing aspect allows parties to make submissions to National Grid to either buy or sell electricity into/out of the market at close to real time in order to keep the system from moving too far out of phase. The settlement aspect relates to monitoring and metering the actual positions of generators and suppliers (and interconnectors) against their contracted positions and settling imbalances when actual delivery or off-take does not match contractual positions.” (http://www.ofgem.gov.uk/Licensing/ElecCodes/BSCode/Pages/BSCode.aspx)

time the electricity supplied equals the demand for electricity. To do that, it regularly procures a variety of balancing services (also known as 'ancillary services') which it can use to make up generation shortfalls or to absorb generation excesses (for example, on very windy days).

The network is interconnected with Northern Ireland, the Republic of Ireland the Netherlands and France. This is via the following bi-directional interconnectors:

- **Moyle Interconnector:** connection to Northern Ireland, with a capacity of 450 MW export and 80 MW import;
- **East West Interconnector:** connection to Ireland, with a capacity of 500 MW;
- **BritNed:** connection to the Netherlands, with a capacity of 1000 MW; and
- **IFA:** connection to France with a capacity of 2000 MW.

In addition, new interconnectors are at different stages of development. An interconnector to Belgium, with capacity of 1000 MW, is currently being considered with commissioning proposed for 2018. A 1400 MW interconnector to Norway is also under consideration.

In addition to building new interconnectors, to address the expected demands on the NETS National Grid has planned several investments that will increase the capacity on the transmission network, especially on the boundary separating Scotland and England.

It is expected that this extra capacity will contribute to relieve congestion on the system, although its actual impact will depend on the evolution of generating capacity and demand patterns.

As in the case of generation, the transmission component of the power supply chain is expected to undergo significant investments over the next decade. These will increase its transportation capacity and its flexibility, enabling it to cope with forthcoming changes in generation. This also provides a significant opportunity for the system to adapt effectively to the challenges that climate change may bring.

4.2.3 Demand

Total UK electricity demand in 2011 was 374 TWh, down 2.6% from 384 TWh in 2010 (DECC 2012b) [28].

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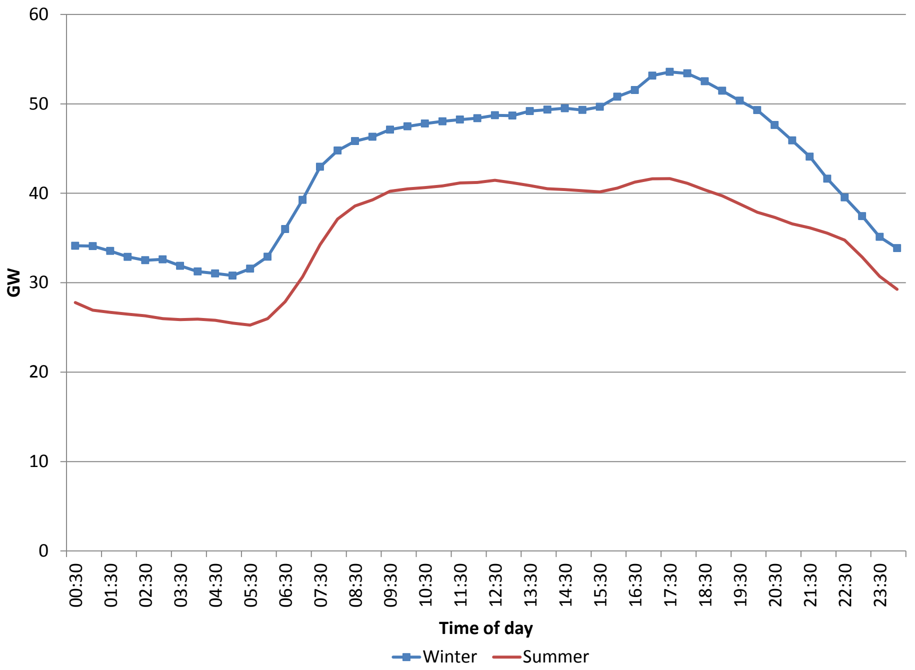
[28] Total demand is equal to total generation plus net imports (about 6 TWh in 2011).

As estimated by National Grid (National Grid, 2011), current maximum peak demand - that is the maximum level of demand that the system needs to serve - is around 60 GW. The peak occurs in the evening, between 5.30pm and 6pm. The average winter peak demand is around 53 GW.

Great Britain has a winter peak, driven by demand for lighting and heating. The average summer peak is around 41 GW, significantly lower than the winter peak. This is due to the fact that the demand for lighting and heating are much reduced in summer, while the demand for cooling is currently small.

Figure 5 compares the load profiles of a typical winter day and a typical summer day. The difference in typical peak demand between summer and winter is about 12 GW. This is a significant gap that is unlikely to be filled in the short-to-medium term by an increase in the demand for cooling. We consider this issue in more detail in the following section.

Figure 5. Comparison of typical winter day and typical summer day load profiles



Source: National Grid (2011)

Note that the peak in energy demand is significantly below the level of installed capacity owing to the need for a reserve margin to ensure security of supply.

Having described the structure of the sector, it is important to consider the role of policy, as this influences the nature and extent of adaptation.

4.3 Regulatory and policy framework

The electricity sector is expected to undergo structural changes over the period to the 2050s in terms of supply, demand and the policy environment. Such changes are driven by the UK's legally binding greenhouse gas emissions targets, as set out in the Climate Change Act (2008), which requires emissions by the 2050s to be at least 80% lower than base year[29] (1990 for carbon dioxide); while maintaining energy security and minimising consumer energy cost burdens (DECC, 2011a).

Such large-scale changes could provide a valuable opportunity for the sector to adapt to climate change. This could be achieved by building in resilience to projected climate change as part of the decision-making processes surrounding the location, timing and type of investments, as well as the policy and regulatory frameworks in which the sector operates. This section outlines the structural changes expected, and those policy frameworks.

The network components (transmission and distribution) of the electricity sector are regulated by Office of the Gas and Electricity Markets (Ofgem). Ofgem seeks to incentivise companies to be efficient and to innovate technically by setting limits to the revenue that energy network owners can take through the charges they levy on their customers.

4.3.1 The role of OFGEM

Until recently, Ofgem regulated distribution and transmission networks through five-year price control periods. Price limits were set according to the RPI-X formula, with the key focus of regulation being on cost reduction.

While such an approach would have been suitable to extract efficiencies from a sector which was perceived to be largely in steady-state, Ofgem has now recognised that the regulatory framework needs to adapt to respond to the challenges that the networks will be facing in the coming years.

Specifically, networks will be expected to play a key role in supporting the evolution of the electricity sector in four ways:

- by ensuring that new generation (especially renewable generation) is connected to the network in a timely fashion;
- by accommodating the growth in distributed generation (e.g. micro-generation);

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[29] This is 1990 for carbon dioxide, nitrous oxide and methane, and 1995 for hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride.

- by supporting the increase in electricity demand, ensuring that the network has sufficient capacity to transport and distribute electricity from the areas of production to the areas where demand is concentrated; and,
- by managing supply and demand effectively to guarantee security of supply.

To address these challenges, Ofgem recently reformed its approach to regulation by introducing the new RIIO framework. RIIO (Revenues = Incentives + Innovation + Outputs), shifts the focus of regulation away from cost reduction per se towards a more holistic approach focused on the delivery of desirable outputs.

This new approach provides a higher level of flexibility in identifying desirable outputs as all stakeholders (regulator, regulated companies and consumers) would be directly involved in the regulatory process. Under RIIO, companies can take a more prominent role in defining the outputs to which they would be able to commit.

In the context of adaptation to climate change, the RIIO framework provides the opportunity for specific outputs to be embedded in the regulatory determination and for associated incentives to be provided. For example, in the context of the electricity distribution review (RIIO-ED1), Ofgem has stated that "[it] is consulting on whether to place an incentivised output metric on flood resilience (Ofgem, 2012)."

Incorporating the consideration of climate change and the potential threats that may arise in the near-and longer-term into the regulatory framework provides an opportunity for appropriate adaptation to be taken. For example, accounting for climate change would require probabilistic climate change scenarios to be considered to reflect uncertainty to the 2050s and beyond, and for assessment to be both at the local scale and system-wide. The associated costs and benefits of action if taken at different points in time would need to be assessed and weighed up.

4.3.2 Electricity Market Reform (EMR)

In the context of policy, the most significant innovation that will affect the sector is Electricity Market Reform (EMR).

The EMR is intended to facilitate the introduction of measures to attract investment, reduce the impact on consumer bills, and create a secure mix of electricity sources including gas, new nuclear, renewables, and carbon capture and storage (DECC, 2012a). These aspects of the reforms are expected to increase the potential for appropriate adaptation of the sector, as long as potential climate change threats, (such as the changing risk of flooding, increasing average temperatures etc.), are appropriately accounted for within investment planning and operational resilience considerations. For example, through analysis of alternative probabilistic climate change emissions scenarios and using analytical techniques, which may include robustness-based approaches and real options analysis (Ranger *et al.,* 2010).

Specifically, the proposed EMR has four components[2]:

- a Carbon Price Floor (announced in the Budget, 2011) to reduce investor uncertainty, putting a fair price on carbon and providing a stronger incentive to invest in low-carbon generation now;
- the introduction of new long-term contracts (Feed-in Tariff with Contracts for Difference) to provide stable financial incentives to invest in all forms of low-carbon electricity generation. A contract for difference approach has been chosen over a less cost-effective premium feed-in tariff;
- an Emissions Performance Standard (EPS), set at 450g CO_2/kWh, to reinforce the requirement that no new coal-fired power stations are built without Carbon Capture and Storage (CCS), but also to ensure necessary short-term investment in gas can take place; and,
- a Capacity Market that is open to demand response storage and interconnected capacity as well as generation, which is needed to ensure future security of electricity supply.

The latter would be particularly important to ensure that the system has sufficient generation capacity to:

- support the long-term demand increase trend, expanding the ability of the system to serve a higher peak load, both in winter and in summer; and,
- make the system more resilient to shocks (both related to more extreme weather events and the natural intermittency of renewable generation) by incentivising the construction of back-up capacity.

Therefore, the EMR should, if climate change is appropriately taken into consideration in decision-making, enhance the sector's capabilities to adapt to climate change. **However, it will be important that these policy objectives are appropriately channelled through the institutional and regulatory framework of the sector, and that careful monitoring and review is put in place to allow learning and modification over time**.

Annex 2 explores the EMR and the wider policy context in more detail.

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[2] http://www.decc.gov.uk/en/content/cms/legislation/white_papers/emr_wp_2011/emr_wp_2011.aspx

4.4 Evolution of the sector

This section provides a brief overview of the expected evolution of the power sector over the period covered by this study. Based on the Government's Carbon Plan (DECC, 2011a) projections as well as the work on the 2050 Pathways (DECC, 2011b), it considers the ways in which generation and demand could evolve.

4.4.1 Electricity supply

The Carbon Plan

The Carbon Plan (DECC, 2011a), published in December 2011, presents the Government's strategy for how the UK will achieve decarbonisation within the energy policy framework. The Plan sets out the roadmap to a low carbon economy, while aiming to maintain energy security and minimising costs to consumers.

The Plan has been developed on the basis of a central scenario. However, the Government recognises that the level of uncertainty surrounding the evolution of the power sector (and the economy and socio-economic factors as a whole) over the next forty years is very high. To account for this uncertainty, the Plan also considers three alternative future scenarios, the so-called '2050 Futures'. The decarbonisation targets are reached under each of them, albeit in different ways.

The four scenarios are:

- **Core MARKAL.** This is the central scenario underpinning the plan. Under this scenario, by the 2050s, electricity generation is split between nuclear (33 GW), thermal[30] (76 GW) and renewables (45 GW). Demand is assumed to grow to 2050 by about 40% over 2007 levels.

- **'Higher renewables; more energy efficiency'**. This scenario assumes a higher share of installed renewable capacity by the 2050s (106 GW), while nuclear installed capacity is about half the level assumed in the central scenario (16 GW). The demand increase is assumed to be about the same as in the core scenario.

- **'Higher CCS; more bioenergy'.** In this scenario, the contribution of thermal plants to decarbonisation (via CCS technologies) is more significant than in the core scenario. The assumed installed capacity by the 2050s is 94

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[30] Thermal generation is an umbrella term that includes all generation that relys on the production of steam to generate electricity. This would include gas, coal and oil-based plants

GW. Renewables installed capacity is therefore lower (about 36 GW). Demand is assumed to grow by about 30% over 2007 levels.

- **'Nuclear; less energy efficiency'.** Under this scenario, nuclear capacity would be the key driver to decarbonisation, with 75 GW of installed capacity. As a result, renewables installed capacity by the 2050s is only about 22 GW. At 62 GW installed capacity, thermal generation too is assumed to be lower than in the core scenario. Demand is assumed to grow by 60% over 2007 levels.

Table 9 summarises the four '2050 Futures' as defined in the Plan. In the remainder of this section, illustrations are provided in a qualitative way of how each of these scenarios may change the conclusions reached above regarding the scale of the climate change challenge.

Table 9. Summary of 2050 futures: electricity demand and generation (in 2050)

	Core MARKAL	Renewables; more energy efficiency	CCS; more bioenergy	Nuclear; less energy efficiency
Energy demand increase (2007-2050)	38%	39%	29%	60%
Nuclear installed capacity (GW)	33	16	20	75
Thermal installed capacity (GW)	76	75	94	62
Renewables installed capacity (GW)	45	106	36	22

Source: DECC Carbon Plan (2011a)

4.4.2 Electricity demand

As shown in the table, electricity demand is expected to grow between 29% and 60% by 2050.[31] The DECC 2050 Pathways work considers the potential evolution of demand from the main energy demand sectors.

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[31] More recent analysis by DECC shows that electricity demand is likely to increase by between 30% and 100%. Source: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65633/7086-annual-energy-statement-2012.pdf

The 2050 Pathways analysis identifies four energy demand sectors. These are:

- lighting and appliances;
- transport;
- industry; and,
- heating and cooling.

To assess the evolution of demand across the demand sector, the 2050 Pathways study considers four groups of primary drivers of change.

- **Behavioural and lifestyle change:** this group covers those behaviours that may help reduce electricity demand (e.g. wasting less food, accepting lower indoor temperatures and using public transport);
- **Technological improvement and change:** this group includes those technological changes that may lead to an increase in energy efficiency, which is associated with a reduction in overall demand (e.g. LED lighting and more efficient consumer appliances).
- **Different technological or fuel choices:** this group includes those choices that might affect future demand, such as choices between district heating and heat pumps, or between fuel cells or batteries for cars.
- **Structural change:** the last group considers more in-depth changes to the economy, such as the development of specific industries (e.g. manufacturing or air transport).

Below we summarise the 2050 Pathways analysis for each of the key energy demand sectors.

(i) Lighting and appliances

While the popularity of electrical appliances has steadily increased since the early 1990, overall demand per household has changed very little. This has been due to technological progress, which has delivered ever-increasing levels of energy efficiency. Therefore, the increase in usage has almost been offset by technological improvements.

While this trend may continue, there is a high level of uncertainty surrounding this sector, given the unpredictability of technological improvement. It is already clear, however, that lighting and cold appliances represent the greatest opportunity to achieve higher levels of efficiency savings. In addition, appliances such as televisions and personal computers have steadily improved their energy efficiency over time. Higher energy efficiency could be achieved by applying technologies that are already available. Similar opportunities appear to be available also for the non-domestic sector. Technological progress may bring about further improvements.

It should be noted that increases in energy efficiency in this sector may have an impact on heating and cooling. This is because inefficient appliances release heat, which makes homes, offices and shops warmer. As appliances become more efficient, the demand for heating may increase to compensate this effect.

(ii) Transport

As far as the power sector is concerned, the transport sector would be a key source of additional demand. Electrification is seen as one of the key enablers to reduce carbon emissions from this sector. This would come from two main sources, namely an increase in the uptake of electric vehicles and a shift to public transport, which is expected to be fuelled increasingly by electricity.

However, there are some potential uncertainties surrounding these developments, which make forecasting the evolution of electricity demand by the transport sector particularly difficult. These are:

- the evolution of electric vehicles, with should lead to a reduction in the cost of batteries and an increase in the driving range between charges;
- the development of a reliable charging infrastructure; and,
- the provision of adequate rail infrastructure.

(iii) Industry

The UK manufacturing sector is the sixth largest in the world and accounts for a large share of total carbon emissions. Therefore, it provides the potential for a significant reduction in energy usage and emissions. The 2050 Pathways analysis identifies five key drivers of emissions: energy intensity, process emission intensity, carbon capture and storage, fuel switching and production output levels.

While the increase in production efficiency may help reduce overall demand, it should also be noted that a switch towards using more electricity is a key enabler to achieving lower carbon emissions. The 2050 Pathways analysis assumes that in theory, most industrial energy could be supplied in the form of electricity, with the exception of some high-temperature heating processes.

This suggests that, all things being equal, the electricity demand from this sector is expected to increase significantly above current levels.

(iii) Heating and cooling

Several factors would contribute to the evolution of electricity demand related to heating and cooling. There are factors which point towards a reduction in overall demand. These include an increase in energy efficiency of dwellings and other public spaces, which would be achieved via construction of new building as well as a refurbishment of the existing stock. Users may also be persuaded to accept slightly lower average temperatures indoors, without any notable impact on their comfort. For example, as stated in the 2050 Pathways document, 1 degree Celsius reduction would reduce heating system energy demand by up to 10%. An increase in average temperatures may also reduce the demand for heating during the coldest months. These issues are discussed in detail in the ECR "Overheating in Residential Housing" report.

On the other hand, there are factors that point in the direction of an increase in demand. For example, rising temperatures may lead to an increase in the demand for cooling, which is entirely electricity-dependent. An increasing uptake of heat pumps may also lead to an increase in energy demand.

Overall, it is hard to predict what the net effect from these opposing factors would be. The changing nature of demand and, in particular, the greater reliance on electricity of a greater number of individuals and sectors, increases the importance of ensuring the system is resilient. The greater level of interdependency across sectors suggests that the costs of any interruption in energy supply could affect more people at the same time, and be more far-reaching and complex to manage. For example, a 2001 study in the US indicated costs to companies[32] associated with the outage of power supply of about £900 for the first second of outage, £1,300 per 3 minutes and £4,755 per hour. The non-linear nature of damage emphasises the very high cost of an interruption in the modern economy. The estimated costs of outage were even higher for high energy consumption companies: for those using 5 GWh or more annually, the costs were estimated to be $32,000 for a one-second outage and more than $59,000 for a one-hour outage (Lineweber and McNulty, 2001). Costs today would be likely to be higher given rising economic activity and the value of lost productivity during an outage.

Having considered the key characteristics of the sector, its adaptive capacity now needs to be considered. This is assessed in the following Section, along with the adaptation actions that are being taken, and would be expected to be taken, by those in the sector.

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[32] This was based on a survey of 985 industrial and digital economy companies in the US in 2001.

4.5 Adaptive capacity

For the purposes of the ECR, adaptive capacity, or the ability to adapt, is analysed using a simplified framework informed by the Performance Acceleration through Capacity Building (PACT)[33] model (Ballard *et al.,* 2011) and the "weakest link" hypothesis[34] (Yohe and Tol, 2002; Tol and Yohe, 2006). Both PACT and the weakest link models introduce the idea of discrete levels of an attribute and allow identification of where an actor is now and where they would like to be, while illustrating the areas that need most development to get to the desired end point (Lonsdale *et al.,* 2010).

This project defined adaptive capacity using the CCRA definition:

Adaptive capacity

"The ability of a system/organisation to design or implement effective adaptation strategies to:

- Adjust to information about potential climate change (including climate variability and extremes);
- Moderate potential damages; and,
- Take advantage of opportunities, or cope with the consequences"

Source: Ballard *et al.,* 2011 (CCRA – modified IPCC definition to support project focus on management of future risks)

Adaptive capacity refers to both the structural capacity within the overall sector, and also the capacity of different actors in the power sector. The assessment of these factors allows exploration of the ability of actors to implement effective climate change adaptation measures.

In assessing the ability of the power sector to adapt to projected impacts of climate change, this project considers two factors: the **structure** of the sector in general terms (i.e. the role and size of different organisations involved), and the

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[33] This model was chosen as it was used in the CCRA, which this project follows, and because in a UKCIP review of adaptation tools it was ranked as the most robust (Lonsdale *et al.,* 2010). The PACT model identifies six clear stages of development when organisations take on the challenge of climate change. These are called response levels (RLs) rather than stages as each level is consolidated before moving to the next. RLs 2 and 3 are characteristic of 'within regime' change, RL4 is characteristic of 'niche experimentation' (or 'breakthrough projects') and RL5 is conceptualised as regime transformation. RL6 would be conceptualised at the landscape level. In this report, the RLs were used very simplistically as a comprehensive assessment of the adaptive capacity of the sector using PACT could not be undertaken. It is recommended that this be undertaken in further work.

[34] The weakest link hypothesis enables assessment of the potential contribution of various adaptation options to improving systems' coping capacities by focusing on the underlying determinants of adaptive capacity. In this report, the determinants were used to assess capacity of an actor rather than an adaptation option. This was used as it provides socioeconomic indicators by which an actor's adaptive capacity may be categorised. It enables the weakest part of an actor's capacity to be shown providing an area to focus adaptation responses.

organisations in the sector - the function of key players who make critical decisions and their performance (i.e. gross margins, outputs and benefits delivered). An analysis of these two factors will describe the ability of the sector to adapt to climate change and the extent to which the opportunities and risks described in Section 5.2 are likely to be addressed. It should be noted that adaptive capacity is not only needed to optimise decisions based on climate change adaptation, but for other decisions with long term implications (Ballard *et al,* 2011).

4.5.1 Structural adaptive capacity

This description of structural adaptive capacity can be used to **identify specific types of decisions where further assessment of climate change implications will be important**. These include decisions related to the investment in new assets (generation, transmission, etc.), as well as ongoing operations and maintenance.

In general, the power sector has comparatively few structural barriers to adaptation actions. Supply and demand implications of natural weather and climate variability are key operational parameters for day-to-day operations within the sector. The longer term challenges of resource adequacy and effective emergency planning are understood and picked up in regular reviews by DECC and Ofgem. The sector is primarily operated by a small number of organisations with deep experience and with a high concentration of well-resourced in-house expertise.

Sector complexity

The UK power sector has undergone radical change since privatisation in 1990. Today the sector operates as a complex system of competitive generation and supply, delivered through regulated transmission and distribution networks. End users are served by competitive energy suppliers. At an aggregate level, the power sector is complex. However, the complexity of the individual subsectors is relatively low, with relatively few large companies with long-established working relationships with each other and with regulators (McColl *et al.,* 2012). The relatively low subsector complexity means that, in the absence of the adoption of disruptive technologies and business models, sector-wide decision-making can be made by a small number of actors.

Dependencies

The power sector covers a broad range of interconnected sectors and stakeholders. Dependencies with other sectors span commodity supply chains, real time operations, waste and decommissioning. As such, the adaptive capacity of the power sector is critically dependent on the adaptive capacities and actions of a number of other actors. Sectors which are particularly important to ensuring on-going operations include communications (for real-time information transmission) and transport (for commodity supply and fuel procurement) (RAENG, 2011). Consequently, assessment of power sector adaptive capacity cannot be taken in isolation and must consider broader interdependencies with other sectors, and in particular, the climate resilience of sectors integral to the on-going operational functioning of the power sector.

Decision lifetime

Power sector investments are characterised by large capital allocations with long planning, decision and development time-frames, with long economic lives (20 or more years), and "life extension" investments that maintain an asset for up to 50 years. This presents a challenge for adaptation, as investment decisions must take into account the uncertainty related to potential climate change impacts in the future (McColl *et al.,* 2012). This suggests potential for 'high regret' costs and for maladaptation.

For these reasons, utility planners have begun to develop financial and engineering solutions that provide a degree of optionality. Financial "real options[35]" analyses have been developed in an effort to build some flexibility and optionality into investment decisions. An example where flexibility is already being built is the DECC requirement that plans for new combustion plant with an installed capacity >300 MWe are designed "Carbon Capture Ready". This necessitates space to be set aside to accommodate future carbon capture equipment (DECC, 2009).

Activity levels

High levels of activity are expected to commence across the entire electricity value chain, driven by the threefold policy drivers of: a move to low carbon economy, maintaining security of supply, and assuring affordability (DECC, 2010). This is coupled with the regulatory drivers of enabling wholesale and retail competition, encouraging new entrants into the market and the introduction of smart energy technologies (DECC, 2010).

Maladaptation

Maladaptation refers to actions or investments that enhance vulnerability to climate change impacts rather than reducing them (UKCIP, 2012).

Industry stakeholders interviewed noted that the long-lived nature of power sector investment decisions means that investments exhibit a strong potential for "lock-in".

Generators operate in a strongly competitive market in which measures that are beneficial are expected to be commercially rewarded (AEP, 2011). In the absence of "investment grade" information, assessments of those climate change resilient design choices that exceed those specified in regulation are unlikely to meet Internal Rate of Return (IRR) requirements.

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[35] Real Option Analysis (ROA) offers a nuanced approach to strategic investment that considers the value of the opened options for budget decision-makers. The Real Option problem can be viewed as the optimisation of available options amidst uncertainty over real assets like project investment capital.

Current technical design and planning regulations require that new power generation facilities are designed to exceed minimum standards - standards that mean developers would expect to be resilient under the worst case climate change scenarios over the expected life of the assets (as advised by industry interviews). **Project developers consequently report being strongly reliant on the foresight of regulation and sector-wide standards and regulation in the absence of climate change information with the appropriate degree of certainty to inform investment decisions.** The standards are based on the individual plants and the wider systemic risks are not necessarily captured.

In addition, large thermal generation plant in the UK operates under the European Emission Trading Scheme (EU ETS). Consequently, for large fossil fuel-fired generators, the impact of measures to improve climate resilience must account for potential changes in operational profile both in terms of energy inputs and output and carbon externalities. The parasitic loads required for some technological solutions, such as turbine air intake pre-chillers, may consequently add additional costs via a carbon penalty (as advised by industry interviews for this report).

The transmission system is regulated by ex-ante decadal pricing controls (Ofgem, 2010). Inadequate provision for climate change in investment planning cycles could potentially constrain the ability of Transmission System Operators to amend capital and operating expenditure to account for climate change (as advised by industry interviews for this report).

On the demand-side, there are high levels of technological uncertainty, both in terms of cost and efficacy, and the lives of energy assets (such as smart meters and higher efficiency commercial cooling technologies). This means that early investment may lead to potentially sub-optimal investments relative to Best Available Technology (BAT) or be impeded by rationale to delay investment (as advised by industry expert interviews).

4.5.2 Organisational adaptive capacity

Table 10 summarises the adaptive capacity of actors in the power sector. The actors are key entities within the electricity value chain, from generation to end-use. They do not represent the complete value chain owing to project scope limitations. Unless otherwise specified, the data in **Table 10** have been compiled from interviews with private sector stakeholders (AEP and individual electricity utilities, Transmission System Operator, regulators and discussions with sector experts.

Table 10. Organisational and adaptive capacity

Actor	Resources	Processes	Organisation	Summary
Generators	- Investments must pass IRR hurdle rates. - Strong technical and commercial expertise. - Require access to water and fuels. - High levels of understanding of emerging technologies.	- Strong links with academia and technology innovators. - Advanced risk assessment processes (climate change risks represents a small subset of overall business risk).	- Accustomed to dealing with the impact of environment constraints on operations. - Cross-sectoral organization is strong and assisted by active industry groups. - Climate change may create competitive advantages for particular generation portfolios.	**MEDIUM-HIGH** **There is system-wide medium-high adaptive capacity through a combination of physical resilience and technical ability.** Climate change is likely to modify the probability distribution of risks that generators already face on a day-to-day basis.
Transmission System Operators	- Investment levels managed though regulated regime. - High concentration of skilled workforce and technical knowledge. - Expansion constrained by planning process and land-ownership rights. - High levels of understanding of emerging technologies.	- Strong links with academic and technology innovators. - Implementation set out in 5-10 year regulation cycles.	- Concentrated responsibility and control of critical infrastructure. - Interface between Generators, DNOs and regulators.	**HIGH** **Transmission System Operators are incentivised to make networks resilient to climate change through the indirect effects of availability, asset health and transmission loss targets.** With the exception of Northern Ireland, transmission is controlled by a single regulated System Operator.

Actor	Resources	Processes	Organisation	Summary
Energy users	- Economic capacity is highly variable across both domestic and commercial sectors with both presenting strong short-term price sensitivities. - Knowledge and skill to make long-term decisions constrained for all but most energy-intensive users. - Technology access limited by knowledge.	- Prominence of short-term, price sensitive decision-making. - Decisions driven by price sensitivity.	- Limited collaboration except industry-level organization by major energy users.	**LOW-MEDIUM** Extremely variable adaptive capacity owing to differing ability to make energy efficiency savings, capture the benefits of distributed generation and undertake demand-side management measures.

Note: whilst distribution networks are identified as a major component of the power sector and extensive network exposure to climate change, they are outside the scope of analysis of the ECR project.

4.5.3 Key messages on adaptive capacity

Adaptive capacity in the sector **is considered to be high.** Supply side adaptive capacity is high and simplified by the relatively small number of actors. Stakeholders from the power sector interviewed for this study stressed that impacts of projected climate change are primarily expected to modify the probability of risks already managed under existing risk and operational management procedures. The collective influence of affinitive, non-climate change measures means that the impacts of climate change are not likely to introduce any new types of risk to operation, but rather to change the likelihood or severity of risks which are currently managed (AEP, 2011; Centrica Energy, 2011; InterGen UK, 2011; International Power, 2011; RWE Npower, 2011).

On the demand side, adaptive capacity is generally weaker except for major energy users. This is primarily a consequence of the large number of disparate actors as well as a range of real and perceived market barriers.

There are a number of key sensitivities arising from this analysis:

- There is uncertainty in the extent to which climate change alters the probability of extreme weather events to within parameters of existing plant and transmission infrastructure design specifications. Power sector stakeholders interviewed for this study noted that a key challenge for generators will be to establish critical thresholds for plant operations suitable for assessment against future climate projections.

- The detailed policy and regulatory design outcomes of the on-going Electricity Market Reform are still not finalised. The Energy Bill, when passed, is expected to create an investment environment that can support the deployment of a sustainable generation mix.

- Generation and transmission is dependent on real-time communications for both market and networks operations. At the same time, ICT is primarily dependent on grid-sourced electricity. The impacts of climate change in each sector will therefore have a bearing on the other. In the future, the development of Smart Grid technology is expected to significantly increase this inter-dependency (RAENG, 2011).

- Network reliability, particular of remote assets, is highly dependent on the transport sector. Climate change adaptation in the transport sector will be important to the power sector (as advised by interviews with transmission System Operators, 2012).

Having assessed the adaptive capacity of the key actors, the adaptation actions that are currently being implemented and are planned for the future are now assessed. Barriers to implementation or effectiveness are also explored.

The context for adaptation

5 Adaptation actions

Key messages

Adaptation actions may be planned or reactive. A range of adaptation actions are currently being taken and are planned for future implementation in relation to power generation and transmission infrastructure.

Such actions are primarily expected to modify the probability of risks that are already being managed under existing risk and operational management procedures.

The key measures currently being taken include engineering and design measures (e.g. flood defences), investment decisions to increase capacity and network expansion, as well as demand-side measures.

While most of these actions are in response to drivers other than climate change (e.g. market pressures, business case, regulatory requirements), they are likely to result in an effective response to the threats posed by climate change for the power supply sector.

5.1 Introduction

This section provides an overview of some of the categories of actions different actors in the sector are already taking, and would be expected to take in order to maximise opportunities or minimise risks. The categories include actions to build adaptive capacity as well actions that reduce the particular risks of climate change. These categories of actions were informed by literature review and discussions with sector experts. They were then refined and verified in the stakeholder interviews (Annex 1). The interviews were conducted under Chatham House Rules, and so stakeholders are not referred to individually or by name in this report.

Much of the literature on adaptation to climate change has been at a conceptual or generic level (Adger *et al.,* 2007; Howden *et al.,* 2007). This has shaped the understanding of what adaptation is, and the importance of the processes and responsibilities regarding adaptation. However, less research exists to quantify the predicted effects of adaptation actions on electricity supply and transmission.

For the purposes of the ECR, the adaptation actions considered are those that are already being taken, or are expected to be taken. The actions include:

- **Planned adaptation:** this tends to be (but is not exclusively) anticipatory adaptation, undertaken or directly influenced by governments or collectives as a public policy initiative. These actions tend to represent conscious responses to concerns about climate change (Parry *et al.,* 2007).

- **Reactive adaptation:** is taken as a reactive response to climatic stimuli as a matter of course (without direct intervention of a public agency) (Parry *et al.,* 2007).

In some cases, actions could be considered both planned and reactive (for example, a reactive response to a current risk could lead to planned adaptations to limit future exposure). Both planned and reactive adaptations might be 'wrong' or lead to maladaptation, in the long term or for wider society, and may need to be countered with further action, such as building adaptive capacity and by taking specific actions to change and deal with the consequences.

5.2 Adaptation actions

This section provides an overview of the actions some actors in the sector are currently implementing and are expected in the future in relation to climate risks to generation and transmission. Importantly, high adaptive capacity does not necessarily translate into actions that reduce vulnerability as there are other barriers that prevent adaptation actions being implemented or from being effective.

The ***groups*** of adaptation measures explored in this Section were informed by published or grey literature and the expert panel, in the first instance. They were subsequently refined and verified in stakeholder interviews to ensure that this report considered the key options to address the particular risks assessed. The adaptation options discussed below are categorisations of a number of individual actions, which could be disaggregated in the future.

Two sorts of adaptation measures can be considered: those that build adaptive capacity and those actions that facilitate reductions in vulnerability to climate risks or to exploit opportunities. There is a suite of actions that could form part of an effective adaptation strategy. The choice of actions will depend on the adaptive capacity of the organisation, the sector in which it operates, the sector it is interdependent with and the climate change risks under consideration. These factors need to be considered systematically together with all non-climate risks

Most of the adaptation actions in this report focus on strengthening the electricity system and therefore represent generic measures to build capacity. A few actions (i.e. operational response to flooding, flood defence), respond to specific risks.

The list of actions set out here is not exhaustive and is, instead, intended to illustrate the key types of responses to projected climate change that actors in the power sector are taking or would be expected to take in the absence of further intervention by government or other bodies.

The categories considered are:

- Capacity expansion;
- Power plant flood defences;
- Load and non-load related transmission system capex planning;
- Increased or improved demand-side measures;
- Energy efficiency in response to cooling load increases; and,
- Distributed generation.

5.2.1 Capacity Expansion

The impact of climate change on the operating profile of power plants, and, in turn, on the capacity margins can be attenuated through the development of additional new capacity. Such capacity can ensure short-term operating reserves[36] or overall capacity margins[37] (or both) are maintained. Actions in this category therefore include important initiatives to strengthen the adaptive capacity of the electricity system.

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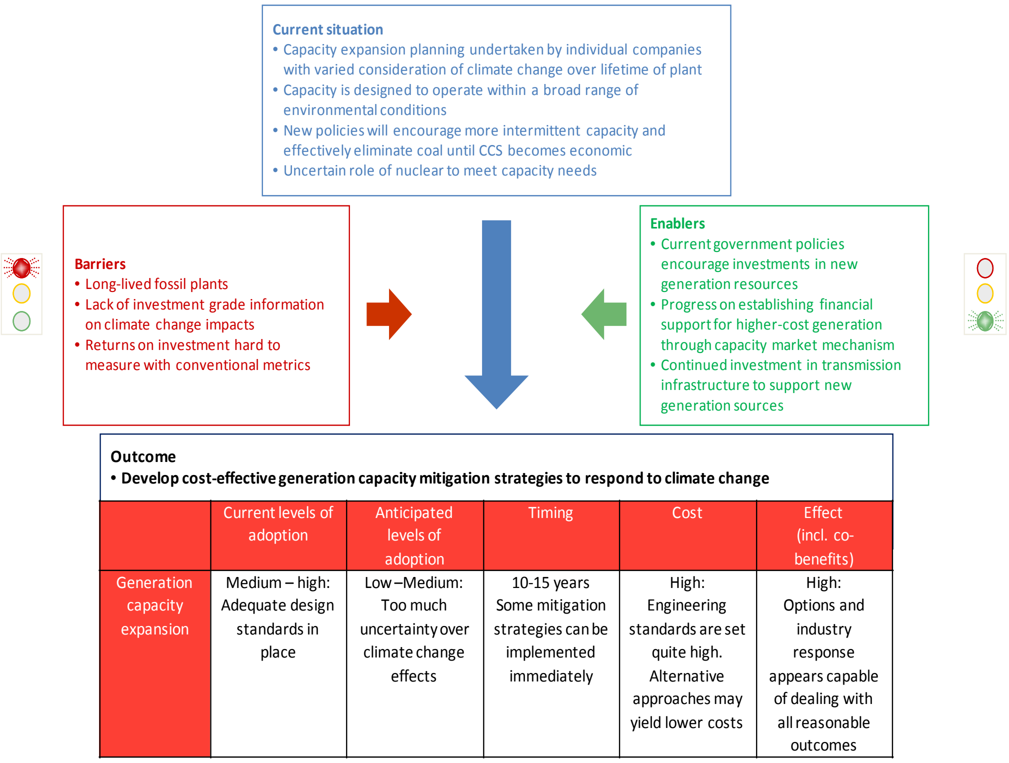
[36] Short Term Operating Reserve (STOR) is a service for the provision of additional active power from generation and/or demand reduction. There are two forms of the STOR service: Committed and Flexible.

[37] The difference between peak demand and installed capacity, adjusted for probable availability at peak

Figure 6. Summary of capacity expansion adaptation action



Current situation
- Capacity expansion planning undertaken by individual companies with varied consideration of climate change over lifetime of plant
- Capacity is designed to operate within a broad range of environmental conditions
- New policies will encourage more intermittent capacity and effectively eliminate coal until CCS becomes economic
- Uncertain role of nuclear to meet capacity needs

Barriers
- Long-lived fossil plants
- Lack of investment grade information on climate change impacts
- Returns on investment hard to measure with conventional metrics

Enablers
- Current government policies encourage investments in new generation resources
- Progress on establishing financial support for higher-cost generation through capacity market mechanism
- Continued investment in transmission infrastructure to support new generation sources

Outcome
- **Develop cost-effective generation capacity mitigation strategies to respond to climate change**

	Current levels of adoption	Anticipated levels of adoption	Timing	Cost	Effect (incl. co-benefits)
Generation capacity expansion	Medium – high: Adequate design standards in place	Low – Medium: Too much uncertainty over climate change effects	10-15 years Some mitigation strategies can be implemented immediately	High: Engineering standards are set quite high. Alternative approaches may yield lower costs	High: Options and industry response appears capable of dealing with all reasonable outcomes

Source: Based on evidence presented in this report and stakeholder views

Extent of adoption of adaptation actions

As part of the Energy Act, the Government will implement a Capacity Market[38] (DECC, 2012) that will be initiated if necessary. At the time of writing, the details of the GB[39] Capacity Market are not yet final but it will be designed to bring forward sufficient investment in reliable capacity in order to ensure security of electricity supply (DECC, 2012). This will help to ensure that there is sufficient capacity in place to cope with demand peaks as well as anticipated increases in total load. Stakeholders interviewed for this study and experts noted that a critical element of the Capacity Market will be the extent to which potential climate change risks are captured when setting the capacity level. This can help to ensure capacity margins are robust against the potential impacts of climate change.

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[38] Policy instrument designed to help ensure security of supply by providing a more secure capacity margin than that which would be determined by the market without intervention

[39] The Capacity Market will cover Great Britain, not the entire UK

Key barriers

The development process (scoping, planning, construction, testing) for new large scale power generation facilities (in the absence of government fast-tracking) is long, owing to the technical complexity and necessarily detailed planning process of the development. Once developed, a power plant is a long-lived asset – particularly in the case of coal and nuclear. This combination means that power plants have the potential to operate in conditions that are different – both in terms of market and environmental conditions – to those that they were originally planned to operate under. Power plant developers must, consequently, make long-term predications of market demand and deploy design specifications that feature considerable operational margins and resilience. Power sector stakeholders noted that in the absence of clarity around policy design and potential future environmental operating conditions, there is the potential for sub-optimal (i.e. non-climate resilient) capacity development.

Effect of response

An optimal level of capacity available for dispatch will deliver security of supply by ensuring that climate change influences on plant reliability (measured through the Equivalent Forced Outage Rate) can be managed at a system level. An optimal capacity will yield an attendant improvement to the capacity reserve margin, ensuring that climate change impacts do not impact system-wide reliability.

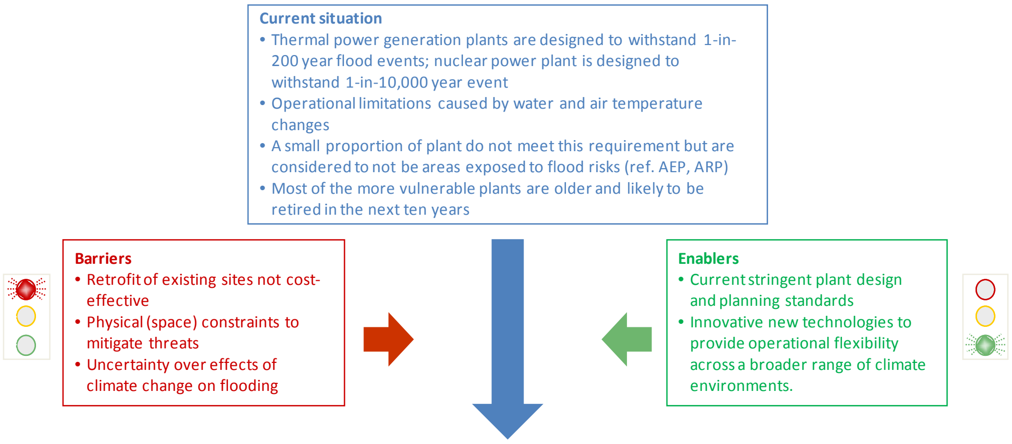
5.2.2 Power plant flood defences

Following the Fukushima Daiichi nuclear accident, flooding of power stations has become a key area of concern for the power sector and government. A common list of climate change-related hazards has been identified by major UK power producers (AEP, 2011). Flood and storm surge events give rise to the potential for possible partial or complete equipment shutdown, water damage, staffing issues and commodity supply disruption. Measures in the category therefore represent actions to address specific risks.

Analysis contained within the CCRA (McColl *et al.* 2012) did not account for adaptation actions such as flood protection and asset-specific local defences that meet a higher standard of protection than assumed in the national overview. Consequently, power sector experts interviewed for this study shared concerns that the CCRA overstates the risk of flooding to power stations. Nevertheless, stakeholders interviewed for this study in both power and transmission recognised that there remains a proportion of plant that does not meet the requisite level.

Key information in relation to flood defences is summarised in **Figure 7**.

Figure 7. Summary of power plant flood defence adaptation action



Current situation

- Thermal power generation plants are designed to withstand 1-in-200 year flood events; nuclear power plant is designed to withstand 1-in-10,000 year event
- Operational limitations caused by water and air temperature changes
- A small proportion of plant do not meet this requirement but are considered to not be areas exposed to flood risks (ref. AEP, ARP)
- Most of the more vulnerable plants are older and likely to be retired in the next ten years

Barriers

- Retrofit of existing sites not cost-effective
- Physical (space) constraints to mitigate threats
- Uncertainty over effects of climate change on flooding

Enablers

- Current stringent plant design and planning standards
- Innovative new technologies to provide operational flexibility across a broader range of climate environments.

Outcome

- **Develop improved flood defences to minimise outages and increase operational flexibility**

	Current levels of adoption	Anticipated levels of adoption	Timing	Cost	Effect (incl. co-benefits)
Flood defence development	High	High	10-15 years	High	High
Operational Flexibility	High	High	10-15 years	High	High

Source: Based on evidence presented in this report and stakeholder views.

Extent of adoption of adaptation actions

Since the introduction of the Electricity Act (1989), applications to construct and operate a generating plant greater than 50 MW have required the development of a Flood Risk Assessment. This assessment identifies the flood risk to the site based on the available information. The majority of existing thermal generation plants has been designed to withstand a 1:200 year flood event, whilst nuclear generation facilities are required to withstand a 1:10,000 year event and H++ UKCIP scenarios. New non-nuclear plant developments comprise "essential infrastructure" requiring protection to the 1:1000 year flood level. It should be noted that 1:200 year limit represents a probability that the given event will be equalled or exceeded in any given year. From discussions with expert and stakeholders, it is unclear the extent to which the 200 year return period flood event may require re-definition under climate change.

Key barriers

Of the outstanding UK power plants that do not meet minimum standards, the upgrading or installation of flood defences is complicated by the fact that flood defences represent commercial investment decisions that are undertaken in a competitive market (AEP, 2011). The ECR project was unable to obtain detailed information from industry stakeholders on these facilities. Electricity generating companies derive the economic rationale and optimal timing for investments through the application of full discounted cash flow analysis that evaluates the net present value (NPV) relative to a predefined internal rate of return (IRR) expectation, commonly around 8%[40]. In the case of flood defences, particularly for older plant, it is possible that an NPV evaluation is likely to be negative and the investment rejected as the present value of the investment is unlikely to repay the original investment and meet specific rate of return requirements. In addition, qualitative evidence cited by industry stakeholders suggests that power plants with less than 10 years of expected operational life remaining lack the payback period required to make such investments worthwhile. In some cases, the ability to develop flood defences may be constrained by potential impacts on downstream communities and businesses and limited physical space at the site. There may therefore be a need to set up specific contingencies, on a case-by-case basis, to deal with this temporary barrier to adaptation.

Effect of response

Ensuring that all plant that is expected to be generating in 2020 is resilient to a 1:200 year flood event will limit the impact of flood event frequency and flood extent expected in the UK climate projections. The calculation of the total cost of ensuring defences to flooding risk is complex owing to the array of options available and the diversity of plant types, designs and configurations. It should be noted that in assessing flood risk costs and benefits, differentiation must be made between zero or low cost options, such as siting decisions of particular pieces of plant infrastructure, and high cost options, such as enhanced flood walls.

Nuclear power stations have been built to 1:10,000 year flood protection standards. If the risks to a nuclear power station change, it should upgrade its safety protection. After the Fukushima events in 2011[41], HM Chief Inspector of Nuclear Installations researched the consequences for the UK Nuclear Industry. This assessment concluded the following: “Flooding risks are unlikely to prevent construction of new nuclear power stations at potential development sites in the UK over the next few years. For sites with a flooding risk, detailed consideration may require changes to plant layout and the provision of particular protection against flooding” (Weightman, 2011).

In addition, the CCRA analysis focused on known large thermal generation plant. The expected expansion of renewable generation capacity means that the future generation mix is likely to be significantly different both in terms of geographic

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[40] Based on expert opinion. Detailed evidence of IRR rates is considered commercially sensitive information

[41] Following an earthquake and Tsunami in 2011, equipment failure and nuclear meltdowns meant that radioactive materials were released.

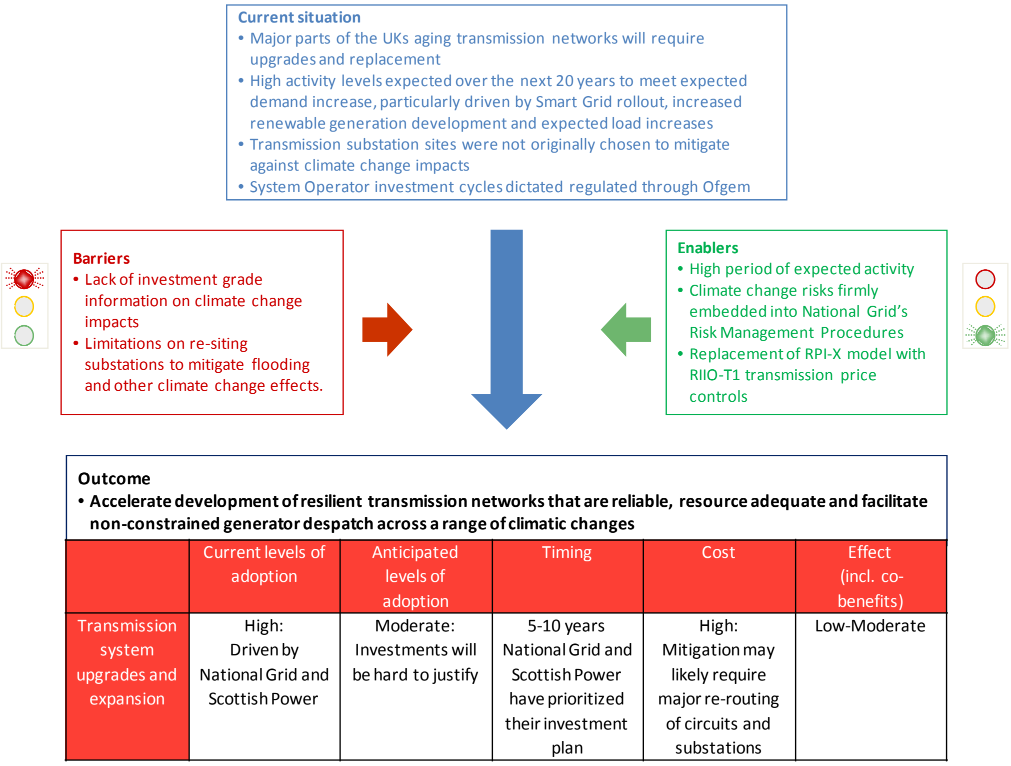
diversity, geographic coverage and technology type. In the absence of further detailed modelling of the potential system-wide flooding impacts that capture the full range of potential generation mixes, a critical knowledge gap may exist.

5.2.3 Load and non-load related transmission system capex planning

National Grid Electricity Transmission plc (NGET) anticipate high activity levels in both the near and longer terms in order to meet expected demand increase, particularly driven by smart grid rollout, increased renewable generation development and expected load increases (NGET, 2012). At the same time major parts of the UK's ageing transmission networks are approaching the end of their useful life (House of Commons Energy and Climate Change Committee, 2010). Actions in this category therefore include important actions to strengthen the adaptive capacity of the electricity system.

Key information in relation to this category of actions is in **Figure 8**.

Figure 8. Summary of load and non-load related transmission system capex planning adaptation action



Current situation
- Major parts of the UKs aging transmission networks will require upgrades and replacement
- High activity levels expected over the next 20 years to meet expected demand increase, particularly driven by Smart Grid rollout, increased renewable generation development and expected load increases
- Transmission substation sites were not originally chosen to mitigate against climate change impacts
- System Operator investment cycles dictated regulated through Ofgem

Barriers
- Lack of investment grade information on climate change impacts
- Limitations on re-siting substations to mitigate flooding and other climate change effects.

Enablers
- High period of expected activity
- Climate change risks firmly embedded into National Grid's Risk Management Procedures
- Replacement of RPI-X model with RIIO-T1 transmission price controls

Outcome
- **Accelerate development of resilient transmission networks that are reliable, resource adequate and facilitate non-constrained generator despatch across a range of climatic changes**

	Current levels of adoption	Anticipated levels of adoption	Timing	Cost	Effect (incl. co-benefits)
Transmission system upgrades and expansion	High: Driven by National Grid and Scottish Power	Moderate: Investments will be hard to justify	5-10 years National Grid and Scottish Power have prioritized their investment plan	High: Mitigation may likely require major re-routing of circuits and substations	Low-Moderate

Source: Based on evidence presented in this report and stakeholder views.

Load-related investment will be driven by changes in the pattern of generation and demand, both through connection applications, and through the need to ensure that the interconnected transmission system fulfils security of supply requirements (National Grid, 2012). Non load-related expenditure will be driven primarily by the need to manage the on-going safety, reliability and environmental performance of the asset base. The CCRA listed the possible adaptation actions required in order to make the transmission grid resilient to climate change as "to increase line height, re-conduct circuits to a higher operating temperature conductor, replace underground cables with larger cables or install additional circuits or substations to increase the capacity of the network" (McColl *et al.,* 2012).

The anticipated high activity provides a significant opportunity to make the transmission networks resilient to climate change by ensuring load and non-load related investments fully consider the range of potential climate change impacts over the lifetimes of the assets, not just the depreciation period (National Grid interview for this study, 2012)

Extent of adoption of adaptation actions

Transmission System Operators (TSO) already apply comprehensive risk assessment frameworks that consider climate change. In addition, they have undertaken analyses that have identified assets that require further assessment using more refined data (NGET, 2010a). To a large extent, TSOs are therefore likely to undertake climate change adaptation.

Key barriers

The transmission networks are funded by a price control mechanism set by Ofgem. Under RIIO-T1[42] each TSO is required to develop and publish a detailed business plan which demonstrates how they will deliver in the interests of both existing and future consumers. Consequently, TSOs rely heavily on projections in order to assess future revenues and investment, and consequently climate change actions. These investments have to be justified as necessary and efficient in advance of climate change (NGET, 2010a). TSO consequently rely heavily on the **investment grade climate information** and projections, which, at present, are limited with regard to their coverage of physical characteristics (NGET, 2010a).

Effect of response

Load and non-load investments that fully consider the climate change risks will result in transmission networks that are reliable, resource adequate and facilitate non-constrained generator dispatch. There will remain a degree of residual risk at a small proportion of sites, typically those at the interface of the transmission and

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[42] The RIIO model (Revenue = Incentives+Innovation+Outputs) builds on the previous RPI-X regime, but better meets the investment and innovation challenge by placing much more emphasis on incentives to drive the innovation needed to deliver a sustainable energy network at value for money to existing and future consumers

distribution networks. In such cases, investments to protect from flood risks may either not be practical or cost-effective. For such sites, National Grid has developed mobile defence measures that can be deployed within 4 hours (National Grid interview for this study, 2012).

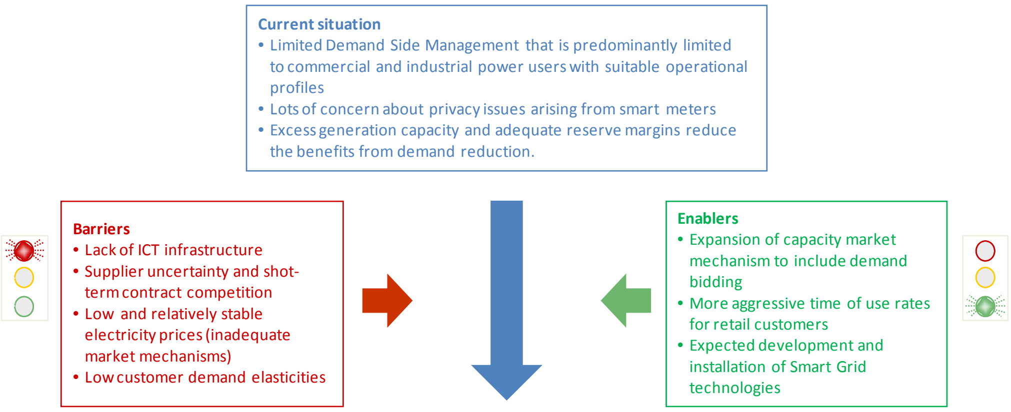
5.2.4 Increased or improved demand-side management

Demand-side management (DSM) programmes are designed to encourage energy users to modify their level and pattern of electricity usage. They consist of the planning, implementing, and monitoring activities of electric utilities. DSM refers to energy and load-shape modifying activities undertaken in response to utility-administered programmes (EIA, 2002). Actions in this category therefore include important actions to strengthen the adaptive capacity of the electricity system, as well as potential measures to respond to specific risks.

At present DSM programmes are generally undertaken through bilateral contracts between major energy users and utilities. The advancement of Smart Metering technology will offer the potential for more widespread embedded DSM to household and commercial appliances (DECC, 2009).

Key information on these measures is summarised in **Figure 9**.

Figure 9. Summary of increased or improved Demand Side Management adaptation action



Current situation
- Limited Demand Side Management that is predominantly limited to commercial and industrial power users with suitable operational profiles
- Lots of concern about privacy issues arising from smart meters
- Excess generation capacity and adequate reserve margins reduce the benefits from demand reduction.

Barriers
- Lack of ICT infrastructure
- Supplier uncertainty and shot-term contract competition
- Low and relatively stable electricity prices (inadequate market mechanisms)
- Low customer demand elasticities

Enablers
- Expansion of capacity market mechanism to include demand bidding
- More aggressive time of use rates for retail customers
- Expected development and installation of Smart Grid technologies

Outcome
- **Develop low cost mitigation strategy to control peak winter and summer demands for electricity**

	Current levels of adoption	Anticipated levels of adoption	Timing	Cost	Effect (incl. co-benefits)
Enabling Market Rules and Customer Participation	Low but trending upwards	Medium – High: Can be ramped up quickly if conventional capacity is not sufficient or reliable	5-10 years	Medium-High: Especially for meters, data collection and billing systems	High: May provide highest benefits for costs incurred

Source: Based on evidence presented in this report and stakeholder views.

Extent of adoption of adaptation actions

According to industry experts, DSM is currently mainly limited to commercial energy users whose energy demand profiles are amenable to time-of-use modification. A significant proportion of UK transmission and distribution assets are reaching the end of their useful life and replacement will provide a major opportunity for large-scale smart energy technology development (Strbac, 2008). The extent of implementation of DSM measures is, in part, influenced by climate change mitigation priorities and represents an example of close linkage between adaptation and mitigation.

Key barriers

Industry experts noted that there were four common barriers to DSM. Firstly, a **lack of ICT infrastructure** and standards – including control technology and settlements - limits the ability for DSM for domestic customers. Secondly, **supplier uncertainty** arising as a consequence of retail competition mean that suppliers are often reluctant to invest in customer specific equipment due to the customer's ability to change supplier at short notice. Thirdly, **low stable prices** with little volatility in either the forward market or the Balancing Mechanism. Fourthly, according to industry experts, relatively **low customer demand elasticities** (i.e. low change in demand relative to price movements).

Effect of response

DSM provides the opportunity to undertake two types of load shifting.

- Critical peak shifting, whereby customer demand is shifted during the ~20 hours per year with the highest demand for electricity.

- Daily peak shift, whereby customer demand is shifted during the ~1 hour per year with the highest demand for electricity.

In the context of climate change, widespread DSM provides the prospect of peak shifting – particularly under expected increases in summer cooling loads – and the potential to alleviate capacity constraints of extreme weather events (Strbac, 2008).

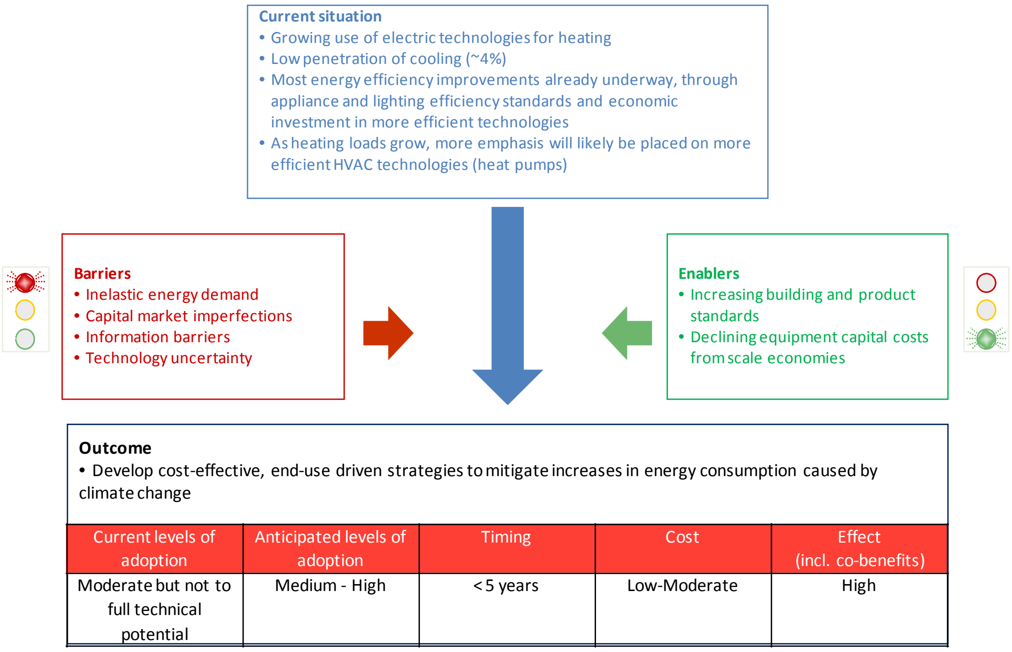
5.2.5 Energy efficiency in response to cooling load increases

The UK system is expected to remain a winter peaking system under climate change (National Grid interview for this study, 2012). At the same time, cooling loads are expected to increase and contribute to elevated summer peaks.

Consequently, the annual load profile may flatten relative to today, offering benefits to certain generation types with cooling loads potentially a prime load driver in the summer months. Energy efficiency improvement provides the opportunity to reduce average user load, or at least partially offset expected growth, according to industry experts. Actions in this category therefore include important actions to strengthen the adaptive capacity of the electricity system and at the same time address specific climate risks.

Figure 10 summarises key information about these actions.

Figure 10. Summary of energy efficiency in response to cooling load increases adaptation action



Current situation
- Growing use of electric technologies for heating
- Low penetration of cooling (~4%)
- Most energy efficiency improvements already underway, through appliance and lighting efficiency standards and economic investment in more efficient technologies
- As heating loads grow, more emphasis will likely be placed on more efficient HVAC technologies (heat pumps)

Barriers
- Inelastic energy demand
- Capital market imperfections
- Information barriers
- Technology uncertainty

Enablers
- Increasing building and product standards
- Declining equipment capital costs from scale economies

Outcome
- Develop cost-effective, end-use driven strategies to mitigate increases in energy consumption caused by climate change

Current levels of adoption	Anticipated levels of adoption	Timing	Cost	Effect (incl. co-benefits)
Moderate but not to full technical potential	Medium - High	< 5 years	Low-Moderate	High

Source: Based on evidence presented in this report and stakeholder views.

Extent of adoption of adaptation actions

By the end of 2012, minimum EU performance standards and labelling conventions will have been agreed for most domestic and commercial appliances (DECC, 2011a). The Government is also currently assessing whether sufficient support and incentives already exist to make efficiency improvements in electricity usage, or whether there is a need for additional measures. The results of this work will be published in summer 2012 (DECC, 2011a).

A number of energy efficiency improvements represent "negative cost" options (i.e., net cost savings). However, there remain a large number of energy efficiency options that are not undertaken owing to a range of key barriers. In the absence of interventions, these options are unlikely to undertaken in the future.

Key barriers

Inelastic energy demand. Economic theory states that as energy prices increase, the quantity of energy demand decreases. International empirical evidence suggests that energy changes less than proportionately to changes in price (Bernstein *et al.,* 2005). This suggests less than elastic demand which could dampen the benefits feeding through to some extent, though evidence on price elasticity largely relates to price increases.

Capital market imperfections. Energy efficiency investments involve relatively large upfront costs and long break-even periods. While resulting efficiency improvements result in energy bill saving, the payback periods are long (typically 10-20 years) according to industry experts. This payback period is longer than typical home ownership or the average life of many businesses.

Information barriers. Energy efficiency investments suffer from information barriers. Information about potential solutions is often limited to "partisan" advice by equipment manufacturers, installers or industry associations interested in promoting a particular approach (Sarro and Weiss, 2009).

Technology uncertainty. Even with sufficient financial resources in place, it may still be rational to delay an energy efficiency investment as technology incrementally improves. Energy efficiency investments therefore represent a balance of optimal waiting based on the perceived gap between current and new technologies and the opportunity cost of investing now (Sarro and Weiss, 2009).

Effect of response

Cost effective, end-use driven energy efficiency investment offers the potential to reduce peak loads and potentially offset anticipated peak load growth, particularly in relation to climate change-related peak cooling loads.

Analysis undertaken for the ECR "Overheating in Residential Buildings" report suggested that the role of energy efficiency improvements is important in relation to the cooling systems in residential properties. The potential for improvements of 1% to 2% per year in the efficiency of air conditioning systems was explored.

Energy efficiency was explored using the following assumptions:

- a medium emissions p50 climate change scenario;

- low market penetration of cooling systems (1% of households by the 2050s with cooling systems), based on current trends in uptake but with more efficient units accounting for a greater share over time); and,
- heat-waves double sales every 5-years.

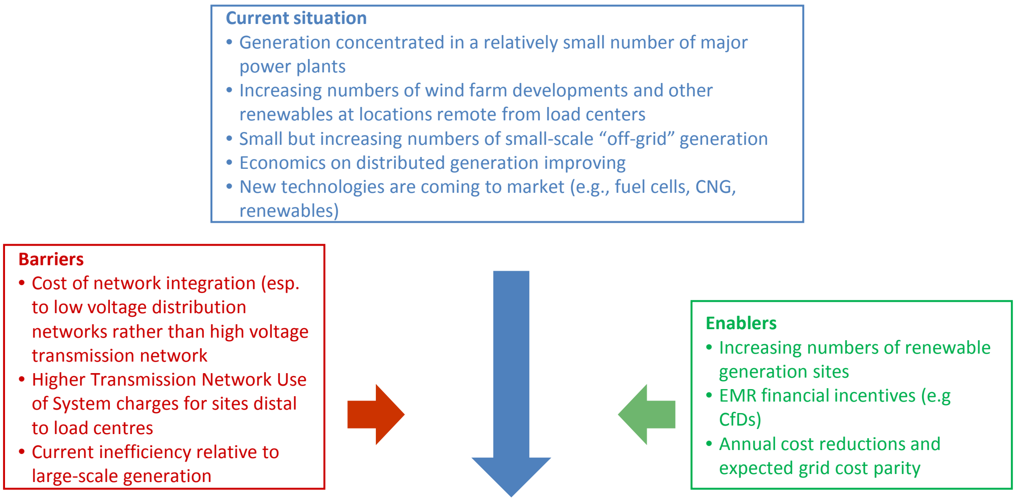
Efficiency improvements could result in a reduction in energy demand for cooling of 34% in the 2050s for the two regions modelled (London and the West Midlands). **Improvements in energy efficiency of cooling system technologies could off-set the effects of climate change in the 2050s (under a p50 medium emissions scenario) for the given level of cooling system uptake**.

5.2.6 Distributed generation

The term Distributed Generation (DG) covers the heat and electricity generated at, or near to, its point of use. These are typically small installations (<50 MWe) and can take the form of grid-connected distributed generation (embedded generation) and off-grid distributed generation (self-generation). DG (and in particular flexible DG systems) offers the ability to source energy from alternative sources in the event of transmission or power stations outages as well as offset the impacts of load and peak load growth on central power networks. Actions in this category therefore include important actions to strengthen the adaptive capacity of the electricity system.

Figure 11 presents some of the key information.

Figure 11. Summary of distributed generation adaptation action



Current situation

- Generation concentrated in a relatively small number of major power plants
- Increasing numbers of wind farm developments and other renewables at locations remote from load centers
- Small but increasing numbers of small-scale "off-grid" generation
- Economics on distributed generation improving
- New technologies are coming to market (e.g., fuel cells, CNG, renewables)

Barriers

- Cost of network integration (esp. to low voltage distribution networks rather than high voltage transmission network
- Higher Transmission Network Use of System charges for sites distal to load centres
- Current inefficiency relative to large-scale generation

Enablers

- Increasing numbers of renewable generation sites
- EMR financial incentives (e.g CfDs)
- Annual cost reductions and expected grid cost parity

Outcome

- Leverage smaller-scale distributed generation to provide an alternative source of electricity if central power stations or transmission systems incur an outage

Current levels of adoption	Anticipated levels of adoption	Timing	Cost	Effect (incl. co-benefits)
Low Technologies marginally cost-effective	Medium	5 – 10 years	Medium - High	High But depends on how quickly and broadly distributed generation is embraced

Source: Based on evidence presented in this report and stakeholder views.

Extent of adoption of adaptation actions

Currently, generation is concentrated in a relatively small number of major power plants with 95% of UK generation deriving from major power producer output (AEP, 2011). However, there are several small but increasingly numerous small-scale "off-grid" generation installations. By the 2020s, National Grid expects that there will be a significant increase in embedded generation, consisting of approximately 7 GW of CHP and 8 GW from other technologies, such as photovoltaic, energy from waste, biomass and anaerobic digestion (NGET, 2011a).

Key barriers

Relative efficiency: Despite on-going technology efficiency improvements, small-scale installations are less cost effective in terms of cost per MWh (IEA, 2010). Any Government incentivisation of DG must therefore balance the expected cost premium per unit of energy with the benefits such generation provides.

Grid connection: Existing transmission networks were designed for the connection of large scale power plants. Connecting large numbers of small-scale embedded generation installations represents considerable technology and operational complexity for the energy networks, in particular for distribution networks (which would serve as the primary DG point of connection) (National Grid interview, 2012).

Effect of response

Penetration of DG improves geographic diversity of generation, serving to make system more resilient to localised climate change impacts. In addition, it offers the potential to reduce peak load requirements and the attendant need for expensive peaking plant[43].

5.2.7 Uncertainties and limitations

There are a number of uncertainties and limitations of the analysis of adaptation actions including:

Interaction between measures: The measures discussed in this section are in many cases closely related. For example, the implementation of DSM measures will interact closely with the demand for further capacity. As such, it is difficult to consider each measure in isolation.

Nature of the evidence: Although there is some evidence on costs of specific options, there is little readily available evidence as to the economic impacts of different options in a dynamic market context. Furthermore, much of this evidence is held by companies and is considered commercially sensitive.

There is little data generally available on the quantified impacts of adaptation decisions and whether or not, and to what extent, decisions will mitigate climate risks. In particular, data on behavioural responses, such as demand response, are considerably less detailed than that of infrastructure investment assessments.

Subjective assessments: Assessing the extent of adaptation measures and their likelihood of increasing in extent in the future is subjective and based on the views and opinions of stakeholders and experts. In many cases, the effectiveness of different measures is dependent on expert opinion.

Comprehensiveness: Available evidence is not comprehensive in scope and is limited by the expertise of the particular experts and stakeholders. In particular, compared to other sectors considered in the ECR series, it was difficult to secure engagement from diverse set of experts within industry and elsewhere.

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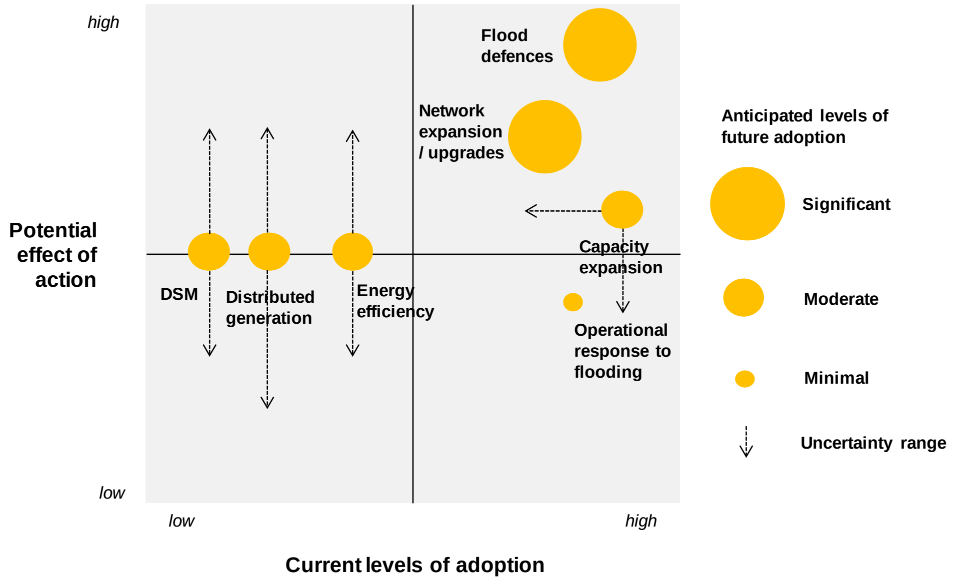
[43] A cost benefit analysis of distributed generation versus centralised power generation is beyond the scope of the work.

Modelling electricity systems: Due to the power sector operating as an integrated system, in order fully to assess the implications of climate change, comprehensive bottom-up modelling is required that considers the both plant-specific resilience and system-wide dispatch and network constraints. This project was unable to access these models held by DECC and by the major power companies.

5.2.8 Extent of adaptation

In order to illustrate the extent to which adaptation is currently occurring and is likely in the future, **Figure 12** presents an assessment of the current levels of uptake (adoption) and levels of adoption anticipated by the 2050s (without further intervention). **Figure 12** provides a simplified summary, based on evidence presented in this report and informed by stakeholder discussions. Justification for the positioning and anticipated levels of future adaptation is based on the analysis in this Section.

Figure 12. Summary of current and anticipated uptake of adaptation and associated effectiveness



Source: Based on published evidence and stakeholder views

Note: Scales are qualitative. The current levels of adoption include both discrete decisions such as investment in capacity, as well as on-going measures (e.g., operational responses) Effectiveness varies from limited scope due to impact on performance, time-frames or effort involved to major changes in risk management.

The position of each measure is based on the classification within main text in this chapter and, given the factors discussed above, could vary considerably depending on sector and company.

The yellow dots positioning the measures in **Figure 12** are scaled according to the expectation of future increase in prevalence in the absence of further intervention to promote uptake (larger dots indicate a greater level of expected increase in the near future, to the 2020s).

Scales are qualitative and relative to the sectors being considered. "Current levels of adoption" reflects the extent to which types of measures are currently being implemented (either planned or reactively, or both); it is also influenced by the frequency of decisions made. "Effectiveness" varies from limited to major impacts on generation or transmission capacity or output. Increases in future adaptation assumes no further intervention to increase adoption and is essentially over the next 10 years or so. The position of each measure is based on the classification within main text in this report.

Where actions are in the top-right quadrant, they have been assessed as relatively effective in addressing a particular climate threat or in maximising an opportunity and are currently being implemented. A cost-benefit analysis of actions would need to be undertaken to guide the extent of such measures. In the top-left, the current low levels of adoption imply that, despite actions being relatively effective, there may not be a case for extensive adoption (i.e. costs could outweigh the benefits), or there are barriers affecting greater uptake. In the bottom-left, actions are not likely to be particularly effective and are not widely implemented. In the bottom-right, actions are widely implemented but are not likely to be very effective in managing climate risk. As the electricity sector is a dynamic system, it is noted that any change related to effect of extent of adoption of one action will affect another; for instance, increases in energy efficiency can affect generation.

In most cases, the measures that are mapped in **Figure 12** are underpinned by other drivers (such as the security of supply, socio-economic development and the low-carbon agenda).

It is important to note that adaptation is not necessarily effective, and can lead to maladaptation if action is taken without full consideration of the longer term risks. In these cases, intervention is required to correct the maladaptation.

The key measures to respond to climate change include engineering and design measures (e.g. flood defences), investment decisions to increase capacity and network expansion. The potential effect of DSM, energy efficiency and distributed generation is notably uncertain owing to a strong degree of dependence on non-climate-related policy developments, technology development and the ability to remove market barriers.

While most of these actions are in response to drivers other than climate change, many would form an effective response to climate change risks currently faced today or projected. Owing to the integrated nature of power generation and transmission subsectors and operations, adaptation actions must be considered from a system-level perspective to ensure resilience and address issues arising as a result of interdependencies.

5.2.9 Barriers to building adaptive capacity and delivering adaptation actions

Although there are strong commercial and regulatory drivers for actors in the power generation and transmission sub-sectors to be sustainable and ensure the security of supply, **Figure 12** suggests some barriers to uptake and effective implementation. Some measures are in the top-left quadrant (implying a barrier to uptake of effective measures where they may be justified on cost-benefit assessment grounds) or in the bottom right (implying actions are being implemented but their effectiveness could be improved).

Understanding these barriers is important because overcoming them is likely to need intervention – by government or other bodies – to build adaptive capacity and facilitate businesses to adapt effectively.

These barriers are considered in terms of:

- **Market failures:** relating to pricing signals; externalities[44]; public goods, and where information may not be timely, accurate, relevant or is incomplete;
- **Policy:** the framework of regulation and policy incentives;
- **Behavioural:** for example, ‘short-sightedness’ and willingness to act; and,
- **Governance:** institutional decision-making processes.

The discussion of adaptive capacity and the policy framework in Section 4 and the assessment of adaptation actions in this Section suggests the barriers below.

Market failures

Interdependencies and external costs or benefits: In many of the measures discussed, there are strong interdependencies and cross-sectoral linkages that act to both support and impede adaptation actions. Examples identified through this report include:

- **Intra-sector interdependency:** the complex system-based nature of activity and operation in the power generation and transmission sub-sectors means that measures, such as flood defences and operational responses to flooding, should account for the risks faced at the level of the operator but also from the system-perspective too. This is particularly important given that long-

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[44] Where there are costs or benefits imposed on others that are not accounted for in individual decision-making.

term climate change, extreme weather events and climate variability could affect more than one operator simultaneously. The costs to society of any adverse impact could therefore exceed those identified in any individual operator-level assessment. Actions are therefore linked to other infrastructure providers, communities, and businesses.

- **Adaptation actions implemented by other sectors:** the effectiveness of actions in the power sector can also be influenced by adaptation actions (or lack thereof) in other sectors. For example, flood defences implemented at the community level, whether hard engineering or natural flood management, and changes in land-use upstream, can affect power infrastructure.

- **Technology interdependency:** generation and transmission is dependent on real-time information and communication technologies (ICT) for both market and network operations. In the future, the development of smart energy technology is expected to significantly increase this interdependency (RAENG, 2011). At the same time, ICT is primarily dependent on grid-sourced electricity. Therefore, the resilience of those other sectors is likely to influence the resilience of the power sector – unless such interdependencies are accounted for in assessments of actions and decision-making, an inefficient level of adaptation action could be taken.

Misaligned incentives and external costs: investment horizons associated with energy efficiency measures may mean that consumers do not have the compelling economic incentive to make such investments. This may occur if, for example, a residential efficiency investment has a payback period which exceeds the investment horizon that individual investors are willing to consider. In addition, where tenants are reliant on landlords to implement such measures, there is likely to be a disincentive for the landlord to do so owing to the lack of private return. The cases in which the benefits for society exceed those for individual investors should be recognised so that appropriate policies could be developed to address them.

Information and uncertainty: the uncertainty over climate change and its potential impacts, likely developments in technology over future decades and non-climate change drivers, such as socio-economic developments and demand, means that uncertainty underpins decisions in the sector. Being able to account for uncertainty, learn over time and be flexible to account for emerging information will be important.

Policy

While the Capacity Market is expected to be effective and is likely to be implemented, its final **policy and regulatory design and implementation** are still uncertain. The Energy Act (2011) is expected to create an investment environment that can support the deployment of a sustainable generation mix. Ensuring a stable and supportive policy environment will be important.

As noted in Section 4, it will be important that the EMR's policy objectives are appropriately channelled through the institutional and regulatory framework of the sector, and that careful monitoring and review is put in place to allow learning and modification over time. A potential barrier could arise if climate change is not adequately accounted for as part of these processes.

From the regulator's perspective, the RIIO framework provides the opportunity for specific outputs to be embedded in the regulatory determination and for associated incentives to be provided. A potential barrier could arise if climate change, and management of associated uncertainty, is not embedded and adequately accounted for in relevant output metrics and incentives.

Behavioural

Residential energy consumers have a generally low level of responsiveness to fuel price signals. For example, research by the Committee on Climate Change in 2008 found that DECC's models assume a long-term price elasticity for electricity demand is -0.14 and in Cambridge Econometric's MDM-E3 model for aggregate residential demand (all fuels) used an elasticity of -0.3 (Committee on Climate Change, 2008). This implies a barrier in the degree to which they change their behaviour to increase energy efficiency.

Governance

Related to the issues identified above, the extent of interdependency in power generation and transmission means that co-ordination of decision-makers and policy makers is required. This could be a potential barrier, so should be noted and addressed as the new policy and regulatory frameworks are decided in the near-term.

Importantly, the substantial change that the sector is likely to undergo over the coming years in terms of infrastructure and asset replacement, the continued development of the regulatory framework, and wider government energy policy, create an important opportunity for climate change to be adequately accounted for and integrated appropriately.

Having assessed the extent to which adaptation actions may be likely to be taken in the power supply sector, the next section explores the case for intervention.

6 The case for intervention

This Section presents analysis to demonstrate the case for intervention to both build adaptive capacity of businesses in the UK, and to facilitate the implementation of effective adaptation strategies by businesses and others.

The circumstances where a case for government (or other) intervention may exist include the following:

- Where there are **significant barriers or constraints** to taking effective adaptation action. This may be because of a lack of adaptive capacity such as when markets lack the required information to allow appropriate signals to be sent to parties to take appropriate action.
- Where **the UK may become 'locked in'** to a path that could lead to maladaptation or removes **the flexibility required to effectively manage uncertainty.**
- **Where organisations lack the adaptive capacity** to be able to prepare for climate change.

The barriers to effective adaptation were discussed in Section 5. This Section focuses on those that are most likely to be important for power generation and transmission to the 2020s and suggests interventions that would address them. Such interventions may not all be for government to take directly because effective adaptation would require businesses, government and stakeholders to work together.

The focus of this chapter is therefore on the following:

- Continuing to manage uncertainty as the sector undergoes substantial change over coming years in terms of infrastructure, regulatory framework and wider energy policy, and to manage interdependencies; and,
- Making the most of the opportunity afforded by replacement of ageing assets to integrate climate resilience and avoid 'lock-in' to a set of actions that could lead to inefficient adaptation.

6.1 Managing uncertainty and interdependencies

There are different types of uncertainty regarding future impacts of climate change on the UK (see **Annex 3**) and in particular over how they are expected to impact at the local level, and when. This should not be taken as a reason not to do anything.

These uncertainties are particularly problematic for planning large, high cost adaptation options with long lifetimes, as such investments are costly to reverse and their design is dependent on what assumptions are made today about climate over its lifetime. If forecasts are incorrectly made, the action can lead to maladaptation, wasted investments or unnecessary retrofit costs (Reeder and Ranger, 2011). Adaptation decisions must therefore be resilient to a fast changing and uncertain climate (Hall, 2007).

Adaptive management can be illustrated through **adaptation roadmaps** as a pragmatic and effective way to provide a preliminary mapping of when and how appropriate actions could be taken (where there is a case for doing so) in the presence of uncertainty around the potential impacts of climate change (see **Annex 3** for a more detailed discussion on climate uncertainty).

This approach allows **flexibility to be incorporated into adaptation measures from the start** where possible, (e.g. by using measures that are suitable over a broad range of possible future climates or by designing the adaptation measure so it can be adjusted over time (Fankhauser *et al.,* 1999)). **Flexibility is also incorporated into the overall adaptation strategy**, by sequencing the adaptation, so that the system adapts to climate over time, but options are left open to deal with a range of possible future scenarios.

Adaptive management encourages decision-makers to pose 'what if' outcomes and take an approach whereby decisions are made over time to continuously adapt while maintaining as much flexibility as possible for future options. The essence of the approach is to be clear on the direction of travel, or the vision for the desired outcomes or management goals, and the uncertainties about how to achieve these outcomes (Murray & Marmorek, 2004). Having chosen a course of action, decisions are made with learning, reviewing and modifying actions as appropriate along the way.

6.1.1 Adaptation roadmaps

The adaptation roadmaps developed here are intended to illustrate "packages" of measures that can be implemented over time. Prioritising adaptation options in the face of uncertainty leads to focus on those options that are:

'No-regrets': those actions which are worthwhile (i.e. they deliver net socio-economic benefits) whatever the extent of future climate change. These types of measures include those justified under current climate conditions (UKCIP, 2007). This may include building adaptive capacity - enhancing climate knowledge, technical skills, improving use of building space;

Win wins: actions that minimise climate risks or exploit opportunities, but also have other social, environmental or economic benefits (UKCIP, 2007).

Low-regrets/low cost: actions with relatively low associated costs, and with relatively large associated benefits, although the benefits will primarily be realised under projected future climate change (UKCIP, 2007); and,

Strategic options: These can include longer term decisions related to investments in new physical infrastructure.

These options are classified into adaptation roadmaps that address the evolving nature of climate change risks over time, and the development of policy (such as the CCRA, the National Adaptation Programme and building policy). It is intended that these roadmaps will be iterated over time. This aims to ensure that actions taken will not be maladaptive if climate change progresses at a rate different from that expected today, and to review any and all unintended consequences.

It should also be recognised that any action chosen should be taken with the engagement of stakeholders and availability of data to allow progress and emerging outcomes to be monitored and reviewed.

Figure 13 is intended to be an indicative roadmap which sets out some of the adaptation actions that are currently being taken and could be effective by the 2050s, along with when key review points will occur. The measures in **Figure 13** were chosen based on the measures identified in published literature and stakeholder evidence, as set out in Section 5. The column to the right of the figure shows where the example measures fit within the categories used in Section 5. Building adaptive capacity is included within the actions, as illustrated by a dark outline around the relevant actions. Some of the actions within the roadmap will occur reactively, whilst others will require further support.

Underpinning all of these roadmaps is the need to consider the wider market conditions and policy landscape. Addressing the impacts of climate threats appropriately, whilst maximising opportunities, requires the development of policy frameworks and other overarching support mechanisms. Importantly, regular review points must be embedded into the approach.

The roadmaps are not intended to be comprehensive or exhaustive, as there are many other roadmaps the sector will need to consider. In particular, this report has not set out a detailed adaptation pathway such as the Thames Estuary 2100 Report Project because the "known thresholds" for climate change (Reeder and Ranger, 2011) have not been assessed and there are multiple risks and receptors (those operators in the sector affected by climate change) that are considered in the scope of this report.

The development of adaptation pathways to address specific climate change risks is an important piece of analysis that should be undertaken in future work to assess the thresholds; it was not possible to be carried out for this project.

Figure 13 shows that in the short-term (pre-2020), given the nature of current risks faced and the change that the sector is going through, there are a number of measures required to build adaptive capacity. These focus on evidence building in order to provide primary information for subsequent decisions. These measures will develop a degree of optionality that will ensure options are kept open where appropriate.

Specific immediate priorities comprise measures to improve the understanding interdependencies with other sectors and understanding implications for emerging technologies (e.g. electric vehicles, smart energy technology). These were noted as particular barriers in Section 5.

While many of the actions identified will be on-going, there will be a need for regular reviews of the resilience of the sector, players and specific investment decisions in the context of a changing climate. For strategic options with long lead times, notably siting and design of new generation facilities, there is a need to avoid lock-in and therefore to build in flexibility where possible. A range of analytical tools can help with this approach, including, for example, real options analysis, as is commonly used in the sector to manage a range of uncertainties – this must also be sure to incorporate climate change uncertainty.

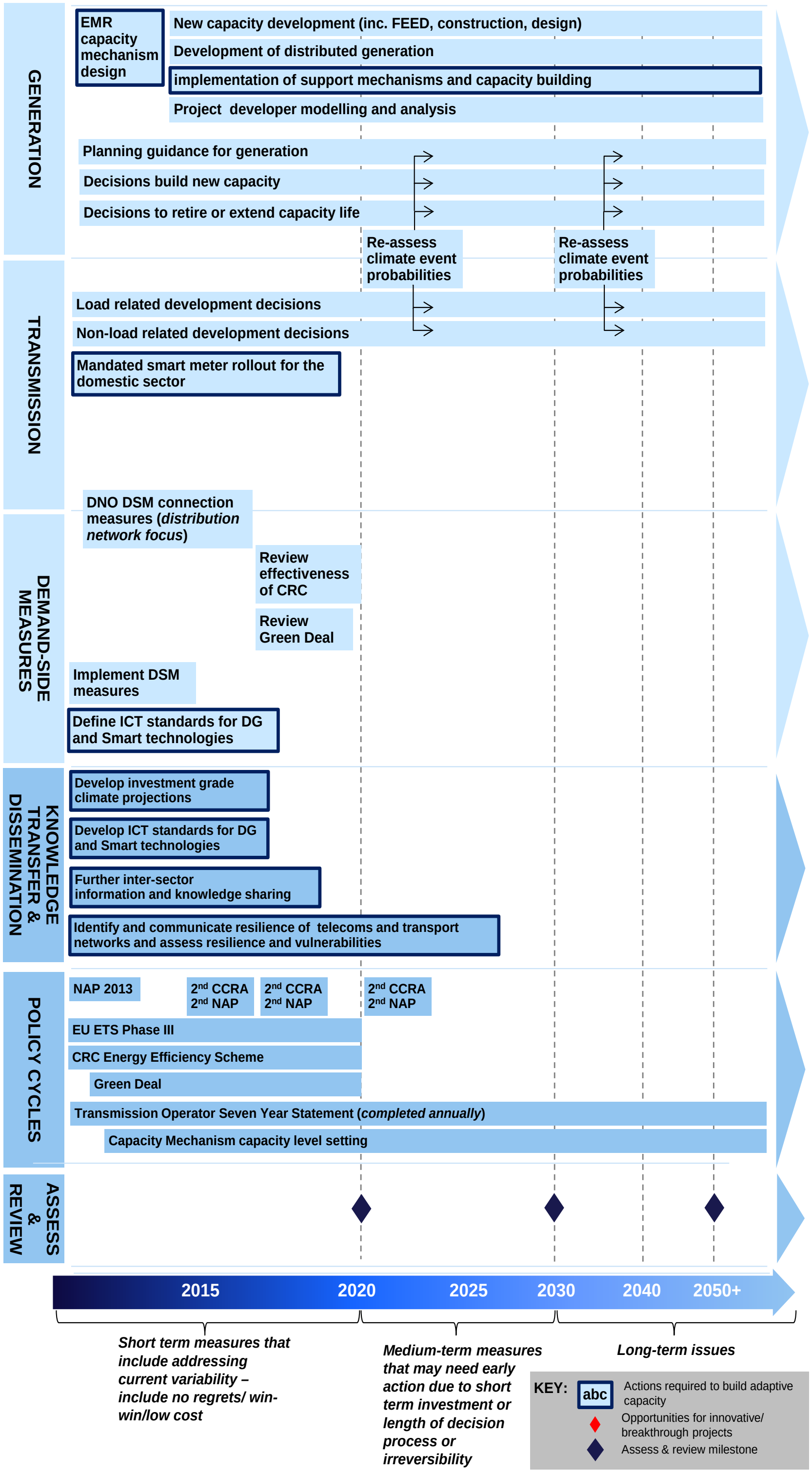
Some actions, such as demand-side management measures or other approaches for the development of distributed generation, represent innovative or breakthrough initiatives. Such initiatives would be more transformative in nature, as opposed to incremental modifications to current processes or guidelines. Further alternative or innovative business and service delivery models can be considered in addition to those considered above.

The adaptation roadmaps incorporate review points, where policy and practice can be assessed and evaluated in light of recent developments, new information and better understanding of climate risks and research outputs. This includes on-going review of adaptation (as part of all adaptation processes) to ensure trade-offs, conflicts or synergies are identified. The review points are designed to coincide with policy cycles (e.g. NAP and CCRA) as well as developments in electricity market policy (e.g. the Energy Act) and points where adaptation actions should be maturing. Earlier review points allow analysis of short-term measures, with no regret/win-win characteristics, and particularly those that build adaptive capacity. The review points will also allow for consideration of the options in the context of developing evidence on evolving climate risks. Some options may be more or less appropriate in the future, depending on the level of projected change in terms of climate risk, but also socio-economic and technological developments. At each review point, the options must be considered as portfolios of short-term, medium-term and long-term responses, to identify early actions to address long-term issues and to ensure there is enough time for decisions with long lead-in times. There may be additional review points where major review and consultation is required, if there is an extreme event, or if the upper end of climate projections and uncertainty ranges were approached.

There are important inter-dependencies between the options in the roadmaps. For example, many of the options (e.g. investment in new generation) rely on the capacity building (e.g. knowledge sharing) and the actions of others in the sector or other sectors. This base must be understood and established before more costly options can be taken later on. The adaptation roadmaps focus on the risk of flooding and heat stress in the power sector given the scope of the question set by Defra, but there are many connections to other sectors that need to be considered in order to lead to effective adaptation.

Coordination of responses across actions and sectors is needed, along with consideration of other risks (e.g. implementation of DSM measures will also relate to the ICT sector). Roadmaps must also be co-ordinated with policy reviews and assessments.

Figure 13. Summary of selected illustrative adaptation roadmaps



Source: Based on evidence in this report, stakeholders and experts

6.2 Maximising opportunities afforded by asset and infrastructure replacement and development

To explore the potential effectiveness of action to maximise opportunities for integrating the management of climate change risk into policy and decision-making processes, this Section explores a series of illustrative 'what if?' scenarios. The scenarios are intended to be indicative of the relative gain from taking particular actions. Further research would be needed to assess the full range of costs and benefits under different climate change scenarios – this was beyond the scope of this particular analysis.

6.2.1 Illustrative 'what- if?' scenarios

What if scenarios are tools which allow a range of alternative outcomes to be explored given the uncertainty over future climate change.

The analysis in Section 5 indicates that a high level of adaptation is expected in the sector, given the market and regulatory incentives that will be in place. However, two important issues are that firstly, this requires policy and regulatory frameworks to adequately take climate change into account when setting output metrics, for example. Secondly, the level of asset replacement over coming decades means that the resilience of the sector could change markedly as it would be expected to increase.

Three illustrative 'what if?' scenarios have been explored below to demonstrate the potential impacts of various forms of climate change events individually. Climate change could lead to extreme events in the form of, for example, flooding and temperature change. Each is assessed separately below, though if they occur simultaneously, the outcomes would be different to those shown.

Scenarios have been illustrated for:

- managing the impact of flooding on power generation;
- managing the impact of heat on power generation; and,
- managing the impact of heat on transmission.

The impact of increased heating and cooling on residential energy demand in the context of climate change is considered separately in detailed analysis within the separate ECR report "Overheating in Residential Housing".

Below, each scenario illustrates the potential outcome with:

- potential effect of climate change without the adaptation measure;

- potential effect with adaptation measure implemented; and,
- the difference between the impact with no adaptation and the impact with adaptation.

'What if' scenario 1

This scenario explores the potential effectiveness of taking the opportunity to build appropriate consideration of projected climate change into design when replacing generation capacity.

This is based on a hypothetical coastal site with a variety of plants clustered together, and a total installed capacity of 10 GW. No specific climate change emissions scenario is used, instead, the potential impacts are explored by considering a scenario which explores 'what if a flood that would otherwise result in capacity being out of commission for six months is, in part, alleviated by replacing a quarter of the capacity at risk by the 2020s with flood resilient infrastructure?'. The adaptation action considered here is the extent to which the policy framework and commercial incentives mean new capacity is resilient to climate change through infrastructure flood protection measures.

Table 11 summarises the assumptions regarding the installed capacity for each type of technology. Based on a 'typical' site, capacity in this scenario consists of 5 GW of CCGT (gas), 3 GW of coal, and 2 GW of nuclear generation. Total annual generation by the site is 48.7 TWh, assuming load factors reported by DECC (2012b).

Table 11. Assumptions for the hypothetical site

	Gas	Coal	Nuclear	Total
Installed capacity (GW)	5	3	2	10
Average load factor[45]	62%	42%	60%	-
Generation without extreme weather event (TWh)	27.2	11.0	10.5	48.7

Source: Load factors from (DUKES (DECC, 2012b).

Without the extreme weather event, it is assumed that output would be just under 50 TWh. For illustration, if for example, 20% of current plants on the site do not have sufficient flood barriers, up to 2 GW of the site would be affected in the event of a flood[46]. Assuming flooding results in capacity being de-commissioned for six months, the total generation loss following a flood could be up to 5.0 TWh.

The plants that do not have adequate protection against flooding would be expected to be the oldest ones, due to changes in design standards over time. As these reach the end of their life, they will be replaced. If opportunities are taken to provide appropriate incentives through the policy framework, coupled with commercial incentives, to ensure that new capacity is resilient to climate change, then the management of climate change risk should be accounted for in design.

If older assets are replaced meaning that, for example, the capacity at risk of flooding by the 2020s in this scenario is assumed to have fallen from 20% to 15%. This implies lost generation could be reduced by up to 1.5 TWh by the 2020s.

The scope for further intervention arises from the capacity that remains affected in the event of a flood (if the benefits outweigh the costs). In this scenario, 3.5 TWh could still be at risk for the illustrative plant in the 2020s because the infrastructure has not been replaced or adequately protected.

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[45] DECC, DUKES Table 5.10. Averages calculated using data for period 2007-2011.

[46] Higher existing requirements for nuclear flood defences mean that this capacity will not be affected by flooding.

Table 12 shows the results of the analysis for the potential impact of flooding on electricity generation in the 2020s and 2050s.

Table 12. 'What if' analysis: The impact of flooding on generation

State of the world	Potential loss in capacity in the 2020s (TWh / annum)	Potential loss in capacity in the 2050s (TWh / annum)
Extreme weather event occurs causing 6-month off-line	5.0 TWh	5.0 TWh
Re-building one-quarter of capacity at risk	3.5 TWh	0 TWh

Source: ECR analysis

By the 2050s, on the basis of the anticipated operation of the Capacity Market, it would be expected that all plants in operation would have been built to a standard that allows them to withstand the increased flooding risk brought about by climate change. Therefore, flood barriers or other forms of adaptation built into design would be expected. If the framework works effectively, there would therefore be little case for intervention.

When assessing the case for further intervention, based on the illustrated scope for the 2020s, it should be noted that the system would be expected to have enough capacity to meet a temporary shortfall in generation in the event of a flood. By the 2050s, as long as the Capacity Market gives appropriate incentives to provide sufficient reliable capacity, one could expect adequate protection to be integrated into the design and location of power stations when they are replaced. Therefore, **by the 2050s, it would be expected that there is little case for further intervention.**

'What if' scenario 2

This "what if" scenario investigates a current risk and asks 'what if CCGT power plants are affected by an extreme heat-wave lasting 2 weeks in August, during which average temperatures are 6.5 °C higher than average, at 27 °C compared to an assumed baseline of 20.5 °C (no specific emissions scenario is assumed)?' [47].

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[47] A heat Health Watch System is operated by the Met. Office in the UK. This system comprises "four levels of response based upon threshold maximum daytime and minimum night-time temperatures. These thresholds vary by region, but an average threshold temperature is 30 °C by day and 15 °C overnight" (Met Office website, accessed 2012). The duration of the heat-wave is based on the duration of extreme past weather events. For example, the Met. Office reports that "during the long hot summer of 1976,

As described in Section 3, extreme weather events are likely to increase in the future. This scenario therefore explores what might happen if these same temperatures were experienced but opportunities are taken to ensure climate change is built in to the policy framework such that adequate incentives are provided to ensure the provision of sufficient spare capacity to ensure the system as a whole is resilient to such effects.

As in Section 3, the focus is on gas plants, which are more affected by heat than coal or nuclear plants. The same assumptions as in Section 3.3 are used regarding the extent of heat rate degradation, and total generation is illustrated to be that of August 2012 at 11.5 TWh (DECC, 2012). As calculated in Section 3.3, the heat-wave results in a 1.2% efficiency reduction for all CCGT power plants, which is equivalent to 62 GWh of reduction in generation.

As the system peak occurs in winter and the difference between winter and summer peak is about 12 GW (see Section 3), the system already has sufficient spare capacity to deal with such an impact. With new capacity being built in the coming years in any case, such an effect, in isolation, would be expected to be absorbed entirely.

By the 2050s, assuming that the winter peak remains higher than the summer peak, then the incentives placed on generators, as a system, would mean that sufficient spare capacity would be available to absorb the impact of heat on generation during the summer months. This is shown in **Table 13**.

Assumptions and results are illustrated in **Table 13**.

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temperatures exceeded 32 °C (90 °F), somewhere in the UK, on 15 consecutive days starting on 23 June. During the summer of 1976, Heathrow had 16 consecutive days over 30 °C from 23 June to 8 July (its highest number of consecutive days above 30 °C) (Met. Office website, accessed 2012).

Table 13. What if analysis, the impact of heat on generation

State of the world	Estimated lost output in the 2020s (GWh / annum)	Estimated lost ouput in the 2050s (GWh/annum)
Heat-wave effect from loss of efficiency	62 GWh	62 GWh
System loss of efficiency	0 GWh	0 GWh

'What if' scenario 3

Table 15 illustrates the impact of increased temperatures on the transmission network and it explores 'what if the opportunity to account for climate change when replacing transmission network assets is taken?'

For this illustration, an overhead 'typical' transmission link[48] is considered. The link is assumed to come under increasing pressure over the coming years, due to the increase in distributed renewable generation, and the bulk of demand being concentrated in the South East. A one-off 8 °C temperature increase above the summer average is explored (this is equivalent to the assumption underpinning analysis by the National Grid (2010) for the 2080s using the p90 high emissions scenario, outlined in Section 3). The key assumptions are presented in **Table 14**.

Table 14. Assumptions on the overhead transmission link between Scotland and England

Factor	Assumption
Capacity at normal summer temperature (MW)	2000
Rating reduction following 8°C summer temperature increase (high emissions scenario p90)*	3%
Estimate of implied capacity reduction (MW)	60

Source: * National Grid (2010)

The higher temperatures lead to a reduction in capacity of around 60 MW.

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[48] This is based on an actual link, for illustration.

Significant investment in renewing the transmission grid is likely, owing to the age of transmission grid assets (as discussed in Section 3). Therefore, capacity would move back up to the original level **as long as the replacement assets are more climate-resilient (i.e. the opportunity to account for climate change is taken**.) The need for additional capacity also arises from rising demand for energy and the increasing levels of distributed and intermittent renewable energy generation. The loss in capacity owing to heat is therefore likely to be relatively low, and less than new generation capacity being added.

Table 15. 'What if' analysis, the impact of heat on transmission

Case	Estimated lost capacity in the 2020s (MW / annum)	Etimated lost capacity in the 2050s (MW / annum)
Climate change with no replacement of an old asset	60 MW	60 MW
Assets replaced ensuring they are climate-resilient	60 MW	60 MW

Conclusions of these scenarios are:

- The replacement of capital assets expected in terms of generation and transmission investment provides opportunities for adaptation to be duly accounted for in the longer term. It will be important that the Capacity Market accounts for the changing nature of risks to resilience that climate change is likely to bring about. The commercial incentives on generators to ensure their resilience are also likely to play an important role.

- Increases in temperature may have an impact on generation as it causes heat rate degradation with a consequent loss of efficiency. The overall effect on power output is likely to be relatively low (and the impact will vary across the country, depending on the extent to which the temperature changes). The Capacity Market would be expected to ensure the overall system-wide capacity margin would remain resilient to this effect.

- Where areas at risk of flooding cannot be avoided when locating new capacity, it will therefore be important for flood risk to be fully accounted for in planning and design.

This section has explored the role of adaptation roadmaps and the potential effectiveness of actions to prepare the UK for climate change. The next section pulls together the findings of the whole report by assessing the potential case for further action.

6.3 Recommendations

In summary, in this Section analysis has made the following recommendations to address barriers:

Build adaptive capacity of the sector by enhancing knowledge and understanding of interdependencies of the energy sector and adjacent sectors. In particular:

(i) Undertake system-wide modelling, or case study, assessments, as appropriate, to explore different climate risk and adaptation scenarios to understand how the resilience of one sector is affected by actions in another, as well as how adaptation actions can affect the system more widely.

(ii) Ensure climate change is appropriately factored into assessments of potential future interdependencies across infrastructure sectors, particularly in terms of technology, operations and actions taken in other sectors.

Require the assessment of potential climate threats – including extreme weather events – as a core component of the decision on how much capacity to contract through the Capacity Market. Government's current thinking is that the decision on capacity will be taken with reference to a reliability standard.

Ensure that the policy and regulatory framework is kept under review in order for it to be able to provide the sector with the right incentives for climate change adaptation in a timely fashion.

Review and identify appropriate opportunities to embed appropriate consideration of climate change threats into the location, design and construction of new generation capacity. Key decisions will be taken over coming years as generation capacity is de-commissioned and replaced and as the transmission grid is updated – these offer important opportunities for the sector to develop solutions which deliver a higher level of resilience

Recommended further work

This analysis has focused on power generation and transmission. Evidence reviewed as part of this work and engagement with stakeholders suggests that the **distribution network could be more significantly affected**, for example, in terms of the impact on flooding on distribution sub-stations. There is therefore a case for exploring this in more detail.

More detailed analysis is also required of the energy demands for cooling and heating in the commercial and industrial sectors.

Annex 1: Stakeholders

The ECR team is grateful to the following for their valuable input to this work:

D. Acre (EDF).

R. Bagi (EDF)

R. Baxter (Scottish Power)

P. Durante (ex-Shell, ex-Irbaris)

A. Limbrick (AEP)

S. Mathieson (Scottish Power)

P. O'Rourke – an expert adviser with over 40 years' of power industry expertise.

J. Rixham (E.ON)

S. Samuel (Ofgem)

G. Thornton (National Grid)

Annex 2: Policies relevant for adaptation

Policy impacts

All economic activities take place within the context of the policy environment. Policy therefore plays an important role in influencing the incentives of the power supply sector to prepare for climate change.

The Office of the Gas and Electricity Markets (Ofgem) regulate distribution and transmission networks through five-year price control periods. It incentivises companies to be efficient and to innovate through technology by setting limits to the revenue that energy network owners can take through the charges they levy on their customers.

Arguably, the most significant recent policy change is the proposed Electricity Market Reforms (EMR). At present, energy infrastructure networks have a certain level of inbuilt resilience from extreme events because of plant capacity margins, diversity in generation technology and the geographical diversity of stations.

However**, energy supply is expected to be transformed over coming decades.** Around a fifth (some 19GW) of capacity available in 2011 has to close by the end of this decade (DECC, 2012). In addition, the introduction of intermittent and inflexible generation will require more flexible capacity to ensure electricity supply when these sources are not available.

The proposed EMR has four components (DECC, 2011e):

- a Carbon Price Floor (announced in Budget 2011) to reduce investor uncertainty, putting a fair price on carbon and providing a stronger incentive to invest in low-carbon generation now;
- the introduction of new long-term contracts (Feed-in Tariff with Contracts for Difference) to provide stable financial incentives to invest in all forms of low-carbon electricity generation. A contract for difference approach has been chosen over a less cost-effective premium feed-in tariff;
- an Emissions Performance Standard (EPS) set at 450g CO2/kWh to reinforce the requirement that no new coal-fired power stations are built without CCS, but also to ensure necessary short-term investment in gas can take place; and
- a Capacity Market that is open to demand response storage and interconnected capacity as well as generation, which is needed to ensure future security of electricity supply.

Each of these would be expected to affect the ability of the sector to adapt to the projected impacts of climate change. For example, the Carbon Price Floor may hasten the retirement of coal plants, bringing on new capacity that is more resilient to climate change. With the capacity market, a central body will contract for the required volume of capacity needed to deliver security of supply. The contracting of capacity to meet peak demand will be done via an auction, in which both generation and non-generation (demand & storage) forms of capacity could take part.

A Capacity Market mechanism is intended to ensure sufficient reliable capacity to meet demand. The Capacity Market, if initiated, will centrally contract for the required amount of capacity as determined with reference to a security standard. The contracting of capacity to meet peak demand will be done via an auction, in which both generation and non-generation (i.e. demand & storage) forms of capacity could take part. It provides a predictable revenue stream for providing reliable capacity while imposing financial penalties for failing to do so. Thus it is intended to incentivise investment in reliable capacity, while still retaining the appropriate incentives to generate and dispatch electricity in the electricity market. This would be expected to improve the capacity of the electricity sector to deal with the impacts of climate change. For example, if an increased risk of extreme weather events meant that there was a greater likelihood of plant failures, the amount of capacity contracted for any given level of demand could be increased.

Therefore, **as long as the risk and potential impacts of extreme weather events was adequately monitored and accounted for within contracted levels, the system should remain resilient.**

Feed-in tariffs with Contracts for Differences were also introduced under the EMR and are designed to encourage investments in low carbon generation, helping achieve carbon emission targets.

Devolved Administrations

Scotland

The Energy Sector Action Plan looks to identify the key impacts of climate change on the energy sector and details responses that can build the Scottish energy sector's resilience to these impacts. These plans will also be updated on a regular basis as the understanding of these issues changes and adaptive actions evolve.

The Scottish Government are committed to reducing energy demand by 12% by the 2020s, as outlined in Scotland's Energy Efficiency Action Plan - Conserve and Save. Together with existing commitments - including the Renewables Action Plan, the National Renewables Infrastructure Plan, the Energy Efficiency

Action Plan and the Offshore Wind Route Map – the Scottish Energy Sector Action Plan will help improve the resilience of Scottish energy supply.

Wales

Under the Welsh Government's *A Low Carbon Revolution: Wales' Energy Policy Statement* the Welsh Assembly aim to renewably generate up to twice as much electricity annually by 2025 compared to current usage. By the 2050s, the statement pledged that almost all of Wales' energy needs will be met by low carbon electricity production.

This statement, combined with the *Climate Change Strategy for Wales,* outlines the Government's intentions to develop large scale renewable energy generation capacity in Wales.

Northern Ireland

In February 2011, the Northern Ireland Executive approved a Northern Ireland Greenhouse Gas Emissions Reduction Action Plan, which when combined with the Carbon Reduction Carbon Efficiency Scheme, outlines the targets and required actions to reduce emissions.

The country's Department of the Environment Climate Change Unit supports adaptation policy, including the development of the UK's risk assessment and subsequently the Northern Ireland Adaptation Programme, significantly enhancing the resilience of Northern Ireland's energy infrastructure.

6.3.2 Other UK policies relevant for adaptation

The Sector Resilience Plan for Critical Infrastructure 2010 and National Policy Statement for Energy

The National Policy Statement for Energy outlines how the impacts of climate change on design, location, build and operation need to be accounted for in energy infrastructure. The statement requires that adaptation measures are identified for the infrastructure's lifecycle and that any critical safety elements of the proposed infrastructure be assessed against the more extreme climate change scenarios, ensuring that future major energy infrastructure projects are resilient to the potential future impacts of climate change.

This potentially plays an important role in ensuring the resilience of infrastructure. It is important however that the degree climate change considered appropriately considers a wide range of uncertainty through scenario planning. This should include due consideration of extreme weather events that are arguably lower probability, but high impact. Climate variability is more difficult to project, so appropriate analytical tools would be needed to make sure it is accounted for.

The Sector Resilience Plan (2010) aims to improve the energy sector's resilience by protecting gas and electricity networks from the impacts of flooding, storminess, rising temperatures and other hazards. It also stated that "Future Energy Sector Resilience Plans will be progressively extended to cover all natural hazards and critical infrastructure, and to plan for future climate parameters". This demonstrates that climate change features within the appropriate planning processes, though how this will be done is not clear. It will, again, be important to ensure that a wide range of potential future climate outcomes are considered.

Climate Change Act 2008 and other environmental policy

Many companies focus on short term mitigation action i.e. improving energy and resource efficiency.

As a means of expanding this thinking, the Adaptation Reporting Power (ARP) plays a potentially significant role in preparing the UK for climate change. By identifying and detailing adaptation plans, the ARPs ensure good practice is shared between the UK's key infrastructure companies, facilitating adaptation. Constraints created by the systems interdependencies are somewhat alleviated as plans for the major infrastructure networks are shared.

In combination with the National Policy Statement for Energy, the Adaptation Reporting Power should help planning decisions and encourage the major energy generation companies in the UK to properly adapt to climate change.

Other environmental policy is important to recognise in the context of adaptation. The Government announced in the Water White Paper that it intended to **reform the water abstraction regime**. In order to do this, Defra, the Welsh Government and the Environment Agency are funding a major programme of research to develop an evidence base to assess the impacts of different options for reform of the regime. Key areas of work include improving our knowledge of:

- Future availability of water, particularly the effects on water availability of power sector and agricultural sector future demands for water;
- The relationships between water levels and water ecological status;
- Regulatory design options and their technical feasibility; and
- Abstracter response strategies to changes in water availability under different regulatory options.

This work will be carried completed by June 2013 in order to feed into a formal consultation document and draft impact assessment to be published at the end of 2013. With a significant demand for abstracting water for cooling processes, the outcomes of this review will affect the power supply sector.

Other policies are also important. The **2009 Renewable Energy Directive** sets a target for the UK to increase its energy consumption from renewable sources from 3% in 2009 to 15% of energy consumption by the 2020s. Many schemes are in place to try and reach this target:

- Renewables Obligation (RO)

The RO places an obligation on UK electricity suppliers to source a large amount of electricity from renewable sources. The RO for Scotland, Northern Ireland and England and Wales all operate separately but are complementary.

- The Renewable Heat Incentive

The Renewable Heat Incentive (RHI) was introduced for commercial properties in 2011 and is set to be introduced to households in September 2012.[49]

The RHI allows those who install a form of renewable heat technology to receive payments related to the heat generated by the system, with a fixed income provided for every kilowatt hour of heat produced. Any excess heat generated can be exported to the grid where possible, improving capacity.

- Feed-in Tariffs with Contracts for Difference

Feed-in tariffs with Contracts for Difference were introduced under the EMR and provide stable financial incentives to encourage investments in renewable generation. Low carbon generators are able to enter into long-term contracts that provide them with some stability and certainty via feed-in tariffs with Contracts for Difference. These are intended to increase certainty for investors in low-carbon generation, improving incentives for investment and ensuring a more reliable and resilient energy generation system.

These would be expected to help achieve carbon emission targets and may improve security of supply. However, the vast majority of renewable installations encouraged by feed-in tariffs with Contracts for Difference are intermittent sources of energy generation and so are likely to have a minimal impact on security of supply and will require non-renewable sources to be in place as back up[50].

- EU Emissions Trading Scheme

The European Union Emission Trading Scheme (EU ETS) operates on the 'cap and trade' principle, placing a limit on the level of greenhouse gases that can be emitted by the plants, factories, power stations and other installations in the system. The EU ETS allocates company emission allowances that they can sell or

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[49] http://www.decc.gov.uk/en/content/cms/meeting_energy/Renewable_ener/incentive/incentive.aspx

[50] The feed-in tariffs with contract for difference will also apply to CCS and nuclear, which are not intermittent forms of generation

buy from one another as needed[51]. Over time, the number of allowances will fall, reducing emissions and incentivising a move away from less sustainable forms of energy generation, increasing the resilience of the energy generating infrastructure.

The Planning Act 2008

The Planning Act 2008 introduced an application system for nationally significant infrastructure that aims to facilitate the authorisation of energy and other large infrastructure projects. Many power plants in the UK are clustered in regional concentrations, which if affected by a severe weather event could pose a significant problem for the continuity of energy services on a national scale.[52]

Key infrastructures on the coast and within flood plains are particularly vulnerable, and with power stations commonly grouped into regional concentrations near water sources. Without adaptation, this raises the risk of flooding affecting the operation of the plant.

Whilst the Planning Act 2008 includes prescriptions for nationally significant energy infrastructure projects, current land use categorisations may restrict adaptation. As the climate changes, plant location and relocation will be restricted by current land classifications, which may mean plants are built in areas that are susceptible to climate change (e.g. near water courses that are vulnerable to flooding). Whilst many hard and soft engineering responses to climate change pose few technical barriers, this potential policy constraint could be significant in determining new plant location. To ensure this does not undermine the adaptation, land use categories in certain areas may need to be reformed.

For context on the location of supply infrastructure in Great Britain, this is shown in **Figure 14**.

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[51] http://www.decc.gov.uk/en/content/cms/meeting_energy/renewable_ener/renewable_ener.aspx

[52] URS, Adapting Energy, Transport and Water Infrastructure to the Long-term Impacts of Climate Change. January 2010, p.4

Figure 14. Location of energy infrastructure in the UK

Source: DECC electricity supply system map (2011)

Annex 3: Background on UKCP09

UKCP09 projections[53]

The UK Climate Projections (UKCP09) provides projections of climate change for the UK. These projections cover changes in a number of atmospheric variables, using different temporal and spatial averaging. They are given for several future time periods under three future emission scenarios. Climate change over land includes more variables, at a higher resolution, than those over sea.

Projections of the climate variables in UKCP09 methodology are made using multiple climate models. The output of the climate models is used to estimate probabilities, rather than giving single values of possible changes. Probabilities are introduced to treat uncertainties associated with climate projections.

This annex begins with an explanation on the background on uncertainties associated with climate projections. It is followed by a paragraph that explains the UKCP09 methodology and how uncertainties are accounted for. The next paragraph explains how to interpret probabilities in UKCP09 output and the annex ends with a discussion on the limitations of UKCP09.

Background on uncertainties in climate projections

There are three major sources of uncertainties in estimating future climate change:

- Natural Climate Variability;
- Incomplete understanding of Earth System process and the inability to model the climate perfectly; and,
- Uncertainty in future greenhouse gas emissions

The major sources are discussed individually below.

Natural Climate Variability

Natural variability has two principle causes. One arises from natural internal variability which is caused by the chaotic nature of the climate system. Ranging from individual storms, which affect weather, to large scale variability due to interactions between the ocean and the atmosphere (such as El Nino). Climate can also vary due to natural external factors. The main causes are changes in solar radiation and in the amount of aerosols released (small particles) from volcanoes.

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[53] This annex is largely based on Murphy et al., 2009 and UKCP09, © UK Climate Projections, 2009.

Representation of Earth's System in Climate Models

The second main source of uncertainty arises due to modelling of the future climate. The only way we can calculate how the climate will change due to human activity is through the use of mathematical models of the earth's climate system. These models are known as Global Climate Models (GCMs). They describe the behaviour of different climate components and interactions between them. The components include the atmosphere, the oceans, the land and the cryosphere. Each interact to produce many types of feedbacks, both positive and negative. The net effect will determine how climate evolves in response to changes in greenhouse gasses.

Uncertainty in models is caused by an incomplete knowledge of the climate system and the inability to model it perfectly. Representations of physical processes within the climate system are based on a mixture of theory, observations and representation. Representations may be limited by physical knowledge, as well as by computing power, and lead to errors, which inevitably cause uncertainty. All modelling groups seek to represent climate processes in the best possible way in their models. This is based on subjective judgement, which causes different strengths of feedbacks in different models. This means that different models give different results, although they all use plausible representations of climate processes.

Future Greenhouse Gas Emissions and SRES

The final source of uncertainty arises due to future emission scenarios of greenhouse gases and aerosols. This will depend on many socio-economic factors such as changes in population, GDP, energy use and energy mix. The Intergovernmental Panel on Climate Change (IPCC) published a Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000), in which climate-relevant emissions were calculated based on a number of storylines. Each of these storylines describes a possible way of how the world might develop. Differences between them arise due to the different assumptions about future socio-economic changes. They assume no political action to reduce emissions in order to mitigate climate change.

UKCP09 methodology

In UKCP09, uncertainties mentioned above are accounted for when doing climate projections. Uncertainties are treated by generating projections of change as estimated probabilities of different outcomes. This means that probabilities are attached to different climate change outcomes, which provides information on the estimated relative likelihood of different future results.

To do this, UKCP09 assumes that uncertainties manifest themselves in different climate projections from different climate models. Probability distributions of the future climate can then be generated by using projections from a large number of models or variants from a single model.

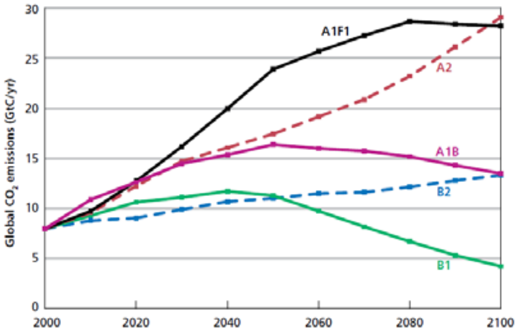
UKCP09 use a combination of projections from the following models:

- A very large number of variants of the Meteorological Office Hadley Centre model; and
- 12 international models used in inter-comparison studies of the fourth IPCC report.

Probabilities are based on a large number (ensembles) of climate model simulations, but adjusted according to how well different simulations fit historical climate observations. This is done in order to make them relevant to the real world. By presenting probabilities based on ensembles of climate models, UKCP09 takes into account both modelling uncertainty and uncertainty due to natural variability.

It does not however include uncertainty due to future emissions. Currently there is no accepted method of assigning relative likelihoods to alternative future emissions. UKCP09 therefore presents probabilistic projections of future climate change for 3 future emission scenarios. They are selected from three scenarios developed in SRES and referred to as Low, Medium and High emissions, which corresponds to A1FI, A1B and B1 scenarios in SRES. **Figure 15** indicates these scenarios in terms of CO_2 emissions with solid lines (black: High Emissions, purple: Medium Emissions, green: Low Emissions). Each scenario also includes emissions of other greenhouse gases. Although the three UKCIP emission scenarios span the range of marker scenarios in SRES, there are additional scenarios, both higher and lower, that they do not encompass.

Figure 15. Global annual CO_2 emissions under the three IPCC SRES scenarios



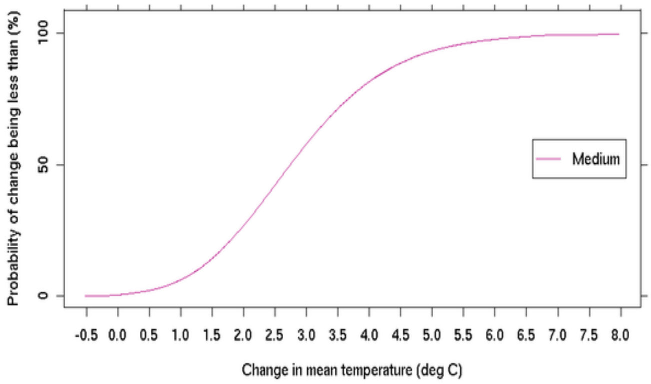
Source: Murphy *et al*., 2009
Note: The dotted lines are two SRES emission scenarios used in previous UK Climate Projections, but not in UKCP09.

Probability in UKCP09

Probabilistic projections assign a probability to different possible climate change outcomes. Probability given in UKCP09 output is seen as the relative degree to which each possible climate outcome is supported by the evidence available. It takes into account the current understanding of climate science and observations.

Probability in UKCP09 does not indicate the absolute value of climate changing by some exact value. Instead it states the probability of climate change being less than or greater than a certain value using the Cumulative Distribution Function (CDF). This is defined as probability of climate change being less than a given amount. An example is given in **Figure 16**. The CDF (for the 2050s mean summer temperatures in the London area, with a medium emission scenario) shows that there is a 10% probability of temperature change being less than 1 degree and 90% probability of temperature change being less than 5 degrees. These statements also work inversely, where one could say there is a 10% probability of temperature change being greater than 5 degrees and a 90% probability of temperature change exceeding 1 degree.

Figure 16. Example of cumulative distribution function for 2050s mean summer temperatures in the London area for the medium emission scenario



Source: UKCP09

The figure above does not say that the temperature rise will be less than 5 degrees in 90% of the future climates, because there will only be one climate. It rather indicates that there is 90% probability (based on data and chosen methodology) that the temperature rise will be less than 5 degrees.

Limitations

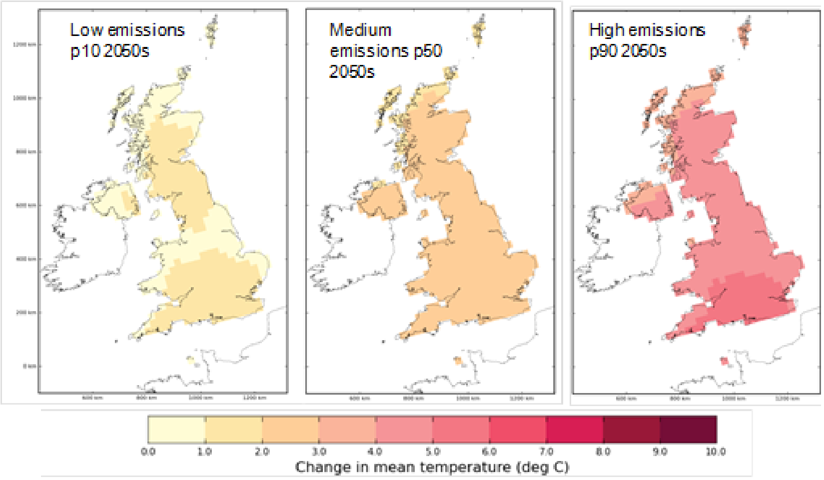
The procedure used in UKCP09 to convert ensembles of climate models into probabilistic estimates of future climate also includes some subjective choices and assumptions. This means that the probabilities themselves are uncertain, because they are dependent on the information used and how the methodology is formulated. Furthermore, the system cannot be verified on a large sample of past cases. Current models are, however, capable of simulating many aspects of global and regional climate with considerable skill. They do capture all major physical and biochemical systems that are known to influence our climate.

Mean summer temperature

Climate projections indicate an increase in summer temperature. By the 2050s, for the central estimate (p50) of the UKCP09 medium emissions scenario, the southern part of England could see temperature rises of between 2.3 °C and 2.7 °C (Murphy *et al.,* 2009). However, temperature increases will vary regionally. Parts of northern Scotland could experience temperature increases of around 1.5 °C for the p50 medium emissions scenario. UK-wide, the projections for increases in mean summer temperatures range from 0.9 °C under the p10 low emissions scenario, to 5.2 °C under the p90 high emissions scenario.

The projected changes in mean summer temperature in the UK for the p10 low emission scenario (left), p50 medium emission scenario (middle) and p90 high emission scenario (right) are shown in **Figure 17**.

Figure 17. Projected changes in mean summer temperature



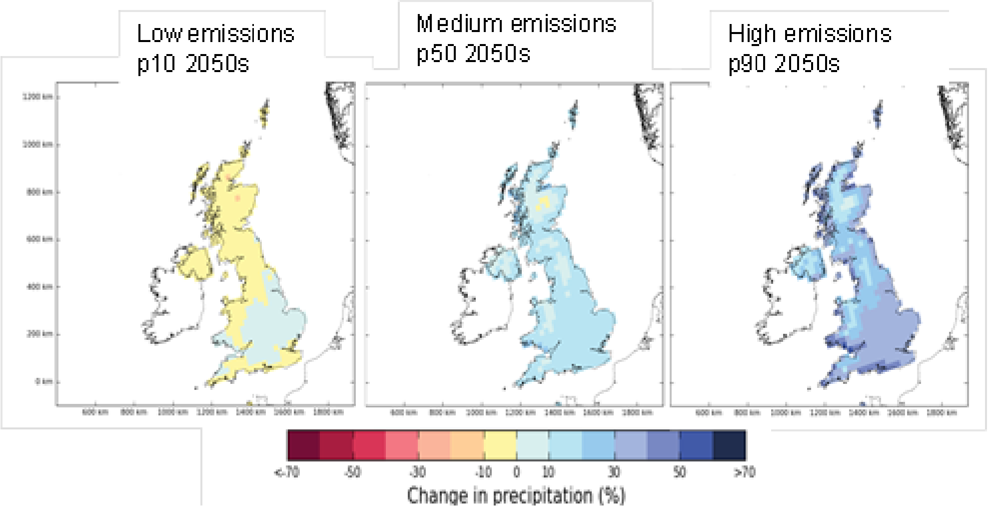
Source: UKCP09

Mean winter precipitation

In the p50 medium emissions scenario, mean winter precipitation is projected to increase by 9 - 17% (depending on location) in the 2050s, relative to the 1961-1990 baseline. The spread in projections is wide however, ranging from -2% for the lower bound of the UKCP09 low emissions scenario in Scotland East to +41% for the upper bound high emissions scenario in South West England (Murphy et al., 2009).

Changes in winter precipitation for the p10 low emission scenario (left), p50 medium emission scenario (middle) and p90 high emission scenario (right) are presented in **Figure 18**.

Figure 18. Projected changes in mean winter precipitation by the 2050s (emissions scenario from left to right: low p10; medium p50; high p90)



Source: UKCP09

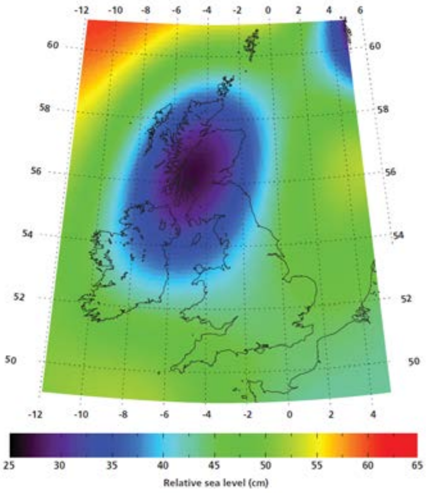
Sea level rise

According to the central estimates of relative sea level changes with respect to 1990s, sea level will rise between 18 and 26 cm between the low and high scenario in London and between 11 and 18cm in Edinburgh (Lowe *et al.*, 2009).

As the earth's crust is moving upward in the northern parts of the UK, relative sea level rise will differ over the regions. The north will be less affected by sea level rise compared to the south (Lowe *et al.*, 2009).

Figure 19 combines the absolute sea level change estimates averaged around the UK for the medium emissions scenario and vertical land movement. Values are shown for 2095 (Lowe *et al.*, 2009).

Figure 19. Relative sea level rise (cm) around the UK for the 21st century



Source: Lowe *et al.*, 2009
Note: This combines the absolute sea level change estimates averaged around the UK for the medium emissions scenario and vertical land movement. Values are shown for 2095

Table 16 displays the sea level rise forecast by the UKCP09 models by 2050, for the central estimates of the emissions scenarios. These estimates are equivalent to a sea level rise of roughly 1.8-4.3 mm per year.

Table 16. Central estimates of relative sea level changes (in cm) by 2050 compared to 1990 levels

	Low	Medium	High
London	18.4	21.8	25.8
Edinburgh	10.5	13.9	18.0

Source: Lowe *et al.*, 2009

Extreme weather events

As the climate warms, weather patterns and the frequency of extreme events may also change (Solomon *et al.*, 2007). Heavy rain days (>25 mm) will likely to be more frequent over most of the lowland UK, central estimates show an increase by a factor of 2 – 3.5 in winter and 1 – 2 in summer by the 2080s under the medium emissions scenario (UKCP09).

The frequency and intensity of heatwaves could increase in future, especially in southern parts of England. The results of the ARCADIA project suggest that by the 2050s, one third of London's summer may exceed the Met Office heatwave temperature threshold (32 °C). (CCRA: Capon and Oakley, 2012; Hall *et al.*, 2009).

Annex 3: Background on UKCP09

Annex 4 References

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