Chapter 4:
Infrastructure

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This report should be referenced as:
Dawson, R.J., Thompson, D., Johns, D., Gosling, S., Chapman, L., Darch, G., Watson, G., Powrie, W., Bell, S., Paulson, K., Hughes, P., and Wood, R. (2016) *UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure*. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.

Implications of the vote to leave the European Union

This chapter was written before the results of the EU Referendum were known. Leaving the European Union is unlikely to change the overall scale of current and future risks from climate change, but in some areas it may affect policies and programmes important to address climate-related vulnerabilities.

If such policies and programmes are changed, it will be necessary for UK measures to achieve the same or improved outcomes to avoid an increase in risk. The Adaptation Sub-Committee will consider the impact of the EU Referendum and the Government's response in its next statutory progress report on the UK National Adaptation Programme, to be published in June 2017.

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Key messages

Increased frequency of **flooding from all sources** is the most significant climate change risk to UK infrastructure, including energy, transport, water, waste and digital communications. Assets and networks across all infrastructure sectors are already exposed to multiple sources of flooding, and the number of assets exposed could double under expected changes in climate by the 2080s. Coastal infrastructure is particularly at risk from **storm surges and rising sea levels**, as well as higher **rates of coastal erosion** in some areas. Infrastructure networks near rivers will also be increasingly at risk from projected **higher flows and subsequent bankside erosion**.

Projected changes in **temperature and rainfall** will place additional pressures on infrastructure, in particular the rail, road, water and energy sectors. High temperatures create a risk of buckling on the rail network, cause electricity cables to sag, and road tarmac to soften and rut. Components such as signalling equipment can overheat and fail. Changes in rainfall, coupled with population growth, are projected to lead to supply/demand deficits in water resource zones across England and in some other parts of the UK by the 2050s, with widespread deficits projected by the 2080s. Adaptation, beyond what is currently planned by water companies, will be required to manage this risk. Projected extended periods of rainfall will also increase the risk of slope and embankment failure. Approximately 8% of the UK's transport and road network is at medium to high risk of landslide disruption.

While future projections remain uncertain, increases in **maximum wind speeds** experienced during storms would have significant implications for overhead power lines, data network cabling and the rail network, as well as for offshore infrastructure. Vulnerability to this risk is expected to increase with **higher rates of vegetation growth**, resulting in more tree-related failures for electricity and transport networks.

Following extreme events, most notably in summer 2007 and winter 2013/14, there is evidence that **significant adaptation steps have been implemented, or are underway, across most infrastructure sectors.** Reporting has improved, but could be made more transparent across the board – through better recording and provision of data on climate risks to infrastructure, and how adaptation investment contributes to risk reduction. Current reporting is incomplete and inconsistent.

While understanding of sectoral risks has improved over the last few years, the impacts of climate change could be amplified by **interconnectivities and interdependencies** between infrastructure sectors. Understanding of these is less comprehensive, and current governance arrangements mean that responsibilities for assessing and managing risks from interdependencies are unclear.

Uncertainties and the high capital costs of some adaptation measures that are designed to cope with extreme events that may not materialise for many years are regularly identified as major barriers to releasing funds for adaptation investment.

The key risks and opportunities identified for infrastructure are summarised in Table 4.1. The assessment of the urgency is based on the expert judgement of the ASC, in consultation with the report authors and peer reviewers. See Chapter 2 for more detail on the method taken to assess urgency.

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Table 4.1. Urgency scores for infrastructure risks

Risk/opportunity (relevant section(s) of chapter)	More action needed	Research priority	Sustain current action	Watching brief	Rationale for scoring
In1: Risks of cascading failures from interdependent infrastructure networks (Section 4.4 to 4.9)	UK				More action needed to enhance arrangements for information sharing in order to improve understanding of critical risks arising from interdependencies.
In2: Risks to infrastructure services from river, surface water and groundwater flooding (4.4 to 4.9)	UK				More action needed to manage increasing risk to existing assets and networks and ensure increased risk is accounted for in design and location of new infrastructure.
In3: Risks to infrastructure services from coastal flooding and erosion (4.4 to 4.9)	England, Wales	Northern Ireland, Scotland			More action needed to manage increasing risk to existing networks (including flood and coastal erosion risk management infrastructure) from sea-level rise and increased rate of erosion.
In4: Risks of sewer flooding due to heavy rainfall (4.5)	UK				More action needed to deliver sustainable drainage systems, upgrade sewers where appropriate and tackle drivers of increasing surface runoff (e.g. impermeable surfacing in urban areas).
In5: Risks to bridges and pipelines from high river flows and bank erosion (4.5, 4.7, 4.8)		UK			More research needed on implications of projected changes in river flows on future risk of scour/erosion.
In6: Risks to transport networks from slope and embankment failure (4.7)	UK				More action needed to locate and remediate embankments and cuttings at risk of failure.
In7: Risks to hydroelectric generation from low or high river flows (4.8)				UK	Monitor impacts and be ready to adapt operations given observed impacts.

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In8: Risks to subterranean and surface infrastructure from subsidence (4.5, 4.6, 4.7, 4.8)				UK	Monitor changes in temperature and rainfall patterns to update assessments of subsidence risk.
In9: Risks to public water supplies from drought and low river flows (4.5)	England, Wales		Northern Ireland, Scotland		New policies needed to deliver more ambitious reductions in water consumption and establish strategic planning of new water-supply infrastructure. More action needed to put in place reforms of the water abstraction licencing regime.
In10: Risks to electricity generation from drought and low river flows (4.8)				UK	Continue to monitor risks including as a result of deploying carbon capture and storage. Ensure appropriate siting of new infrastructure and use of cooling technologies.
In11: Risks to energy, transport and digital infrastructure from high winds and lightning (4.6, 4.7, 4.8)		UK			More research needed on the implications of increased vegetation growth rates on future risks of damage from falling trees during storms.
In12: Risks to offshore infrastructure from storms and high waves (4.7, 4.8)		England, Scotland, Wales		Northern Ireland	More research needed to assess climate risks to existing and planned off-shore renewable energy infrastructure.
In13: Risks to transport, digital and energy infrastructure from extreme heat (4.6, 4.7, 4.8)			UK		Continue current actions to reduce risks, maintenance and renewals of infrastructure networks.
In14: Potential benefits to water, transport, digital and energy infrastructure from reduced extreme cold events (4.5, 4.6, 4.7, 4.8)			UK		Continue current actions to reduce risks, including cold-weather planning and response.

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Flood damage and disruption to infrastructure

Flooding is the most significant climate change risk to UK infrastructure, affecting all sectors. There is the potential for lengthy disruption and high costs of repair. Significant assets are already situated in locations that, without further protection, are exposed to river or coastal, groundwater and surface water flooding. These include power stations (41%, 6% and 18% of all power stations in England are at risk of river and coastal flooding, surface water, and groundwater flooding respectively), proportions of railway track (17, 9 and 17%) and railway stations (14, 3 and 16%), A-roads and motorways (9, 6 and 9%) and clean and wastewater treatment sites (33, 12 and 24%). Flood risk from all sources is projected to increase across the UK, and even the most ambitious adaptation plans by national and local authorities will be unable to prevent flood risk rising in some parts of the country. Scenarios involving 4°C of global warming by the 2080s suggest large increases in expected flood damage in every UK nation and under all adaptation scenarios. This 4°C of warming would lead, for example, to the 2,400 km of the UK rail network presently vulnerable to flooding rising by 120% by the 2080s. More intense rainfall under climate change will also increase sewer flooding and combined sewer overflow (CSO) events. Rising sea levels of 0.5–1m by the end of the century will increase the proportion of assets vulnerable to coastal flooding. The need to realign coastal defences in some areas in response to rising sea levels will have implications for infrastructure assets in the coastal zone, increasing their annual cost of maintenance by 150–400%.

Droughts and reduced water availability

Across the UK, there is currently a supply/demand surplus of water of around 2000 Ml/day, but in many water resource zones supply and demand is already finely balanced and more water is being withdrawn than the environment can sustain. Supply–demand deficits are projected to be widespread by the 2050s under a high population growth and a high climate change scenario, in the absence of any further adaptation interventions. The south-east of England and the large conjunctive use zones in the north of England are particularly susceptible, but deficits are projected in other parts of the UK as well. Extended periods of low rainfall, and associated low river flows and groundwater levels, will limit the availability of water for consumption as well as for freshwater abstractions to cool power plants – with inland power capacity in England most at risk. Water demand for energy increases most acutely for power generation scenarios involving high levels of carbon capture and storage, doubling freshwater consumption by the 2050s under a high carbon capture and storage scenario.

Storm damage and disruption

Storms – wind and lightning – are the biggest risk for disruption to overhead cables which are vulnerable to tree- and debris-related damage, particularly for energy distribution infrastructure, but also to some Information and Communications Technology (ICT) networks such as those delivering broadband to rural areas. Changes to wind climate are uncertain, but lightning strike disruptions to the energy network may increase by up to 36% by the 2080s based on the A1B SRES climate scenarios with a similar increase in the incidence of damage to mobile base stations. The impact of such events are relatively low, compared to events such as flooding, as damage can usually be repaired quickly and services restored.

Geohazards

Extended periods of rainfall increase the risk of slope and embankment instability. These risks are most significant for road and rail infrastructure, where nearly 2% of the UK's network is at high risk of landslide disruption, with a further 6% at medium risk. On average, 50 landslides per year disrupt rail services. During the winter of 2013/14 there were 105 earthwork failures on the rail network. Network Rail has 18,200 km of cuttings and embankments, most of which were not built to modern engineering standards. The site-specific characteristics of slopes and lack of comprehensive datasets makes it

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difficult to improve slope stability on a proactive, as opposed to reactive, basis. Ground subsidence due to shrink–swell processes driven by cycles of drought and heavy rain can damage railway track, road surfaces and buried infrastructure including waste and water pipes. Risks are most significant in areas where shrink–swell susceptible clay soils dominate, such as around London and the east of England. Prolonged periods of rainfall can act as trigger events for the formation of sinkholes such as the one that closed a section of the M3 for two days in February 2014. Whilst there are significant uncertainties in the projected changes in rainfall, droughts are expected to become more likely because of the effect of increased temperature more quickly drying soils and plants.

Impacts of extreme heat

Railways, ICT and electricity generation, transmission and distribution infrastructure are particularly vulnerable to extreme heat. The 2003 heat wave cost £2.5 million in repairs to the rail network, and the frequency of rail buckling events is expected to be four times higher under a low climate change scenario (five times higher under a high climate change scenario). Track can be pre-tensioned to suit prevailing temperatures but the increasing range of high and low temperatures likely to be experienced over a year may cause operational difficulties. Track maintenance and tensioning are also more difficult when temperatures are high. Increases in air and water temperatures affect the power output and efficiency of steam and gas turbine-based generators. Increases in mean temperature could reduce the rating of overhead lines in the distribution network on average by 6 – 10% by the period 2070 – 2099 (high emissions scenario, p50), although this could be as much as 27% for some components on the hottest days in the 2080s, reducing the effective capacity of the network. However, expected growth in demand, which is already reported to be up to 1.5-2% per year in some regions, will have a more significant impact on network capacity.

Interdependencies

Infrastructures are increasingly reliant on each other – for power, control (via ICT) and access for deliveries or servicing. Most sectors identify failure of another infrastructure sector as a risk, but they typically have insufficient information to appraise the risks to other systems properly and rely on their own expert judgement. Led by the Cabinet Office, there has been effort in recent years to encourage infrastructure operators to work together and address vulnerabilities. Commercial and security sensitivities, along with a lack of a formalised framework for engagement and collaborative working, remain barriers to routine data sharing and co-operation.

Box 4.1. Comparison with the first UK Climate Change Risk Assessment 2012

- CCRA1 reported on risks to transport, energy and water infrastructure separately. Here, all infrastructure risks are brought together within one chapter.
- Additionally, this chapter reviews risks to solid waste, ICT and Flood and Coastal Erosion Risk Management infrastructure.
- New insights into risks resulting from infrastructure interdependence are also reported here.
- Research since CCRA1 has improved analysis of risks from flooding, bridge scour, rail buckling and windstorms. However, there has been no manifest change in the trends of key risks.
- This chapter takes account of current policies and adaptation efforts in assessing long-term risks. There is evidence that significant steps have been implemented, or are underway, across most infrastructure sectors that will help avoid an increase in future climate risks.

4.1 Context

This chapter reviews the climate-related risks and opportunities to infrastructure in the UK. It updates the understanding of climate change risks to infrastructure given the new evidence that has emerged since first Climate Change Risk Assessment in 2012 (CCRA1). The approach taken to assess climate risks to infrastructure has involved a review of the evidence of relationships between infrastructure performance and climate change, and of the impacts (such as magnitude and spatial extents) of infrastructure failure. Additionally, this chapter reports on work done to adapt to, and manage, the risks of climate change.

4.1.1 UK infrastructure

Infrastructure provides services such as heating, lighting, mobility and sanitation that are essential for modern society. Table 4.2 demonstrates the large number of infrastructure assets in the UK, and the usage statistics highlight the importance of the services this infrastructure provides. Current variability in weather already impacts the performance of the UK's infrastructure. Extreme events, such as the winter storms of 2013/14 and 2015/16, are associated with disruption or complete loss of these infrastructure services which are costly to repair and also have significant impacts on people's health and wellbeing.

Substantial investment is planned to replace, upgrade and extend UK infrastructure. The UK's National Infrastructure Plan (HM Treasury, 2015a) sets out over £320 billion planned investment in infrastructure up to 2020/21. Infrastructure is a priority for adaptation because its performance is sensitive to climate (particularly extreme events) and decisions on design and renovation have long-lasting implications and are hard to reverse. To avoid longer term impacts on people and the economy, it is essential that future infrastructure investments, as well as the adaptation of existing infrastructure, are considered in the context of the potential climate risks.

Table 4.2. Headline statistics on UK infrastructure

Infrastructure assets	Annual usage	Source
55 major airports	255 million passengers (2015)	Civil Aviation Authority (2016)
2537 railway stations	1.68 billon rail journeys (2015, GB)	Office of Road and Rail (2016)
245,800 miles of road	6,488 miles per person (2014, GB)	Department for Transport (2016)
52 major ports	503.2 million tonnes cargo (2014)	DfT Port and Freight Statistics (2015)
>100 drinking water reservoirs	53,000 litres drinking water per person	Environment Agency (2015a)

Table 4.2. Headline statistics on UK infrastructure

Infrastructure assets	**Annual usage**	**Source**
>9,000 waste water treatment plants	1.4m tonnes dry sludge produced, of which 1.1m tonnes is reused (2012)	Defra (2012a)
10,200 km flood defence (England)	748,000 properties with a 1-in-100 annual chance of flooding or greater (England)	Environment Agency (2015b)
594 landfill sites 87 incinerators 3,500 other waste recovery facilities	48 million tonnes waste received 8.3 million tonnes waste received	Defra (2015)
463 major power stations (2015)	339TWh electricity produced (2014)	Department of Energy and Climate Change(2015a)
Almost 520,000 miles of electricity distribution network overhead lines and cables (2013, GB)		Electricity Networks Association (2013)
>54,000 mobile phone base stations (2012)	137 billon minutes call time (2014)	Ofcom (2012a, 2015)
3.6 million m^2 data centres (2014) supporting 23.7 million broadband connections (2014)		DatacenterDynamics (2014)

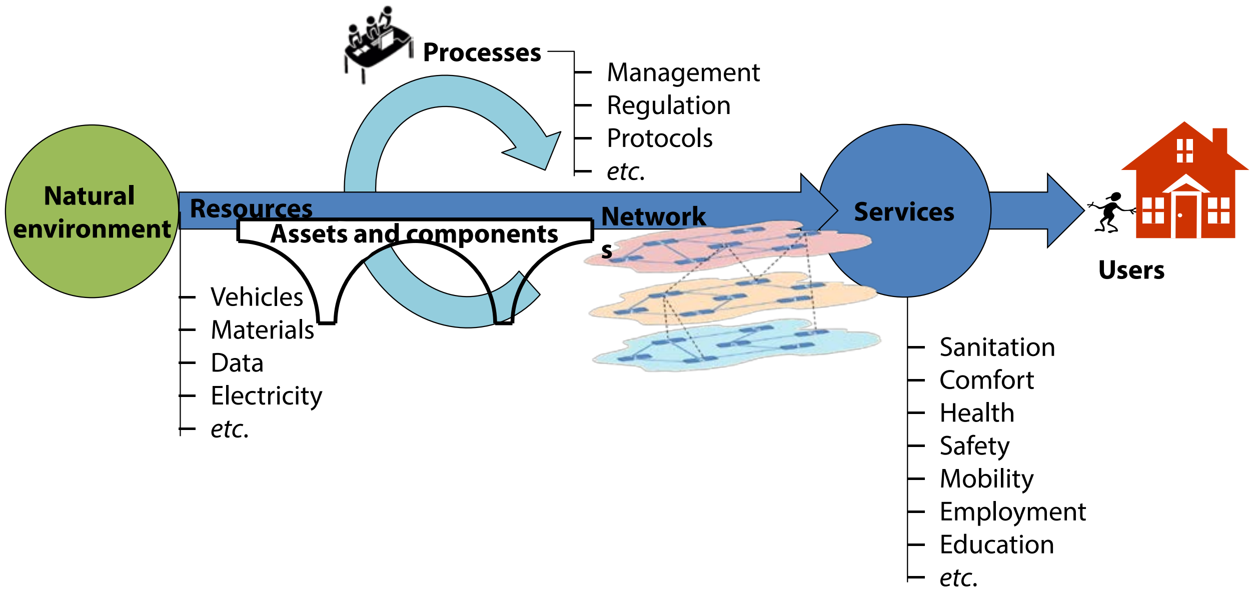
Source: As indicated.
Notes: This table is intended to provide an indication of the scale of infrastructure assets and the volume of services they provide. Not all infrastructure, including underground transport or sewer networks, is summarised. Data is not always readily accessible for different regional geographies.

4.1.2 Climate change risk assessment of infrastructure

Understanding risks to infrastructure requires a broad systems view (iBuild, 2015) that comprises (Figure 4.1):

- *Natural environment* – infrastructure plays an important role in modulating both the use of natural environment resources and mitigating environmental risks.
- *Physical artefacts* – includes the physical components and assets such as roads, bridges, pipes and cables.
- *Networks* – the physical artefacts interconnect to provide a network that connects locations of demand with supply.
- *Processes* – includes actors, institutions, management, regulation, protocols and procedures that govern the infrastructure over its life cycle.
- *Resources* – includes people, vehicles, water, electricity and data that are conveyed by the physical artefacts and the materials used in the construction of the artefacts.
- *Services* – such as warmth, mobility, sanitation, transportation, welfare services and communication that benefit a wide range of users.

Figure 4.1. A systems view of infrastructure



Source: Adapted from iBuild (2015).

Climate risk is a function of the likelihood of a climatic event, and the magnitude of the associated impacts. A risk analysis must consider a wide range of possible climatic conditions and their outcomes, both positive and negative. A climate change risk assessment of infrastructure, taking a systems view, therefore involves a number of stages (Figure 4.2).

(i) Analysis of climate variables (e.g. rainfall, temperature and wind) to understand how these change over time, and how the frequency and magnitude of hazards such as floods or heatwaves may be altered. An update of the latest climate science is presented in Chapter 1 of this CCRA Evidence Report.

(ii) Characterisation of each infrastructure asset, in particular its fragility and capacity, to understand its response to extreme events and changes in climate. Typically, climate loadings of higher magnitude or wider spatial coverage increase the likelihood of failure or lead to greater reduction of performance of individual assets, and consequently the impacts of failure. These risks are considered in Sections 4.4 – 4.9.

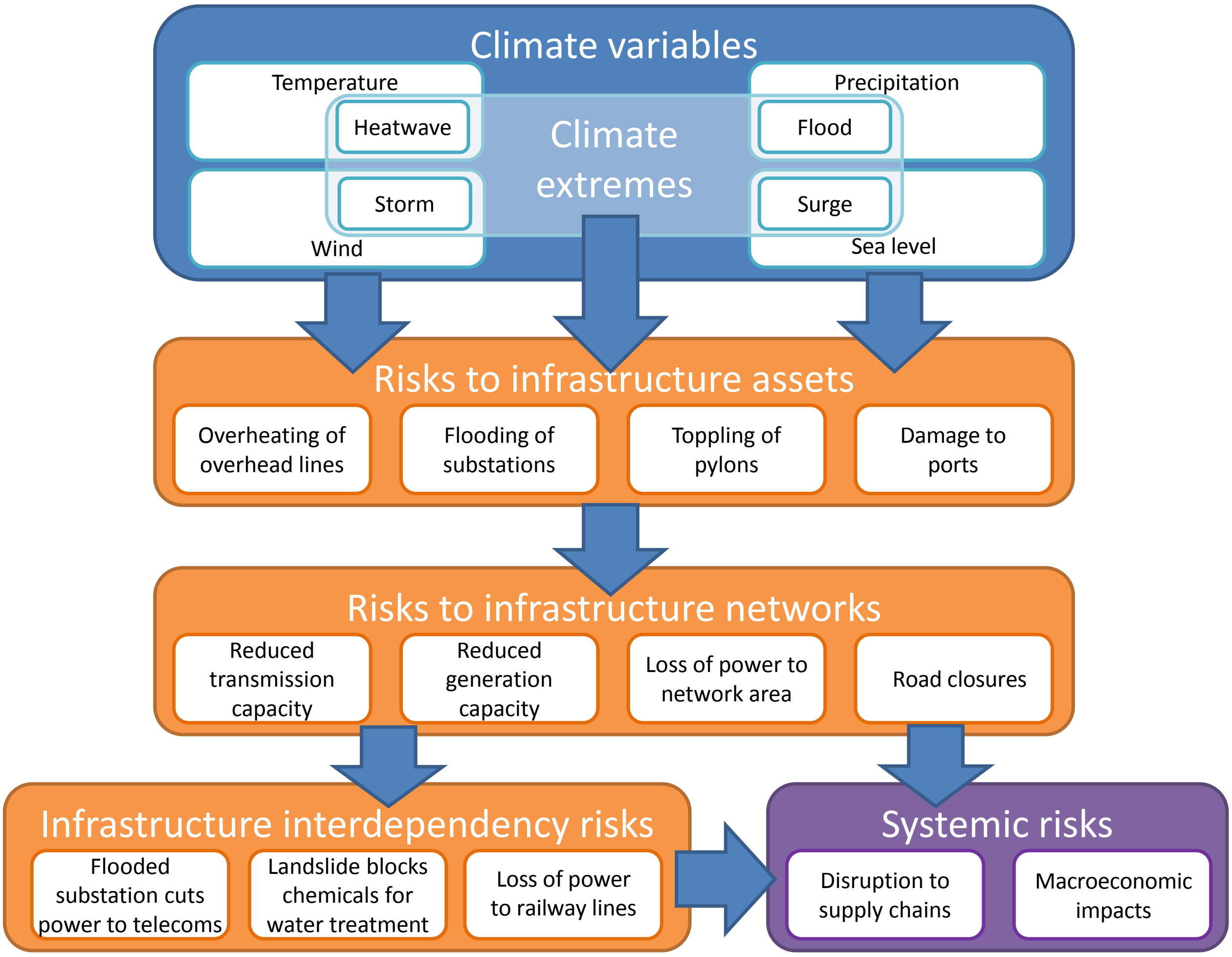
(iii) Analysis of network-wide effects that occur as a result of impacts on individual or multiple components and system functions. Typically, higher climate loadings, and events that directly impact more of the network, lead to increased impacts. However, the magnitude of impacts is also mediated by network properties such as the number of backup or redundant components. These risks are considered in Sections 4.4 – 4.9.

(iv) Analysis of interactions and interdependencies between infrastructure networks to understand cascading impacts. These risks are considered in Section 4.3.

(v) Assessment of systemic risks that are related to the loss of infrastructure services that consequently lead to indirect impacts on economic growth, social wellbeing and environmental protection. These risks are considered in Chapter 8 as they involve the interaction of infrastructure with other systems.

(vi) Adaptations may be implemented across the infrastructure system. This may involve asset- or network-scale engineering, policy or regulatory interventions, or working with users to manage demand for services. Current adaptation actions for each infrastructure sector are considered in Sections 4.4 – 4.9 and are reflected in the urgency scores. Priorities for future action are summarised in Section 4.10.

Figure 4.2. Overview of the climate change risk assessment framework for infrastructure



Source: Adapted from iBuild (2015).
Notes: Adaptation actions can be taken to address asset, network or higher order risks.

The significance of a risk depends on the balance of the likelihood of a climatic event and its impacts. The magnitude of impacts is often mediated by asset characteristics, including fragility, capacity and redundancy. Furthermore, they are mediated by the capacity and vulnerability of organisations and users affected. Low likelihood, high impact, events require different management to more frequent, low impact, events. In particular, very extreme events require special attention in terms of warning and community preparedness as it may not be possible to protect against them. Where possible a climate change risk assessment should consider a full range of loadings, impacts and possible responses.

Infrastructure adaptation options can be compared on the basis of the impact that they are expected to have on reducing the frequency and severity of climate effects. Informed choices can subsequently be made by comparing the expected outcomes and costs of alternative adaptation strategies. The Cabinet Office (2011a) identified four strategies to manage infrastructure risks and build resilience:

(i) Increase the **resistance** of infrastructure components by providing enhanced protection.

(ii) Improve the **reliability** of infrastructure components so they are able to operate under a range of possible conditions.

(iii) Provide **redundancy** to increase the capacity, number of alternative connections and diversity of backup systems.

(iv) Build capacity in organisations and communities to deliver a fast and effective **response** to, and **recovery** from, climate disruption.

Adaptation should therefore not be thought of as exclusively 'major' engineering interventions, but as a wider set of interventions at all scales to manage the impacts of climate change across the wider infrastructure system. Adaptations include technical options but also regulatory, policy and community responses are crucial to enhancing the adaptive capacity (potential to adapt to climate variability and change) of infrastructure systems. However, much of the evidence for the benefits of adaptation of infrastructure that is reviewed here tends to focus on engineering strategies as the benefits of these are typically easier to assess quantitatively.

This assessment of climate risks to infrastructure has considered evidence of relationships between infrastructure performance and weather, of how weather patterns might be altered by climate change, and consequently the impacts (e.g. magnitude and spatial extent) of infrastructure failure under current and future climates. Information on climate risks is in a variety of formats; quantitative evidence has been sought as much as possible, but is supplemented by qualitative information on the causal relationships between weather and infrastructure failure, and the limited number of observed extreme events and modelling studies. These have been summarised and used to identify priority risks in the present day and under future climatic and socio-economic conditions. Subsequently, and taking into account reported adaptation actions, recommendations are made about the urgency and type of action required over the next five years to manage these long-term risks.

4.2 Headline risks and key policies

4.2.1 Key risks to UK infrastructure

Each infrastructure sector faces specific climate-related challenges, which are considered in Sections 4.3 – 4.9. While specific geographical or engineering features may create very localised vulnerabilities, a number of consistently significant risks for UK infrastructure are identified and summarised here. Table 4.3 provides an overview of key risks for each sector and Table 4.4 provides some illustrative examples that link climate hazard, with infrastructure assets, and impacts.

Table 4.3. Overview of key climate risks for each infrastructure sector

Hazard Sector	Floods	Water scarcity	High temperatures	(Wind) Storms	Geohazards (inc. subsidence and landslides)
Water and waste water	✓✓	✓✓	✓		✓
Transport	✓✓		✓	✓✓	✓✓
Energy generation	✓✓	✓	✓	✓	
Energy distribution	✓✓		✓	✓✓	✓
Flood and coastal defences	✓✓			✓	✓
Solid waste	✓		✓		
ICT	✓✓		✓	✓✓	✓

Source: Expert judgement arising from the literature reviewed in this chapter.
Notes: A single tick denotes a relationship; a double tick denotes a strong relationship. These do not consider dependencies between infrastructures.

Table 4.4. Examples of infrastructure impacts from climate-related hazards

Loading	Example infrastructure	Magnitude and mechanisms of impact
Rainfall	Drainage networks (surface and sub-surface)	High Heightened runoff; increased flood flows
River flows	River embankments, culverts, barriers and pumps	High Crest overflow; by-passing; accelerated deterioration; erosion of pipe crossings; reduced maintenance window; increased chance of failure

Table 4.4. Examples of infrastructure impacts from climate-related hazards

Loading	**Example infrastructure**	**Magnitude and mechanisms of impact**
Groundwater	Cliff slopes, foundations of raised structures, coastal wetlands	Low to Moderate Infiltration and overwhelming of the drainage network; soil instabilities (slope failure); differential settlement (instability); greater or less saline intrusion
Coastal storm surges	Hard and soft shoreline structures (seawalls, beaches to wetlands), tidal barriers	Very High Increased chance of failure due to, for example, increased overtopping; scour; beach lowering; flooding of coastal infrastructure; coastal squeeze[1].
Temperature, solar radiation and drought	Earth embankments and other 'soil'- and 'vegetation'-based infrastructure	Moderate Accelerated desiccation of soils; freeze–thaw induced spalling; loss of strength in surface cover; loss of vegetation for green infrastructure; surface drying; increased cliff erosion
Unwanted animal or plant species, bacterial attacks and algal blooms	Potential to affect both hard and soft infrastructure in fluvial, coastal and estuarine settings	Moderate Unwanted species (e.g. mosquitos around standing water); zebra mussels in wastewater treatment pipework; aquatic plants clogging reservoir inlets; Japanese knotweed reducing channel conveyance; increased cases of accelerated low-water corrosion in estuaries

Source: Adapted from Sayers et al. (2015a).

Table 4.3 highlights that flooding from all sources (i.e. rivers, the sea, surface water and groundwater) is a common risk to all infrastructure sectors. Many studies have provided evidence of the relationship between flood risk and climate change (Hall et al., 2003; Foresight, 2004; Environment Agency, 2009a, 2014). Building on these, Sayers et al. (2015b) for the ASC takes a consistent approach to projecting future flood risk across the UK and maps infrastructure assets against risk projections in each part of the country (Box 4.2).

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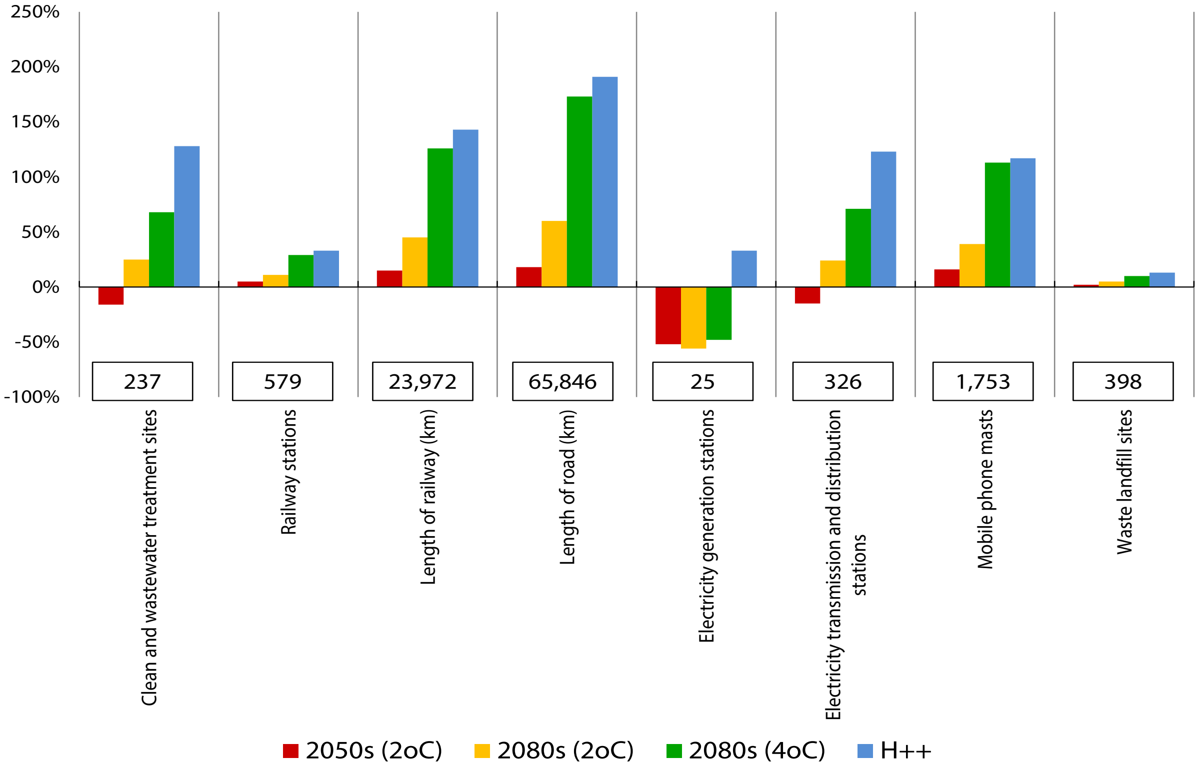
[1] Coastal habitats trapped between a fixed landward boundary, such as a sea wall, and a low water mark that is migrating as a result of rising sea levels or eroding beaches.

Box 4.2. Future Flood Risk Projections for CCRA2

Sayers et al. (2015b) for the ASC provides the first consistent set of future flood projections for all four UK nations under both a 2°C and 4°C rise in mean global temperatures for the 2020s, 2050s and 2080s, as well as for plausible high-end climate change (H++) scenarios developed for CCRA2 by the Met Office. The study developed a model, the Future Flood Explorer (FFE), which uses the latest data on flood risk from rivers, the sea, surface water and groundwater for all four UK nations and data on the location of exposed receptors (including infrastructure networks of various types). The FFE accounts for different scenarios of UK population growth and also assesses the impacts of a range of different adaptation scenarios on future flood risk.

The study finds that infrastructure assets will be subject to significant increases in risk; with the number or length of assets located in areas exposed to a significant chance of flooding (i.e. more frequently than 1-in-75 years on average) increasing by between 10% (under 2°C climate change projection) and 160% (4°C climate change projection) by the 2080s. Under a H++ scenario, some infrastructure networks see an increase in exposure of nearly 200% (Figure 4.3). However, if the current level of adaptation actions being undertaken to protect many infrastructure assets continues into the future, then the projected increase in flood risk can be offset, or even reduced, for some assets in the 2050s. Protection to an even higher standard, which might be achieved with more engineering intervention or via other adaptation strategies, would be required to cope with climate changes anticipated for the 2080s, particularly under a 4°C rise in mean global temperatures.

Figure 4.3. Projections of future flood exposure for UK infrastructure assets

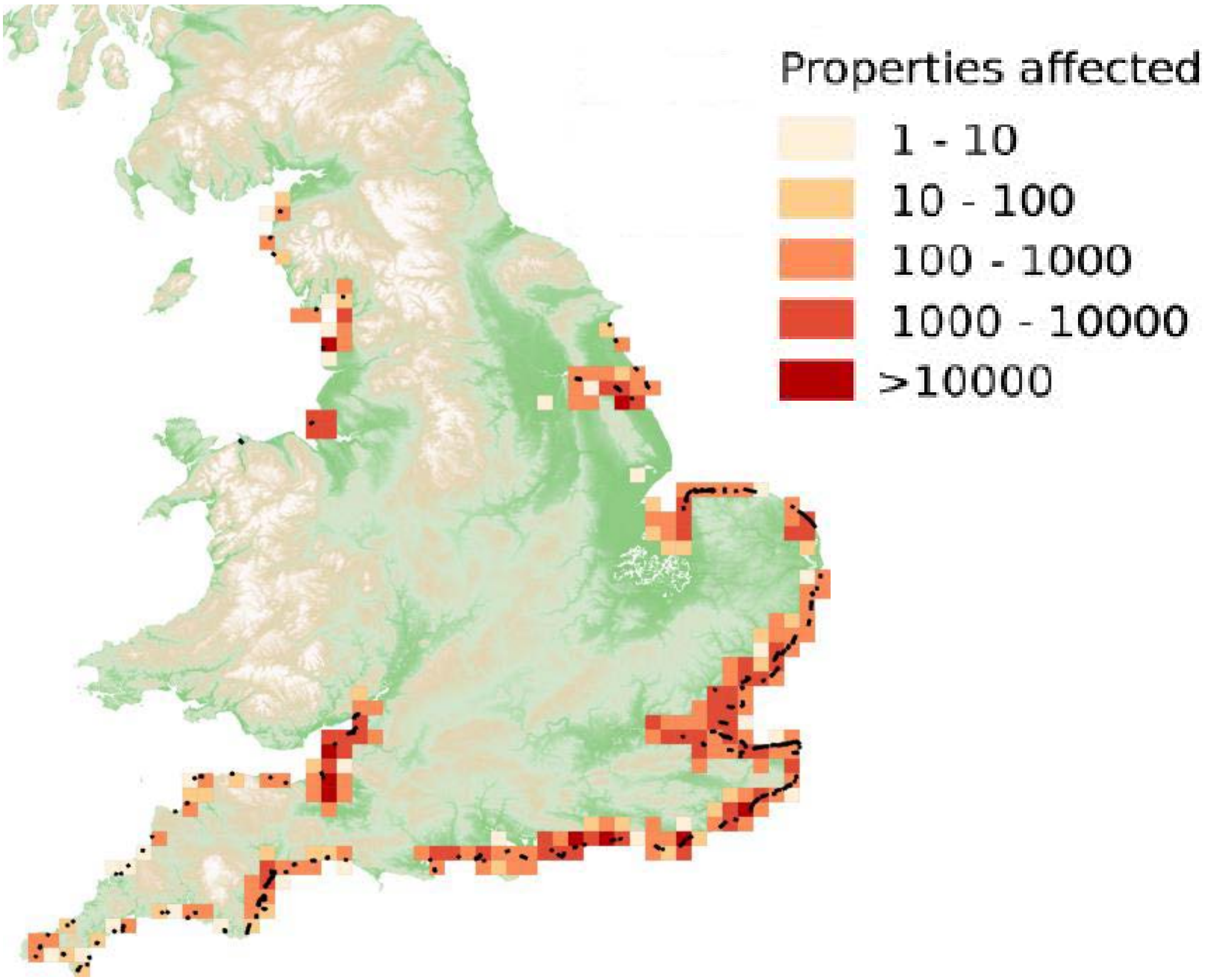


Notes: Numbers in boxes are the estimated number or length of assets currently located in areas exposed to a 1:75 or greater annual chance of fluvial, coastal or surface water flooding. Only those major electricity generation stations and transmission and distribution stations that serve over 5,000 customers were included in the analysis. Data on clean and wastewater treatment sites in Scotland was unavailable. The above projections are based on high population growth scenarios and do not account for any additional adaptation beyond that already planned.

Box 4.2. Future Flood Risk Projections for CCRA2

Existing flood risk models generally assume that climate change will increase the likelihood of flooding, but do not account for how the physical extent of the floodplain may change, especially on the coast. Sayers et al. (2015b) also considers the potential vulnerability of current coastal defences to increases in mean sea levels by identifying where the 'toe' height of defence foundations will be exposed to stronger and near continual wave action. The analysis suggests a positive correlation between mean sea-level rise and the length of defences in England that become vulnerable to potentially rapid deterioration. With 1m of sea-level rise, the length of coastal flood defences becoming highly vulnerable doubles, from 110 km at present to around 220 km (Figure 4.4).

Figure 4.4. Location of coastal defences that are highly vulnerable to a1m rise in mean sea levels in England and the number of properties potentially affected by a future 1-in-200 year coastal surge.



Notes: This map shows the location of coastal defences (black lines) assessed as highly vulnerable with a 1m rise in mean sea levels and the number of properties that would be exposed to a 1-in-200 year coastal surge event, assuming this causes the highly vulnerable coastal defences to fail. The exact scale of the impact would depend on where in the country the tidal surge occurs. Assuming vulnerable defences fail over time, the area at risk of coastal flooding in England would grow by 2000 km^2 and create additional risks for 400,000 properties under a 1m rise. For context, UKCP09 projects relative sea level around the UK to increase by 12-76cm by 2100.

Source: Sayers et al. (2015b) for the ASC.

4.2.2 Key policies relevant to infrastructure adaptation

The 2008 Climate Change Act and 2009 Climate Change (Scotland) Act creates a power for the Secretary of State to direct infrastructure operators and other relevant organisations to produce climate change adaptation reports (known as the Adaptation Reporting Power or ARP). The Scottish Government has adopted a similar reporting requirement for public bodies in Scotland (Scottish Government, 2015).

The ARP is a means of monitoring and motivating climate risk management and preparedness in key organisations across the UK. A total of 91 infrastructure providers and regulators were directed to provide assessments in the first round of reporting in 2011 and 2012, including Network Rail, the Highways Agency, water companies, port and airport authorities, energy generators, electricity and gas transmission and distribution companies and regulators such as Ofwat, Ofgem and the Environment Agency. Most of these organisations have volunteered to report again in Round 2 during 2015 and 2016.[2] The risks highlighted in the first round of ARP reports, along with evidence from CCRA1, informed the UK Government's National Adaptation Programme (NAP) in 2013 as well the national adaptation strategies and programmes in Wales, Scotland and Northern Ireland.

Other relevant legislation for infrastructure adaptation includes the National Policy Statements (NPSs) that have been produced for England and Wales. These provide statutory guidance to those developing infrastructure projects of national importance (Nationally-Significant Infrastructure Projects or NSIPs). The National Networks NPS (2014) is the most recent produced, with an NPS now in place for almost all infrastructure sectors, with the exception of water supply infrastructure. Each NPS has a section related to climate change adaptation, which requires an assessment of climate change risks and impacts and how these will be managed. A review of recent NSIP applications found evidence that the most significant climate change risks to UK infrastructure were being assessed and accounted for at the design stage, and in the approval process by planning inspectors (HR Wallingford for ASC, 2014). In Scotland, the Climate Change Adaptation Programme (Scottish Government, 2013) has a core theme of Climate Ready Buildings and Infrastructure Networks.

The National Infrastructure Plan (NIP) is produced by HM Treasury to enable more visible, efficient and coordinated delivery of major infrastructure projects in the UK (HM Treasury, 2015a). However, consideration of climate change adaptation in the NIP is limited, and not mentioned at all with respect to impacts on transport infrastructure. The Treasury Green Book Supplementary Guidance on Accounting for the Effects of Climate Change (HM Treasury, 2009) provides uniform guidance to all government infrastructure spending, whilst the Supplementary Guidance on Valuing Infrastructure spend (HM Treasury, 2015b) sets out wider economic considerations for appraising infrastructure. Organisations such as the Natural Hazards Partnership, the Infrastructure Operators Adaptation Forum and the UK Regulators Network are helping to improve collaboration and sharing of information across infrastructure sectors and organisations.

Government departments responsible for national infrastructure sectors work with owners and operators to produce Sector Security & Resilience Plans (SSRPs). This is coordinated by the Cabinet Office Civil Contingencies Secretariat. These plans set out the resilience of the UK's most important infrastructure to the relevant risks identified in the National Risk Assessment and are given to ministers to alert them to any perceived vulnerabilities, with a programme of measures

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[2] The evidence from the second round of ARP reporting has been referred to in this chapter, although not all reports have been published in time for them to be considered.

to improve resilience where necessary. A public-facing summary of the SSRPs is available. Because risks and sector resilience changes over time they are reviewed annually. However, there is no formal relationship between adaptation planning and these resilience plans.

Cities and other sub-national areas are playing an increasingly important role in infrastructure adaptation. Many cities now have their own infrastructure plan (for example Newcastle and Gateshead City Councils, 2011; Greater London Authority, 2014 and climate change adaptation strategies (Reckien et al., 2014), although these are of varied quality and often limited effectiveness (Heidrich et al., 2013). Larger regional agglomerations, such as the 'Northern Powerhouse' have produced plans for transport infrastructure at a regional scale (TfN, 2015). This is being assisted by the 2016 Cities and Local Government Devolution Act, which is enabling the transfer of some powers to cities and sub-national transport bodies.

4.3 Cross-cutting climate risks to infrastructure

Infrastructure sectors are increasingly interconnected and interdependent; failure of one infrastructure network can cause disruption and failure in other dependent networks, amplifying risks (e.g. Rinaldi et al., 2001). A large number of potential interactions and relationships have been identified (RAEng, 2011), but the additional complexity, and limited data on the nature of many interactions, means there is limited quantitative evidence of the magnitude of many of these risks.

Dawson (2015) identifies a number of key dimensions of interdependency, and information required to characterise them, in the context of climate change risk assessment, whilst Rosenberg et al. (2015) have developed a process of infrastructure interdependency planning and management. In addition to climate change, UK infrastructure is subject to a number of socio-economic drivers. Population growth and changing demographics such as an ageing population, can alter demand for (or between) infrastructure services, or increase vulnerabilities associated with the disruption of infrastructure services. Governance, regulation and financial appraisal methods typically focus on timeframes of 1-8 years, whereas, with the exception of digital infrastructure, the majority infrastructure assets are expected to last over 50 years. Regulatory cycles can also impact upon maintenance and renewal schedules of each infrastructure sector and, when not aligned, result in inefficiencies in the management of risks.

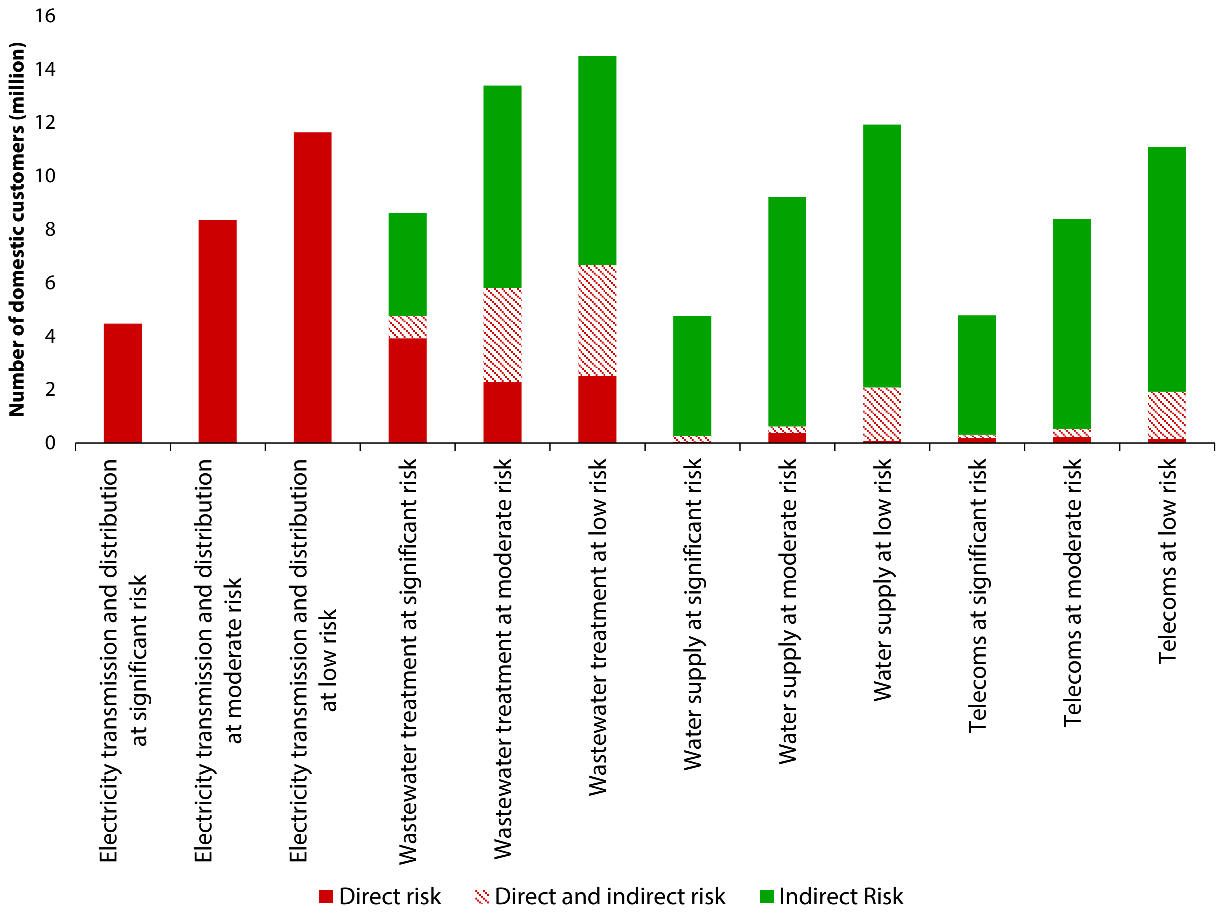
Key climate risks that arise from interdependencies in UK infrastructure are discussed below, including reliance on power, ICT, transport and water.

4.3.1 Reliance on power

All infrastructure sectors require power for some (if not all) of their assets. This includes flood protection assets such as gates and pumping stations. Some assets have backup generators on-site, although their capacity is finite.

Pant et al. (in press, a) assessed the exposure of infrastructure to flooding and disruption in the Thames catchment, a region that was inundated during the winter 2013/14 storms. Figure 4.5 considers the potential number of infrastructure customers who could be disrupted by flooding of electricity, water supply, wastewater treatment, telecoms and air transport infrastructure as result of those sectors being flooded. The figure also shows the number of customers disrupted due to the indirect failure of a sector due to loss of power caused by flooding of the electricity sector. Some assets can be disrupted directly or indirectly, but this analysis highlights how indirect disruptions can extend beyond the boundary of the flooded area. Other studies support these observations at a range of spatial scales and network structures, for example, work by Fu et al. (2014) and Pant et al. (in press, b) report that indirect impacts do not scale proportionally with the magnitude of disruption to the primary network affected.

Figure 4.5. Estimated number of customers within the Thames catchment exposed to risk of losing infrastructure services from a 1 in 1000 year flood event.



Source: Pant et al. (in press, a).
Notes: The figures shows the number of customers susceptible to direct disruption (i.e. as a direct result of infrastructure flood damage) and indirect disruption as a result of cascading failures from flood damage infrastructure due to interdependencies.

Electric vehicles

Uptake of electric vehicles (EVs) is one example of a new technology that is at the nexus of two infrastructure sectors. EVs create a new demand on electricity infrastructure, placing further pressure on the system. Most scenarios assume growth in EV demand over the coming decades (National Grid, 2015a). If development of charging infrastructure is sensibly designed, EVs can provide greater opportunities for demand-side management of peak loads (Neaimeh et al., 2015). A shift from liquid to electric fuels displaces risks from disruptions to fuel distribution and supply, to disruption to electricity transmission and distribution networks.

Decentralisation of energy systems

Construction of decentralised energy systems may also alter climate risks. Decentralisation of electricity networks may reduce vulnerability to extreme events (Bollinger, 2015): it improves the geographical diversity of electricity production and reduces the average network distance, and hence likelihood of failure, between generation sites and demand centres. There are also potential benefits from increased deployment of small-scale renewable technologies to provide additional local capacity, as well as other local benefits to air quality, fuel poverty and the economy (Roelich and Bale, 2014).

However, large-scale deployment of decentralised systems poses challenges to grid-wide functions such as frequency control and allocation of reserves, which can be exacerbated during an extreme weather event (Bollen and Hassan, 2011). The change in climate risk will depend significantly on the geography and topology of the decentralised network architecture. Decentralisation of other infrastructure systems such as water, or the effect of multiple interdependent decentralised systems, are poorly understood.

4.3.2 Reliance on ICT

Modern infrastructure is increasingly reliant on ICT for monitoring, remote operation and clock synchronisation across networks. ICT also plays a crucial role in coordinating emergency response during extreme events. The significance of interdependencies between ICT and power systems was exposed in September 2003. Failures in the power network caused by flash-over between a conductor cable and a tree directly led to the failure of internet communication hubs, which in turn led to failure of other power stations. An estimated 56 million people were impacted, mainly in Italy and Switzerland (Buldyrev et al., 2010).

Insufficient information about the location of ICT and the criticality of its function in managing other infrastructure sectors has hindered comprehensive analysis (as discussed in Section 4.6). However, analysis by Pant et al. (in press, b) suggests that, after electrical power, ICT is the second most important infrastructure network for the running of the UK's rail network. The analysis shows that flooding of the 5% of the rail network's electrical assets in the low flood risk zone (at less than a 1-in-200 annual chance of flooding) would disrupt 17% of passengers, while inundation of the 7% of signalling assets in the same low flood risk zone would disrupt 46% of passenger journeys.

Other infrastructures may currently be less vulnerable to ICT disruption, but increased pervasiveness of ICT, particularly as a result of increased uptake of 'smart' systems, is altering the interdependent risk profile of many infrastructure sectors and little is understood about the longer term implications of this for climate change risks.

4.3.3 Reliance on transport

A number of systems are dependent on transport infrastructure for continued operation. Although many types of disruption to transport services do not have the same immediate cascading impact as loss of ICT or electricity, the impacts can be significant when emergency materials cannot be transported, or if transport access is vital to the emergency response during an extreme event. For example, in July 2007, the delivery of a temporary flood defence at Upton-on-Severn was unable to be deployed due to severe disruption to the transport infrastructure caused by surface water flooding (Rickard, 2009).

Failure of key infrastructure components such as bridges, or landslides that block important transport corridors, can significantly increase travel times as a result of rerouting of journeys. In extreme cases the loss of transport networks can isolate communities completely. For example, failure of the Workington Bridge in the 2009 Cumbria floods required residents to make two-hour detours to reach the other side of the river, a journey that previously took less than 15 minutes. The nature of the town meant that some key services were only available on one side of the river causing significant social impacts (Affleck and Gibbon, in press). Similar impacts are currently being felt among residents of Tadcaster, North Yorkshire, following the loss of a bridge in December 2015 that joins up the town. Analysis of the current climate 1-in-200 year flood event in Newcastle-upon-Tyne shows that many route options would be simultaneously blocked. The aggregate disruption to all journeys in Newcastle-upon-Tyne during peak travel time was equivalent to 1000 passenger days (Pregnolato et al., 2016).

In their ARP reports, a number of infrastructure operators have identified risks to the continued operation of their facilities due to delivery vehicles with fuel, chemicals (e.g. for wastewater treatment) or other supplies being disrupted. The magnitude of the risk is highly context-specific, depending on the criticality and location of the asset, on-site reserves and surrounding geography. The increase in electricity generation using biomass or waste feedstock is likely to be increasing vulnerabilities to the risk of transport disruption, as the storage and transportation of waste is generally more complex than other fuels, making it harder to have large reserves on-site (Iakovou et al., 2010).

In New York, following Hurricane Sandy in 2012, fuel and food supplies were rapidly exhausted because consolidation of supply chains meant over half of these resources were routed through just one location, and key routes were blocked by high winds and flooding. A model developed to analyse the impacts of disruption to resource movements from Hurricane Sandy in New York was applied to the Shetland Islands (Brown and Dawson, 2013). This highlighted how the magnitude of impacts of disruption are highly non-linear and that a 1-in-200 year event inundating key resource infrastructure (e.g. fuel and food depots) can lead to a cascade of resource disruption, depleting stocks across the region within a few days. This is broadly supported by Pant et al., (2016) that shows the indirect impacts of infrastructure disruption from a 1,000-year extreme event are 15 times larger than those from a 100-year event.

4.3.4 Reliance on water

The UK's national energy generation mix is heavily dependent on the abstraction of significant volumes of water for cooling. The majority of cooling water is abstracted from coastal or tidal waters, whilst 23% of the UK's energy is generated from power plants cooled from freshwater sources (Environment Agency, 2013). Energy generation mixes with more nuclear and carbon capture technologies could increase total water demand for cooling six-fold.

Temperature increases of cooling water (and increasing salinity levels) can reduce the thermal efficiency of power plant (Ibrahim and Attia, 2015). Disruptions to coastal thermal plant using sea water as a coolant have been reported due to water intake systems becoming clogged with seaweed and jellyfish. Torness power plant was shut down temporarily in 2011 when jellyfish blocked intake filters at a reported loss of £1 million a day in revenue (Schneider et al., 2015). The increasing occurrence of jellyfish blooms have been correlated with rising sea temperatures and overfishing over the last decades, but predicting future effects is not currently possible (Lynam et al., 2011; Reid et al., 2011) (see Chapter 3, Section 3.7).

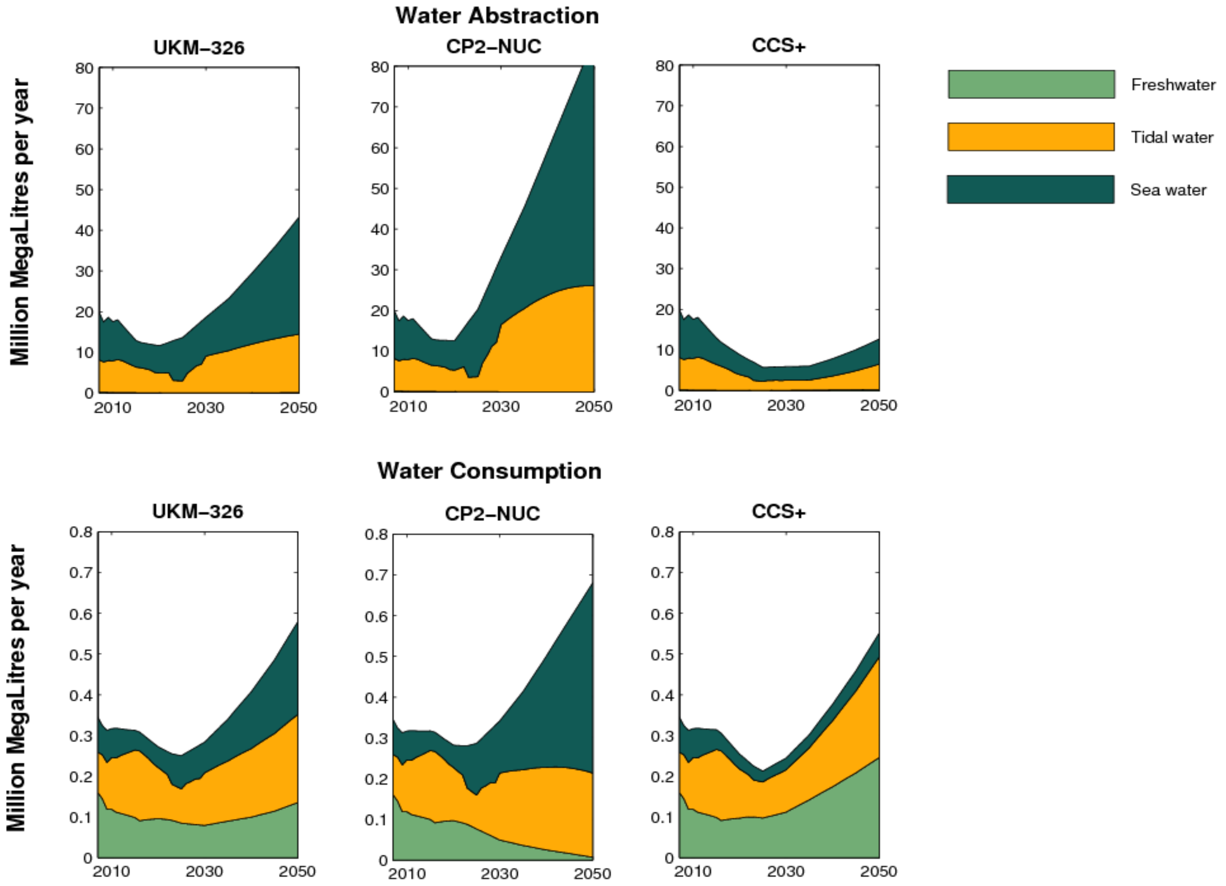
Cooling systems for thermoelectric power plants vary in the efficiency of water use. Power stations located away from the coast or from estuaries, which rely on freshwater for cooling, often use relatively water efficient air or hybrid cooling systems to minimise abstractions. However, increases in ambient water and air temperatures, and reduced freshwater availability, are likely to impact on generation operations, particularly for inland thermoelectric plants (Murrant et al., 2015). Quantifying risks to thermoelectric power supply and freshwater resources is complicated through multiple uncertainties associated with climate scenarios, impacts and adaptation measures in other sectors.

CCRA1 assessed the impacts of climate change on water abstraction by existing power generation. Naughton et al. (2012) demonstrate for a single catchment how meeting cooling water demands would exceed abstraction limits. In a national assessment, Byers et al. (2014) considered the implications of different energy mixes (including decarbonisation scenarios) and technologies. A scenario with an energy mix of high nuclear or carbon capture technologies could require as much as six times the current cooling water demands (CCS+ in Figure 4.6). However, the volume of freshwater abstraction depends on the choices made for locating power plants and the cooling water technology used (Environment Agency, 2011a).

Clustering generation capacity compounds these issues further. For example, a more detailed analysis by Byers et al. (2016) on the River Trent, the cooling water source for the largest concentration of electricity generation capacity in the UK, showed that even with no climate change impacts the projected growth of cooling water abstractions might reach the current licensed abstraction limit (for all sectors) by the 2040s. Growth in industrial demand and for public water supply would further amplify this risk.

Figure 4.6. Scenarios of freshwater use for energy production

Water abstraction and consumption by generation class for freshwater from 2007 to 2050



Label	Name	Scenario description
UKM-326	UK MARKAL 3.26	*Core run of cost-optimised UK MARKAL 3.26.* A steady mix of renewables, nuclear and carbon capture and storage is combined with ambitious energy demand reductions across all sectors; this is a least-cost pathway.
CP2-NUC	Carbon Plan 2 – Nuclear	*Higher nuclear and less energy efficiency*. Nuclear dominates and CCS not commercially viable. Gas meets peak demands and energy efficiency is low. Heat and transport are largely electrified.
CCS+	CCS+	*Higher carbon capture and storage (CCS) and no nuclear.* Similar to CP3-CCS although nuclear is replaced with further coal CCS, biomass, waste and renewables.

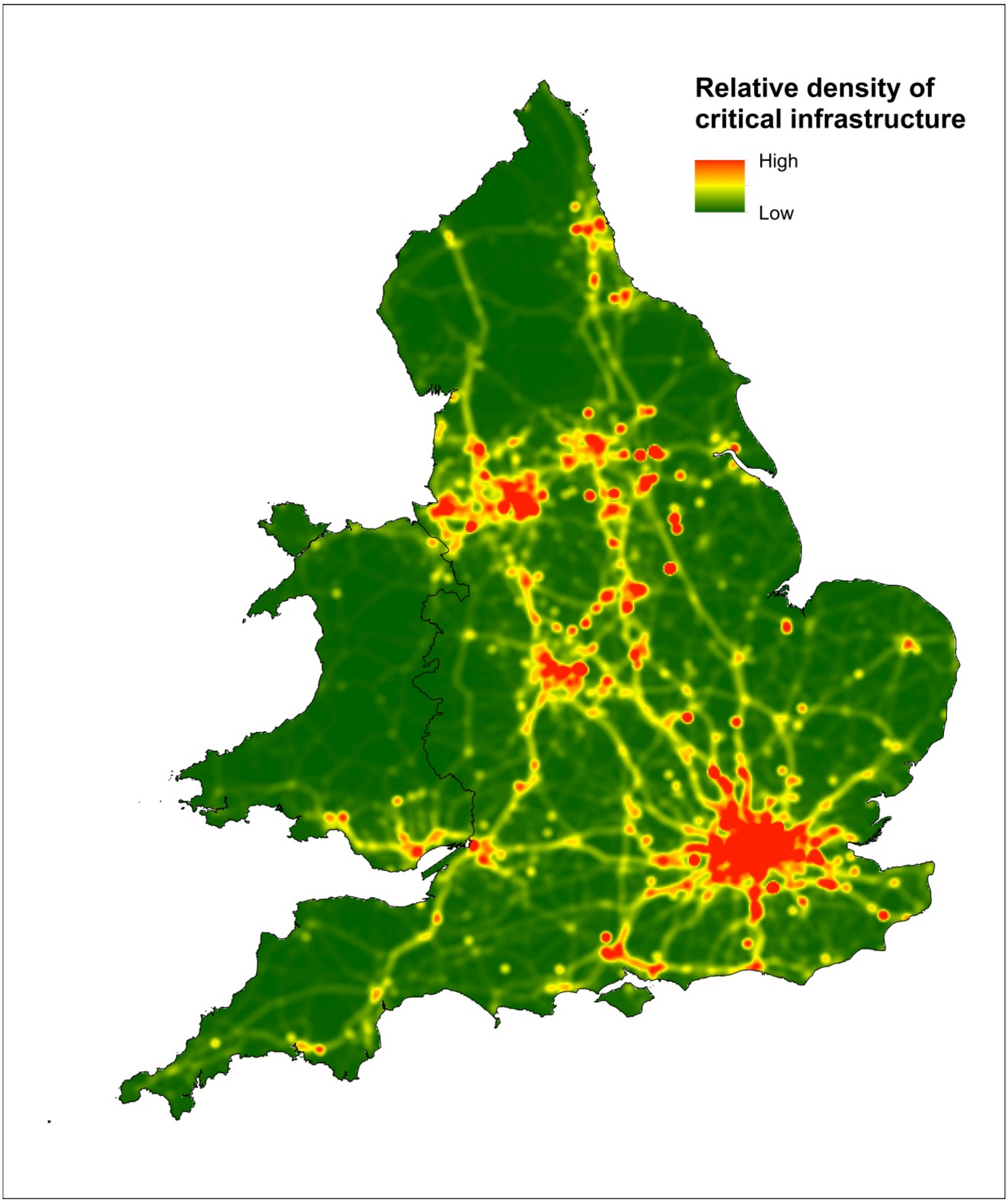
Source: Adapted from Byers et al. (2014).

4.3.5 Geographical proximity and multi-infrastructure conduits

Co-sited cables, fibre optics, road, railway, pipe and other infrastructure – even if not physically connected but running in parallel along the same route – can amplify vulnerability as a storm, flood or landslide can simultaneously impact multiple infrastructure networks. Bridges, for example, typically convey multiple infrastructures. For example the Workington Bridge carried telecoms, water and gas (Affleck and Gibbon, in press). However, Khoury et al. (2015) demonstrate that multi-purpose infrastructure also has the potential to enhance network reliability (for example, a tunnel in Kuala Lumpur designed for vehicles can also be used for floodwater during extreme rainfall events).

Inadequate data exists, or is not readily available, on the location of multi-infrastructure conduits in order to be able to assess vulnerability. However, using best available data on the location of national infrastructure, Thacker et al. (in press) devised and implemented a composite criticality hotspots analysis for England and Wales, measured according to the number of users directly or indirectly dependent on all infrastructure in that location. Figure 4.7 shows that London is a major focus of criticality; it has a large spatially continuous hotspot, with other smaller but notable hotspots around Manchester, Liverpool, Leeds, Birmingham and Tyneside. The hotspots are often located in the periphery rather than the centre of cities. A cluster of smaller hotspots in the Sheffield, Derbyshire, Nottinghamshire and Humberside areas are a result of important electricity assets being located in these areas. However, there is likely to be far more redundancy available in critical assets in large conurbations.

Figure 4.7. Composite assessment of the concentration of critical infrastructure from all sectors



Source: Thacker et al. (in press).

Notes: Composite score measured according to the number of users directly or indirectly dependent on the infrastructure in that location.

4.4 Flood and coastal erosion risk management infrastructure

This section summarises the climate change risks and opportunities relating to the management of flooding and coastal erosion risks using engineered solutions (both 'hard' and 'soft'). Flood risks to key receptors are discussed elsewhere, most prominently in Chapter 5 for people and the built environment, but also Chapter 6 (business), Chapter 3 (agriculture and the natural environment) and Sections 4.5 – 4.9 in this chapter in relation to individual infrastructure sectors.

4.4.1 Overview of sector and policy

Flood and coastal erosion risk management infrastructure (FCERMi) includes any feature that is actively manage the risk of flooding or erosion (Sayers and Dawson, 2015; Sayers et al., 2015a). The most common sources of flooding include:

- River flooding.
- Coastal flooding.
- Surface water flooding (including sewer flooding caused by rainfall overwhelming sewer capacity).
- Groundwater flooding.

The broad definition of FCERMi used here includes a wide variety of individual asset types that operate at local and regional scales. Most floodplains that contain significant economic assets are protected by some form of FCERMi, and many watercourses, lowlands and estuaries have managed flow regimes. Flood infrastructure therefore provides a crucial risk management service to the UK economy. Erosion is also a significant risk. Of the 4,500 km of coast in England, 1,800 km is liable to erosion, 340 km of which is defended.

The Flood and Water Management Act 2010, the Flood Risk Management (Scotland) Act 2009 and the EU Floods Directive set out responsibilities for flood risk management. Flood policy and funding of flood infrastructure are the responsibility of the Department for Environment Food and Rural Affairs (Defra) in England, while responsibility is devolved to the Scottish Government, the Welsh Government and the Northern Ireland Executive. Delivery of flood risk management is overseen by:

- Environment Agency (England);
- Rivers Agency (Northern Ireland);
- Scottish Environment Protection Agency (Scotland); and
- Natural Resources Wales (Wales).

In England, Wales and Scotland local authorities have varying levels of responsibilities for managing local flood risk and for coastal management. In Scotland, SEPA has a strategic role in flood risk management planning and local authorities have the main responsibilities and powers for implementing flood risk management actions. In England, local authorities are responsible for delivering a coordinated approach to local management of flooding from ordinary watercourses, surface runoff and groundwater, and have powers to do necessary flood risk management works and also to maintain or restore natural processes and manage water levels in relation to these sources of flooding.

The impact of climate change and sea level rise on flood risk has been taken into account in legislation, policy and guidance for nearly two decades. Examples of relevant policy documents include Policy Statement on FCERM Appraisal (Defra, 2009), guidance on climate change allowances in design (Environment Agency, 2016), the National Flood and Coastal Erosion Risk Management Strategy for England (Defra and Environment Agency, 2011) and the policy statement on Flood and Coastal Resilience Partnership Funding (Defra, 2011). There are various exemplar projects designed to manage flood risk in the context of long-term changes in the climate, most notably the Thames Estuary 2100 plan which developed an adaptive pathway to manage flood risk in London and the surrounding area. Through successive incremental action the adaptive strategy considered flood risk management for up to 4m or more of sea-level rise (Environment Agency, 2011b).

4.4.2 Climate risks

Flooding is a key risk to all infrastructure sectors, evidently FCERMi plays a crucial role in mitigating these risks and FCERMi assets are typically managed separately to the infrastructure and built environment they protect. However, the performance of FCERMi is also subject to climate change impacts (Sayers and Dawson, 2015; Walsh et al., 2015. The most significant of these is a reduction in a standard of protection. For example, by the 2080s, Sayers et al. (2015b) for the ASC calculate that, even if current adaptation efforts continue, the number of residential properties in the UK at a 1-in-75 or greater annual chance of flooding will almost double from 860,000 today to 1.7 million by the 2080s as a result of rising sea levels and altered river flows under a 4°C scenario, not accounting for population growth (see Chapter 5 for further details).

Along the coastline, the impacts of climate change on coastal infrastructure will vary according to structure type and location. However, even lower projected rises in mean sea-level could increase overtopping volumes by 50 – 150%, depending on structure type and location, while scour potential will increase by 16% for vertical structures but only 2% for sloping embankments and shingle beaches (Sutherland and Wolf, 2002; Sutherland and Gouldby, 2003). Burgess and Townend (2004) estimated that by the 2080s the annual cost of coastal dyke structures will, depending on the climate change scenario, be 150 – 400% of the current levels. Sayers et al. (2015b) considers the potential vulnerability of current coastal defence lines to failing as mean sea levels rise to the 'toe' height of defence foundations (leading to stronger and near continual wave action on the weakest point of defence structures). The length of coastal defences that will be highly vulnerable to failure is expected to double under 1m mean sea-level rise, from 110 km to 220 km in the absence of additional adaptation action. This would mean that 20% of the total length of coastal defences in England would be highly vulnerable (see Box 4.1 above for further details).

Few infrastructure systems have the sole purpose of managing groundwater flood risk, yet groundwater flows can have an important impact on FCERMi. High groundwater can (i) bypass a raised defence and flood the land behind (Macdonald et al., 2012), (ii) exacerbate scour (Loveless et al., 1996), (iii) drive progressive erosion and piping of the embankment or foundation soils (Schweckendiek et al., 2014) and (iv) destabilise soil slopes and cliffs, increasing the chance of a catastrophic slip (Iverson and Major, 1986). In urban areas, increased groundwater levels may enter into piped drainage systems by means of belowground pathways (but limited evidence exists). During extended periods of lower than average rainfall, low groundwater levels can lead to differential settlement and resulting instability (Wols and van Thienen, 2014), with significant impacts on urban infrastructure, including FCERMi assets (Foster, 2001). Low groundwater levels at the coast can also lead to saline intrusion, exacerbating the corrosion of engineered infrastructure and reducing the natural capital of coastal freshwater water and brackish lagoons (Hiscock et al., 2011). The interaction between groundwater and climate processes is poorly understood (Taylor et al., 2013) and groundwater flooding tends to be slow to respond to rainfall conditions. Thus changes in the temporal sequencing and spatial coherence of rainfall events are likely to be important.

Concrete FCERMi infrastructure will deteriorate faster if subjected to more frequent and extreme periods of freeze–thaw (Auld et al., 2007; Environment Agency, 2013). Prolonged hot dry periods are likely to accelerate desiccation of surface soils on earth embankments. Extreme hot and cold temperatures can restrict or even stop mechanical and electrical assets from operating (Rowan et al., 2013) although most of these assets are designed for use in countries with greater climate variability than the UK so this is not currently a substantial risk.

Green or blue infrastructure (which can be referred to as soft engineering or natural flood management) encompasses all green and blue spaces regardless of size or ownership. This includes parks, gardens, agricultural fields and trees, as well as green roofs, wetland storage, shelter belts, urban ponds and floodplain reconnection with the aim of restoring or mimicking natural processes. These can be implemented at a range of scales from river catchments and coastal stretches to help manage river and coastal flooding and erosion, and also at the urban area scale (including sustainable urban drainage systems) to help manage urban drainage networks and surface water flooding. Green and blue infrastructure typically provides additional environmental and social benefits beyond flood risk management. In many cases, if managed well, they offer some degree of natural resilience to change. However, high temperatures can reduce their infiltration capability, alter the mix of the vegetation and/or encourage the formation of standing water and associated undesirable outcomes such as disease or increased mosquito populations (Armitage et al., 2012; Demuzere et al., 2014). Sustainable drainage systems and green infrastructure are explored in more detail in Chapter 5.

Marine nutrients and microbes can attack concrete and steel structures (Gu et al., 2011). For example, accelerated low-water corrosion (ALWC, the attack of concrete and steel structures by nutrients and microbes in the marine and estuarine environment) reduces the performance of flood defence structures (Melchers, 2014). Infrastructure in tidal and brackish water, such as the Thames Estuary, are particular susceptible to ALWC and can experience rates of corrosion exceeding 1 mm/year (CIRIA, 2005), a rate that is expected to increase with higher temperatures (Stewart et al., 2011).

Vegetation within some watercourses needs to be managed to maintain conveyance and avoid blockage. Conveyance of river channels, afflux at structures and the stability of flood defences can also be influenced by invasive species such as Japanese knotweed (Defra, 2013a). Preferential growth and survival of such species can be influenced by their adaptation to conditions of high temperatures or drought. Internationally, climate change has been associated with the potential increase in more aggressive, non-native, animal burrowers that undermine the stability of flood defences, although there is currently no evidence to suggest this is occurring in the UK.

4.4.3 Adaptation actions

The expected reduction in standard of protection provided by FCERMi as a result of climate change will require adaptation. This will be challenging: in England alone there are ~10,200 km of flood defences (Environment Agency, 2009b), while the length of public sewers in the UK is estimated to be ~356,000 km (Defra, 2004; Scottish Water, 2014).

The Environment Agency has been accounting for climate change in the design of FCERMi systems since the mid-2000s. Current guidance is for a climate change allowance to be added to loading conditions, and this varies according to region and design life (Environment Agency, 2016). Climate change is also considered in asset management planning and long term investment strategies (Environment Agency, 2011c; Environment Agency, 2014). Depending on the growth in population and change in climate, current adaptation plans can offset 20 – 70% of the expected increase in risk (Sayers et al., 2015b for the ASC).

While there may be opportunities for efficiency savings, FCERMi funds are finite. Since policy change in 2011, funding for flood defence infrastructure can also be provided in partnership with other public, private or third sector organisations. While the appraisal system values all economic and wider benefits of flood alleviation in line with established guidance (e.g. HMT Green Book, Defra Policy Statement on Appraisal 2009, Multi-Coloured Manual), the allocation of national funding to specific projects is deliberately skewed in favour of protecting residential properties, especially in areas of deprivation (Defra, 2011). As a result, infrastructure operators may need to increase their own investment, and work in partnership, to ensure the resilience of their sites and networks. Examples, such as the partnership between Teesport, Northumbrian Water, the local authority, and landowners which reduced the vulnerability of the port entry/exit road, show how multiple parties can collaborate in this way (Royal Haskoning, 2014).

4.5 Water infrastructure

This section summarises the climate change risks and opportunities relating to water and wastewater infrastructure and the security of potable water supplies. Issues relating to abstraction from the water environment are considered in Chapter 3, other than by energy generators (Section 4.6) and industry (Chapter 6). Impacts on water quality are also discussed in Chapter 3.

4.5.1 Overview of sector and policy

In the UK, water supply and sewerage services are delivered by 26 organisations, whose responsibilities were set out in the Water Industry Act (1991). In Scotland and Northern Ireland, public drinking water and sewerage services are provided by public sector corporations, in England and Wales these services are provided by private companies. Over £25 billion will be invested in the UK's water infrastructure over the next five years (Ofwat, 2014; Scottish Water, 2015). The long-term nature and significant value of water company investments requires consideration of climate change and other drivers, including future energy costs, changes to environmental regulation, population growth and economic growth. Moreover, the water industry has an ageing asset base which includes over 800,000 km of sewer and water supply pipes with an estimated average age of 70 years (ICE, 2012; UKTI, 2015). For these reasons, the industry has been actively involved in climate change adaptation since the 1990s, with commitments on environmental improvement and inclusion of climate change. However, this has focused largely for water supply issues through publication of Water Resources Management Plans with horizons of 25 – 40 years (Ofwat, 2014, 2010; Charlton and Arnell, 2011; Environment Agency, 2012).

Water supply in the UK is managed under the Water Acts of 2003 and 2014 (England and Wales), Water Resources (Scotland) Act 2013 and Water and Sewerage Services Order 2006 (Northern Ireland). This is supported by UK reservoir safety and flood management legislation and acts and regulations that implement various EU Directives, including the Water Framework Directive, the Urban Waste Water Treatment Directive, the Drinking Water Directive and the Floods Directive.

Together, these implement principles for the sustainable use of water resources, promote water conservation, strengthen the voice of consumers, ensure the safety of key infrastructure and improve the environmental quality of water bodies and catchments. Water companies are legally obliged to produce a Water Resources Management Plan every five years that covers the 25-year period ahead. The plans are intended to show how water companies can maintain a sustainable balance between water supply and demand, taking into account factors such as the changing climate and population growth. The UK Government is reforming the system of water abstraction management in England so that all abstraction licences would be converted into permits that are made up of different elements including water accounts, local conditions and standard catchment rules, although changes are not expected to come into force until the early 2020s (Defra, 2016). In Northern Ireland, the Sustainable Water - A Long-Term Water Strategy 2015 – 2040 provides a long-term approach to water resource planning.

Water companies and regulators may be requested by the Secretary of State to prepare a climate change risk assessment and adaptation strategy under the Climate Change Act 2008 (Adaptation Reporting Power). All 26 water and wastewater companies along with the economic regulator for England and Wales (Ofwat) were directed to report under the first round of ARP. As of April 2016, 11 water companies had voluntarily reported under the second round of the ARP.

4.5.2 Climate risks

Rainfall and potential evapotranspiration (the amount of evaporation and transpiration that would occur if a sufficient water source were available) are climate-sensitive processes, so climate change impacts can be categorised as those that affect the physical infrastructure and those that alter the availability of the (water) resource that it conveys. Disruptions to water supply are reported to Ofwat but there are no industry-wide classifications that allow the cause of disruption to be determined (ASC, 2014).

Water supply

Water companies supply around 16,600 Ml/day of clean drinking water across the UK (UKTI, 2015). A number of studies show (Charlton and Arnell, 2011; Rance et al., 2012; Wade et al., 2013; HR Wallingford, 2015, for the ASC) that across the UK, there is currently a supply/demand surplus of around 2,000 Ml/day, but that there are modest deficits in some water resource zones. However, the deficits in these zones are lower than the target headroom, the safety buffer companies should plan to have between water supply and demand in order to continue to provide an agreed level of service to their customers.

Deficits are projected to be widespread by the 2050s under a high population growth and a high climate change scenario, in the absence of additional adaptation interventions beyond those included in the current water company Water Resources Management Plans (HR Wallingford, 2015, for the ASC). The north-west of England and Yorkshire and Humber are projected to be highly susceptible, as well as London and the south-east. However, deficits are projected in other parts of the UK as well including areas of south Wales and the central belt of Scotland.

At a national scale, Great Britain is projected to be in deficit by 800 – 3,000 Ml/day (5 – 16% of the total demand for water at that time) in the 2050s, and by 1,400 – 5,900 Ml/d (8 – 29% of the total demand for water at that time) in the 2080s. Figure 4.8 and Table 4.5 summarises the results of the updated water availability projections compiled for the CCRA (HR Wallingford for the ASC, 2015).

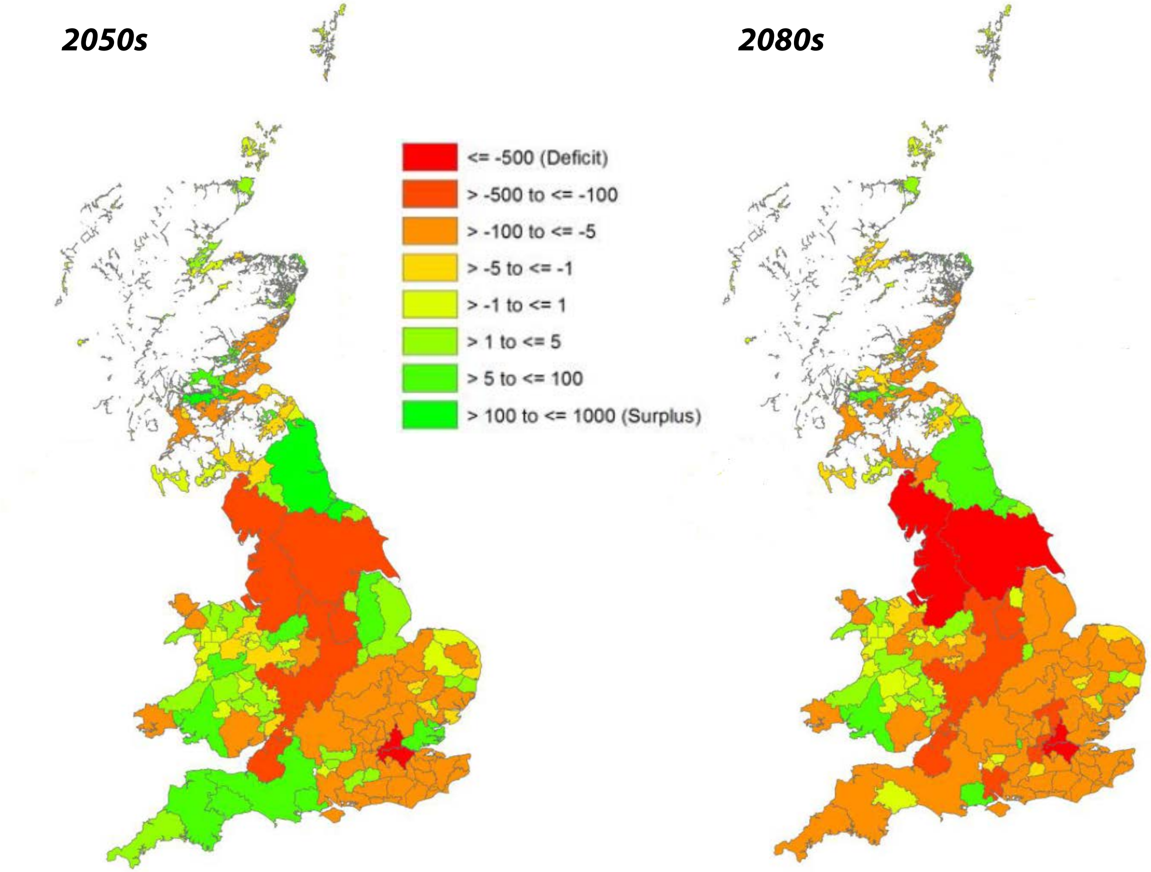
Analysis by AECOM (2015) highlights the importance of considering a wide range of events in a climate change risk analysis. The impact of a 1 in 100 year drought is analysed in each of the 23 aggregated Environment Agency Catchment Abstraction Management Strategy (CAMS) areas in England. Under current climate conditions, the analysis shows that six CAMS areas would be unable to meet demand; without demand restrictions London would face a substantial water deficit with lesser, although still significant, deficits in the south and east. Projected changes in climate would see a 1 in 100 year drought event in the 2050s leave 17 CAMS areas unable to meet demand in the absence of additional adaptation. As well as the south-east, deficits are projected in the midlands and Yorkshire. The same study evaluated the economic losses of such an event as £880 million (present-day), and as much as £44 billion by the 2050s.

Table 4.5. Water availability projections for public water supplies by GB country

Country	**Current supply/demand surplus**	**2050s**	**2080s**
England	• +1,426 Ml/day • Represents10% of the water available for supply • Some water resource zones in the south-east report small deficits	• -1,173 Ml/day (low population, medium emissions) • -3,060 Ml/day (high population, high emissions)	• -1,862 Ml/day (low population, medium emissions) • -5,657 Ml/day (high population, high emissions)
Wales	• +104 Ml/day • Represents 12% of the water available for supply • No water resource zones showing any deficits	• +26 Ml/day (low population, medium emissions) • –69 Ml/day (high population, high emissions)	• +39 Ml/day (low population, medium emissions) • –136 Ml/day (high population, high emissions)
Scotland	• + 414 Ml/day • Represents 22% of the water available for supply • A number of smaller water resource zones reporting deficits.	• +321 Ml/day (low population, medium emissions) • +96 Ml/day (high population, high emissions).	• +334 Ml/day (low population, medium emissions) • –88 Ml/day (high population, high emissions).

Source: HR Wallingford, 2015, for the ASC.

Figure 4.8. Water availability projections (Ml/day) for public water supplies in Great Britain in the 2050s (left) and 2080s (right) under a high climate scenario



Source: HR Wallingford, 2015, for the ASC.
Notes: UKCP09 high emissions p90 scenario based on ONS central population projection and assuming no additional adaptation. The supply-demand balance shown is absolute for each zone, not a per person balance. Note that both scenarios assume no additional adaptation beyond that already planned.

Water demand

Growing population, changing per person demand (e.g. as individuals use showers instead of baths, or purchase more water-efficient washing machines) and changing living practices (e.g. water use is lower in multiple occupancy homes because of economies of scale in use of washing machines, cooking and dish-washing) are important contextual factors for long-term change in water demand.

Public water demand is also linked to many other factors, such as human behaviour, with increases in demand at weekends, bank holidays and during large sporting events. It is also linked to temperature, with evidence to show that demand is higher on hot days (Parker and Wilby, 2013), during warmer months (HR Wallingford, 2008) and during droughts – for example demand increased by 120 – 140% over much of England and Wales during the 1976 drought, which aggravated distribution problems in some districts (Rodda and Marsh, 2011). However, there is no clear evidence that historical trends in increasing average temperature have led to increases in demand, not least because it is difficult to unpick this from other socio-economic factors (Watts, 2010). However, studies have suggested an increase in water demand by 2050 by 2 – 5% for domestic consumption, 4 – 6% for industrial and commercial use and 26% for agriculture (Downing et al., 2003; Rance et al., 2012).

Over the past 40 years, the UK has experienced a number of droughts, most notably in 1975 – 1976, 1984, 1989 – 1992, 1995 – 1996, 2004 – 2006 and 2010 – 2012 (SEPA, 2014; Dŵr Cymru Welsh Water, 2015; Environment Agency, 2015a). Despite this, stringent water saving measures such as rota cuts or use of standpipes are relatively rare. Less severe measures, including hosepipe bans, are more common and have resulted in consumer resentment during some UK droughts (Marsh, 1996) which could reduce the effectiveness of demand-side water saving measures. Because standpipes have not been used significantly since 1976, there is little evidence to judge how consumers might react to any widespread reintroduction. However, the financial impact, as a result of reduced economic activity, of rationing the amount of water available for public use has been assessed to be in the range of £236m - £329m per day, for London alone (NERA, 2012).

Dams and reservoirs

The primary impacts of climate change on dams and reservoirs are likely to be increased flood risk and reduced yields of water.

Dam failures in the UK are rare. There has been no loss of life since 1925 due to dam disasters in Great Britain (Environment Agency, 2011d) although any failure could have significant consequences. The impact of extreme weather was illustrated by the damage to Ulley Dam near Rotherham in 2007, leading to the evacuation of more than 1,000 people downstream (Wade, 2015). Flood risk may increase as a result of extreme rainfall due to seepage, overtopping and erosion of the dam (where there is a clay core or HDPE liner) and spillway. Dams with erodible (earthfill) embankments are likely to be most vulnerable (Atkins, 2013). Impacts could be exacerbated during extended dry periods by desiccation and shrinkage and loss of vegetation cover. There may also be direct damage by high temperatures increasing block cracking of asphaltic concrete liners and possible cracking of concrete spillways (Atkins, 2013).

Dams and reservoirs provide water storage supply during periods of shortage. However, reduced yields may result in the future from a combination of a reduction in the quantity of water (due to drought and low flows, especially multi-seasonal droughts), increases in evaporation and reduced water quality (due to low inflows, contaminants washed in following intense rainfall events, higher temperatures, algal blooms and invasive species). These risks are covered in more detail in Chapter 3 (Section 3.6).

Water abstraction, treatment and distribution

Climate impacts on water abstracted from rivers and groundwater relate to water availability and quality. With the exception of reservoirs, these are considered elsewhere (Chapter 3, Section 3.6).

Water treatment infrastructure is vulnerable to flooding, with around 300 clean and wastewater treatment plants located in areas at 1-in-75 annual chance of flooding or greater from rivers, the sea or surface water across the UK (Sayers et al., 2015b). The 2007 floods affected five clean water treatment works (Pitt, 2008), most dramatically at Mythe in Gloucestershire which cut off supply to 350,000 people for up to 17 days (Wade, 2015). A further 322 waste water treatment works were also affected (Pitt, 2008).

Modelling for the CCRA estimates that, under a 4°C rise in global mean temperatures, the number of clean and wastewater treatment sites located in areas of high flood risk will increase by 33% by the 2080s (Sayers et al., 2015b for the ASC). Increased risk of flooding will also increase the likelihood of plants becoming inaccessible to staff and/or suppliers of essential chemicals due to disruption of the road network (Holmes, 2015).

Various water treatment processes are likely to be impacted by climate change due to changes in raw water quality including periods of increased concentrations of sediments, metals and dissolved organic carbon, nitrogen and phosphorus. Raw water quality may also be at increased risk of contamination by pesticides and other agricultural chemicals as a result of changing distribution of agricultural pests and diseases (see Chapter 3, Section 3.6). Processes affected include rapid gravity filters (especially direct filtration), sludge blanket clarifiers, chlorine dosing, chemical conditioning and the treatment of groundwater (Arkell et al., 2011b).

Waste water collection will also be affected by dry weather, especially when it is warm. Overall, treatment processes are expected to improve. Prolonged low flows will enable longer retention time of sewerage in settling tanks, reducing the loading on secondary treatment steps. Higher temperatures increase the rate and efficiency of wastewater treatment processes (Campos and Darch, 2015a). Improvements in primary processes will result in reduced suspended solids and biological oxygen demand loadings on secondary processes (Arkell et al., 2012). However, climate change is likely to result in reduced river flows, in summer at least, requiring increased treatment to meet consents (Defra, 2012b; Campos and Darch, 2015a). The contribution of treatment works effluent to summer river flows can be significant and this will become more so under climate change. As with distribution networks, buried waste water infrastructure is also susceptible to shrink–swell processes.

For water distribution infrastructure, flooding of pumps is the primary risk as many are located on treatment and abstraction sites, but the number of other pumps for water distribution in the floodplain is unknown. Other impacts are likely to be an increase in trihalomethane (THM) formation and a decrease in pipe bursts. THMs form as a by-product of chlorine dosing which may be required more often for water treatment and the dosing of water in distribution networks due to increased temperature (Arkell et al., 2011b). There is limited quantitative evidence of the impact of climate change on these water treatment and distribution processes, and these issues are typically managed as part of plant operations.

Increased pipe bursts (e.g. as seen in Northern Ireland in 2010) in cold winters are a widely reported phenomenon. Warmer winters should reduce the overall frequency of pipe bursts which are particularly sensitive to extremes in temperature (UKWIR, 2013a), but this risk is also mediated by many other factors such as antecedent conditions, pipe age and ground condition (Boxall et al., 2007; Laucelli et al., 2014). For example, shrink–swell susceptible clays are currently estimated to cost the UK between £300 million and £400 million per year in pipe bursts, and expected changes in climate will increase intra-annual fluctuation of soil water content, particularly in clay soils in south-east England, increasing differential movement at pipe/foundation depth (Sanders and Phillipson, 2003).

Sewer capacity

The UK sewer system has evolved over centuries. Early sewers combined sewerage and surface water drainage, whilst more recent systems separate sewerage and surface waters. Consequently, the majority of urban centres in the UK contain both combined and separate systems. Projected changes to the climate are expected to impact on sewer operations and ultimately reduce the capacity for new development to be incorporated into existing systems, and increase operating costs such as pumping and treatment.

There is some uncertainty on the impact of climate change on convective storms, but analysis by Kendon et al. (2014) suggests that intense rainfall, similar to that experienced in Boscastle in 2004, may be almost five times more likely by 2100 in a high emissions scenario. Resultant rainfall intensity change estimates from UKWIR (2015) are, in general, higher than existing UK guidance which poses significant challenges for urban drainage infrastructure. These are typically designed to manage a 1-in-30 year storm event with no allowance for climate change required by the industry design manual (Sewers for Adoption, 7th edition, WRc 2012).

Increased rainfall is projected to increase sewer flooding and CSOs (Arkell et al., 2011a; Mott MacDonald, 2011; Dale et al., 2015). One study suggests CSO discharges may increase by 33 – 83% by 2071-2100 (Nilsen et al., 2011). Increased tide-locking (when drainage is restricted by a higher tide and reduced time for discharge) of coastal discharges will also increase flood risk (Campos and Darch, 2015a).

Widespread flooding in 2007 damaged 55,000 properties, with the majority of damage blamed on drains and sewers being overwhelmed by heavy rain (Pitt, 2008). The floods highlighted that traditional piped sewer systems cannot readily be adapted to deal with increased rainfall, particularly in densely populated urban areas. Half of the national sewer network is reported to be currently at or beyond capacity (Mott MacDonald, 2011).

The risk of sewer flooding is being exacerbated by population growth and expansion of urban areas that usually involves converting permeable land to impermeable surfaces that increases runoff. Furthermore, front gardens in urban areas being increasingly paved over, with the proportion of urban front gardens that are paved jumping from 28% in 2001 to 48% in 2011 (ASC, 2012). Only 4% of all UK residential paving sales were of permeable design in 2013. Almost all the other surfaces being used are therefore likely to be impermeable, such as concrete block paving and asphalt (ASC, 2014).

There is less quantitative evidence regarding other (non-flood) impacts on sewer systems. Prolonged dry weather will result in increased sedimentation in sewerage systems, producing more significant 'first flush' pollutant loads and concentrations of untreated wastewater from CSOs. Lower flows, combined with higher temperatures, increase the probability of hydrogen sulphide gas production, septicity and associated odour-related issues, and produces an increasingly corrosive effluent (Campos and Darch, 2015a).

4.5.3 Adaptation actions

The UK water industry has been actively involved in climate change adaptation since the 1990s, with commitments on environmental improvement and inclusion of climate change in long-term plans with horizons of 25 – 40 years (Ofwat, 2008a, 2008b, 2010; Charlton and Arnell, 2011; Environment Agency, 2012). The emphasis of climate change risk assessments has typically been on water availability and sewerage, but a wider range of issues are now being explored with the aims of managing total expenditure, maintaining service levels, improving resilience and reducing long-term risks. UK Water Industry Research (UKWIR) has produced assessments of climate change impacts on many aspects of water infrastructure including water resources (Vidal and Wade, 2006), water demand (UKWIR, 2013b), water quality (UKWIR, 2006) and treatment processes (Arkell et al., 2011b, 2012). UKWIR has also published guidance for water companies on topics such as asset management planning (Dyke et al., 2012), monitoring (Arkell et al., 2013), reporting (Bain et al., 2012) and sewer modelling (Dale et al., 2015).

Public water supply and demand

Many supply-side and demand-side measures are considered within company plans (Table 4.6). While Water Resources Management Plans show how companies are planning for projected changes in demand with climate change, it would be financially infeasible for companies to plan to meet all future unconstrained demand. Therefore the companies also produce Drought Plans that show how they will respond to extreme events when they occur in a planned-for changed climate.

In England and Wales, the economic regulator (Ofwat) has made changes to the regulatory framework for the current price review period (2015 – 2020) to remove the previous bias towards water company investment in large capital projects. This should prompt a greater focus on demand management. As a result, water companies appear to be prioritising demand management measures in long-term plans. Water consumption per person and leakage losses are falling and the proportion of households with water meters is increasing, and has been shown to reduce consumption by nearly 17% (Ornaghi and Tonin, 2015). Building regulations also put in place minimum requirements for water efficiency in new homes, minimising the added pressure on water resources.

The projected supply–demand deficits presented above could be substantially reduced if leakage and household consumption reductions are successfully implemented. Around three-quarters of water companies have made commitments to reduce per person consumption during the current price review period. If met, these commitments would reduce consumption per person from 141 l/day today to around 137 l/day by 2020. In the longer term, the current water resource management plans suggest that consumption per person will fall to 135 l/day by 2040. Previous analysis by the ASC (2012) suggests the uptake of cost-effective water efficiency measures could reduce consumption to 115 l/day. This suggests greater ambition on demand management is readily achievable. However, the behavioural changes necessary to achieve such significant reductions may be extremely difficult to achieve under current policy. In short timeframes, public campaigns can reduce demand by as much as 12%, but coupled with sprinkler and hosepipe bans reductions in water demand as significant as 32% per person have been reported (UKWIR, 1998).

The implementation of supply-side measures outlined as preferred and feasible options in water company business plans for the current period (2015 – 2020) would also contribute to reducing the projected deficits. From 2025, supply-side measures such as effluent reuse, reservoir construction and the development of new and existing groundwater sources account for nearly all of the proposals to deal with future deficits in existing water resource management plans. Additional supply and demand-side measures that are not in the current plans may also potentially be available.

If the current adaptation objectives are delivered, this would provide significant benefits; however, this is projected to be insufficient in the longer term, as the analysis projects by the 2050s that 16 water resource zones (one in Wales and the others in England) will have supply deficits under medium climate change and population growth scenarios. This would increase to 31 zones (three in Wales and the others in England) by the 2080s. Thus, even if the objectives of the latest water company plans are delivered there is a residual risk. Substantial additional adaptation action would be required to mitigate supply deficits in all water resource zones under a high climate change and population growth scenario by the 2080s. To manage reputational risks, and the associated reduced effectiveness of demand management, water companies are actively seeking to enhance consumer relations as part of their business planning process, which includes an opportunity for customers to challenge their plans at the drafting stage. Work on flood risk and public perceptions of climate risk in the UK has demonstrated that individuals' experiences of hydrological extremes can influence their perceptions of climate risk and their willingness to change their behaviours, such as to save energy (Spence et al., 2011). Droughts operate over larger spatial domains than floods and thereby can affect significantly more people. However, it is unknown whether more frequent droughts under climate change would result in a shift in perceptions across large areas of the UK that would make consumers less complacent about water supply risks and therefore more likely to accept demand-side water savings under climate change when they are imposed.

Table 4.6. Drought actions available to water companies, which often appear in Drought Plans and Water Resource Management Plans required under legislation

Measures that target customers	**Measures based on engineering**
• Introduction of temporary water use restrictions such as hosepipe and sprinkler bans • Seek restrictions on non-essential uses • Seek implementation of standpipes to provide water supply, or restrictions on water supplies to certain days or times, and/or impose lower pressures (these are known as rota cuts) • Encourage water awareness and promote efficient water use	• Use alternative water sources, or unused sources • Change discharge regimes such as the supply of water from a reservoir to a stream • Reduce leakage • Introduce bulk transfers of water between water companies • Improve the distribution network • Lower groundwater pumps

Source: Based upon Table 2.4 in Nickson et al. (2011).

Reducing flood risk to assets

There is no published account across the whole of the water sector of what has been achieved by efforts in recent years to improve the resilience of water infrastructure systems to flood risk. There is no centralised reporting on the resilience of water company assets, networks and services or any systematic recording of the disruption to water supply directly caused by flood events (ASC, 2015).

Water companies are investing in network resilience, which will include flood protection measures. An estimated £660 million was proposed by water companies for resilience measures in the current price review period (2015 – 2020), including £60 million for wastewater services. An example of water company investment in resilience is the connection of customers to more than one source of water, to avoid single points of failure. However, the lack of an agreed 'resilience' investment category makes period-to-period comparisons difficult.

Based upon current estimates of current investment and action on resilience, flood risk to water infrastructure assets is projected to be reduced by 50 – 60% by the 2020s. However, by the 2080s, without additional adaptation measures beyond those already planned, this risk could be one-third higher than today (Sayers et al., 2015b).

Maps of flood risk are now available for all significant reservoirs and flood plans are in place for high-risk reservoirs.

Sewer capacity

Water companies in England and Wales are expected to develop Drainage Strategies to inform their business planning and future delivery, so that they manage sewer flood risk and pollution incidents in a changing climate. As a result, water companies have committed to reduce the number of properties affected by sewer flooding by 33% over the forthcoming Asset Management Plan period (AMP6, 2015 – 2020). There is no such requirement in Scotland.

While water resources have a carefully managed regulatory process for long-term planning, there is no equivalent for the sewer and urban drainage network. Moreover, industry standards (WRc, 2012) provide limited consideration of climate change or other drivers of change. Expanding existing urban drainage capacity is impractical and often prohibitively expensive; adaptations include deployment of sustainable urban drainage systems and green infrastructure, and use of roads and developments to manage flood water on the surface and thereby reduce the water entering the sewerage systems over the longer term. However, there are a number of regulatory, financial, technical and organisational barriers to implementing these.

In England and Wales, lead local flood authorities (the unitary or county council in each area) are developing local flood risk management strategies which should consider drainage issues and the risk of sewer flooding. In Scotland, Scottish Water have responsibility for sewer flooding, local authorities for surface water flooding and road authorities for road drainage. Although governance structures vary across the UK, in all regions there are a number of organisations with responsibility for aspects of flood management. This poses challenges for delivering coordinated adaptation actions.

The National Planning Policy Framework (2012) expects local planning authorities in England to plan for the development and infrastructure required in the area, including infrastructure for wastewater, and to work with other authorities and providers to assess the quality and capacity of infrastructure and its ability to meet forecast demands. The NPPF also requires local planning authorities to prioritise SuDS when determining planning applications for development in flood risk areas. The policy was strengthened with effect from 2015 so that SuDS should also be an expectation for all major developments (> 10 dwellings and major commercial development). The government said that it would keep this under review, and the new Housing and Planning Act 2016 introduces a new requirement for the Secretary of State to review the provision of sustainable drainage in developments.

Scottish Planning Policy (2014) promotes avoidance of increased surface water flooding through requirements for SuDS and minimising the area of impermeable surface. Surface water from all new development is to be treated by SUDS before it is discharged into the water environment, except for single houses or where the discharge will be into coastal water. Scotland's Statutory National Planning Framework 3 states that water management and flooding issues will become increasingly important and development plans prepared by planning authorities must take account of this.

Concerns have been raised as to whether surface water flood risk in England is being fully managed. The ASC's progress report to Parliament (ASC, 2015) noted that:

- Lead local flood authorities (LLFAs) are not sufficiently resourced, and progress is slow. One-third of LLFAs in England responding to a 2012 survey said at least some of the funding provided by Defra had been allocated to other council services. The Flood and Water Management Act set no deadline for statutory summaries of the local flood risk management strategy to be published. As a consequence, only five out of 152 LLFAs had published strategies by April 2013. This had increased to 24 by April 2014, less than one-sixth of all LLFAs in England. Defra ministers have written on three occasions to LLFAs to encourage faster progress, including to state their desire for strategies to be completed and published by the end of December 2014. Results due out later in 2015 are likely to show an increase in the number of finalised strategies, but with more than half still outstanding (ASC, 2015).
- The limited data available suggests that SuDS uptake in new developments remains low and the changes to planning policy has not addressed key barriers identified by the Pitt Review including developers retaining their automatic right to connect new homes to the public sewer system (for surface water) with no regard given to their capacity. It is also unclear to what extent water companies will employ SuDS to reduce sewer flooding over the next five years.

4.6 Digital communications (ICT) infrastructure

This section summarises the climate change risks and opportunities relating to fixed line and mobile telephony, for voice and data communication, and data and application services more generally.

4.6.1 Overview of sector and policy

ICT is here taken to mean the 'whole of the networks, systems and artefacts which enable the transmission, receipt, capture, storage and manipulation of voice and data traffic on and across electronic devices' (Horrocks et al., 2010). ICT and data services support every aspect of a functioning economy, from controlling traffic lights to handling the billions in daily investment trading on the London Stock Exchange. Every aspect of modern living is becoming increasingly digitised, with sensitive personal information stored and mission-critical data and application services supported by 'cloud' based computing. The cloud in practice consists of server farms that provide secure, reliable and scalable data processing and storage solutions to businesses and the public sector. Consolidating services into fewer, larger, sites helps with managing security (including cyber security) risks, but increases the impact should those sites be compromised.

ICT infrastructure consists of elements with a wide range of expected lifetimes. End-user equipment, such as mobile phones and computers, have life expectations as short as a year. Over five to ten years, expectations of quality and level of service can increase dramatically, leading to infrastructure renewal. Masts and antennae have lifetimes of approximately 30 years, while buildings that house equipment may be in use for 50 years or more. Over longer time periods, the communities being serviced and the services provided will change significantly. Furthermore, infrastructure such as bridges and railways routes that often carry cables will change and require maintenance.

Regulation of the telecommunications sector is based on UK implementation of the EU regulatory framework for telecommunications, first adopted in 2002 and updated in 2009. The Communications Act of 2003 made Ofcom the independent regulator for both the telecommunications and broadcasting industries in the UK, responding to the growing convergence of ICT industries. A major feature of this Act is the requirement that Ofcom secures optimal use of the electro-magnetic spectrum for communications. The Digital Economy Act 2010 set up new regulations for digital communications and broadcasting, including Ofcom's role. Ofcom is required to ensure that the operators of public networks take appropriate steps to maintain availability. Ofcom were also directed to report under the first round of the Adaptation Reporting Power in 2009. As of April 2016, there have been no reports from the ICT sector submitted voluntarily under the second round.

4.6.2 Climate risks

Climate-related risks have the potential to disrupt the availability and reliability of the ICT sector and consequently push up operational costs for users (ITU, 2014). Projected changes in climate may increase the risk of damage to ICT infrastructure in a number of ways.

ICT networks typically exhibit considerable resilience due to diversity of systems and their network topology and redundancy. Failure of a part of a network is likely to have little or no effect on communications outside the area directly serviced by the failed component. Coupled with mass production, standardisation and relative ease of transportation of many ICT infrastructure components, means disruptions are typically short-lived. The exception is at the edges of networks where diversity is at its least – typically near low population regions, or remote locations such as islands where loss of ICT for communication or control of other systems can cause the greatest problems.

Increased frequency of coastal, fluvial or pluvial flooding will damage key ICT assets such as cables, masts, pylons, data centres, telephone exchanges, base stations or switching centres (Fu et al., 2016). For example, the winter 2015/16 floods in the north-east of England inundated a number of key ICT assets in Leeds and York. This led to loss of communications for thousands of local homes, businesses (who were unable to process card payments), bank machines and even police hospital services as far away as Tyneside (Hill, 2016 House of Commons Library, 2016; York Press, 2016). Flooding of a sub-station in Lancaster disrupted power supply to broadband cabinets, leading to loss of service there (Royal Academy of Engineering et al., 2015).

Fixed line calls and broadband data services rely on a root and branch network comprising trunk cables and exchanges, telephone lines strung between telegraph poles, and street cabinets that serve individual areas. An increase in the frequency or intensity of storms would increase the risk of wind, ice and snow damage to overhead cables and damage from wind-blown debris.

More intense or longer droughts and heatwaves can affect a range of ICT infrastructure because ground shrinkage can lead to failure of electrical, gas and water pipes, thereby damaging co-sited ICT infrastructure (Fu et al., 2016). Similar climatic conditions, further aggravated in cities by the urban heat island effect, place additional demands for cooling on energy networks increasing the risk of 'brown out' due to a reduction or restriction in power (Chapman et al., 2013). High summer temperatures, as well as rapid fluctuations in temperature and humidity, pose challenges particularly to data centres, which need to be kept cool to operate.

There is limited information on the location of UK ICT infrastructure, making it difficult to make a rigorous and quantitative assessment of risks to ICT networks and services. The ownership of a large proportion of ICT infrastructure, particularly data centres, is spread across the private sector. Information on location and connectivity is not publicly available, for commercial or security reasons, and so it is difficult to assess vulnerability to extreme events.

International design standards for equipment increase resilience. For example, most cables are designed to operate in global extremes of temperature, and so current and projected changes to UK temperature extremes are unlikely to have detrimental effects. The communications industry has to deal with problems caused by severe weather conditions on a regular basis. The most serious issue for telecoms providers during periods of severe cold, snow or flooding, is the denial of access to affected sites, or loss of power (EC-RRG, 2014). These risks decline as more robust, underground, fibre optic cables parallel or replace aerial cables and wireless links.

In the past five years, the direct effects of climate change on radio propagation have become clearer. A large proportion of communications is over radio links, to mobile or nomadic devices, on fixed links as part of backbone networks or last-half-mile connections to a fibre network, or via satellites. All radio systems experience periods of unavailability due to variable attenuation associated with weather parameters. Changes in several weather parameters have been observed, associated with climate change, affecting different frequency ranges. The availability of fixed links operating at frequencies above 5 GHz is limited by the incidence of moderate or heavier rain. Over the last 20 years in the UK, the incidence of rain causing unavailability has increased and almost certainly led to increased rates of outage on these links (Ofcom, 2012a). This may require a future reduction in link densities or the retrofitting of systems for interference cancellation. General warming will lead to changing experience of mixed phase hydrometeors[3] (sleet) on many links that could lead to dramatic changes in availability rates, either for the better or worse. The increasing altitude of the boundary between liquid and solid hydrometeors leads to greater rain attenuation on links to satellites (Paulson and Al-Mreri, 2011). At lower frequencies, changes in interference due to ducting has been postulated. Higher temperatures are associated with stronger atmospheric ducts[4] near the sea surface caused by water vapour from evaporation, but less ducting at higher altitudes. Ducts over the North Sea and English Channel lead to higher levels of unwanted signals coming from Continental Europe that interfere with signals originating from the UK. Projected increases in sea surface temperatures (see Chapter 3, section 3.6) is likely to lead to stronger ducting effects and communications

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[3] A hydrometeor is an atmospheric phenomenon or entity involving water or water vapour, such as rain, snow, sleet or a cloud.

[4] A duct is a horizontal layer in the lower atmosphere in which refraction is such that radio signals are guided or ducted, tend to follow the curvature of the Earth, and experience less reduction in signal strength than if the ducts were not present.

disruption (Naveed and Siddle, 2013), including increased interference with emergency service VHF/UHF systems.

4.6.3 Adaptation actions

Ofcom's statutory responsibilities provide an oversight role to ICT. The rapid refresh rate of technology, coupled with competition between multinational communications network operators, largely ensures the robustness of infrastructure. Digital communications providers compete on the basis of service reliability, and there are legal requirements for telecoms providers to take steps to protect the security and resilience of their networks and services.

The short lifespan of end-user equipment allows gradual adaptation. Support infrastructure such as buildings, masts and cable routes may have life expectancies of many decades making it more vulnerable to gradual change. Although there are large uncertainties (and opportunities to adapt) in future communications requirements and systems, many exchanges and key facilities remain on sites selected decades ago. As observed in the winter 2015/16 floods, inundation of several key facilities can have far-reaching impacts, but fibre to the home was shown to be more resilient than the (more prevalent) fibre to the cabinet, as cabinets require a power supply (Royal Academy of Engineering et al., 2016; Brunnen, 2016).

The emergency services network, Tetra, is overseen by the Home Office, and it is critical that availability is maintained during periods of extreme weather. The next generation emergency services network is under development and this is overseen by the Cabinet Office. The development and maintenance of networks for use in civil emergencies and by the emergency services is specified by the Civil Contingencies Act.

The industry-led group, the Electronic Communications Resilience and Response Group (EC-RRG), includes the main infrastructure-owning telecoms providers in the UK and government representatives. The group leads on cross-sector planning and response to major incidents which threaten the resilience of telecoms networks and services, including the development of the Telecoms Emergency Plan and the National Emergency Alert for Telecoms, which ensures industry and government communication during incident handling and recovery processes.

4.7 Transport infrastructure

This section summarises the climate change risks and opportunities relating to road and rail networks in the UK, ports and airports, and inland waterways.

4.7.1 Overview of sector and policy

Transport infrastructure includes roads (strategic and local), ‘main line’ and local/metropolitan rail services, passenger and freight distribution via the UK’s ports and airports, and inland waterways. The impacts of recent severe weather episodes on transport services are well documented, such as in June 2012 (see Jaroszweski et al., 2014) and the winter storms of 2013/14 that prompted an independent review of road, rail, port and airport infrastructure in England and Wales (DfT, 2014a). This review made 63 recommendations, all of which were accepted by the Government. The largest share of sector-specific recommendations (40%) was for the rail industry (ASC, 2015).

Transport infrastructure operators and regulators may be requested by the Secretary of State to prepare a climate change risk assessment and adaptation strategy under the under the Climate Change Act 2008 (Adaptation Reporting Power). Network Rail, the Highways Agency, Transport for London, Eurotunnel, the rail regulator (ORR) and Civil Aviation Authority were directed to report under the first round of ARP in 2009. A further 10 strategic airport operators, 12 major ports,[5] and two lighthouse authorities also reported. As of April 2016, 11 transport organisations had voluntary reported under the second round of the ARP.

Road transport

There is 10,620km of strategic road network (motorways and trunk A-roads) in Great Britain. In England, this is managed and maintained by Highways England, a new government company created in April 2015 from the Highways Agency. The newly expanded remit on the Office of Road and Rail (ORR) oversees performance and agrees on long-term funding. The Government's Road Investment Strategy will see £15.2 billion invested in over 100 road schemes between 2015 and 2021 (DfT, 2014b). Of this total, some £300 million has been allocated to address issues including flooding, carbon emissions, landscape and biodiversity. The Highways Agency Climate Change Adaptation Strategy and Framework (2009) has led to modifications in existing standards on the national network. Strategic roads in Wales, Scotland and Northern Ireland are maintained by the Welsh Government, Transport Scotland and Transport NI (part of the NI Department for Regional Development).

Local roads are maintained by upper tier and unitary local authorities in Great Britain, and by Transport NI in Northern Ireland. For local roads, the UK Roads Liaison Group Code of Practice for Well Maintained Highways sets out a regularly updated set of recommendations for dealing with climate change by local authorities. It is worth highlighting that the road network covers a range of modes (e.g. bus, coach and tram) as well as private transport. The majority of high value freight is carried on roads. The road network is also the main integration mechanism for other elements of the transport network such as ports and airports.

Rail transport

Almost all 'mainline' rail infrastructure in Great Britain is owned and operated by Network Rail. Rail services are divided into regional franchises run by Train Operating Companies (TOCs). Network Rail and the TOCs are regulated by the ORR. The Network Rail Strategic Business Plan (2013) recognises the importance of embedding climate change adaptation into operations and management. The knowledge base is continuing to be developed by the Rail Safety and Standards Board Tomorrow's Railway and Climate Change Adaptation project (e.g. RSSB, 2015). The overall aim is to increase adaptive capacity and provide an informed knowledge base for effective climate change adaptation decision-making in the rail sector. All regional rail 'routes' now have Weather and Climate Change Resilience Plans (Network Rail, 2014). In Northern Ireland, the railways are owned and operated by Translink, the Northern Ireland transport authority. Separate ownership and management structures are in place for regional metropolitan tram and light rail services such as the London Overground and Underground (Transport for London, owned by the Greater London Authority), and for example those in Manchester, Leeds, Nottingham and Glasgow.

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[5] Defined as those that carry over 10 million tonnes of commercial cargo per year.

Ports and airports

Ports and airports are owned and operated by private-sector companies, with some operating several sites across the UK (e.g. PD Ports own a number of major ports on the east coast of England). The Civil Aviation Authority regulates airports from a public safety perspective, but standards in terms of the resilience and performance of port and airport operations are generally left to the operators to determine based on their own commercial interests. However, as of April 2014, Gatwick and Heathrow Airports are required to produce operational resilience plans as a requirement of CAA licence conditions. The ASC (2015) recommended that the Cabinet Office implement minimum resilience standards for ports and airports that are in the national interest.

Inland waterways

Britain's inland waterways (canals and navigable rivers) have a range of owners but designated 'main rivers' are maintained by the Environment Agency in England, Natural Resources Wales, Scottish Environment Protection Agency and Rivers Agency in Northern Ireland. In England and Wales, the majority of canals are operated by the Canal and Rivers Trust and in Scotland they are operated and maintained by Scottish Canals.

4.7.2 Climate risks

All modes of transport are susceptible to damage or disruption from climate-related hazards. Extreme weather is already a key cause of serious disruption to transport services. However, not all climate impacts are threats and there are also likely to be opportunities. The modes of transport discussed below do not operate independently and are reliant on each other to provide multi-mode journeys and preserve supply chains. Weather-related transport disruption is rarely limited to a single mode and although having multiple modes as options helps towards the resilience of the system, the substitution of an alternative mode cannot be taken for granted. Identification of critical points in the network needs to take account of both the existence of diversion routes and the density of traffic on the route (Pregnolato et al., 2016; Pant et al, in press, c). Furthermore, building redundancy into a network can incur substantial cost and existing appraisal approaches do not always capture the associated resiliency benefits. For example, analysis of alternative route options, in case of another failure along the Devon coastal railway as occurred at Dawlish in 2014, identified seven route options that cost from £470m-£3.1bn, but all had a benefit to cost ratio below 1.0 (Network Rail, 2014).

This situation is most acute in regions where there are limited transport options (e.g. north-west Scotland) or where alternative modes lie along the same corridor (e.g. river valleys in Wales). The key risks to transport infrastructure discussed here are consistent with those identified in the first CCRA.

Bridges

Fluvial flooding poses a particular risk to bridges of all transport modes, and their failure has a prolonged disruptive effect on transport network resilience. Across the UK a flood event in which one or more bridges fail due to high river flows is currently expected to occur once every 2.6 years, with most bridge failures occurring with flow rate return periods of 50 – 500 years, with an average of 1-in-160 years (van Leeuwen and Lamb, 2014). Projected increases to winter precipitation and river flows would increase scour at bridges, potentially putting 1 in every 20 bridges at high risk by 2080 (HR Wallingford, 2014). Even damage, rather than absolute failure, can be disruptive. For example, high water at Lamington Viaduct in December 2015 damaged piers and led to its closure for seven weeks (Shirres, 2016).

Embankments and earthworks

Embankment stability remains a key issue for the surface transport network. Over 20,000 km of engineered cuttings and embankments support the UK's transport infrastructure (Loveridge et al., 2010) and 1,651 km are at risk from natural landslides (HR Wallingford, 2014). Maintaining and renewing these assets is costly: an average of £100 million a year is due to be spent on earthwork renewals on the rail network in England and Wales during the current price control period (2014/15 to 2018/19), an increase from the average of around £75 million a year in the previous period (2009/10 to 2013/14) (ASC, 2014). The cost of emergency repair is ten times greater than the cost of planned works (Glendinning et al., 2009). A number of failure modes for infrastructure slopes (cuttings and embankments) are mediated by changes in the water content and pore water pressure within natural and engineered soils. Different types of earthworks are more vulnerable to deterioration due to these failure mechanisms and deterioration of strength with age. Older, less well-compacted earthworks such as those supporting the rail network are deteriorating at a faster rate than newer earthworks built to more modern construction standards (Glendinning et al., 2014). On the rail network in England and Wales, 5% of earthworks (embankments, cuttings and rock cuttings) were classed as being in a poor condition in 2012/13, with a further 48% classed as marginal. There were on average 67 earthwork failures a year across the rail network between 2003/04 and 2013/14, of which 55 were in England and Wales and 12 in Scotland. There were some significant fluctuations during this period, with 107 failures in 2007/08 and 144 failures in 2013/14 (ASC, 2014).

Climate change will affect the processes and parameters that determine the stability of these earthwork slopes (Kilsby et al., 2009; Dijkstra and Dixon, 2010). Modelling shows that across low to high emissions scenarios, soil moisture fluctuations will lead to increased risk of shrink–swell related failures (Clarke and Smethurst, 2010) and desiccation cracking with associated reduction in stability (Glendinning et al., 2014). This will be most acute in the high plasticity soils of south-east England and likely to be the most significant geohazard to UK infrastructure (Pritchard et al., 2014). The impact of climate change on modes of failure that are deeper within the slope (e.g. deep rotational failure) is less clear (Scottish Executive, 2005; Rouainia et al., 2009; Network Rail, 2011). However, increased incidences of natural and engineering slope failure affecting the road and rail network in the winters of 2012/2013 and 2013/2014 (Winter et al., 2010; BGS, 2015) demonstrate their vulnerability to the projected changes to rainfall frequency and duration.

Heavy rainfall can lead to increased incidences of sinkholes that also cause disruption to transport infrastructure. Twenty-one sinkholes were reported across England after the winter 2013/14 storms (Muchan et al., 2015), and whilst their occurrence is dependent on very local geotechnical conditions projected changes to rainfall are expected to increase the frequency of sinkholes.

Road transport

The weather can have a significant negative impact on the road network, which can often be running close to or at capacity in parts of the UK. In addition to landslips, the key impacts are associated with flooding as well as increased thermal loadings on roads and control equipment. Currently 6,600 km of the road network is located in areas susceptible to flooding, which could increase by 53-160% by the 2080s (Sayers et al., 2015b for the ASC). The cost of disruption from widespread flooding in 2007 was £200 million and a flood event of this scale could be possible on an annual basis by the 2080s (Chatterton et al., 2011).

The length of the major road network located in areas at risk of coastal erosion is projected to increase from 1 km now and in the short-term (next 20 years) to 12 km by the 2100s (HR Wallingford for ASC, 2014). This is a very low proportion of the total network; however, the implications can be far-reaching especially if rerouting is the only viable long-term option.

Warmer summer temperatures will increase thermal loading on bridges and pavements causing expansion, bleeding and rutting which will need repairing. Repairs cannot be performed until temperatures reduce. The 2003 and 2006 heatwaves provide a useful temporal analogue of this impact (Willway et al., 2008; Defra, 2012b). Cold weather (including snow and ice) is currently a major cause of damage and disruption, causing 16% of all weather-related delays to the strategic road network in England between 2006 and 2014 (ASC, 2014). This is likely to reduce in the future, along with reduced winter maintenance costs (Arvidsson and Chapman, 2011).

Wind effects road operations as high sided vehicles can become unstable in gusts of wind over 45mph, this is particularly significant on exposed sites such as bridges. High winds can also damage roadside furniture, such as traffic signs, and blow nearby vegetation onto the road. There is no evidence for increased incidence, and most failures of objects such as road signs are considered to be due to inadequate foundations (Galbraith et al., 2005).

Rail transport

As with road transport, weather already significantly impacts upon the rail network (Figure 4.9), particularly in winter (storms and flooding), autumn (leaf-fall) and summer (buckling). Weather causes approximately 1.6 million delay minutes on the railway each year and a comprehensive overview of all causes of disruption is available in RSSB (2015). Due to the increasing number of passengers using rail travel, weather- and climate-related train delays will have an increasingly greater impact. Landslides are also a key factor for the rail network, which is disrupted by approximately 50 landslides per year as highlighted by the recent failure between Leamington and Banbury (Dixon, 2008).

Presently, 580 stations and 2,400 km of the railway in the UK cross areas at a high risk (>1-in-75 years) of flooding (Sayers et al., 2015b for the ASC). Based on this methodology, the number of stations that cross areas at high risk is projected to increase by 10 – 28% by the 2080s, while the length of track in areas of high risk could increase by 41 -120%. However, much of this infrastructure is elevated and can be above flood levels.

Less than 1% (11 km) of the rail network in England is located in areas potentially at risk of coastal erosion now and within the next 20 years (HR Wallingford, 2014, for ASC).[6] These areas are all protected by sea walls. However, coastal defences can fail, with potentially highly disruptive consequences. This was seen at Dawlish during the 2013/14 winter storms where an 80 m section of sea wall collapsed, severing the main rail connection to south-west of England for around two months (Dawson et al., 2016). Less publicised was the loss for 17 weeks of the link between Harlech and Barmouth in North Wales. The length of the rail network in England exposed to coastal erosion is expected to increase to 38 km by the 2050s and to 62 km by 2100 (HR Wallingford, 2014, for ASC).

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[6] Of the 11 km currently at risk, none is classed as Category 1, 16% is in Category 2 (including Dawlish), 40% is in Category 3 (mostly in the south-east in areas like Hastings), 8% in Category 4 (mostly in the south-west) and 36% in Category 5 (in the north-west and south-west). These categories are based on the average cost of a delay, Category 1 being the highest.

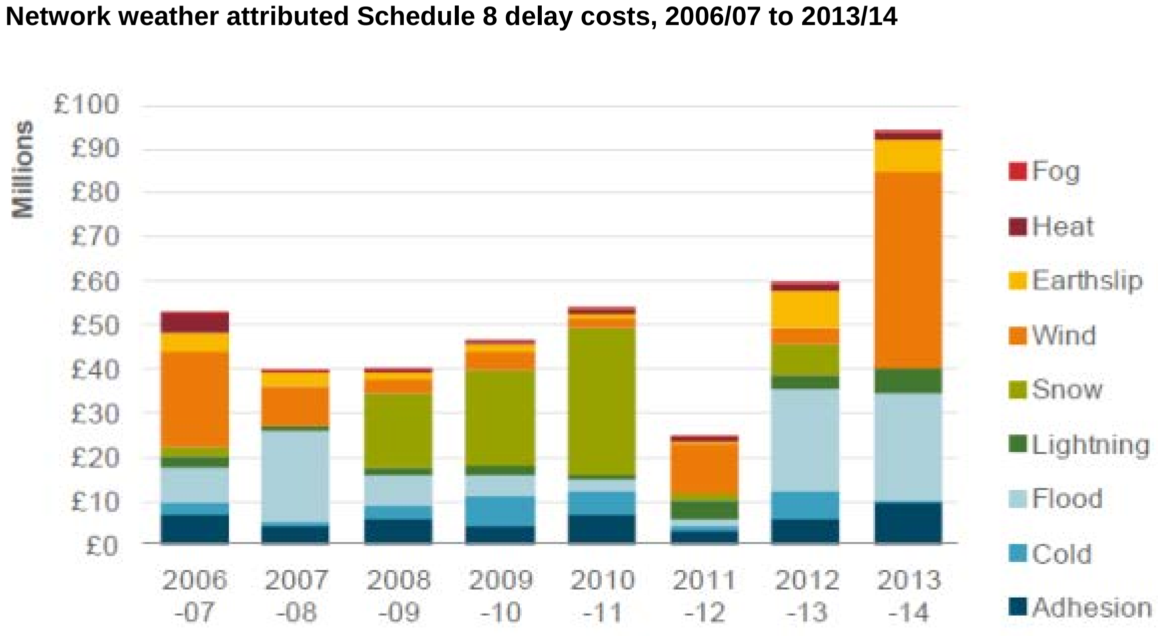
The most significant risk from higher temperatures is buckling. In 2003, 137 rail buckles cost £2.5 million in delays and repairs. Buckling events are expected to be four to five times more frequent by the 2050s (Jenkins et al., 2012). By the 2080s, the annual cost of buckling and heat-related delays under a high climate change scenario could increase eightfold (Dobney et al., 2009). Temporary speed restrictions are imposed to manage the potential likelihood and consequences of track buckles on the rail network. They are projected to increase by a factor of four, from 0.5 days to two days per summer season (range: by a factor of 2.5 – 7, based on south-west England for the 2040s). More extreme temperatures will also:

- Increase the number of days where track maintenance cannot be carried out, this will be significant across the UK but even in Scotland there will be a threefold increase,
- Increase overhead power cable sagging in hot weather. For example, the frequency of sagging is projected to be 2 – 7 times higher in south and east of England,
- Increase the exposure of staff working outdoors to heat stress, most significantly in the south and east of England where events could be 2 – 9 times more frequent by the 2040s (Palin et al., 2013).

On the rail network, 5% of all passenger disruptions between 2006 and 2013 were due to high winds. The majority of damage is caused by trees or substantial branches being blown on to railway tracks, blocking lines, causing damage to trains and bringing down cabling. There are an estimated 2.5 million trees growing near to the rail network, and during the winter of 2013/14 there were 1,500 incidents of trees and other foreign objects being blown onto tracks. It is estimated that 60% of wind-blown trees came from land not owned by Network Rail. There are large uncertainties surrounding the impact of climate change on vegetation which are crucial to better understand to mitigate potential changes to vegetation growth rates, species, and leaf-fall (Carey, 2015).

There will be opportunities arising from fewer snow and ice days to reduce winter maintenance costs (Dora, 2015). Snow and ice currently account for 30% of weather-related delays (~7% of all delays) to rail services in England and Wales (ASC, 2014).

Figure 4.9. Current extreme weather impacts on Network Rail routes



Source: Network Rail (2014) *Weather and Climate Change Resilience Adaptation Plans*.
Note: Section 8 costs are those payments made by Network Rail as a contractual financial transaction to pay Train Operating Companies for non-availability of timetabled train paths. These figures only relate to Network Rail costs with other costs attributed to other rail organisations.

Underground infrastructure can be of particular concern, both for pluvial and groundwater flooding and for thermal comfort (e.g. Transport for London, 2015; COLC, 2014). Under high climate change scenarios, all deep London Underground lines could experience near complete passenger discomfort, and while cooling on trains provides substantial benefits it may not be enough (Jenkins et al., 2014). See Chapter 5 for further details on this risk.

Air transport

The impacts of climate change on UK aviation are expected to be the least significant of all transport modes. The largest challenges are currently due to extreme weather (Heathrow Airport, 2011). Snow and ice continue to be a problem as evidenced by the heavy snow of December 2010 (Begg Report, 2011), although this risk is expected to be reduced with climate change (Brown et al., 2010). Fog is a perennial problem, but the projections for fog impacts with climate change are limited and of low confidence (Boorman et al., 2010). Flooding impacts are generally limited for airports but can cause problems for surrounding infrastructure (e.g. McMilan, 2014). Gatwick Airport did, however, experience major flooding on Christmas Eve 2013, with intense rainfall leading to flooding of power and IT equipment in the basement of the North Terminal. The disruption of power systems led to the loss of baggage reclaim facilities, check-in and flight information systems, telephone communications and luggage screening equipment. Flooding of the M23 and closure of the Gatwick train station also affected staff and passenger travel to the airport.

Higher temperatures may cause problems with runway conditions and the flashpoint of aviation fuel. These factors, combined with changes in air density, would result in greater fuel usage and potentially longer runways for take-off (Heathrow Airport, 2011) – although expected changes are well within the range of other international airports and can be managed operationally. Changes in airfield grasses or other changes in climate space could affect species of nesting birds close to airports, increasing or decreasing the risk of bird strike.

Water transport

Ports and harbours have a vital economic role, receiving 95% of the UK's imports and exports as well as more than 40 million passenger journeys (Brooke, 2015). Presently, extreme weather causes the most disruption to operations (Wade et al., 2013) and climate change will increase this. Half of the UK's port capacity is located on the east coast, where the risk of damage from a tidal surge is greatest. A number of ports were affected by the December 2013 tidal surge, though most were able to resume services promptly. However the Port of Immingham near Grimsby was severely impacted when tide levels reached 0.5m above the dock gates. Critical power and IT services were lost and the port ceased operation for a number of days. Of the port area, 75% was flooded, which also impacted businesses located within the port boundary. Immingham is strategically important for petro-chemicals and fuel, including biomass for energy generation. Many ports only handle specific cargos, with the largest specialised ports handling twice or more traffic than their next biggest competitor. This lack of redundancy means any disruption to major ports will have wider economic consequences (ASC, 2014).

Sea-level rise of around or beyond 50cm by 2080 is a particular concern (MCCIP, 2013), especially for some ageing port infrastructure, but flooding and physical damage to harbour infrastructure will also become an increasing threat. It is unclear how dredging requirements will change in the sector. While ports will be resilient to erosion, the impact of changes in erosion and sediment transport in the wider catchment are likely to lead to an increased need for dredging (Brooke, 2015). Additional impacts on shipping and navigation could arise from changes in high winds and wave action but these are also uncertain. This includes ferry services that connect islands around the UK, and analysis by Coll et al. (2013 showed that any deterioration of the wave climate will result in a disproportionately large increase in ferry-service disruption to the Western Isles of Scotland.

Inland waterways in the UK are presently mostly used for recreation. The infrastructure is ageing and therefore particularly vulnerable to the impacts of climate change. The impact of climate change on canal and river flows is highly uncertain with potential changes relative to the present ranging from −20% to +80% by the 2080s. Low flows during droughts (exacerbated by water supply and demand in others sectors, see Chapter 3, Section 3.6) will restrict navigation, whereas high flows caused by high rainfall could increase localised flooding and erosion. High rainfall in November 2012 led to breaching of the Grand Western Canal in Devon (Devon County Council, 2013). Tackling these issues will require significant adaptation, particularly of older infrastructure.

4.7.3 Adaptation actions

As well as negative impacts, climate change offers a number of potential opportunities for transport infrastructure. Transport infrastructure will need to evolve to meet the needs of the growing population, particular in densely populated regions. As such there are opportunities to design and maintain new transport infrastructure for a broader range of climate conditions, thus improving resilience in the sector. The most pertinent example of this opportunity is presently

High Speed Rail 2 which has been specifically designed to have a high level of climate resilience (as an example, see HS2, 2013). With respect to existing infrastructure, there is evidence of adaptation across the sector.

Increasing adaptation measures (including both engineering solutions and new smarter technologies) are likely to be needed to keep the road network running efficiently regardless of changing weather conditions. Transport and local authorities are developing, and starting to implement, a range of actions to understand and map risks, inform users, and implement actions to manage risks (Transport for London, 2015; Newcastle City Council, 2016). Additionally, new codes for pavement design and improvements in existing and new road drainage systems have been developed (Highways Agency, 2009) underlining the continued need for increased dialogue between those responsible for local and national maintenance.

There is much evidence of site-specific measures being incorporated for each of Network Rail's eight routes in Great Britain (Dora, 2015). This has mostly centred on embankment stability, coastal defences and bridge stability (Network Rail, 2011). Network Rail has launched a Vegetation Management Capability Development Programme to introduce new standards and action to manage lineside growth. The budget for vegetation management was increased by £10 million (60%) in 2014/15. Some train operators have altered the specification of future rolling stock. Analysis by Jenkins et al. (2012) shows that upgrading to high-quality track (designed to be operational at temperatures of 39°C) reduces the frequency of buckling events, even under high climate change scenarios in the 2050s, to below present levels. However, systemic adaptation is not strongly evident across the railway network and there is a significant legacy challenge of ageing infrastructure, with both the industry and regulator recognising that historic investment in ageing structures has been insufficient to deliver acceptable levels of risk in the long term (ASC, 2014). There is a significant backlog that will require sustained investment over the next 40 – 50 years to clear. Models have been developed by Network Rail to forecast the amount of investment and volume of renewals required for civil engineering structures, including earthworks, tunnels, bridges and sea walls. However, these models do not account for projected changes in climate but instead assume that the weather experienced in the future will be similar to what is has been in recent years. In the regulator's assessment, Network Rail has not sufficiently embedded climate resilience into specifications for the design of its assets, or in the standards the company sets for asset maintenance and renewal (ASC, 2014). Future progress largely depends on reviews of weather and climate change risk programmes and, ultimately, the level of investment allowed for by the regulator.

The rail network has a range of funding pressures, and it is unclear if there will be adequate investment over time to avoid heat-related impacts on passenger and freight travel. Overall, further research is needed to establish the scale of the long-term adaptation challenge (including reassessment of critical thresholds: RSSB, 2015), improve dialogue between operators, and prioritise areas for cost-effective investment. Indeed, 120 recommendations were made following the first phase of work in Tomorrow's Railway and Climate Change Adaptation project (RSSB, 2015) but the amount of investment needed to adapt rail assets to higher temperatures is unknown at present.

Airports have focused on actions to minimise disruption from extreme weather, including from flooding. The cascade of failures from the Christmas 2013 flooding of Gatwick Airport led to the McMillan report (David McMillan, 2014) that identified a number of failings in Gatwick's infrastructure resilience and operational procedures with the recommendations now being used as a blueprint for airport resilience more generally.

Ports are not subject to economic regulation. As a result, there is a general lack of data regarding the overall resilience of ports compared to most other regulated sectors. This means it is difficult to tell whether lessons from the winter of 2013/14 have now been learned and whether the disruption witnessed is likely or not to be repeated. Equipment in ports typically has a 20 – 100 year design life. Modern assets will already be resilient to sea-level rise, but retrofitting ageing infrastructure (e.g. raising quays) is technically complex and expensive (Brooke, 2015), although ARP2 returns show some ports are raising quays by as much as 50cm, as well as taking action to protect supporting road infrastructure from flooding. Several ports are collaborating with other local partners to co-fund adaptation options to the benefit of ports and surrounding areas.

4.8 Energy infrastructure

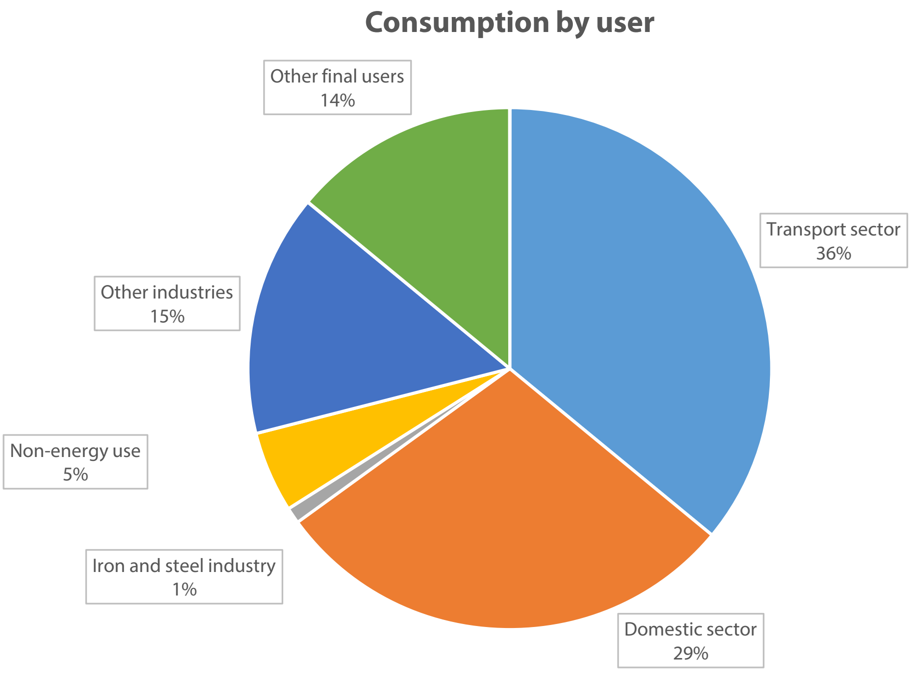
This section summarises the climate change risks and opportunities relating to the generation, transmission and distribution of electricity together with oil and gas networks and supply chains.

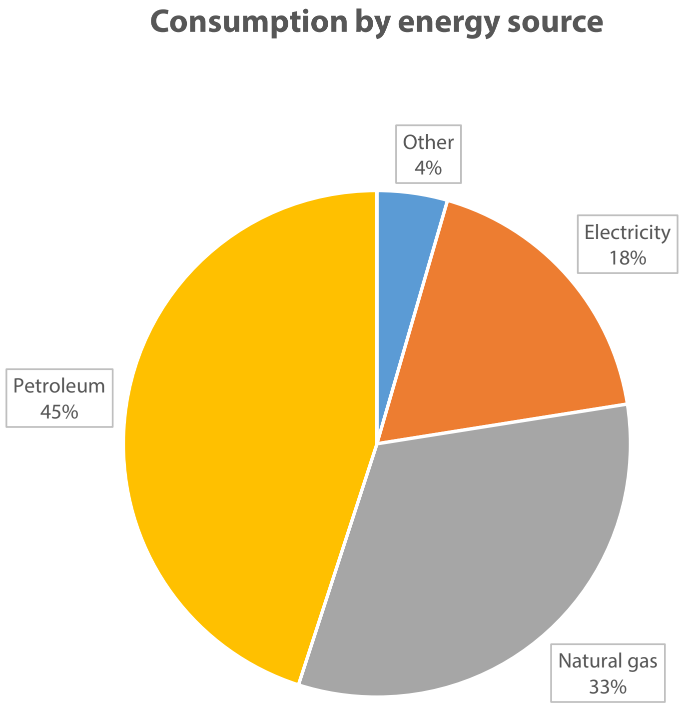
4.8.1 Overview of sector and policy

The UK energy industry provides the country with around 200 Mtoe each year (million tonnes of oil equivalent), dominated by fossil fuels – 84.5% in 2014 – and has exported 70 – 80 Mtoe (930MWh) annually over the last five years (DECC, 2015a). In 2014, 46% of primary energy supply was imported following a record high of 47% in 2013. The imports are primarily in the form of oil and petroleum products – following a downward trend of output from the North Sea oil and gas fields coupled with maintenance and closures of facilities. Although the share of imported energy supply is increasing, primary energy demand fell by 6.3% during 2013 – 2014, attributed to record warm weather in 2014 resulting in a reduction in demand for heating (DECC, 2015a). On a temperature-corrected basis, during 2000 – 2014 primary energy consumption fell by 17% reaching a low level of demand not seen since prior to 1970 (DECC, 2015b). The major users of energy in the UK and relative contribution of fuel and power are presented in Figure 4.10, which highlights current dominance of the transport sector and domestic households as major energy consumers and of petroleum and gas products in meeting their demand. When discussing climate impacts on the UK in the 2050s and 2080s it is important to do so in the recognition that the energy system will likely have changed significantly from that of today; however, no one can predict for certain how it will change.

Future scenarios of the UK's energy system from the National Grid illustrate how the relative balance between fuel and power supply and demand levels may change out to 2035 in response to drivers including prosperity and climate policy (National Grid, 2015a). They depict a diverse set of futures, each with potentially different exposure to climate impacts than today's system. These are discussed in more detail in Section 4.3 above (cross-cutting issues).

Figure 4.10. Final consumption of energy in 2013 by user and energy source





Source: DECC (2014), Chart 1.5. Other final users include services and agricultural sector. Other energy sources include coal, manufactured fuels, renewables and waste, and heat sold.

Long-term changes to the UK energy system are anticipated in response to climate mitigation policy. These changes are likely to affect both supply and demand, and include a greater use of lower carbon energy sources, including renewables, nuclear power and carbon capture and storage technologies, and supporting the increased electrification of transport and heating. These changes in supply and demand will likely be accompanied by changes to the electricity transmission and distribution system as smart technologies and practices are increasingly integrated into energy infrastructure, and interconnection capacity is increased. The changes present opportunities to enhance the overall resilience of the energy infrastructure network to climate change, as well as potential trade-offs. However, reducing the diversity of energy supply through electrification can reduce the resilience of individual households in certain circumstances – for example a power cut would affect cooking and transport to a far greater extent and thereby reduce householders' abilities to cook food, prepare hot drinks, keep themselves warm, or travel to somewhere with power during extended power cuts (Abi Ghanem et al 2016; Mander et al., 2015). Studies which assess the relative exposure of alternative and distributed energy systems to climate change impacts are limited.

The different components of the energy system and current trends are described in further detail below.

Oil and gas

Indigenous oil and gas production currently supplies approximately 38% of UK primary energy (DECC, 2014). Offshore oil and gas is piped or shipped to the UK mainland to one of the five oil terminals and seven gas terminals currently in operation on the coast (DECC, 2014). While onshore oil and gas fields represent a small fraction of current production, recent discoveries of shale gas lends potential for growth in this area. Crude oil (both produced indigenously and imported) is refined at one of six UK refineries, each located in close proximity to a terminal and port. Refinery products are stored on-site and, coupled with imported petroleum products, distributed via pipeline, inland waterways or rail to additional terminals located closer to major conurbations, and from there to end-users by road.[7] Natural gas (both indigenous production and imported) and liquefied natural gas (LNG) are distributed around the country from gas terminals by the high-pressure National Transmission System operated by the National Grid in England, Wales and Scotland (National Grid, 2015a), and from there on to consumers via the lower pressure Local Transmission System operated by a number of different companies. Northern Ireland receives gas via an interconnector with Scotland, from which it is distributed by local companies.

Renewables

Renewable energy sources have grown over the last decade, from less than 3% in 2000 to 19.7% of electricity generated in 2014 (DECC, 2015b). Electricity dominates the contribution of renewable energy, followed by heating then transportation fuels. Bioenergy sources have the greatest share of renewables in terms of input; however, wind, hydro and solar provide a larger contribution as output due to conversion losses from the generation of power (DECC, 2014). The UK currently generates 1.2TWh from waste through combustion technologies, which is expected to rise to 3.1-3.6TWh by 2020, and energy from anaerobic digestion is expected to rise from 1.1TWh to between 3-5TWh on the same time frame (DECC and Defra, 2013). Although

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[7] http://www.ukpia.com/docs/default-source/default-document-library/ukpia-2015-statistical-reviewf72b5c889f1367d7a07bff0000a71495.pdf?sfvrsn=0

anaerobic processes are sensitive to temperature, higher temperatures will accelerate rates, and the risks from climate change are low.

Renewable sources are growing, between 2012 and 2013 wind output grew by 30% and generation from plant biomass doubled (DECC, 2014). Microgeneration has grown significantly after the introduction of feed-in tariffs; units installed by domestic consumers produced 940 GW in 2014, which equates to 0.9% of domestic electricity consumption compared to 0.2% in 2012 (DECC, 2015a). Contributions of renewables to the UK's energy mix are expected to continue to grow in compliance with the 2009 Renewable Energy Directive and greenhouse gas mitigation objectives set out by the UK Climate Change Act 2008. Most renewable energy sources are heavily influenced and even reliant on the weather: wind power is only operational within average wind speeds of 3 – 25 metres per second; hydropower is reliant on precipitation and river flow; solar on irradiance; and bioenergy production, as an agricultural (by) product, is intimately linked with climate and the growing seasons. Renewable generation capacity varies across the UK with implications for adaptation; in 2015 Scotland provided 26.4% of the UK's total renewable generation, whilst 57.7% of Scotland's electricity was from renewables.

Electricity generation, transmission and distribution

Non-renewable UK generation comes from large thermoelectric plants comprising nuclear, coal, gas, oil (as well as biomass). Thermoelectric plants rely upon a supply of cooling water (occasionally they may be air cooled) and most are situated on rivers or coasts to ensure a ready supply of water (Murrant et al., 2015). All nuclear power stations use seawater for cooling and all major fossil-fuel power stations in Wales, Scotland (of which only one will remain from spring 2016) and Northern Ireland are similarly located on the coast. However, there a number of major producers in England that draw on freshwater sources (as discussed in Section 4.3). Due to their locations and reliance upon cooling, electricity generation plants may be exposed to flooding and are vulnerable to climate impacts that affect cooling water supply. The Government has announced that existing coal-fired power stations will be closed by 2025 and their use restricted by 2023; a number of nuclear plants including Hinkley Point B and Hunterston B are also due for closure over the same time period. However, there are plans in progress for a number of new nuclear, combined-cycle gas turbines and new biomass plants to be built. Pumped hydroelectric schemes in Wales (Dinorwig and Ffestiniog) and Scotland (Foyers and Cruachan) provide energy storage and balancing services on the network with a total installed capacity of 2,888MW. There are plans to expand the current capacity to support increases in intermittent generation with new schemes under consideration in Scotland.

Electricity is distributed through a 400,000V and 275,000V transmission network (which also includes 132,000V in Scotland) and the lower voltage distribution networks of 132,000V and below. Generation has historically been dominated by large installations directly linked to the transmission network. However, policies that have encouraged micro and embedded generation are increasing the amount of supply feeding into distribution networks. For example, installed photovoltaic (PV) capacity provided 0.7% of domestic consumption in 2013, and is projected to increase. These trends contribute to the challenges of climate change on the network; however, the use of 'smart' grid or network technologies that can support the uptake of microgeneration (and increases in the use of EVs and heat pumps) may have an additional role in adaptation – this potential is not yet fully identified (ENA, 2011; Blake et al., 2015).

Interconnections and supply chain

The UK's energy system is connected to mainland Europe by electricity interconnectors to France, Ireland and the Netherlands. Over the next decade, there are plans to increase the number of electricity interconnectors and overall capacity, including connections to France (IFA2 and FAB), Belgium (Nemo) and Denmark (Viking Link) (National Grid, 2016). Increasing interconnections is important for security of supply and for balancing increasing levels of intermittent renewables (National Grid Interconnectors, 2014). Increasing the capacity of interconnectors may offset any temporary losses in UK supply due to climate change impacts. The risk of simultaneous stresses (including extreme weather) across a number of interconnected countries are being considered by DECC and Ofgem as part of the arrangements for new interconnectors (DECC, 2015c; House of Lords, 2015).

Net imports of primary energy to the UK have increased over the last decade, following the closure of coal mines alongside long-term declines in oil and gas outputs (DECC, 2014). Imports are mainly in the form of fossil fuels, via three gas pipelines connecting the Sleipner gas field to Easington Gas Terminal and linking Belgium and Netherlands to the Bacton Gas Terminal. In addition, imports of oil and petroleum products arrive by sea to ports around the coast and LNG is received into three import terminals in Great Britain (National Grid, 2015a). Bioenergy imports accounted for approximately 40% of the UK's total wood- and plant-based biomass supply in 2014 (DECC, 2015a).

Key policies

The overall approach to energy supply is set by the Energy Acts and described in the UK Government Energy Security Strategy (DECC, 2012). Under the Energy Act 2013, DECC may charge fees for providing energy resilience services in the event of any disruption or threatened disruption to energy supplies including those caused by extreme weather conditions.

Energy infrastructure operators may be requested by the Secretary of State to prepare a climate change risk assessment and adaptation strategy under the Climate Change Act 2008 (Adaptation Reporting Power). For the first round of the ARP in 2009, Energy UK reported on behalf of 10 major electricity generation companies,[8] along with the Energy Networks Association (ENA), National Grid and the economic regulator (Ofgem). A further 11 electricity transmission and distribution companies and 8 gas transporter companies also reported. As of April 2016, 17 organisations had voluntary reported under the second round of the ARP.[9]

For new major energy infrastructure projects (including in some cases changes to existing assets) the consideration of climate impacts are required. In England and Wales, an overarching National Policy Statement (NPS) exists for new energy infrastructure (DECC, 2011), together with separate NPSs for fossil fuel and nuclear generation, renewables, electricity networks and oil and gas infrastructure. NPSs set out the considerations that should be made by infrastructure developers when planning the location, design, build, operation and decommissioning of new energy infrastructure. These include consideration of the impacts of climate change on the development and the resilience of the project to climate change impacts.

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[8] Defined as those that generate over 10TWh.

[9] Note that Energy UK has produced a sector report on behalf of 10 electricity generation companies. All 14 Distribution Network Operators (DNO) in Great Britain have reported, although this makes up only 7 reports in total as a number of DNO licences are held by the same companies.

For existing and new oil and gas offshore industry, guidance on the preparation of safety cases include consideration of the structural standards of offshore infrastructure and the weather events to which it may be exposed. This is particularly in regard to wind and wave height through the Offshore Installations and Wells (Design and Construction, etc) Regulations (DCR) (SI 1996/913) and the Offshore Installations (Safety Case) Regulations 2005 (SCR) (SI 2005/3117). Offshore renewable energy installations (including wind, wave and tidal) are subject to consent through a regulatory regime established by the Energy Act 2004, managed by the Marine Management Organisation (England and Wales) and Marine Scotland. The relevant NPS (England and Wales) requires applicants of both offshore and onshore wind farms to set out how their proposals will be resilient to storms. There is currently no guidance for offshore tidal or wave energy as these are seen as emerging technologies (DECC, 2011).

New energy infrastructure and extensions to existing schemes will generally require an environmental impact assessment under the Infrastructure Planning (EIA) Regulations 2009 that cover England, Scotland and Wales and the Planning (Environmental Impact Assessment) Regulations (Northern Ireland) 2015. Current legislation does not explicitly consider the impacts of climate change on infrastructure; however, the 2014 update of the EU EIA Directive extends the list of impacts to be considered to include climate change vulnerability impacts where this may go on to cause environmental impact if the site were affected.

4.8.2 Climate risks

The energy system is designed to operate under the range of weather conditions experienced in the UK. Design specifications for equipment and assets are based on the significant variations in weather within the current climate. Operational activities, such as maintenance are normally timed to reduce the risk of being disrupted by high winds or lightning.

Byers et al. (2015) distinguish between short-term effects of extreme weather events, such as intense rainfall or high air temperatures which may exceed asset design standards causing failure, and long-term (chronic) impacts such as changes in mean temperature or rainfall patterns which may alter the long-term performance of the energy systems. Both types of impacts were covered in the CCRA1 for the energy sector, which gave a comprehensive overview of the key climate risks to the energy sector. Since CCRA1 there is a greater understanding of the impacts of climate change on UK electricity distribution and transmission networks as well as renewable generation. However, there are a number of risks highlighted by CCRA1 that have not been further quantified. These include:

- impacts of higher water and air temperatures on thermal plant;
- future bioenergy yields;
- offshore infrastructure (including oil and gas extraction, wind, tidal and wave);
- LNG, oil and gas terminals;
- international supply chains and the infrastructure they rely upon
- confounding impacts across the energy system (e.g. drought and temperature increase on demand and supply);
- underground coal gasification;
- carbon capture and storage;
- shale gas extraction, and;
- future energy demand.

The updated evidence published since CCRA1, for a number of the key risks described, provides some additional evidence with respect to emerging challenges and is set out below.

Electricity generation, transmission and distribution

Thermoelectric generation plants can be exposed to flooding, due to their location proximal to cooling water supplies and are vulnerable to temperature increases or restrictions on cooling water availability. Electricity transmission and distribution assets, primarily substations, are often located near population centres, including those on the river and coastal floodplain.

Sayers et al. (2015b) for the ASC identifies 25 major electricity generation stations and 326 major electricity transmission and distribution sub-stations[10] in the UK located in areas currently exposed to a 1-in-75 or greater annual chance of flooding from rivers, the sea or surface water. In 2013, 683,000 customers along with three water treatment works and one hospital were directly reliant on the 57 major substations located in areas at the highest risk of river or coastal flooding.[11] This is projected to rise to nearly 1.2 million customers by the 2020s due to increased flood risk (ASC, 2014).

HR Wallingford (2014) for the ASC indicate that in England, 18% of power stations are located in areas that are highly susceptible to ground water flooding with most in the East Midlands, and 6% in areas that may be susceptible to surface water flooding at a depth of 0.3 – 1.2m. Whilst major generation assets typically benefit from a high level of flood protection (Energy UK 2015; Scottish and Southern Energy Power Distribution 2015), only a proportion of substations currently have flood protection (ENA, 2015).

Nearly 14,000 customer minutes were lost from the high-voltage electricity network due to flooding between 1995 and 2011. This amounts to around 1% of all disruption (ASC, 2014). In December 2015, Storm Desmond caused at least 40 weather-related faults to Electricity North West's network, including the flooding of a substation in Lancaster resulting in a loss of power to 55,000 customers (ENW, 2015). Although less frequent than other weather-related causes of disruption, flooding causes the longest average length of disruption per incident. McColl et al. (2012a) projects the frequency of faults caused by flooding as a result of heavy rainfall could increase by 25 – 125% in the 2080s (high emission scenario). However, the location and depth of flooding also depends on topography, soil moisture and land use which have not been considered in this analysis.

Other extreme weather events that currently lead to faults on the electricity transmission and distribution network include high winds, solar heat, lightning, heavy rain, snow and sleet. McColl et al. (2012a) report 62 weather-related faults on the transmission network and over 9,000 on the distribution network between April 2008 and March 2009, causing 1.9 million customer interruptions of 3 minutes or longer. Without adaptation, increases in weather-related faults in the electricity distribution and transmission network can be anticipated (McColl et al., 2012a).

High winds are a significant cause of disruption to electricity networks, causing 20% of all customer disruption between 1995 and 2011 (ASC, 2014). Over 2 million customers suffered power cuts in the winter storms of 2013/14, of which 16,000 were without power for more than 48 hours (ENA, 2015). The majority of damage and disruption to the electricity distribution network from high winds is due to trees and branches falling onto power lines. Tree-related faults on the UK's network significantly increased between 1990 and 2006. The observed

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[10] Defined as substations that provide electricity to 5,000 customers or over.

[11] Defined as a 1-in-30 or greater annual chance of inundation.

increase in the duration of the growing season, which has gained ten days in Northern Europe since the 1960s, is likely to be contributing to this trend. Drought or periods of heavy rain followed by high winds can increase the risk of trees falling onto overhead lines and projected extensions in the time that deciduous trees are in leaf due to climate change can increase the risk of storm damage (ENA, 2011). Research for the Energy Networks Association, suggests that significant increases in vegetation management are needed to counteract expected increases in the duration of the growing season and potentially increased rates and density of growth (ENA, 2011), although possible changes vary according to species and are uncertain (Carey, 2015). No statistically significant changes in impacts caused by wind or gale were identified based on current relationships between weather and faults (McColl et al., 2012a). Analysis by Panteli et al. (2015) assessing impacts of extreme wind speeds on the structural integrity of the transmission network concludes that the system has a low probability of failure even with high wind speeds.

Lightning strikes were responsible for just over 7% of customer minutes lost due to disruption of electricity distribution networks between 1995 and 2011 (ASC, 2014). McColl et al. (2012a) project an increase in the numbers of faults on the electricity transmission and distribution networks, between 4 – 36% by the 2080s in the region analysed. This study used the SRES A1B scenario (UKCP09, 2009), i.e. between a 2°C and 4°C climate scenario by the 2080s.

Cold weather (snow and ice) were responsible for 5% of customer minutes lost due to disruption of the electricity distribution network between 1995 and 2011 (ASC, 2014). Electricity network faults due to snow, sleet and blizzard are projected to decrease across Great Britain, analysis for one region shows a 70 – 90% decrease in faults by the 2080s (McColl et al, 2012a).

ENA (2011) estimate that increases in ambient temperatures across the UK due to climate change would lead to line de-ratings (reduction in maximum capacity) of 6 – 10% for typical distribution lines and 2 – 4% for typical transmission lines under a high emissions scenario for the 2080s. ENA (2011) also estimates that de-ratings on underground low voltage cables would be within 2 – 4% in the 2080s (high emission scenario) and 2 – 7% for cables carrying 11 kV and above for the same timeframe (ENA, 2011). Higher temperatures also reduce the efficiency of transformers, with ENA (2011) estimating a reduction of 4 – 7% for 11kV and 3 – 5% for >33kV transformers for the 2080s (UKCP09 high emission scenario at the 90% probability level). Analysis by Hu (2015) supports these assessments of average changes, but shows that some components could de-rate by as much as 27% in some summer days in the 2080s.

This climatic component of de-rating adds to the effect of other drivers that, based on current projections, are expected to place greater pressures on the need to uprate cables. For example load increases, which include low carbon loads such as electric vehicles, have been recorded at up to 2% per year by some distribution network operators.

Changes in climate, in particular mean and extreme temperature, could affect annual UK energy demand and alter the seasonal, daily and spatial variation of demand from buildings (domestic and service sector), transport and agriculture (Wood et al., 2015). For example, McColl et al. (2012b) projected a rise in the number of days when a building requires some form of cooling from 25-50 days per year at present to 125-175 days per year by the 2080s (medium emissions scenario) in the south of England, but a more limited rise of only 25-50 days per year in the north of England and Scotland. Where lines and equipment already operate close to capacity the combination of increased demand from new and low carbon technologies, climatic de-rating, and altered demand profiles as a result of climate change may bring forward upgrade requirements.

The deformation of the ground has the potential to damage the foundations of buildings and other infrastructure. One of the most widespread forms of subsidence is the shrinking and swelling of clay soils due to excessive rainfall, drought or land use changes. Susceptibility to shrinkage of soil is influenced by the rainfall of the preceding two-year period. Increased temperatures also lead to more evaporation and evapotranspiration which, in turn, leads to further drying and shrinking soils. Susceptibility of underground energy assets, such as gas pipelines and electricity cables, as well as some above ground assets like electricity pylons and telecommunication towers is high in areas where clay soils dominate, such as around London and the east of England. Over one-third (35%) of high voltage (132 – 400kV) subterranean electricity cables, 12% of high pressure (>66barg) natural gas pipelines and 8% of high voltage (>400kV) electricity pylons in England are located in areas of high susceptibility to shrink–swell subsidence (HR Wallingford for the ASC, 2014). The same study also identified that less than 1% of underground high-pressure natural gas pipelines in England are located in areas that may be at risk from coastal erosion now and in the long term.

The need for cooling water by thermal generating plant is highlighted in Section 4.3. However, onshore shale gas extraction also requires water resources for drilling and fracturing, with estimates per well reportedly ranging from 7,700 to 31,000m^3 over its life. Alternative petroleum based liquids are being explored but are not yet commercially available (Stamford and Azapagic, 2014). The number of wells that could be drilled in the UK is uncertain at this stage, but analysis has suggested that to meet 10% of UK gas supply would require 27,000-113,000 Ml of water, which is equivalent to between one and six days of public water supply (House of Commons Energy Committee, 2011).

Offshore infrastructure

One of the areas not captured in detail by CCRA1 was the potential impacts of climate change on the offshore energy industry. This includes offshore oil and gas production and distribution as well as offshore wind and wave generation. Offshore infrastructure is vulnerable to high wind speeds, large wave heights, strong currents, fog and lightning, causing disruptions to maintenance, operations and movements of the infrastructure and personnel (HSE, 2005). More extreme events can lead to oil and gas production time being lost (Kaiser, 2008) and wind turbines will cut out and stop producing power at speeds above 25 m/s (Craddon et al., 2015). It has been estimated that extreme weather conditions have caused about 80% of all North Sea offshore turbines to sustain failing grouted connections, causing some turbines to tip and no longer stand vertically. This has primarily been in monopole turbines, which can experience bending movement in the grouted joints between the monopole and the transition piece, resulting in the need for urgent repairs. Moreover, dissolved or cracked grouting has caused these turbines to shift on their foundations (Diamond, 2012). Although these risks are well understood by the industry, information on how climate change could affect these risks is lacking. It is not possible to assess the magnitude of climate change on these sectors without further analysis; a particular limitation is the lack of appropriate climate projections for offshore areas.

Additionally, seafloor conditions such as scour and sand dune migration are often underappreciated risks, as are extreme weather impacts on such conditions (Diamond, 2012). Seafloor dynamics, including wave conditions, tides, currents and water flow velocity, can create chronic scour, or the depletion of seabed sediment. Scour can cause erosion around turbine bases located in sandy soils, making turbine foundation anchoring less sturdy and reducing turbine stability. Many North Sea offshore turbines are located in seabeds of mobile sediments and research by Diamond (2012) shows that turbine foundations on mobile sediments are potentially susceptible to scour impacts. Such effects would be expected to be most significant in monopoles in relatively shallow water, and therefore be of more importance for windfarms in the southern North Sea. Extreme weather causing seafloor sediment to be more mobile than anticipated could result in higher scour incidents than currently envisaged, potentially causing cable exposure. Relaying or repairing cables requires highly specialised vessels and personnel, and the global increase in the demand for these vessels for wind farm installations may make access to them at short notice both difficult and costly.

The coastal infrastructure that supports oil and gas operations in the North Sea includes gas terminals, ports and associated refineries. Climate risks to ports and the road and rail networks needed for distribution of many petroleum products are addressed in Section 4.5. Rough seas can prevent ships docking, temporarily limiting arrivals of fuel to the UK; similarly disruptions to road or rail networks will affect fuel distribution. The infrastructure is also potentially exposed to coastal erosion, sea-level rise and flood risk. A systematic review of the current exposure of all these assets to climate impacts is lacking. However, a number of refinery sites in Great Britain have been identified as being in existing flood risk areas (Environment Agency, 2009b; SEPA, 2015) and plans are at different stages of mitigating these risks.

Renewable energy

Climate change presents both risks and opportunities for renewable energy generation. Burnett et al. (2014) project a 3.9% increase in annual solar resource (medium emission scenario at 50% probability in the 2080s), with most increases in the south of England (6.8% increase) and slight decreases in the north of Scotland (−0.3%). PV panel efficiency decreases with increasing temperatures while solar water heating efficiency improves.

Cradden et al. (2015) conclude that the scale of impacts of wind power generation due to climate change on wind speeds will likely be small, highlighting the uncertainty in climate projections of future wind speeds. The current number of on-shore wind farms in England situated in areas at risk of flooding from rivers or the sea is low (5%), with climate projections this fraction increases to 14 – 43% of medium-sized farms by the 2080s (low–high emission scenarios); 5% of on-shore wind farms are located in areas susceptible to shrink–swell subsidence, mainly in the east of England (HR Wallingford, 2014, for the ASC).

Hydropower output is expected to be reduced in the summer, and increased in the winter, with some studies suggesting an overall increase of up to 7% (Lehner et al., 2005), and others estimating no overall change (Carless and Whitehead, 2013). However, it is not necessarily financially viable to install turbines able to recover maximum energy from the water (Harrison, 2006), so without appropriate infrastructure the net impact of climate change on hydropower generation in the UK is likely to be a reduction. There is low confidence in changes to future projections of climate impacts on wave power resources.

Bioenergy resources in the UK and its international suppliers will be affected by climate change: elevated levels of atmospheric CO_2 and changes in temperature, precipitation and the growing season can all affect crop yields. Haberl et al. (2011) assess the impacts of climate change on global bioenergy yields from energy crops and residues, and highlight considerable uncertainty in the effects of climate change on energy crop yields. However, they find that bioenergy sourced from agricultural residues is less sensitive to climate. The use of bioenergy in steam-driven thermal power plant is susceptible to efficiency losses caused by increased ambient air temperatures. This risk is also applicable to gas-powered plants.

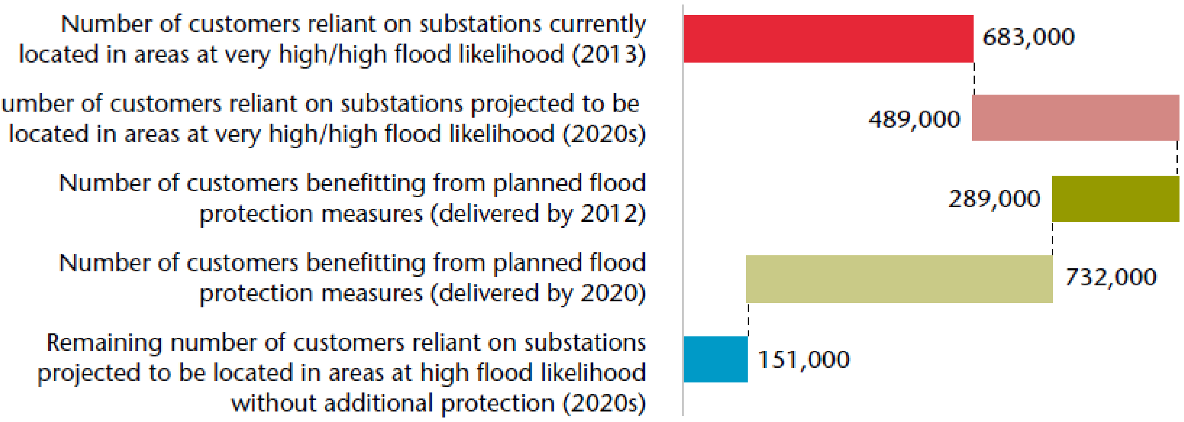
4.8.3 Adaptation actions

The electricity transmission and distribution sector has developed a cross-industry technical standard (ETR 138) for managing current and future flood risks to the network (ENA, 2009). This standard provides a consistent approach across the industry to identifying the most critical existing assets at the highest level of risk in order to prioritise action, and sets out a risk-based approach in line with planning policies for new assets. Application ETR138 is used to make a business case to the regulator for funding resilience measures that provide value for money to the consumer through the price control process. The process includes an assessment of the risks from climate change.

As a result of the ETR138 process, a total investment of £172 million in substation flood protection and resilience measures was agreed by the regulator between 2011 and 2023 (ENA, 2015). Electricity distribution companies had, by 2012, implemented flood resilience measures to 19 major substations located in areas of the highest risk (1-in-30 annual chance or greater), reducing the number of customers potentially at risk by nearly 289,000. The delivery of planned flood resilience measures between 2012 and 2020 will help to reduce the number of customers at risk by a further 732,000. However, without additional action, there will still be around 151,000 customers reliant on substations in areas of the highest risk that will not have benefitted from flood resilience measures (Figure 4.11) (ASC, 2014). This programme is under review, and new guidance (ETR 138) has been revised to include surface water flooding risk and may be reviewed further following the National Flooding Resilience Review.

Figure 4.11. Improved flood protection plans for major electricity substations located in the floodplain

Number of customers reliant on major electricity substations in areas at a high or very high likelihood of river/coastal flooding (1-in-30 annual chance of flooding or greater)



Source: ASC (2014), using data from the Distribution Network Operators' submissions to Ofgem.
Notes: The number of customers benefitting from planned flood mitigation measures delivered by 2020 includes measures taken for those substations currently located in areas of medium likelihood, but that are projected to be in areas of high likelihood by the 2020s.

Ofgem estimate that the percentage of customers in Great Britain supplied by a substation with a flood risk profile of 1-in-100 years has reduced from 59% in 2010 to 41% in 2015 and are anticipated to reduce further to 37% by 2020 (Ofgem, 2016). Sayers et al. (2015b) for the ASC show that current levels of investment in site protection of energy infrastructure will help to limit increases in risk for many decades, with the number of assets at high risk (1-in-75) only starting to increase by the 2080s under a 4°C rise in global mean temperatures. Analysis by Thacker et al. (in press) estimates that investment by the National Grid to protect assets at risk of flooding through their ETR 138 programme would reduce expected annual losses to the UK economy from power disruption caused by flooding of their assets by £14.6 million.

Adaptations to flood risk that have been used by energy generation companies include installing barriers and sea walls, permanent high-volume pumps and pipe systems, and raising the levels of new buildings and equipment. These actions may also be appropriate for other energy infrastructure at risk of coastal flooding, including refineries and gas terminals in coordination with relevant Shoreline Management Plans or Flood Risk Management Strategies. The impacts of weather and climate change on fuel supply chains are also a consideration; expanding fuel storage capacity on-site and installing flood protection measures on access roads and rail networks can mitigate some risks. Drax Power Station has a multi-port strategy with a geographic split to ensure resilience to local weather events disrupting access to a port at a particular time (Energy UK, 2015).

All UK nuclear plants are located on the coast or in tidal estuaries to provide secure cooling water access. CCRA1 identified that 12 of the 19 plants considered would be at risk of erosion or flooding in the 2080s from sea-level rise without the presence of erosion or storm surge protection. With a total cradle-to-grave life cycle of at least 160 years for a nuclear power plant site, long-term adaptation planning is crucial. As information on climate change projections is limited after the 2100s, Wilby et al. (2011) describe how safety margins can be incorporated from the outset with flexibility of design to enable later retrofit and upgrade of protection if necessary. When combined with routine environmental monitoring, long-lasting coastal infrastructure can be adaptively managed throughout its life cycle in a similar way to the Thames Estuary 2100 plan described in Section 4.4.

Significant investments are being made by electricity transmission and distribution operators to manage tree-related faults near overhead lines. Network operators have a statutory requirement to keep overhead power lines clear of vegetation for public safety reasons. Since 2006, operators have also been required to undertake a risk-based programme of resilience vegetation management. The ENA produced an Engineering Technical Report (ETR132) in 2006 to guide implementation against this requirement. The standard requires operators to deliver proactive tree cutting and felling programmes targeted towards critical overhead lines, to improve performance in storm conditions. Across the electricity distribution companies, £8 million a year was spent on implementing resilience vegetation management between 2011 and 2015. This is projected to increase to £15 million a year from 2016 to 2023, resulting in total expenditure of around £158 million over the period 2011 to 2023 (ASC, 2014). However, there is limited modelling of the potential impacts of future increases in the length of the growing season for tree-related faults.

Design standards for plant protection and capacity of new cables are being reviewed with a view to agreeing new standards to take effect from the 2015 price control review. These are typically deployed through scheduled maintenance or new build (ENA, 2015).

With an uptake of carbon capture and storage, Byers et al. (2016) show that cooling water abstractions are projected to increase, exceeding available water for all users, regardless of climate scenario by the 2020s and 2030s. However, the analysis shows that deficits can be reduced when wet/dry hybrid tower cooling is used, which may cost-effectively increase reliability at low flows. In addition, rainwater collection systems can also be appropriate. For example, the Langage Energy Centre collects 12,000m^3 of rainwater a year to reduce the need for fresh water (Energy UK, 2015).

To partly mitigate the de-rating of overhead electricity transmission lines, the use of dynamic ratings has been proposed by Hu and Cotton (2013), which could reduce the de-rating from 14% to 3 – 5%. A similar order of partial mitigation applies to distribution networks, and there are opportunities through the deployment of additional smart network technologies to encompass further adaptation requirements (ENA, 2015). In anticipation of increased sagging of overhead cabling in hot weather, distribution companies are in some areas increasing pole heights by 0.5 – 1 m, so that minimum safety clearances are maintained.

4.9 Solid waste infrastructure

This section summarises the climate change risks and opportunities relating to the infrastructure involved in domestic and commercial waste management.

4.9.1 Overview of sector and policy

Wastes are defined by the Waste Framework Directive (EC, 2008) as 'any substance or object which the holder discards or intends or is required to discard.' Over the last two to three decades, waste management in the industrialised world has gradually shifted from providing safe disposal of unwanted materials, often within a highly engineered landfill, to recovering materials and value from that which is no longer needed through reuse, recycling, composting and energy recovery. However, landfill will still continue to have a role in the safe return of residuals to the environment and the entombment of certain hazardous wastes.

Waste has traditionally been categorised by generating sector, for example, household (often used interchangeably with municipal solid waste), commercial and industrial, construction and demolition, mining and quarrying, and agricultural. Hazardous waste is categorised separately. For household waste, collection is from the kerbside or a bring site, for example bottle and textile banks and household waste recycling centres. Some C&I waste is collected along with green waste from parks and gardens or with household waste from the kerbside; this forms Local Authority Collected Municipal Waste (LACMW). Licensed waste management companies collect the majority of the remaining C&I waste. Waste arisings now reported to the EU consist of Local Authority Collected Waste and the MSW-like component of C&I wastes which collectively are termed Municipal Waste (Defra, 2012d) and are roughly double the MSW.

None of the waste management policies active in the UK explicitly deals with preparations for climate change impacts. Both the Landfill Directive (EC, 1999) and the Waste Framework Directive (EC, 2008) make changes to waste legislation that are intended to reduce the emissions of greenhouse gases from waste processes. These directives are implemented via the Waste (England and Wales) Regulations 2011, Waste (Scotland) Regulations 2012 and Waste (Amendment) Regulations (Northern Ireland) 2013. They aim to reduce the amount of waste disposed in landfill or incinerated without recovery by (i) preventing unnecessary waste streams through reuse and efficient design, (ii) preparing for reuse by repairing, refurbishing and facilitating recovery of spare parts, (iii) recycling and (iv) other recovery options such as anaerobic digestion for energy recovery.

4.9.2 Climate risks

Climate change and extreme weather impacts on the solid waste sector are summarised in Table 4.7. Direct impacts can be through disruption to the solid waste infrastructure and indirectly through disruption to other infrastructure (e.g. failure of the electricity grid, disruption of transportation routes or failure of water supplies) (Ramsbottom et al., 2012; Thornes et al., 2012). Increases in flood risk are the biggest threat to the sector, and increases in temperature are likely to require some changes to operations and management. Analysis by Sayers et al. (2015b) for the ASC identifies 400 landfill sites currently located in areas at high risk of flooding from rivers, the sea or surface water (>1-in-75 years), with increases of 1 – 6% by the 2050s and 5 – 10% by the 2080s under a 2°C and 4°C increase in global mean temperatures. Flooding of landfill sites usually results in an associated pollution event (Laner et al., 2009; Neuhold and Nachtnabel, 2011). A number of other permitted landfills in England and Wales are known to be located in more elevated coastal areas that, in the absence of defences, are at risk of erosion and/or slope instability over the next 100 years (Environment Agency, 2010).

Table 4.7. Effects on solid waste management infrastructure due to climate change

Climate hazard	Confidence	Effect
Increased winter rainfall and/or increased peak winter rainfall	Medium	Increased waste arisings due to flood events.
		Disruption to transport networks (and hence collection and transportation of wastes) due to flooding.
		Flooding of landfill sites leading to increased risk of groundwater and/or surface water contamination and additional treatment of leachate.
		Flooding of waste facilities leading to ground and/or surface water contamination.
		Disruption of energy supply leading to breaks in waste treatment services.
Increased frequency of winter storms	Low	Increased storm damage to waste facilities.
		Disruption to transport network.
Sea-level rise and increases in storm surge	High (sea-level rise) Low (storm surge)	Exposure of historic coastal landfill sites leading to pollution events.
		Disruption to marine transportation of wastes.
Higher summer temperatures	High	Increased incidents of landfill fires.
		Increased incidents of fires in other waste facilities.
		More frequent waste collection required to reduce problems with vermin and odour.
		Disruption to transport network (e.g. rail buckling, highway damage).
Increased frequency of periods of drought	Low	Shortage of water for anaerobic digestion and composting.
		Disruption to river and/or canal transportation due to reduced water levels.
		Reduced river levels may lead to reduction in water available for cooling Energy from Waste plants.

Source: Watson and Powrie, 2015.

Fires in collection vehicles, material recovery facilities, recycle stockpiles and landfill sites are currently uncommon – although reporting is incomplete. Rising mean and extreme temperatures will likely increase the frequency of fires, but the risk is still considered to be low (Foss-Smith, 2010; Moqbel et al., 2010; Ryan, 2012; Hudson and Fulford, 2013). Prolonged hot, dry conditions could increase desiccation and cracking of clay liners and caps with associated pollution risks, similarly this is considered to be a low risk (Sinnathamby et al., 2014).

Climate change will directly affect waste arisings as a warmer climate is likely to lead to a longer growing season (Bebb and Kersey, 2003). This may lead to an increase in garden waste arisings (WRAP, 2011; Phillipson, 2015a) which currently form 14 – 17% of household waste (Defra, 2009, 2012c) and about 4 million tonnes a year. WRAP (2011) cited the example of Cherwell DC which saw a rise of 800 tonnes of garden waste due to the extended growing seasons in 2007 and 2008 (on the basis of 2009 figures from the EA Waste Data Interrogator, this is estimated to be an increase of about 10%). Climate change is likely to lead to increased flood risk which will indirectly increase waste arisings. Flood incidents can produce large amounts of waste within the flooded area; a minimum of 250kg of additional waste per household is likely (Watson and Powrie, 2015). However, the flooded area would need to be a large part of a major city before it had a statistically significant impact on overall UK waste arisings. Rising temperatures are known to be associated with increased problems of odour and vermin at waste treatment sites, but predicted ranges fall within those already handled in continental Europe. This is likely to be more of a problem where high temperatures also lead to transportation or collection disruption, leading to waste accumulating on the street or for those living near to waste management facilities. Waste facilities may need modification to mitigate these effects, for example Phillipson (2015b) reports a landfill closure and remedial works because of excessive odour following heavy rain.

Disruption to waste logistics as a result of extreme events could require the shutdown of energy from waste generation plants. Similarly, drought periods that limit water availability for anaerobic digestion and composting plants could require these to be shutdown. The risk of this is considered low; in the case of the latter, Winne et al. (2012) identify simple adaptation options but it is unknown how many plants are suited to these. Higher temperatures provide an opportunity due to faster biodegradation improving efficiency of anaerobic digestion and composting.

Many waste sites are required to temporarily store wastes (e.g. transfer stations and Materials Recovery Facilities) and the requirement for containment is not as rigorous as at permanent waste storage sites. These sites may also store hazardous wastes (Environment Agency, 2011e) which can exacerbate pollution problems in the event of flooding as occurred in Gloucester, when a fire at a transfer station for many wastes including hazardous waste was subsequently flooded leading to illness in local residents (Hitchings, 2003).

4.9.3 Adaptation actions

Rising population and wealth are likely to increase waste arisings over time. This coupled with the obligations under the Landfill Directive (EC, 1999) and the Waste Framework Directive (EC, 2008), may lead to the requirement for new infrastructure. Much of the planned new infrastructure (65% according to Winne et al., 2012) will be located in central and southern England, where the changes in the relevant climate drivers are expected to be greatest. This region also houses 60% of the UK population and 68% of English major waste sites. Tran et al. (2014) and Hall et al. (2016) examined possible future growth of wastes and found that, for most scenarios considered, there was very little requirement for new infrastructure out to 2050, beyond those already being constructed (listed in Eunomia, 2013) and the replacement of extant. Assumptions in this modelling reflected the reduction in per person waste arisings observed between 2006 and 2012, although this trend is at least in part explained by increasing export of waste to facilities in north-west Europe. Recent figures also suggest that trends may be increasing again. It should be noted that there is considerable debate within the industry about future arisings and the need for further infrastructure. Increases in overall arisings would require construction of new and (currently) unplanned infrastructure in areas of maximum population growth, which the Office for National Statistics (2015) forecasts to be in London and the south-east. New infrastructure will need to be designed for climate change and this will form part of the planning and permitting processes.

Much of the existing infrastructure is likely to have been upgraded or replaced by 2050. For any new waste facility, whether entirely new or constructed for replacement or upgrade, the development of new waste facilities and increased resilience to climate and weather effects can be built in to the planning and permitting processes (the latter is the process by which the Environment Agency grants a permit to allow operation of waste and other facilities) such that most effects of climate change can be mitigated. Despite a recent revision of the NPS, locations handling hazardous waste are not subject to an absolute ban from being located in a flood risk zone (Defra, 2013b). It is likely that most modern landfills will retain the ability to pollute the surrounding environment for decades or centuries (Bebb and Kersey, 2003; Hall et al., 2007) unless steps are taken to change the management process to accelerate the degradation process or remove the waste itself through landfill mining or similar processes (Watson and Powrie, 2013). This would suggest that of all solid waste management infrastructure, landfill sites are the most vulnerable to long-term climate change.

4.10 Conclusion

4.10.1 Discussion and priorities for action

Infrastructure in the UK is already experiencing significant impacts as a result of the natural variability of our climate. Unchecked, the projected increases in the frequency of severe weather events (e.g. flooding) will lead to increased disruption of infrastructure, and projected gradual changes to long-term averages (e.g. a rise in average temperature) will reduce the capacity or efficiency of some infrastructure. Although climate change will offer some opportunities, the risks to infrastructure far outweigh the possible benefits. Projected changes in climate will alter the life expectancy of existing infrastructure, but also the effectiveness of the services infrastructure provides. Many infrastructure sectors need to update standards and guidelines to ensure infrastructure is designed and built for a future climate. Furthermore, climate change will interact with, and exacerbate, the impact of other pressures that include population growth and ageing infrastructure.

There is evidence that significant adaptation steps to manage climate change risks have been implemented, or are underway, across most infrastructure sectors. Where sufficient information is provided, our assessment indicates that these investments will maintain or, in some instances, reduce climate risks over the next decade or two. On longer timeframes, projected changes in climate are likely to outpace current adaptation plans.

Across the UK there are a wide range of approaches to infrastructure governance, regulation, data collection, data accessibility, and adaptation reporting. The regional variability, quality and completeness of information on infrastructure risks and adaptation actions is huge and uses a diverse range of methods. This lack of standardisation and incomplete availability has posed a significant challenge for this risk assessment. A number of other challenges are considered below.

National capability for performing infrastructure climate change risk assessments

A large volume of evidence has been reviewed here, highlighting a wealth of UK expertise and activity in this important area. However, these studies also expose a lack of systematic approach to understanding climate risks on infrastructure. Studies use a wide range of different scenarios, spatial scales, timeframes and impact metrics to assess risk. Much of the evidence is compiled from individual events or smaller studies, with only a small proportion of the evidence providing a complete national assessment of infrastructure, and many of these sources share the same underlying datasets (e.g. NaFRA[12]). The volume of evidence is not evenly distributed across the range of climate risks to infrastructure, with national-scale assessments of flood risk to infrastructure the most abundant (which is appropriate given its importance). In some cases, information is limited to qualitative understanding of infrastructure behaviour.

Given the importance of infrastructure risks to the functioning of a modern society, and the legislative requirement to assess these risks every five years, there is an imperative to develop a national capability for performing infrastructure climate change risk assessments. Such a programme could provide a new generation of national infrastructure risk assessment tools that provides a number of important capabilities, including:

- A common and internally coherent framework for risk analysis that enables different risks to be fairly compared.
- Analysis of the impact of persistent climatic events (e.g. repeated sequence of storms or floods, in the same or multiple locations) and joint hazard events (e.g. wind storm coupled with flooding).
- A national database of the location, function and design of assets, and a record of any adaptation to these assets and its effect on risk reduction that is updated under the ARP.
- Assessment of a range of impacts to the economy, environment and society. First order impacts on the infrastructure itself, as well as higher order and longer term impacts need to be considered to gain the richest possible understanding of risk.
- A common baseline and a number of standardised adaptation scenarios to provide a set of common reference points, as well as the capability to develop and test further scenarios.

This cannot be a singular activity or model. To harness the best knowledge that industry, government and academia has to offer, a modelling framework that is collectively owned and maintained by the wider infrastructure community, needs to be established. This framework could enable a diverse set of existing and new hazard, infrastructure and impact models to be readily integrated and applied. Moreover, a national capacity would facilitate rapid testing of the benefits of changes in policy, for example the benefits in terms of infrastructure risk reduction from the 1.5C scenario that was agreed at the UNFCCC COP21 in Paris in 2016. Without a significant and steered research effort to develop such a national capability, our understanding of climate risks to infrastructure is likely to continue to evolve in a relatively ad hoc fashion.

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[12] https://data.gov.uk/dataset/risk-of-flooding-from-rivers-and-sea1

Building capacity across the infrastructure system

A number of barriers remain to building capacity to implement, use and embed infrastructure climate change risk assessment into all aspects of the infrastructure system and infrastructure decision-making.

Figure 4.1 shows how interlinked natural, human and engineering systems deliver infrastructure services. Systems thinking support the integration of people, purpose, process and performance because it is a framework for seeing and working with the whole, rather than individual components or processes (Godfrey et al., 2014). A national capability in climate risk assessment would improve systemic understanding of climate risk, but will not on its own enable infrastructure to deliver economic, environmental and social objectives in the face of climatic and other uncertainties. Systems thinking capacity must be instilled into the people, organisations processes responsible for policy, regulatory, design and operations through continued professional development and incorporation into the higher and doctoral education curricula of engineering, management and other relevant subjects.

Uncertainties and high capital costs of some adaptation measures, that only realise risk reduction benefits many years later, are regularly identified as a major barrier to releasing funds for adaptation investment. The timeframes of governance, regulation and financial appraisal methods are typically geared towards short-term management. This is at odds with the long operational lifetime of many infrastructure assets over which changes in climate are projected. Overemphasis on short-term cost-savings within standard cost-benefit analysis, do not value the systemic risks and long-term benefits of community safety and economic continuity associated with a resilient infrastructure. Ultimately, this will leave a legacy of increasingly large investment for future generations, who will have to raise funds for maintenance or make difficult decisions such as whether to relocate assets entirely. New approaches to appraisal, and business models more generally, are required that factor the strategic economic sense of adaptation in to standard practices for infrastructure operation, management and replacement.

Many of the risks identified in this chapter require consideration of risks across sectors, yet current regulatory structure focuses on a single sector, meaning that responsibilities for assessing and managing risks from interdependencies are unclear. There is potential to align and share investment profiles and asset management practices across sectors, cities and major infrastructure investments. New approaches to appraisal identified above must therefore be coherent across infrastructure sectors to facilitate collaboration. Joint schemes (e.g. flood defence partnership funding) involving multiple partners are just starting to be explored. Initiatives such as the UK Regulators Network and Natural Hazards Partnership are welcome to improve cross-sector co-operation, similarly the National Infrastructure Commission has a remit to advise on long-term strategic investments. Research is needed to explore and consider the mechanisms, benefits and potential risks, from jointly delivered infrastructure adaptation, joint monitoring and management, alternative regulatory structures, and mechanisms to share information across sectors, scales and with other parties, that may deliver greater efficiencies and reduction of sector specific, but crucially also cross-sector, risks.

Decision-making for infrastructure climate change risk assessment

As information on infrastructure climate risks becomes more sophisticated and incorporates more sectors, interdependencies and systemic effects, it is increasingly challenging to maximise the effectiveness of this information in infrastructure decision-making.

- Many of the adaptation evidence reports quantify the benefits arising from engineering intervention (e.g. protection of asset X was upgraded from the 1-in-50 to 1-in-100 year flood). Many other types of adaptation strategy are under consideration but evidence of their effectiveness can usually not be presented with such apparent confidence. Research has demonstrated the feasibility of assessing the benefits in terms of flood risk to people from investment in warning systems (Dawson et al., 2011a), land use planning (Dawson et al., 2011b) or water pricing (Erfani et al., 2015). Further development of these approaches is required to develop a full suite of appraisal tools that allow the costs and benefits of hard engineering, soft engineering (e.g. green infrastructure) and non-structural adaptation interventions to be objectively compared across the full range of infrastructure systems and climate risks.
- Designing infrastructure against deterministic design conditions is no longer adequate, and future infrastructure design must take into account a much wider set of current and potential future hazards. These include hazards that act in combination, events that are short and intense, and those that persist over many weeks. There are significant challenges in both designing the flexible strategies or real options for climate resilient infrastructure systems that are recommended by HM Treasury (2009) in their supplementary guidance, as well as developing the engineering approaches that can incorporate flexibility into assets and networks.
- To better inform adaptation priorities, and understand climatic impacts, there is a need to develop better metrics that allow performance of the infrastructure system to be measured and monitored over time. For example, for transport this is related to mobility and access, and should not just focus on absolute delays against a timetable. Building on recent research by Carhart et al. (2016), performance metrics can be extended to assess the effectiveness of adaptation action against system performance, capturing resilience but also interdependencies within and outside the sector.
- Handling and interpreting the vast array of information on infrastructure climate risk can lead to sub-optimal, or partially informed, analysis. A number of promising approaches to exploring scenarios (Trutnevyte et al., 2016), long-term decision-making (Reeder et al., 2013) and managing trade-offs between competing risks (Caparros-Midwood et al., 2015) are available. The most promising techniques to support infrastructure climate risk assessment and adaptation should be identified and further developed.

4.10.2 Key knowledge gaps

This review of climate change risks to infrastructure has identified a number of specific knowledge gaps and significant uncertainties in our understanding of infrastructure performance that should be addressed by more fundamental research.

- The number of potential cross-cutting issues and infrastructure interdependencies is huge. The potential impact of cascading failure events has on occasion been shown to be enormous, but even for smaller scale events they can compound impacts. In-depth understanding of these risks is relatively poor and requires systematic attention.
- Infrastructure failures, long-term performance including deterioration, and related impacts are poorly recorded. Given the timeframes over which climate change manifests and the long lifespan of many assets this is a significant gap in knowledge. Research needs to be undertaken to take a robust, forensic and consistent approach to monitoring

and recording the performance and thresholds of failure of infrastructure over the long term in order to construct a comprehensive database of infrastructure fragility.

- Risks to ICT infrastructure are relatively unknown and hindered significantly by limited knowledge of the location of assets. ICT networks are considered to be generally resilient as a result of their nature, but recent events in the UK and internationally have shown that they are still subject to major disruption and cascading impacts from other sectors. Given ICT's pervasive and 'unseen' interdependence with all other infrastructure systems, and its role in underpinning business and social wellbeing, it is crucial to assess the vulnerability of the UK's ICT networks and systems, and its interdependencies particularly with the energy sector, to a changing climate.
- Research is needed to understand the potential of climate risk on UK infrastructure as a result of international interactions. For example, the UK electricity network has a number of international connections, as do ICT systems have many as a result of a global communications network and overseas datacentres. Ports, airports and the Channel Tunnel connect the UK's transport networks to continental Europe and the rest of the world. Continued operation of many infrastructures requires resources (e.g. oil, biomass, raw materials and components) that could be disrupted by extreme events elsewhere. The East Coast Japan Tsunami and flooding of factories in the Chao Phraya River Basin in Thailand have already demonstrated impacts on resource flows to the UK, and continued streamlining of global supply chains may increase this vulnerability.
- There is limited understanding of how climate change may affect a number of weather variables that are particularly significant to infrastructure risks. The impact of climate change on processes such as wind, lightning, offshore waves and currents, and sub-hourly rainfall intensity, is poorly understood, yet these might have significant implications of the reliability of infrastructure assets with long design life (e.g. an increase in wind speed would increase the probability of failure of electricity transmission towers which are typically expected to last over 50 years). Recent developments in high-resolution modelling of convective storms (c.f. Kendon et al., 2014) have potential to provide the necessary information to allow onshore and offshore infrastructure providers to incorporate the projections into their plans. Improvements in understanding of these processes must subsequently be translated into future UK design guidance for infrastructure designers and operators.

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Annex 4.A Policies relevant to infrastructure adaptation

The following tables summarise relevant policy in England, Wales, Scotland and Northern Ireland relevant to climate change adaptation for key infrastructure sectors.

Table 4A.1. Policy frameworks for water infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
Reservoirs Act 1975	England, Wales (but with some provisions for Scotland)	Recording of water levels.	Flood and Water Management Act 2010: preparation of flood plans
Reservoirs (Scotland) Act 2011	Scotland	Similar to above but includes preparation of flood plans	
Northern Ireland Reservoirs Bill	Northern Ireland	As above	
Flood and Water Management Act 2010	England, Wales	Arrangements for flood risk management; national flood and coastal erosion risk management strategy to include climate change; water use temporary bans	Amendments to Reservoirs Act: preparation of flood plans; see also Water Use (Temporary Bans) Order 2010 and Drought Direction 2011
Flood Risk Management (Scotland) Act 2009	Scotland	Similar to above; flood risk assessments to include climate change	
Planning Policy Guidance: Flood Risk and Coastal Change	England and Wales	Constrains development in areas subject to current levels of flood risk and places requirements for flood risk assessment	
Strategic Planning Policy Statement in relation to Flood Risk Northern Ireland 2015	Northern Ireland	The aim of the SPPS in relation to flood risk is to prevent future development that may be at risk from flooding or that may increase the risk of flooding elsewhere.	

Table 4A.1. Policy frameworks for water infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
The Water Environment (Floods Directive) Regulations (Northern Ireland) 2009	Northern Ireland	Similar to above; flood risk assessments to include climate change	
The Water Supply (Water Quality) Regulations 2000	England, Wales	Establishes water supply zones and protected areas, drinking water standards, monitoring, sampling and treatment requirements.	
The Public Water Supplies (Scotland) Regulations 2014	Scotland	Similar to above	
Water Supply (Water Quality) Regulations (Northern Ireland) 2007 (and amendments and other related regulations)	Northern Ireland	Similar to above	
Water Resources Act 1991	England, Wales	Provisions relating to minimum acceptable river flows, abstraction licensing, drought orders and permits, discharges and flood defence.	See Water Act 2003
Water Resources (Scotland) Act 2013	Scotland	Provisions relating to the development of water resources, water abstraction, water quality, protection of public sewers, and water shortage orders.	
Water (Northern Ireland) Order 1999	Northern Ireland	Provisions relating to discharges and abstractions.	Abstraction and Impoundment (Licensing) Regulations (Northern Ireland) 2006

Table 4A.1. Policy frameworks for water infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
Water Industry Act 1991	England, Wales	Established Water Resources Management Plans and Drought Plans; set standards of performance for water supply and sewerage services.	See Water Act 2003
Water Industry (Scotland) Act 2002	Scotland	Establishes Scottish Water and transfers the functions of the water and sewerage authorities	
Water Act 2003	England, Wales (but with some provisions for Scotland and Northern Ireland)	Amendments to abstraction licensing; amendments to standards of performance; provisions for Water Resources Management Plans and Drought Plans; duty for various bodies to conserve water resources; adoption of water mains, service pipes and sewers.	Amends Water Resources Act 1991 and Water Industry Act 1991
Water Act 2014	England, Wales	Additional long-term resilience duty for Ofwat.	
The Urban Waste Water Treatment (England and Wales) Regulations 1994	England, Wales	Provisions for the collection, treatment and discharge of waste water and monitoring.	EC Urban Waste Water Treatment Directive; The Environmental Permitting (England and Wales) Regulations 2010 Schedule 21
The Urban Waste Water Treatment (Scotland) Regulations 1994 (as amended)	Scotland	As above	EC Urban Waste Water Treatment Directive
The Urban Waste Water Treatment Regulations (Northern Ireland) 2007	Northern Ireland	As above	EC Urban Waste Water Treatment Directive

Table 4A.1. Policy frameworks for water infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
Water and Sewerage Services (Northern Ireland) Order 2006.	Northern Ireland	All water companies must produce Drought Plans and Water Resources Management Plans.	
Waste water treatment in the United Kingdom – 2012: Implementation of the European Union Urban Waste Water Treatment Directive – 91/271/EEC	England, Wales, Scotland, Northern Ireland	Sewerage system sized in relation to local climatic conditions; Combined Sewer Overflows.	EC Urban Waste Water Treatment Directive
The Water Environment (Water Framework Directive) (England and Wales) Regulations 2003	England, Wales	Provisions for the characterisation of River Basins, monitoring, setting of environmental objectives and programmes of measures, and development of River Basin Management Plans.	EC Water Framework Directive
The Water Environment and Water Services (Scotland) Act 2003	Scotland	As above	EC Water Framework Directive
The Water Environment (Water Framework Directive) Regulations (Northern Ireland) 2003	Northern Ireland	As above	EC Water Framework Directive
Climate Change Act 2008	UK	Water companies can be required to set out adaptation plans and reviews - if the ARP direction is used.	

Table 4A.2. Policy framework for transport infrastructure

Policy reference	UK Nation	Key effects of this policy in addressing climate risks	Links to other policies
Climate Change Act (2008) http://www.legislation.gov.uk/ukpga/2008/27/contents	UK	The Climate Change Act 2008 makes legal arrangements about climate change mitigation and adaptation. It sets the requirements for the Climate Change Risk Assessment, the National Adaptation Programme and the Adaptation Reporting Power.	Climate Change Risk Assessment National Adaptation Programme Adaptation Reporting Power
Climate Change Risk Assessment (2012) https://www.gov.uk/government/publications/uk-climate-change-risk-assessment-government-report	UK	The first CCRA identified three broad areas of risk that spanned an initial 54 impacts in the transport sector: Direct damage to transport infrastructure and the associated disruption caused by extreme storm events (especially extreme rainfall and strong winds); Direct disruption to transport modes (vehicles, trains, aircraft and ships) caused by extreme storm events; Indirect disruption to transport caused by gradual changes in the climate. The approach then taken was to highlight the key impacts requiring attention from expert discussion with transport stakeholders pertaining to the economic, environmental and social implications as well as likelihood and urgency (road and rail prioritised as they cover 90% of present day needs: Defra, 2012c). The five key risks identified from this approach were: flood disruption, landslides, road carriageway repairs; rail buckling risk and road and rail bridge failures due to scour.	Climate Change Act
Climate Change (Scotland) Act (2009) http://www.gov.scot/Topics/Environment/climatechange/scotlands-action/adaptation/AdaptationProgramme	Scotland	The Climate Change (Scotland) Act 2009 requires Scottish Ministers to develop a Scottish Adaptation Programme which addresses the risks identified for Scotland in the UK Climate Change Risk Assessment.	CCRA 2012 Scottish Adaptation Programme

Table 4A.2. Policy framework for transport infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
National Infrastructure Plan (2014) https://www.gov.uk/government/publications/national-infrastructure-plan-2014	UK	Surprisingly minimal. Although, the 2011 NIP encouraged the sector towards design and engineering changes to increase climate resilience and encouraging dual-use infrastructure. Climate is mentioned just eight times in the 2014 document and none with respect to transport. Although flooding is a major component of the report, this is only mentioned wrt protecting homes.	
Climate Resilient Infrastructure Progress Report (2013) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/225312/pb14008-climate-resilient-infrastructure-progress-report-130725.pdf	UK	Excellent summary document to key current policies.	National Infrastructure Plan National Adaptation Program
National Adaptation Programme (2013) https://www.gov.uk/government/publications/adapting-to-climate-change-national-adaptation-programme	UK	The National Adaptation Programme (NAP) sets out what government, businesses and society are doing to adapt better to the changing climate. The NAP report was published on 1 July 2013 and will be reviewed every 5 years. The Adaptation Sub Committee will assess how well the NAP report has been implemented so far by July 2015. Basically uses CCRA1 as evidence and links to 'climate resilient infrastructure' report. Subsequent focus on flooding of roads and railways. Transport section redirects to various National Policy Statements. Dealing with priority risks is actioned to DfT (Transport, roads and aviation), Civil Aviation Authority, Network Rail	National Infrastructure Plan CCRA 2012 Adaptation Reporting Power Sector Resilience Plans Highways Agency Climate Change Adaptation Strategy and Framework Network Rail Strategic Business Plan

Table 4A.2. Policy framework for transport infrastructure

Policy reference	UK Nation	Key effects of this policy in addressing climate risks	Links to other policies
		and HS2, as well as organisations that produced reports under ARP. Register of actions related to CCRA1 included in appendix.	
National Networks NPS (2014) https://www.gov.uk/government/collections/national-networks-national-policy-statement	England	Highlights the need for suitable adaptation measures (including the provision of green infrastructure) to reduce vulnerability of new developments to the impact of climate change. Reporting authorities are required to build on climate change risk assessments and to report on progress on implementing adaptation actions. The impacts of climate change must be considered and where the asset is to last for >60 years then the 2080 high emissions scenario (50% level) should be applied. UKCP09 should be used until newer scenarios are available. In addition to this, there is a need to demonstrate that there are no features of the new network which may be affected by radical changes to climate beyond that presently projected (e.g. sea-level rise). Designs need to be based on credible scientific evidence. Coastal change is used as a particular example and require particular management plans. Flood risk also gets special mention and specifically states that development should be avoided in flood risk areas and where this is unavoidable, reasonable mitigation measures need to be taken to ensure that the infrastructure remains functional. Land stability is also highlighted.	Adaptation Reporting Power

Table 4A.2. Policy framework for transport infrastructure

Policy reference	UK Nation	Key effects of this policy in addressing climate risks	Links to other policies
Ports NPS (2012) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/3931/national-policy-statement-ports.pdf	England and Wales	Climatic factors and adaptation, flood risk and coastal change are highlighted as key environmental sustainability issues. The focus is on mitigation in NPS, but adaptation is also covered as applicants must consider the impacts of climate change when planning the location, design, build and operation of new port infrastructure. Proposals that are subject to the European Environmental Impact Assessment Directive must be accompanied by an Environmental Statement (ES) describing the aspects of the environment likely to be significantly affected by the project. The ES should set out how the proposal will take account of the projected impacts of climate change. While not required by the EIA Directive, this information will be needed by the decision-maker. Applicants should use the latest set of UK Climate Projections to ensure they have identified appropriate adaptation measures. Applicants should apply, as a minimum, the emissions scenario that the independent Committee on Climate Change suggests the world is currently most closely following – and the 10%, 50% and 90% estimate ranges. These results should be considered alongside relevant research which is based on the climate change projections such as Environment Agency (EA) Flood Maps.	
Aviation Policy Framework (2013) https://www.gov.uk/government/publications/aviation-policy-framework	UK	The Aviation NPS was replaced with the Aviation Policy Framework which was consulted on in late 2012 and published in March 2013. The Aviation Policy Framework highlighted the need to manage the risks associated with climate change as essential for	

Table 4A.2. Policy framework for transport infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
		thesuccessful long-term resilience of the UK's aviation industry and its contribution to supporting economic growth and competitiveness.	
Adaptation Reporting Power (2013) https://www.gov.uk/government/policies/adapting-to-climate-change/supporting-pages/adaptation-reporting-power	UK	ARP aims to ensure that climate risk management is systematically undertaken and enables monitoring of preparedness. The first round of the Adaptation Reporting Power (ARP) has led to 91 published reports from infrastructure providers, regulators and others (22 in the transport sector). Defra published a summary of findings in March 2012. We expect to receive these reports by 2016. They will help inform the next Climate Change Risk Assessment due in 2017 and the National Adaptation Programme expected to be published in 2018.	
Scottish Climate Change Adaptation Program (start 2013) http://www.keepscotlandbeautiful.org/media/636320/99pprox.99-government-climate-ready-scotland-scottish-climate-change-adaptation-programme.pdf	Scotland	Transport Scotland and the Society of Chief Officers for Transportation in Scotland (SCOTS) are developing the Adaptation Programme transport sector element. Policies at the moment include to review existing climate impacts, in particular to assess the suitability of the existing network in extreme events; collate user views on disruption; investigate changes in fog and landslip incidence;	Climate Change Act (Scotland) 2009
Climate Change Strategy Wales: Adaptation Delivery Plan (2010) http://gov.wales/topics/environmentcountryside/climatechange/publications/adaptationplan/?lang=en	Wales	Support consideration of climate change impacts in sustainable infrastructure development and regeneration; Publish and implement strategies addressing flood and coastal erosion risk management; Support Wales Spatial Plan area groups to consider the impacts of climate change on their area; Review the resilience of the transport infrastructure to the effects of climate	Climate Change Act 2008

Table 4A.2. Policy framework for transport infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
		change and develop a programme to address risks	
Northern Ireland Climate Change Adaptation Programme (2014) http://www.doeni.gov.uk/ni_climate_change_adaptation_programme__niap__-_pdf_for_web_page_-_jan_2014.pdf	Northern Ireland	Discussion limited but highlights flooding as the biggest concern for transport.	Climate Change Act 2008 CCRA 2012
EU Climate Change Adaptation Strategy (2013)	EU	Addresses potential adverse impacts on the environment primarily by embedding adaptation into EU policy instruments and promoting information sharing across the EU. The government has supported the inclusion of sustainability criteria and promoting greater interconnection for low carbon energy sources in Trans-European Networks for energy (TEN-E) and sought consideration of climate resilience in Trans-European Networks for transport (TEN-T). The government is in close contact with EU member states to share knowledge and approaches to adaptation. For example, the government supported development of the EU Climate Change Adaptation Strategy which, among other objectives, promotes information sharing and gathering across the EU using the 'Climate Adapt' tool maintained by the European Environment Agency. The EA's Climate Ready Service is reviewing lessons learned from comparing French and German National Adaptation Programmes.	

Table 4A.2. Policy framework for transport infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
Adaptation Supplement to the Green Book https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-goverent	UK	The government is planning to make revisions to its Treasury Green Book Supplementary guidance on climate change adaptation. In particular the new guidance is aiming to: - lay out the principles to build climate resilience into economic analysis of capital projects – explain the need to address critical thresholds where tipping points in levels of service might arise due to a changing climate – provide guidance on the impacts and uncertainties that lie around these impacts – apply to all public sector infrastructure investment. The transport infrastructure sector uses infrastructure design and maintenance standards which are being revised to include consideration of long term climate implications. Department for Transport is including adaptation in its new Transport and Roads Strategies to ensure consideration of climate change in investments and projects.	
Enabling the Transition to a Green Economy, Government and Business Working Together (2011) https://www.gov.uk/government/publications/enabling-the-transition-to-a-green-economy	UK	Economic resilience will improve is we are more prepared for the implications of climate change shich as heatwaves and floods.	
Transport Sector Resilience Plan (2013) https://www.gov.uk/government/publications/2013-sector-resilience-plan	UK	Transport operates on a commercial basis, but DfT has regulatory means. Severe coastal flooding is one of four current priorities, but DfT also has ongoing work to enhance resilience to severe weather of all forms, including long term activities to	

Table 4A.2. Policy framework for transport infrastructure

Policy reference	UK Nation	Key effects of this policy in addressing climate risks	Links to other policies
		mitigate the impacts of climate change.	
Action for Roads: A network for the 21st century (2013) https://www.gov.uk/government/publications/action-for-roads-a-network-for-the-21st-century	UK	No specific mention to adapting the road network, instead minimal focus on decarbonisation.	
Highways Agency Climate Change Adaptation Strategy and Framework (2009) http://assets.highways.gov.uk/about-us/climate-change/CCAF_Strategy_and_Vol_1_Rev_B_Nov.pdf	England	Highways Agency's Adaptation Framework Model (Highways Agency, 2009). This is a seven stage process which highlights vulnerabilities and, following an option analysis, results in an adaptation action plan for each vulnerability. In some cases, this has led to a modification in existing standards (e.g. road surfacing: Highways Agency 2011); however, it often highlights an area in need of further research to reduce uncertainties.	
UK Roads Liaison Group Code of Practice for Well Maintained Highways (Last Updated 2013) http://www.ukroadsliaisongroup.org/en/utilities/document-summary.cfm?docid=C7214A5B-66E1-4994-AA7FBAC360DC5CC7	England	Highlights the ongoing need to work with HA to identify the main issues for local roads. Includes a number of small-scale studies (e.g. Impact of heat on the roads of Cambridgeshire) and a climate change adaptation plan for the three counties of Derbyshire, Leicestershire and Nottinghamshire). The report particularly highlights the need for different resurfacing materials and improved flood protection and states that local authorities should research the likely localised impacts of climate change on their network.	

Table 4A.2. Policy framework for transport infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
Network Rail Strategic Business Plan (2013)	Great Britain	Recognises the importance of embedding climate change adaptation into operations and management. Knowledge base is funded by RSSB TRaCCA. Aim is to increase adaptive capacity to provide an informed base for effective climate change adaptation decision-making.	
National Infrastructure Plan	UK	Does not address slope instability as a consequence of climate change.	Network Rail Delivery Plan for Control Period 5 Department for Transport and Highways Agency Roads Investment Strategy
Network Rail's Delivery Plan for Control Period 5	UK		N/A
Department for Transport and Highways Agency Roads Investment Strategy	England	Does not address slope instability as a consequence of climate change.	--
Wales office – Building a more prosperous Wales: Infrastructure for a modern economy	Wales	Does not address slope instability as a consequence of climate change.	--
Scottish Road Network Climate Change Study: UKCP09 update Autumn 2011	Scotland	Does not address slope instability as a consequence of climate change. But refers to conclusions in SCOTTISH ROAD NETWORK CLIMATE CHANGE STUDY -2005	SCOTTISH ROAD NETWORK CLIMATE CHANGE STUDY - 2005
Scottish road network climate change study – 2005	Scotland	Notes no opinion given by managing agents on increased risk of slope stability due to higher winter ground water levels due to increased rainfall.	DESIGN MANUAL FOR ROADS AND BRIDGES – VOLUME 4 GEOTECHNICS

Table 4A.2. Policy framework for transport infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
		Also notes 'While no formal recommendation can be made without an appropriate climate change model being developed for this issue, it is recommended that consideration be given to carrying out earthworks inspections under the principles of HD 41/03 'Maintenance of Highway Geotechnical Assets' of the Design Manual for Roads and Bridges by parties responsible for maintaining the road network'.	AND DRAINAGE, SECTION 1 EARTHWORKS, LANDSLIDES
Design manual for roads and bridges – Volume 4 Geotechnics and drainage, Section 1 Earthworks	All UK	Does not make specific recommendations regarding climate change and slope stability	
Scottish road network landslides study: Implementation	Scotland	…… 'climate change models generally indicate a potential for such events to become more frequent and/or more intense in the future'. States that research is required to establish threshold values of rainfall required to initiate debris flows that could affect roads.	N/A
Office of Rail Regulation and Network Rail: Part A Reporter Mandate AO/049: Review of updated Earthworks Asset Policy for CP5 years 3-5	England and Wales	Provides a risk-based approach to managing slopes based on an inspection and monitoring regime. List 104pprox.. 10000 sections of earthwork ranked as in 'poor' or 'top poor' condition	--
Transport Scotland – National Transport Strategy	Scotland	Does not make specific recommendations regarding climate change and slope stability	--
Designing Streets	Scotland	Policy statement for street design	Closely relates to 'Designing Places'

Table 4A.2. Policy framework for transport infrastructure

Policy reference	UK Nation	Key effects of this policy in addressing climate risks	Links to other policies
Eurocode 7	All UK	Design code for geotechnical engineering works, including engineered slopes. Does not explicitly mention climate change.	N/A
Network Rail Climate Change Adaptation report In Response to the UK Government's Adaptation Reporting Power – 2011	England and Wales	'The future risk of landslips caused by large monthly rainfall totals has been investigated and there is mixed evidence for whether critical events could become more or less frequent'	--
Highways Agency, Climate Change Risk Assessment – 2011	England and Wales	Does make reference to climate change and slope stability	--
Northern Ireland, Department for Regional Development: Ensuring a Sustainable Transport Future: A New Approach to Regional Transportation	Northern Ireland	Does not explicitly mention climate change impacts	--
Northern Ireland, Department of the Environment: Northern Ireland Climate Change Adaptation Programme	Northern Ireland	Does make reference to climate change and slope stability	--

Table 4A.3. Policy frameworks for energy infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
Energy Act 2013	UK	Enables SoS to require fees to be paid for services or facilities provided or made available by the SoS in the exercise of energy resilience	
EU EIA Directive 2014 Update	UK	Requires climate impact assessment to be carried out on new infrastructure proposals (for those covered by the legislation) – to ascertain how environmental impacts could be altered. This requirement is not transposed as yet into national legislation.	Wales and Scotland or Electricity Works (AEE) (England and Wales) Regulations 2000/ Electricity Works (EIA) (Scotland) Regulations 2000. Nuclear Reactors (EIA for Decommissioning) Regulations 1999; The Pipeline Works (EIA) Regulations 2000 (EWS); Offshore Petroleum Production and Pipelines (AEE) Regulations (UK).
Climate Change Act 2008 Adaptation Reporting Powers	UK	Enables the SoS to request a climate change risk assessment from priority reporting authorities	Climate Change Adaptation Reporting Power – how to report your progress in planning for climate change, Defra 2013; Defra's 2009 Adapting to Climate Change programme
Strategic Planning Policy Statement for Northern Ireland	Northern Ireland	Furthering sustainable development also means ensuring the planning system plays its part in supporting the NI Executive and wider government policy and strategies in efforts to	

		address any existing or potential barriers to sustainable development. This includes strategies, proposals and future investment programmes for key transportation, water and sewerage, telecommunications and energy infrastructure (including the electricity network). Renewable Energy reduces our dependence on imported fossil fuels and brings diversity and security of supply to our energy infrastructure. It also helps Northern Ireland achieve its targets for reducing carbon emissions.	
National Policy Statements for Energy	England and Wales	Sets out considerations that should be made by infrastructure developers when planning the location, design, build, operation and decommissioning of new energy infrastructure. The considerations include the impacts of climate change to be assessed in the Environmental Statement of projects	DECC, 2009. National Policy Statement for Gas Supply Infrastructure and Gas and Oil Pipelines (EN-4) DECC, 2011 Overarching National Policy Statement for Energy (EN-1) DECC, 2011 National Policy Statement for Fossil Fuel Electricity Generating Infrastructure (EN-2) DECC, 2011 National Policy Statement for Nuclear Power Generation (EN-6) Volume I of II.
Offshore Installations and Wells (Design and Construction, etc) Regulations (DCR) (SI 1996/913), and the Offshore Installations (Safety Case) Regulations 2005 (SCR) (SI 2005/3117)	Territorial waters adjacent to GB and the UK sector of the continental shelf	Set the framework for safety case requirements and the structural standards of offshore installations.	

The Electricity Safety, Quality and Continuity (Amendment) Regulations 2006 (ESQCRs 2006)	England and Wales	Specifies safety structures aimed at protecting the general public and consumers from danger. It also covers adequacy of design and continuity of supply including resilience to faults caused by vegetation growth. In accordance with EU Directive 98/34/EC. In accordance with industry standards ENA TS 43-8 and ENA ETR 132.	
The Electricity Safety, Quality and Continuity Regulations (Northern Ireland) 2012 Northern Ireland Regulations	Northern Ireland	Specifies safety structures aimed at protecting the general public and consumers from danger. It also covers adequacy of design and continuity of supply including resilience to faults caused by vegetation growth. In accordance with EU Directive 98/34/EC. In accordance with industry standards ENA TS 43-8 and ENA ETR 132.	
RIIO Framework	GB	A new performance based model for setting the Network companies' price controls and is used by Ofgem to incentivise investment in adaptation by network operators.	

Table 4A.4. Policy frameworks for flood and coastal erosion risk management infrastructure

Policy reference	**UK Nation**	**Key effects of this policy in addressing climate risks**	**Links to other policies**
Flood Risk Regulations (2009)	England and Wales	Transposes EU Floods Directive into law	
Flood and Water Management Act 2010	England and Wales	Arrangements for flood risk management; national flood and coastal erosion risk management strategy to include climate change; water use temporary bans	Amendments to Reservoirs Act 1975: preparation of flood plans; see also Water Use (Temporary Bans) Order 2010 and Drought Direction 2011
Flood Risk Management (Scotland) Act 2009	Scotland	Similar to above; flood risk assessments to include climate change. Transposes EU Floods Directive into law.	
Reservoirs (Scotland) Act 2011	Scotland	Risk-based approach to the regulation of reservoirs	
The Water Environment (Floods Directive) Regulations (Northern Ireland) 2009	Northern Ireland	Similar to above; flood risk assessments to include climate change. Transposes EU Floods Directive into law	
Climate Change Act 2008 Adaptation Reporting Powers	UK wide?	Enables the SoS to request a climate change risk assessment from priority reporting authorities	Climate Change Adaptation Reporting Power – how to report your progress in planning for climate change, Defra 2013; Defra's 2009 Adapting to Climate Change programme
National Planning Policy Framework	England	The Framework expects new development in England to be planned to avoid increased vulnerability to the range of impacts arising from climate change; sets out policy on assessing flood risk,	

		avoiding development in areas at risk of flooding or coastal change where possible, and on mitigating the risks. The Framework expects local planning authorities to work with other authorities and providers to assess the quality and capacity of infrastructure [for transport, water supply, wastewater and its treatment, energy, telecommunications, utilities, waste, flood risk and coastal change management] and its ability to meet forecast demands, and to plan positively for the development and infrastructure provision required in the area.	
Technical Advice Note (TAN) 15 Development and Flood Risk	Wales	Supplementary guidance to Planning Policy Wales	
Planning Policy Statement (PPS) 15: Planning and Flood Risk	Northern Ireland	Prevent future development that may be at risk from flooding or that may increase the risk of flooding elsewhere.	
Planning Advice Note (PAN) 69	Scotland	Advice on planning and building standards in areas where there is a risk of flooding.	
Scottish Planning Policy (SPP) 7: Planning and Flooding	Scotland	Prevent further development which would have a significant probability of being affected by flooding or which would increase the probability of flooding elsewhere.	

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