A Climate Change Report Card for Infrastructure

Working Technical Paper

Nuclear, Coal, Oil and Gas Energy

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1 Highlights and key messages

This report reviews the current knowledge base surrounding **climate impacts on the infrastructure and operations of the nuclear, coal, oil and gas subsectors. This review is limited to upstream and supply-side activities of these sectors, including electricity generation.** It does not include demand-side considerations, neither the electricity transmission system. The four subsectors analysed, are all different yet share many similar operations and are hence vulnerable to a similar set of climate impacts. The sectors' importance as critical national infrastructure coupled with the relatively long existence means it has been long prepared for disruptions. Weather-related disruptions are generally well understood and prepared for. However, climate change will also change mean operating conditions, new and more frequent extremes and changing risk profiles. **Some of the impacts have the potential to disrupt operations, whilst others may have long-term effects on the performance of infrastructure.** This report considers climate risks primarily between now and the 2050s, which is approximately the expected working life of infrastructure recently, or soon to be commissioned.

Sea level rise, storm surges and flooding, extreme (high) temperatures and drought are commonly identified as the greatest risks and are extensively managed within companies. In general there is high confidence in the science of these impacts. Earth subsidence, wind and snow related risks are commonly considered less severe, and subsequently have been studied in less detail, hence only low to medium confidence in these areas. There is a lack of systems level knowledge (i.e. at water resources level) regarding the dependency on water in the sector, an issue that has been investigated in more detail in many other countries.

Information on these risks to energy infrastructure systems and networks (as opposed to on an asset basis) is even less well understood, as are the climate impacts on interdependent systems, namely transport and ICT.

The risks identified within the Climate Change Risk Assessment (CCRA) for the Energy Sector (McColl et al., 2012) were comprehensive. However, **a few areas in need of further investigation in the next Climate Change Risk Assessment. Risks to upstream oil and gas are not covered in detail, and risks to new energy systems, in particular carbon capture and storage (CCS), shale gas and underground coal gasification, are not covered at all.**

A lack of publicly available information and datasets, particularly on the fuel exploration and production side of operations, hinders independent research and scrutiny. It is suggested that **greater accessibility to datasets, models and a common set of energy systems analysis tools is essential if systems-level analysis on the sector,** including the effects of interdependencies and climate change, is to progress and effectively manage the risks of an increasingly complex energy system.

2 Introduction

As one of the most critical economic and infrastructural sectors of a modern economy, the energy sector is well established in the UK and provides a lifeline on which the health, safety and prosperity of the nation depends. The nuclear, coal, oil and gas industries, are referred to as *subsectors* of the energy sector in this paper. The sector has been long prepared for disruptions, of which weather-related disruptions are generally well understood, prepared for, and for which there is a rapidly growing body of evidence, data and knowledge. In preparation for climate change, weather impacts are increasingly studied through a variety of lenses. For example, and most obvious, is the study of the impact of more extreme weather events and climate, such as more intense and erratic rainfall, or higher maximum air temperatures. However, climate change may also alter the long term performance of our energy systems, simply as seasonal mean temperatures change. Furthermore, societal behaviour and responses, to both changing means and extremes, are also likely to change, with particular impacts on demands for energy. This working paper explores the current knowledge base surrounding climate change impacts on the supply side of the nuclear, coal, oil and gas subsectors in the UK, including electricity generation using these fuels. It does not cover demand-side impacts, neither the electricity transmission system. This report considers climate risks primarily between now and the 2050s, which is approximately the expected working life of infrastructure recently, or soon to be commissioned.

2.1 Overview of previous work

UKCP09 is the most up-to-date set of national scale climate projections for the UK, and certainly amongst the most advanced in the world. The UKCP09 work (Murphy et al., 2009) had a specific aim of providing data and information to help a wide range of stakeholders plan adaptation to the changing climate. The introduction of UKCIP02 in 2002 rapidly improved accessibility of climate change impacts information to academics and practitioners in the UK.

The Department for the Environment, Food and Rural Affairs (Defra) has on two recent occasions commissioned reports on the energy sector. Following the Climate Change Act 2008, 'statutory undertakers' such as major power generation companies were obliged to submit 'Climate Change Adaptation Reports' to Defra in 2011. However, none of the major oil and gas companies were called on to report. Since then, Defra has commissioned a multi-sector Climate Change Risk Assessment (CCRA), comprising 10 other sectors in addition to Energy. The Met Office also worked with the energy industry in the EP1 and EP2 working groups, assessing climate change impacts from 2006 to 2008 . A series of tools were created, although the majority of these outputs and expertise remains in industry.

2.2 Summary of infrastructure services, assets and key processes

This section describes briefly the main constituents of the UK energy system in relation to nuclear, coal, oil and gas. We cover exploration, production, transport and transformation

the majority of which summarised from the Digest of UK Energy Statistics (DUKES) (DECC, 2014, 2012a). We bring in a flavour of the international dynamic to these fuels, and list the numbers and locations of the major infrastructure assets that provide the foundations for the nuclear, coal, oil and gas subsectors. Climate change impacts are not considered in this description.

Energy systems can be categorised in many ways, although typically it consists of primary energy sources, conversion and transformation processes, delivery and end-uses.

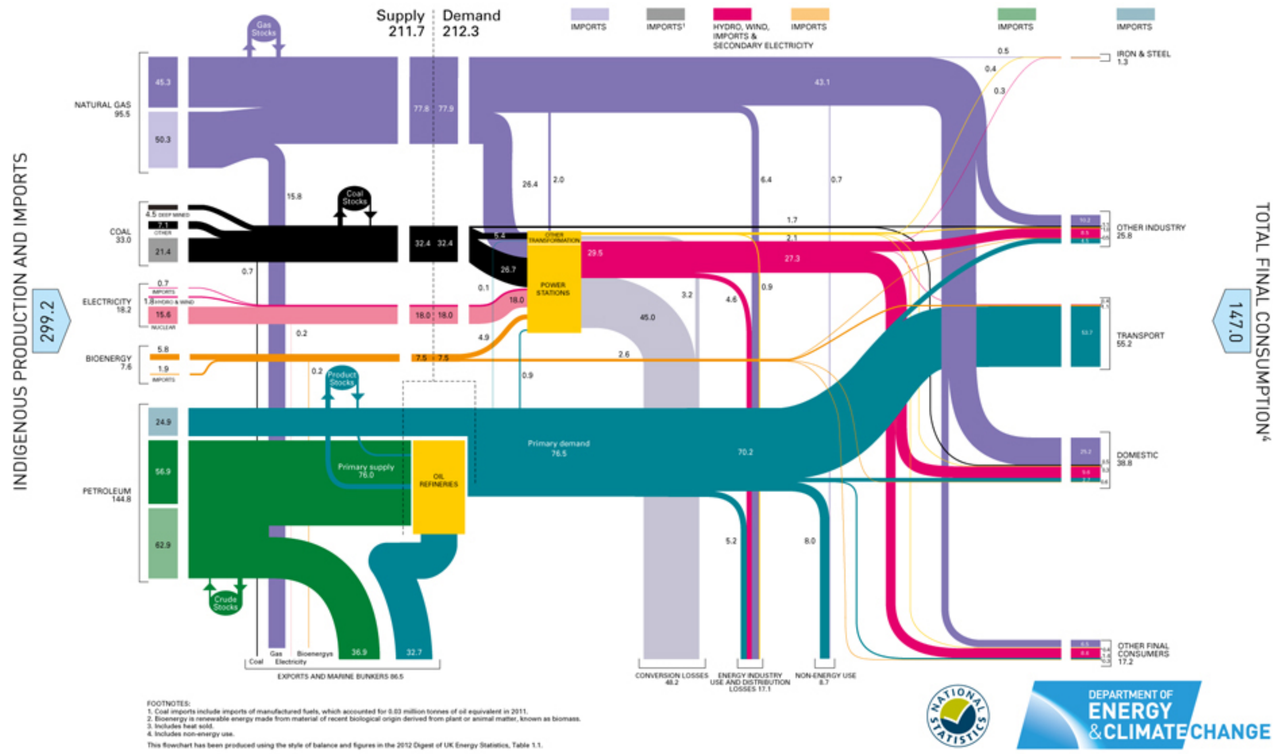
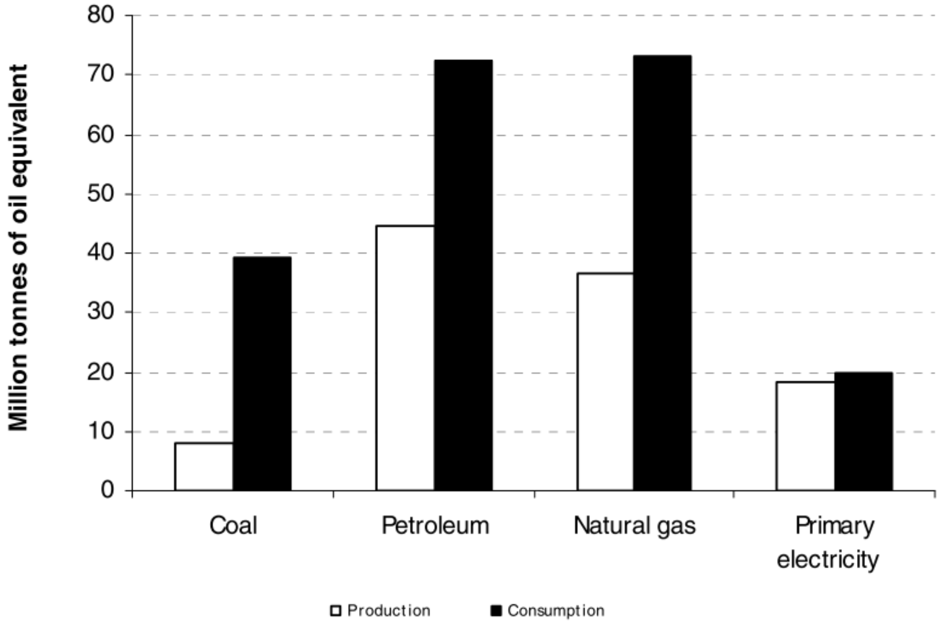


Figure 2-1. Sankey flow diagram of the UK energy system in 2012.(DECC, 2012a)

Coal, oil and gas feature in all of these stages. Being fossil fuels, they are extracted from the lithosphere and transported to places for processing and refinement. They are converted into a variety of products, from which point they are (usually) transported for end-use processes. Nuclear only features in the primary exploration and conversion/ transformation stages and not explicitly in the end-use of energy, unlike coal, oil and gas, if we exclude electricity transmission. However, the final life of nuclear waste and the decommissioned assets, remain important considerations.

The UK is a producer, importer and exporter of coal, oil and gas. In all cases, consumption exceeds domestic production. The infrastructure to support these industries consists of mines, wells and offshore drilling platforms, pipelines, railways, refineries, terminals and ports, compressor stations, transmission grids, storage depots, fleets of ships and approximately a quarter of a million skilled workers.



Note: Includes non-energy use of petroleum and gas. Differences between consumption and production are made up by foreign trade, marine bunkers and stock changes.

Figure 2-2. Production and consumption of primary fuels 2011.(DECC, 2014)

2.2.1.1 Nuclear

Uranium is imported to the UK, mostly from Canada and Australia, with conversion and enrichment occurring at Capenhurst and Springfields. There are currently 16 reactors in operation at 9 sites totalling 10 GWe. closures and decommissioning over the next decade will see installed capacity go from a peak of 12 GWe in 2000 to a low 3.4 GWe in 2019.

All the currently operational plants in the UK are located at coastal or estuarine locations for cooling purposes. The first of the new generation reactors will be built at Hinkley Point C, set for completion in 2023. Waste and spent fuel is reprocessed at two sites at Sellafield, Cumbria.

2.2.1.2 Coal

The UK is the second largest hard coal producer in the EU accounting for 13% of production in 2013. Coal is produced at around 30 sites employing 3,700 people at surface and deep mines. Imports have exceeded production in the UK since 2003, making up 79% of UK consumption. The majority of coal as primary fuel is transported domestically by freight trains. Imports, mainly from Russia (41%), the U.S. (25%) and Colombia (23%), occur at 17 coal ports around Great Britain.

83% of coal used in the UK is for electricity production by the major power producers, often co-fired with biomass to reduce emissions. There are 13 coal-fired power stations in the UK, hence the vast majority of coal is used in the UK is at these discrete locations, providing 36% of the UK's electricity. The remainder is mainly transformed for use in industry and derived fuels such as coke. EU legislation, such as the Large Combustion Plant Directive and the Industrial Emissions Directive, is driving change in the UK coal industry, resulting in mothballing, closure, co-firing and retrofitting.

2.2.1.3 Oil

The UK is the largest producer of crude oil and natural gas liquids in the EU, and second largest in the EEA. The UK imports as much petroleum products as it exports, due to refinery capabilities, changing demands and the variety of uses for petroleum products. The UK is largely dependent on imports from Norway whilst exports go to the Netherlands, USA, France and Germany. The UK stocks 79 days' use to protect itself against oil shocks.

The UK has 7 main refineries and three petrochemcial refineries, all located on the coast and/or near main estuaries. 75% of petroleum that stays within the UK is used by the transport sector. Offshore there are 107 oil platforms and 14,000km of pipelines – these pipelines join the UK at 8 oil terminals and 6 gas terminals. Onshore there are 27,000km of pipelines. Transport accounts for 71% of the petroleum products demand in the UK. There are approximately 250 onshore wells producing between 20,00 to 25,000 barrels per day, approximately 2% of UK production.

2.2.1.4 Gas

The UK is the second largest gas producer in the EU, although production has declined since 2000. Production and imports are approximately the same volumes, following which about 12% is exported. Natural gas is imported from 180 offshore gas platforms via 6 key pipelines, from the UKCS, Norway, Belgium, the Netherlands, and exported to Belgium and the Republic of Ireland. Liquefied Natural Gas (LNG) is imported at 3 locations, half of which from Qatar. There are 7 main gas storage sites.

The National Transmission System (NTS) is 7,600 km in length with 26 compressor stations, whilst the local transmission system consists of 275,000 km of pipes. The shale gas industry in the UK is developing, although not yet operational. Shale gas production will be highly distributed, water-intensive, and relies on high levels of light and often temporary infrastructure. Shale gas is likely to be fed into existing local gas distribution networks. A third of the gas is used in over 80 power stations, whilst a similar amount is used domestically, for heating and cooking. Industrial use accounts for 14%.

2.2.1.5 Electricity generation

Electricity generation is dominated by a mix of coal, gas and nuclear power stations (36% 27%, 20%, in 2013), generating from over 110 locations throughout the UK, connected by the National Grid. The level of gas-fired and nuclear generation is fairly constant throughout the year, whilst coal generation is higher in winter months and lower in summer months.

The National Grid connects the generation assets to balance supply and demand amongst the local distribution grids. Together, they consist of tens of thousands of kilometres of cables and hundreds of thousands of substations, transformers, and circuit breakers.

2.2.1.6 Nuclear, Coal, Oil and Gas subsector asset base summary

Table 1. Asset base summary of the nuclear, coal, oil and gas sectors.

Subsector	Asset type	#	Key indicators

Nuclear			
	Fuel conversion and enrichment	2	5,000 + 6,000 tU/yr
	Reactors (9 power stations)	16	10 GWe, 64 TWh/yr 20% of UK supply
	Waste storage and fuel processing facilities	2	
Coal			
	Mines		
	- Deep	12	4.1 Mt / yr
	- Surface	31	8.8 Mt/yr
	Power stations (incl. biomass co-firing)	13	21 GWe, 124 TWh/yr 27% of UK elec. supply
Oil			
	Oil platforms	112	
	Pipelines		
	- Offshore	3,700 km	
	- Onshore	27,000 km	
	Refineries	8	
	Power stations	7	1% of UK elec. supply
Gas			
	Gas platforms	188	
	Pipelines		
	- Offshore	8,500	
	- Onshore (NTS)	7600 km	
	- Local distribution	275,000 km	
	Gas import terminals	6	
	Gas storage sites	7	4.36 billion m^3
	Power stations - CCGT	39	33 GWe, 94 TWh/yr
	- other	40+	36% of UK elec. supply

2.3 Observations of key vulnerabilities and frequency of problems

Energy networks and systems have high levels of dependency, interdependency and dependents. Changes and failures can have ripple effects throughout regions, countries and event across continents. As observed in the CCRA, the energy sector is generally well prepared for but also most vulnerable to, extreme weather disruptions that have immediate impacts on their ability to maintain energy supply (McColl et al., 2012).

When considering changing climates that may affect the long term performance, small marginal changes such as an increase in 1°C mean temperature, could result and require large asset-scale adaptations. However in the majority of cases change in operation conditions is accommodated and managed. This may result in a slight performance reduction or increase in failure likelihood.

2.3.1 Key interdependencies

The risks to this sector are deeply intensified by the interdependencies with other sectors. Interdependencies were specifically mentioned in the DEFRA reporting guidelines to organisations submitting Climate Change Adaptation Reports.

Whilst most infrastructure systems are dependent on the energy sector, aspects of the energy sector are dependent on other sectors, primarily transport and communications. These interdependencies are considered second-order dependencies, in that a failure in one sector may impact on the energy sector, with impacts for other sectors dependent on energy.

Transport

Transport dependencies are widespread, but primarily important for the delivery of fuels, secondary materials and workforce. Transport infrastructure on which the energy sector is dependent, may be privately or publicly operated, and thus may offer different levels of reliability against severe weather disruptions such as flooding. Climate change impacts on transport infrastructure (related to the energy sector) are assessed in detail in (Highways Agency, 2011; Palin et al., 2013; Thornes et al., 2012).

Communications

Communications are used throughout the industries. In particular ICT and SCADA systems are used in monitoring and remotely controlling assets as well as the networks that connect those assets, particularly for routing gas and electricity supply. Whilst loss of communications can lead to failures in dependent assets, these systems actually prevent failures to a much higher degree. ICT and electricity supply are interdependent. Weather disruptions are most likely to affect underground communications infrastructure but only on a local basis. In some aspects such as the internet, ICT has a strong international dependency. In the energy sector redundancy is used across all subsectors in safety-critical operations. Smart meters will increase the dependency on ICT, but will also improve long-term performance and reliability. Crucially, ICT is also heavily relied on for the incident response to disruptions, from flood alerts to first responders. More information available in: Horrocks et al., (2010).

3 Potential impacts of climate change

Potential impacts of climate change vary considerably, and depend on both objective variables, such as location and exposure to a weather system, as well as subjective perception of impacts, vulnerability and how they are measured. As described in the UKCIP report on *Managing adaptation: linking theory and practice* (2011), there are both top-down (impacts) and a bottom-up (vulnerability) approaches to risk assessment. The UK in general takes the top-down approach.

Key findings of UKCP09 between now and 2100 include warmer and wetter winters, and hotter and drier summers (Murphy et al., 2009).

- Warming of mean temperatures will be greater in summer and south England.
- Mean daily maximum temperatures and warmest summer days increase everywhere and will be greatest in summer.
- Mean daily minimum temperatures increases everywhere, particularly the south.
- Largest increases in winter precipitation will be in the west.
- Largest decreases in summer precipitation will be in the south of England.
- Relative humidity will decrease in summer in the south of England.
- Sea level rises and storm surges are expected to increase with greatest impacts on east coast and large estuaries

The Future Flows Hydrology 2050 central estimate projects changes from +20% to -80% for summertime flows (Prudhomme et al., 2013, 2012).

3.1 UK Climate Change Risk Assessment for Energy

The UK Climate Change Risk Assessment (CCRA) 2012 was commissioned by DEFRA for 11 key sectors under 5 themes in the UK thought to be most impacted by climate change. An evidence report for the Energy sector was produced with the objective of "a consistent picture of risk for the UK and allow for some comparison between disparate risks and regional/national differences".

Various workshops identified 37 *Tier 1* risks and impacts for the Energy sector, categorised by the climate drivers of: *Precipitation, temperature, sea-level rise,* and *wind speed*. Five risks (EN1 to EN4) were classified as *Tier 2* impacts that warranted detailed analysis due to high impacts, high urgency and high likelihood (Figure 3-1 in bold boxes, Table 2). A further 6 were analysed in less detail due to time constraints in the project. These risks were also classed as *marginal* as the impacts would affect performance of the energy sector, but would be unlikely to prevent operations from actually taking place. It is acknowledged that more detailed analysis is required, as the risks of some drivers and impacts coinciding may be increased: i.e. high temperatures and low flows. The 37 CCRA Tier 1 impacts for the Energy sector can be found in Appendix 2.

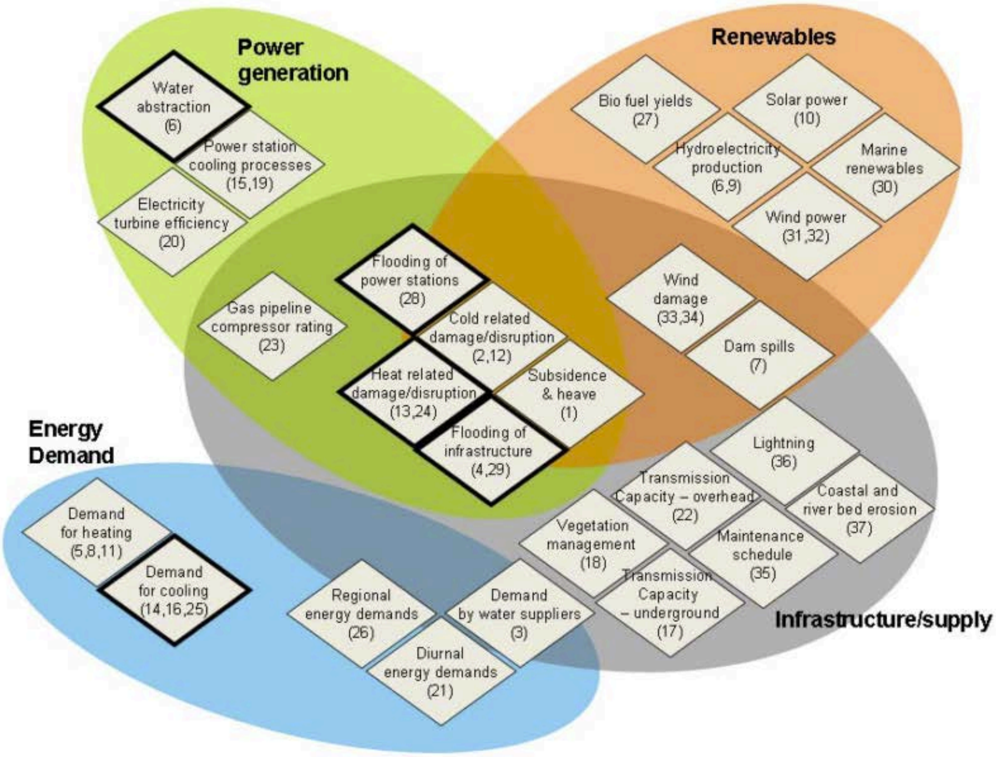


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Figure 3-1. Impacts cluster from the CCRA. Tier 2 impacts in bold boxes. (McColl et al., 2012)**.**

Most notably in the context of this study, the impact cluster and Tier 1 risks Figure 3-1appear to not take into account the offshore oil and gas industry, whilst impacts on offshore renewables are explicitly mentioned. A scoring system of all the identified impacts considered the magnitude of consequences, likelihood of consequences and urgency of action required. Impacts chosen for Tier 2 analysis scored the highest, were classified as *priority* and constituted about 20% of the impacts identified for more detailed analysis.

Table 2. Tier 2 impacts from the CCRA. Impacts relevant to the context of this study highlighted in bold.

Tier 2 Priority impacts	***Tier 2 marginal impacts***

EN1: Flooding of infrastructure	EN5: Demand by water suppliers
EN1b: Flooding of power stations	**EN6: Electricity turbine efficiency**
EN2: Cooling demand	**EN7: Gas pipeline compressor rating**
EN3: Heat related damage/disruption	**EN8: Power station cooling processes**
EN4: Water abstraction	**EN9: Wind damage**
	EN10: Transmission capacity.

* EN2 Cooling demand refers to the electricity demand for cooling buildings, mainly commercial but increasingly domestic. EN5 Demand by water suppliers refers to the energy demand from water suppliers. EN2, EN5 and EN10 are outside the scope of this study.

3.2 Impacts from the National Policy Statements.

The National Policy Statements were produced for key sectors of the UK and set out planning policy guidance to be considered by planning authorities.

Section 4.8 of part 2 of Report EN-1, the overarching NPS for Energy, details the Government's commitments and strategy for mitigation of and adaptation to climate change (DECC, 2011a), including "generic considerations" to be addressed by applicants to ensure that infrastructure is resilient to climate change.

> "*applicants must consider the impacts of climate change when planning the location, design, build, operation and, where appropriate, decommissioning of new energy infrastructure*." (DECC, 2011a)

The proposed projects must consider as a minimum, the emissions scenario identified by the Committee on Climate Change that the world is most closely following, with 10%, 50% and 90% estimate ranges. Safety critical elements of new projects should take a risk averse approach and consider the high emissions scenario, for high impact and low likelihood events.

A more holistic approach may have at least considered a common set of climate drivers, to be considered by all energy infrastructure planning applications. The NPS consistently reference higher air temperatures and increased flood risks, although other impacts have less consistent treatment (Table 3).

Table 3. Summary of mentions for each climate change impact in the climate change adaptation sections of the National Policy Statements for Energy (DECC, 2011a, 2011b, 2011c, 2009)**. N.B. EN-5 excluded from this analysis.**

Impacts	**EN-2 Fossil fuel generating Infrastructure**	**EN-4 Gas supply infrastructure and Gas and Oil Pipelines**	EN-5 Electricity Networks Infrastructure	**EN-6 Nuclear Power Generation**
Flooding	✔	✔	✔	✔
Drought – cooling water and process water	✔			✔
Sea levels, coastal change and storm surges	✔	✔		✔

Higher temperatures	✔	✔	✔	✔
Earth movements and subsidence		✔	✔	
Wind and storms			✔	

3.3 Structural, spatial, temporal and socio-economic impact considerations

3.3.1 Asset-base and network structures

A key vulnerability of the energy sector and the subsectors concerned is through the sheer number of assets involved, both on and offshore. When considering failure and disruptions that usually happen in extreme conditions, it is worth considering the generalisation that: Larger assets that provide high volumes of service tend to be fewer in number and more robust. Frequencies of failure and disruption are similarly inversely scaled; large assets fail infrequently with higher impacts. The opposite for small assets is also true.

Network analysis of the UK's energy systems, has been mostly confined to electricity and gas networks, with little information actually available on network structures and configurations. Some studies have considered impacts on the networks and capacity, such as for gas (Chaudry et al., 2012, 2008; Skea et al., 2012). Other similar studies examine interactions between gas and electricity systems (Chaudry et al., 2014), in particular with high penetrations of wind (Gerber et al., 2012; Qadrdan et al., 2014, 2010a, 2010b). Similar studies of the coal and petroleum (and other liquid fuels) distribution systems were not found.

A table from Munich Re (Coates and Hall, 2009) suggests a change in the incident-loss risk profiles going forwards in the electricity sector due to the increased penetration of renewables. With the exception of nuclear, the frequency/severity profile may change from lower frequency higher loss incidents to higher frequency lower loss incidents, due to the increasingly distributed nature of renewables generation.

3.3.2 Spatial variability

The spatial distribution of the asset-base affects both the severity and frequency of disruptions. For all subsectors concerned, the distribution of assets is relatively evenly spread across the UK, although there is a slight bias for oil and gas infrastructure being primarily east coast based. If carbon capture and storage (CCS) schemes go ahead, these will be predominantly eastern in order to facilitate offshore CO_2 storage. Furthermore CCS infrastructure will be clustered (DECC, 2012b) which may pose additional risk, such as to localised water shortages (Byers et al., 2014; Naughton et al., 2012).

If shale gas (as with renewables), increase in penetration across the UK, the highly distributed and semi-permanent nature of this infrastructure may result in more frequent disruptions as local levels, due to flooding for example. Storage of highly-toxic 'fracking' chemical onsite and the effects of high temperatures and surface flooding, is a specific risk to be researched and regulated. The spatial variability of climate impacts may affect infrastructure on regional levels although the systems for the UK as a whole should manage such disruptions.

3.3.3 Short term impacts

A study by Hammond and Waldron (2008), for UK electricity supply ranked a series of risks, with *severe weather conditions* as the fourth highest risk out of 15. Weather-related incidents tend to bear a disproportionate amount of cost and damage compared to the frequency of occurrence. The global power generation industry accounts for 12% of large losses by type, yet 22% of total cost to the insurance industry (Marsh, 2013). Accidents in the offshore industry also tend to be extremely costly, with loss of a platform costing hundreds of millions of dollars (Marsh, 2011; Willis, 2004). This possibility increases substantially as offshore exploration moves into more hostile environments (Rees and Sharp, 2011), a venture facilitated by melting Arctic sea ice. Analysis of structural risk on the UK Continental Shelf reports that approximately a third of failures on fixed and non-fixed installations are weather-related (OGP, 2010). Marsh research (2011) also highlights that weather-related impacts on the oil and gas industry often affect multiple facilities resulting in amongst the biggest claims in the insurance industry. No studies investigating weather-related risks to the offshore oil and gas pipeline and supply system were found.

3.3.4 Long term (chronic) impacts

Warmer air and cooling water temperatures affects the efficiency of both steam and gas turbine based electricity production (Arrieta and Lora, 2005; Kim et al., 2000; Maulbetsch and DiFilippo, 2006; Valdés et al., 2006), in the order of about 1% per °C above 15°C air temperature. Higher air temperature and humidity reduce the efficiency of gas turbines, which affects CCGT plants although this can be reduced using air-inlet cooling (Boonassa et al., 2006; Pyzik et al., 2012). The efficiency of tower cooling for steam-cycle plants is also reduced by higher humidity and air temperature. Cooling water temperatures are important for once-through cooling systems and will affect some coastal and tidal power stations, particularly nuclear power plants in the order of 0.5% output reduction per °C cooling water increase (Durmayaz and Sogut, 2006).

Whilst there are many theoretical and empirical studies on performance relating to these variables (see Colman (2013)), there are no comprehensive UK studies on the impacts of higher air, humidity and water temperatures that extrapolate these effects across the scale of the UK, for example as shown for California (Maulbetsch and DiFilippo, 2006; Sathaye et al., 2013).

Longer term climate impacts may also affect the supply, availability and price of national and imported biomass feedstock for coal co-fired and biomass power stations.

3.3.5 Disruption and socio-economic impacts

The CCRA Appendix contains qualitative guidance (Table A4.1, pp.120) on relative magnitude of impacts, with 3 classes of high, medium, low across 3 impact types of economic, social and environmental. These impact types were used for scoring impacts in the Tier 2 Assessment as well as the risk levels presented in Chapter 5: Changes in Climate. The qualitative impacts cover both short and long

timescales, and for each impact type gives examples in terms of how losses can be accounted, i.e. *£10 million per event*, and *1000 km river water quality affected.*

Metrics and indicators that are applicable across subsectors are good for comparison, yet usually do not align with how subsectors evaluate their own performance and vulnerability to risk. Under the Utilities Act 2002, gas and electricity supply industries have performance levels for supply restoration, although this could go further.

4 Key impacts and hazards for the subsectors

The following tables present subsector summaries of the key climate change impacts and resultant hazards on the infrastructure, as identified in the available literature from a variety of sources.

4.1 Nuclear

Nuclear	Key impacts and hazards
• **Coastal (incl. sea level rise):** Storm surges and sea level rise are consistently considered the greatest risk to nuclear power stations. Sea defences designed for 1 in 10,000 year flood event are verified under periodic safety review process. Industry-wide review following Fukushima event considering natural hazards investigated flooding risks and safety procedures in detail. • **Drought:** Unavailable town's water for process water considered a medium risk for which usually 24 hours' worth of supply is kept on site. Sea water used as last resort nuclear safety option, with result of considerable equipment damage. • **Cooling water discharge temperature:** Discharge temperatures to estuarine environments are regulated to protect aquatic environments. With expected lower and warmer river flows, breach of discharge temperatures may increase, resulting in ramping down of generation, at considerable cost. Heat exchanger capacity and discharge outfall modifications to be considered. • **Flooding:** Flooding is a risk taken very seriously, well protected against and reviewed periodically. Surface water flooding and drainage problems is also a concern, along with interruption of supply lines and transport links (for several days) – including delivery of stock-limited commodities and spent fuel removal. • **Extreme temperatures:** Low impact on power generation due to controlled conditions. Chemicals used (such as biocides and fuel oils) may incur higher degradation, decomposition and vapour rates with higher temperatures, both mean and extreme, depending on storage. Impacts more likely to have greater impact on infrastructure and services on which nuclear power depends. • **Earth subsidence and landslides:** Increase in risk is expected, but viewed to remain a very low. Site subsidence is routinely monitored, and not expected to increase with climate change. • **Wind:** Not expected to increase the risk, unless winds become more extreme with climate change. • **Snowfall:** Structural snow loading is not expected to increase, and incidence of snow days expected to decrease.	
Uncertainties and unknowns	
• Investigation into drought impacts on local water supplies for process water, to consider whether more than 24h of supply should be kept on site. • Estuarine water temperature increases to be investigated with impacts assessment into whether frequency of (potential) regulatory breaches occurs. • Uncertainty of changing wind conditions with climate change to be reviewed periodically. • Operation-critical chemical storage and transportation to be reviewed with respect to temperature changes. • The safe storage of nuclear waste and its sensitivity to climate impacts, as well as species and habitats sensitivity to radiation due to environmental change, is uncertain.	
Sources	(DECC, 2011c; EA, 2010; EDF Energy UK, 2012, 2011; Förster and Lilliestam, 2009a; Linnerud et al., 2006; World Nuclear Association, 2011)

4.2 Coal

Coal	Key impacts and hazards

- **Coastal (incl. sea level rise)::** Storm surges and sea level rise will impact on port operations and coal imports, risks managed by the ports authorities, who undertake their own assessments and adaptation. Coal is imported at 17 locations. Coastal surge could also lead to flooding of power stations and coal stock sites.
- **Drought:** Drought could impact on coal-processing and washing at the UK's 33 production sites, which provide 37% of the UK coal consumption. Drought may impact on international supplies, although stockpiles and spatial variability of supply negate this impact. CCS plants require almost double the cooling water of conventional generation.
- **Flooding:** Increased flooding will impact on the safety of UK mining operations, through actual inundation, saturated soils and earth movements: all increasing downtime. Flooding may increase risk to coal transport links, which is predominantly rail. Coal power stations usually stock weeks-to-months worth of fuel – there is no specific statutory obligation.
- **Extreme temperatures:** Not expected to impact on the supply production. Extreme temperatures will impact on rail track or roads supplying coal. Both extreme and rising mean change in air temperature will affect electricity generation efficiency and steam cycle cooling efficiency.
- **Earth subsidence and landslides:** Increase in risk expected with climate change may impact on safety of open-cast and deep mines. Climate change impacts on slope stability should be assessed for UK coal mining operations.
- **Wind:** Not expected to increase risks.
- **Snowfall:** Snow days expected to decrease with positive effects.

Uncertainties and unknowns

- Unclear to what extent supply-lines of coal, from pit-to-power station, have been assessed for risks from climate change.
- Coal and water – The water footprint of and water availability on the extraction and production of coal appears to be unknown for the UK, unlike in China and USA. Water footprinting and impacts of water availability recommended for both domestic and imported coal.
- Stability of UK coal mines should be assessed particularly in areas prone to flooding and drought.
- Climate policy and regulation is potentially the greatest risk to UK coal production – potentially leading to stranded assets and dissolution of the UK coal industry if CCS is unviable.
- Underground Coal Gasification (UCG) could increase risk of subsidence and contamination of water resources.
- Thermodynamic relationships in power stations' operation and cooling is well understood, although these efficiency impacts haven't been quantified nationally in detail.

Sources	(Chalmers, 2010; DECC, 2012a; Grubert et al., 2012a; International Power plc, 2011; Jenner and Lamadrid, 2013; Naughton et al., 2012; Pan et al., 2012; Probert and Tarrant, 1989; Rixham, 2011; RWE npower, 2011)

4.3 Oil and gas

Combined because mostly the same risks.

Oil and gas	Key impacts and hazards

- **Coastal (incl. sea level rise)::** Storm surges and sea level rise will have temporary impacts on ports operation for vessels and rigs. Coastal erosion will expose pipeline infrastructure. Storms may increase disruption. Large waves disrupt offshore mooring and operations.
- **Drought:** Drought could impact on freshwater availability at refinery and petro-chemical plants. Drought may impact on onshore shale oil and gas exploration. CCS plants require almost double the cooling water of conventional generation.
- **Flooding:** Flooding will impact on road-based supply and buried assets.
- **Earth subsidence and landslides:** Risk increase expected with climate change due to drought and saturated ground, with impacts on buried assets such as storage depots and pipelines.
- **Wind:** Extreme winds prevent docking of import/export vessels and supply chain vessels. Extreme winds could lead to evacuation of platforms (due to wind and wave loading), as well as prevent crew movements via helicopter. If wind speeds means and extremes increase, this will have impacts, in addition to impacts on wave formations.
- **Snowfall:** Snow days expected to decrease with positive effects.
- **Extreme temperatures:** Higher air temperatures (mean and extreme) will reduce CCGT turbine output and steam cycle cooling system efficiencies.

The highest impact events identified by Ofgem were loss of gas pipelines and import terminals. Expected disruption is 10 days with loss of service in that period of 20-40% of supply from the UKCS and NCS. (Ofgem, 2012)

Uncertainties and unknowns

- None of the major oil and gas companies, neither major petrochemical facilities, were called on by Defra to present Climate Change Adaptation Reports under the Climate Change Act 2008.
- Supply lines in the industry are complex and dependent on actors well outside the UK sphere. International climate risks could impact on the UK industry.
- Forecasting of wave heights is improving, although lack of consensus regarding extreme values for the North Sea. Dependent on currently uncertain climate impacts on wind.
- Water is used in oil exploration for Enhanced Oil Recovery (EOR) as well as hydraulic fracturing. Increased interest in onshore shales, for both oil and gas production, will lead to increase in freshwater use and drought vulnerability.
- Pipeline vulnerability to earth movements. Risks to drought and flooding doesn't appear in literature.

Sources	**General oil and gas -** (Acclimatise, 2012, 2009a, 2009b; CH2MHILL, 2012; Concessi and Curtis, 2008; DECC, 2009; Harrison, 2008; IPIECA, 2013; OGP, 2010; Royal Dutch Shell, 2012; Wilbanks, 2012) **Wave heights –** (Colman et al., 2011; Esteves et al., 2011; Leake et al., 2009; Thornton and de Gusmao, 2008; Zacharioudaki et al., 2011) **Shale gas -** (Entrekin et al., 2011; Ross, 2013; Royal Society and Royal Academy of Engineering, 2012) **CCS -** (Damen et al., 2006) **Gas networks and supply -** (Chaudry et al., 2014, 2008; Gerber et al., 2012; Qadrdan et al., 2014, 2010a, 2010b; Skea et al., 2012)

4.4 In focus: sensitivity to droughts, water availability and climate change

Whilst the UK is at the forefront of research concerning climate change and hydrological risks, dependency of the energy sector on water is poorly understood. There are no known studies of the UK's water footprint that arises from exploration and production of fossil fuels, neither in the UK nor for imported fuels. In particular an assessment is required for the water demands from projections of domestic shale gas production, although these are not thought to be substantial (Royal Society and Royal Academy of Engineering, 2012). Some international work addresses these issues, including forward projections. (Francis et al., 2013; Hadian and Madani, 2013; McMahon, 2010; Pan et al., 2012; U.S. DOE, 2006; World Energy Council, 2010). Water use from UK electricity production is slightly better understood on a national and regional scale (Byers et al., 2014; Environment Agency and Natural Resources Wales, 2013; Naughton et al., 2012; Schoonbaert, 2012; Tran et al., 2014), with the conclusion that rising energy demands, the high water-intensity of CCS generation capacity, and clustering of CCS plants may leave generation capacity vulnerable to droughts or contribute to localised water stress. Studies to date are less comprehensive than those performed by the US (Clark et al., 2013; Grubert et al., 2012b; Jenner and Lamadrid, 2013; King et al., 2008; Macknick et al., 2012a, 2012b; NETL, 2009, 2007; Scanlon et al., 2013; Benjamin K Sovacool and Sovacool, 2009; Benjamin K. Sovacool and Sovacool, 2009; Sovacool, 2000; Torcellini et al., 2003; U.S. DOE, 2006), or internationally (Francis et al., 2013; Müller et al., 2007; Pan et al., 2012; World Energy Council, 2010). There have only been a few high-level studies addressing vulnerability of power generation to climate change and hydrological variability (McColl et al., 2012; Naughton et al., 2012; Tran et al., 2014, pp. 70–73), and other simulation-based and spatially explicit approaches should be investigated (Förster and Lilliestam, 2009b; Koch and Vögele, 2009; van Vliet et al., 2013, 2012).

5 Assessment and management of climate change risks

5.1 Costs and/or relative magnitudes of these impacts

Direct losses of assets in all the subsectors can extend into hundreds of millions of pounds. Loss of service from smaller assets, for example a pipeline, can also result in large indirect losses from lost revenue and contracts. The assets of all the subsectors provide large volumes of service, for example, loss of a nuclear reactor equates to electricity production for over a million homes. Economic losses to the power and water utilities in the 2007 floods accounted for an estimated 10% (£0.33 billion) of total costs. Costs to electricity and gas were £139 million, of which 90% was the cost of disrupted supplies to customers. Most of the electricity supply system coped with the

floods, with the estimated infrastructure damage at only £9 million. Nonetheless, two major power cuts with lost supply to over 150,000 households, mainly in Yorkshire gave a total economic impact of £130 million for affected parties (Chatterton et al., 2007).
Heatwave events exemplify both the strains put on critical infrastructure as well as their importance in resilience to natural hazards. The European heatwave in 2003 caused 70,000 excess deaths. Both energy and water supply infrastructure become strained during heatwaves and both services are critical to providing comfort (ventilation, air conditioning and water) from the effects of a heatwave and minimising excess deaths. Social impacts are discussed in McGregor et al. (2006).

5.2 Adaptation opportunities to manage these risks

The Pitt Report (2008) suggested that Critical National Infrastructure should be protected to at least a 1 in 200 year (0.5%) annual probability events. Some subsectors prepare for much higher levels, for example nuclear (1 in 10000) and electricity transmission (1 in 1000) for key assets. The question of who pays for additional infrastructure resilience and adaptation, remains.
Two similar studies (Chaudry et al., 2012; Skea et al., 2012) investigated in detail the impacts of the loss of the UK's largest gas supply infrastructure assets for different periods and the economic impacts in 2025, in particular with the electricity supply system. They conclude that the additional costs of a more resilient system (whether to climate change or security risks), would unlikely be market-driven and would essentially be a political decision to increase gas security.

6 Broader drivers and interactions

6.1 Technological and decarbonisation

The use of carbon capture and storage (CCS) in the electricity sector presents various risks (Abadie and Chamorro, 2008; Chu, 2010; Huijts et al., 2007; Jacobson, 2009), although climate impacts have not yet been assessed comprehensively. The increased number of assets increases exposure to the range of hazards, and as aforementioned, the increased cooling demands of CCS power stations are likely to increase water use in the sector.
The trend to decarbonise transport is bringing increased penetration of electric and fuel-cell vehicles as well as more efficient petroleum-fuelled vehicles. Depending on perspective and context, the diversification of transport fuel-dependency should bring increased resilience to the system as a whole, ensuring at least some transport modes if either petrol or electricity supplies are disrupted significantly. Furthermore, there is evidence to suggest that electric vehicles will play a role in distribution grid balancing and may provide power in case of outage or peaking capacity (Lund and Kempton, 2008; Nielsen and Ravn, 2011; Srivastava et al., 2010).
A high penetration of wind capacity will have impacts on the gas supply infrastructure needed for back up generation, increasing maintenance costs for CCGT plant and the use of compressor stations. If the UK moves away from gas-fired domestic central heating, this may exacerbate the problem (Qadrdan et al., 2010b).

6.2 Decentralisation and centralisation

The use of coal occurs at opposite ends of the centralisation/decentralisation spectrum. Coal, and to a lesser extent oil, is used as a heating fuel in only a small proportion of domestic users otherwise not connected to the gas distribution networks, as well as being used at large industrial facilities and power stations.
Exploration and production (E&P) of petroleum is largely centralised although its consumption is highly distributed and is likely to remain so. Impacts on the few large refineries and depots can

have widespread ripple-effects on availability and price of fuels throughout the country. These impacts are largely elastic and do not cause wider systemic failure. i.e. the 2005 Buncefield fuel depot fire caused fuel shortages for 3 months, but contingencies ensured that Heathrow and other transport remained operational.

E&P of gas in the UK may also become highly decentralised if shale gas takes off. An increasing number of assets will be exposed to onshore climate risks, such as flooding and drought, although with limited impacts; there is little interdependency between operation of shale gas sites (unlike the electricity networks), unless they depend on common pipelines, workers, access roads or mobile assets.

Decentralisation in the electricity sector can be considered to increase resilience to climate impacts, although this concerns mainly the use of renewables and small-scale generation. Climate impacts could indeed have ripple-effects through mainly centralised systems (as the current electricity grids are), exposing other assets to greater risk than normal. i.e. flooding of generation assets in the south could increase loading on north-south grid connections and generation capacity.

6.3 Preparation for and awareness of interdependencies

Impacts of climate change could increase price volatility and the security of supply if suppliers, particularly those from international markets, fail to adapt to climate change as extensively as proposed by organisations in the UK. Thorough risk assessments should take into account international supply chains. In particular the vulnerability of fuel imports to climate change should be systematically assessed in more detail than currently covered in the Ofgem Gas Security of Supply Report (2012).

7 Confidence in the science

Here we make assessment of the confidence of impacts across the subsectors using an approach based on the IPPC (Mastrandrea et al., 2010). We consider *evidence* as the level of evidence available that the impact has effects specifically on the subsector in question in the UK (as opposed to evidence of the impact on all sectors of society), and *agreement* as the level of agreement on the effects between the sources of available evidence. In brief:

- Coastal – low-medium evidence, medium agreement
- Flooding – low-high evidence, medium-high agreement
- Earth subsidence and landslides – low-medium evidence, medium agreement
- Wind effects – low-medium evidence, medium agreement
- Snowfall – low-medium evidence, medium-high agreement
- Drought – low-medium evidence, medium agreement
- Extreme temperatures – low-medium evidence, medium-high agreement

Table 4. Confidence in the science evaluated across the impacts and individual subsectors, for both extraction and production, and electricity generation.

	Extraction and production			Electricity generation		
Agreement / *Evidence*	Nuclear	Coal	Oil & gas	Nuclear	Coal	Oil & gas
Coastal	Med / Low	Med / Low	Med / Med	Med / Med	Med / Med	Med / Med

Flooding	Med / Low	Med / Med	Med / Low	High / High	High / High	High / High
Earth subsidence	Med / Low	Med / Low	Med / Med	Med / Med	Med / Med	Med / Med
Wind effects	Med / Low	Med / Low	Low / Med	Med / Med	Med / Med	Med / Med
Snowfall	Med / Low	Med / Low	Med / Low	High / Med	High / Med	High / Med
Drought	Med / Low	Med / Med	Med / Low	Med / Med	Med / Med	Med / Med
Extreme temperatures	Med / Low	Med / Low	Med / Low	High / Med	Med / Med	Med / Med

Across the subsectors, there are disparate levels of accessible research available from industry and academia. Information on the upstream exploration and production of nuclear, coal, oil and gas industries is largely held within private companies. Research and knowledge in these areas is extremely high, although rarely accessible and hence difficult to scrutinise. Information on downstream use of fuels, such as in the transport and electricity production sectors is scrutinised to a much higher degree, in part due to the regulators and consumer interests. It is difficult to qualify that there is robust evidence available on climate impacts for any of the subsectors due to the information gap on upstream activities.

The effects of extreme temperatures on the subsectors and their processes is well understood and with high agreement, and companies will have modelled impacts at a power station level. However there is only medium evidence on what wider impacts across the UK will be and what this means for the electricity system. This is similarly the case for drought and streamflow temperatures and how this may affect, for example electricity production cooling or E&P of coal and shale gas. The processes of earth subsidence, landslides and snowfall are well understood, although due to the generally lower risk presented, there is less evidence available on the climate-related impacts for energy infrastructure. Storm surges, sea level rise and flooding are generally considered high risks and subsequently there is a medium-high level of understanding and agreement of the physical processes involved (as there is with air temperature for example), although associated impacts are understood to a medium level, given a high number of complex uncertainties and variables, such as preceding land conditions, asset defence integrity, event duration, intensity and spatial variability and the social responses. There is a low-medium level of agreement of future wind conditions and how these may or may not change with global warming. Responses are generally well understood and agreed, although risks will need to be revisited as the evidence on climate change and wind effects grows. Concerning the sensitivity of the energy subsectors to water specifically, including droughts and streamflow temperatures, there is medium level agreement on the responses and physical processes, although only a low level of evidence on the likely impacts to the sectors.

8 Research gaps and priorities

8.1 Testing of impacts under a consistent set of future UK energy scenarios

Throughout research groups and organisations across the UK, a wide range of future energy scenarios have been developed, often bespoke for the project in hand. There is usually continuity within organisations but otherwise new energy projections and models are being developed on an ad-hoc basis.

Development of a facility similar to UKCP09 with the hosting of various energy systems models would do much to improve accessibility, and particularly the quality of outputs available for academic scrutiny, in a similar way to the availability of climate modelling outputs. A facility whereby a set of common infrastructure databases and datasets was made available, if necessary under license in a controlled environment, could rapidly accelerate the pace of research regarding climate impacts (and much wider) on energy infrastructure systems, as well as associated disruptions and n^{th} order effects. Rigorous investigation of multi-sector infrastructure interdependencies will be impossible without greater availability of infrastructure datasets. This must include both energy supply and demand projections (i.e. DECC 2050 Pathways, UEPs), as well as models of asset structures and configurations such as generation assets and transmission and distribution networks.

8.2 Further investigation into the links between energy, water and land

The water-energy nexus is an area of research gaining prominence across the world. The uses of water in energy exploration, production, transport, generation and end-use are widespread. Before the UK embarks on studying the impacts of climate change and sensitivity to water on the energy subsectors, greater understanding is required on the links between water and energy in the UK. The UK's understanding in this area is significantly behind that of other countries such as the U.S. and Germany. However some UK projects are moving in this direction, such as the Nexus Network (ESRC), SPLiCE (Defra) and the call for Valuing Natural Capital in Low Carbon Energy Pathways (NERC). Wider research into environmental impacts, both national and international is also required in a more holistic approach, that may for example consider wider environmental impacts through life-cycle analysis.

8.3 Climate impacts on systems, not silos

In general most of the impacts are well understood by the subsectors and the actors, as demonstrated in the Climate Change Adaptation Reports. Impacts along supply lines and at asset level will have been modelled by the companies, although not necessarily using consistent methodology or assumptions. Data is often not publically available due to commercial sensitivity. The CCRA began to model climate impacts at higher regional levels. This needs to be done more comprehensively, aggregating the industry expertise and risk modelling to a systems level.

8.4 Climate impacts to new infrastructure systems

The response to climate change will bring new technologies and facilities, particularly if the use of nuclear, coal, oil and gas are to continue in a low-carbon UK. It is not quite clear what research has been done on climate impacts to future energy systems, i.e.

- CO_2 pipeline infrastructure
- Carbon capture and storage facilities
- Underground coal gasification
- Shale gas production pads, distribution networks and water use.
- Safe storage of 'fracking' chemicals and exposure to high temperatures and flooding.

8.5 International dependencies

The CCRA highlights international interdependencies as a knowledge gap excluded from its analysis. As discussed in Section 2.2 and the Appendix, the UK is highly reliant on fuel imports, international pipelines, electrical interconnectors and supporting infrastructures that may also be subject to climate impacts. Climate change may increase the frequency of weather delays to fuel imports. Climate impacts may also affect fuel production (of fossil fuels and biomass), primarily through water shortages, although the severity and the specific impacts on the UK, over other risks such as geopolitical instability, are unclear.

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