- Article type: paper
- April 2015
- Words: ~4900 including tables and citations.
- 4 tables, 1 figure

UK nuclear & fossil-fuel energy infrastructure climate risks

Author 1

- Edward A. Byers, MEng, PhD
- School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK.

Author 2

- Jaime M Amezaga, MSc, MSc, PhD
- School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK.

Corresponding author:
Edward A. Byers,
Devonshire building 3rd floor, School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK. +44 (0) 191 208 4880, e.a.byers@ncl.ac.uk

1 Abstract

The energy sectors' importance as critical national infrastructure means that the sector has been long prepared for disruptions, of which weather-related disruptions are generally well understood. Climate change means changing mean operating conditions, new and more frequent extremes and changing risk profiles. These changes have the potential to disrupt operations, whilst others may have long-term effects on the performance of infrastructure. This paper reviews the current knowledge base surrounding climate impacts on the infrastructure and operations of the nuclear, coal, oil and gas subsectors. We also present assessment of 'confidence in the science'. The risks identified within the Climate Change Risk Assessment (CCRA) were comprehensive, however we note areas in need of further investigation. Risks to upstream oil and gas are not covered in detail and risks to new energy systems, in particular carbon capture and storage (CCS) and unconventional fossil fuels are not covered at all. We recommend Ttheir detailed consideration in the next Climate Change Risk Assessment is recommended, alongside more systems approaches to risk assessment of the UK energy system.

ICE Keywords (max 3): Energy; fossil fuels; nuclear power;

2 Introduction

The energy sector is a critical backbone of any modern economy. The wealth of the UK has been established around its energy systems, fuelling the industrial revolution and securing the UK as a leading and competitive global economy. Originally fired by coal, the UK has developed a variety of dominant energy sources, referred to as subsectors in this paper, largely based on coal, oil, gas and nuclear power. Together, the UK's energy system comprises a critical national infrastructure with a high level of reliability expected at all times, by Government, customers and businesses. These energy subsectors have been established for many decades in the UK and are generally well prepared to avoid disruptions. Weather-related disruptions are common and generally well understood in the UK. However, two issues are driving critical examination of the sector's resilience:

1. Climate change is expected to alter the weather systems of the UK and thus the effects this will have on the energy sector are frequently in need of re-evaluation, particularly as our understanding of climate change processes improves.
2. In mitigating for climate change, which is driven in part by greenhouse gas emissions (GHGs) from fossil fuelled energy systems, there is increased innovation, development and adoption of new energy systems in the sector. Our current understanding of the performance of these new energy systems, such as carbon capture and storage, is lacking.

In preparation for climate change, weather impacts are increasingly studied through a variety of lenses. For example and most prominently, 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, may also change as we adapt. This paper is a shortened version of a working paper produced for the *Living with environmental change* (LWEC) programme Infrastructure Report Card. ~~In this work we have~~ This work explores~~d~~ the current knowledge base surrounding climate change impacts on the nuclear, coal, oil and gas subsectors in the UK. The rest of this section introduces the projected impacts of climate change. Section 2 presents a snapshot of the current asset-base of the subsectors in question, followed by comments on systemic dimensions of climate impacts on energy infrastructure. ~~We then discuss previous~~ Government-led risk assessments of the sectors are discussed in Section 3 and confidence in the science in section 4. The paper~~We~~ finishes with a broad discussion of climate impacts on future energy systems. More comprehensive description of the climate impacts and hazards to energy infrastructure is presented in the *supporting information*.

2.1 Projected 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 UK Climate Impacts Programme (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.

UK Climate Projections 2009 (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, following on from the introduction of UKCIP02 in 2002. Key findings of UKCP09 include warmer and wetter winters and hotter and drier summers (Murphy et al. 2009). More specifically:

- 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 temperature 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.

In terms of water flows, the Future Flows Hydrology 2050 central estimate projects changes from +20% to -80% for summertime flows (Prudhomme et al. 2013; Prudhomme et al. 2012), with more mixed signals in winter ranging between -20% to +40% and up to +60% in a few locations.

3 The current asset-base and systemic considerations

Energy systems can be categorised in many ways, although typically it consists of primary energy carriers, conversion and transformation processes, and end-uses. Coal, oil and gas feature in all three 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. However, the final life of nuclear waste and the decommissioned assets, remains an important consideration.

The UK is a producer and importer of coal, oil, gas and uranium and exporter of the former three. 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. Key components are listed in Table 1~~Table 1~~.

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, 70 TWh/yr 19% of UK supply
	Waste storage and fuel processing facilities	2	
Coal			
	Mines		
	- Deep	12	7.3 Mt / yr
	- Surface	31	11.3 Mt/yr
	Power stations	14	29 GWe, 119 TWh/yr 30% of UK supply
Oil			
	Oil platforms	112	
	Pipelines		
	- Offshore	3,700 km	
	- Onshore	27,000 km	
	Refineries	8	
	Power stations	11	1.5% of UK 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	81	24 GWe, 124 TWh/yr 40%

3.1 Cross-sector 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.

3.1.1 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, with subsequently 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 (Thornes et al. 2012; Palin et al. 2013; Highways Agency 2011). Principal risks include flooding, embankment stability and increased damage and maintenance to infrastructure.

3.1.2 Communications

Communications are used throughout the industries. In particular ICT and SCADA systems (supervisory control and data acquisition) 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 overground communications infrastructure but only on a local basis. Concerning the internet, ICT has a strong international dependency. Redundancy is used across all energy subsectors in safety-critical operations. Smart meters will increase the dependency on ICT, but will also improve long-term performance and reliability. ICT is also critical to the incident response of disruptions, from flood alerts to first responders. More information available in: Horrocks et al., (2010).

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

3.2.1 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. Concerning failure and disruptions that occur from 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 to failure. 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. 2008; Skea et al. 2012; Chaudry et al. 2012). Other similar studies examine interactions between gas and electricity systems (Chaudry et al. 2014), in particular with high penetrations of wind (Qadrdan, Chaudry, Ekanayake, et al. 2010; Qadrdan, Chaudry, Wu, et al. 2010; Qadrdan et al. 2014; Gerber et al. 2012). Similar studies of the coal and petroleum (and other liquid fuels) distribution systems were not found.
An evaluation by Munich Re (Coates & Hall 2009, Table 2) 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.

3.2.2 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 quite evenly spread across the UK, although there is a slight bias for oil and gas infrastructure being primarily east coast based. A large proportion of the UK's energy infrastructure, mainly nuclear power stations and oil/gas/LNG/tanker terminals, is coastal based; hence they are vulnerable to sea-level rise, and in some cases, coastal erosion. Exposure of these assets varies considerably by location, sector, age and design standards; for example nuclear assets are designed to withstand 1-in-10,000 year events (e.g. wave heights), whilst this return period has only been employed on some assets in the UK oil and gas industries more recently (Health and Safety Executive 2005). The UK has three times more coastal energy infrastructure assets, than any other European country (Brown et al. 2013). Subsequently, UK is also considered to be highly aware of it's sensitivity to sea-level rise and climate change (Tol et al. 2008), compared to other countries.
If carbon capture and storage (CCS) schemes go ahead, these will be predominantly eastern in order to facilitate offshore CO_2 (carbon dioxide) storage. Furthermore CCS infrastructure will be clustered (DECC 2012) 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' chemicals 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.

3.2.3 Short term impacts

~~We consider S~~short term impacts may be considered as events (that may be periodically recurring) that cause disruption or significant loss of performance over a short period, compared to the lifetime of the asset. 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 (Willis 2004; Marsh 2011). This possibility increases substantially as offshore exploration moves into more hostile environments (Rees & 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. Extreme air and cooling water temperatures alongside drought are expected to force reduction of power production, with both short and long term impacts (van Vliet et al. 2013; van Vliet et al. 2012; Rübbelke & Vögele 2011; Koch & Vögele 2009; Förster & Lilliestam 2009; Koch et al. 2012).

3.2.4 Long term (chronic) impacts

~~We consider l~~Long term impacts ~~as~~ are conditions that may affect the performance or reliability of an asset over its lifetime, resulting in a marginal change in reliability or performance. Higher air, humidity and cooling water temperatures will affect the efficiency of both steam and gas turbine based thermal electricity production (Maulbetsch & DiFilippo 2006; Arrieta & Lora 2005; Kim et al. 2000; 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 can also be reduced by higher humidity and air temperature. Cooling water temperatures are important for once-through cooling systems and will affect some coastal and estuarine power stations, particularly nuclear power plants in the order of 0.5% output reduction per °C cooling water increase (Durmayaz & 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 (Sathaye et al. 2013; Maulbetsch & DiFilippo 2006).

3.2.5 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, whilst each impact type gives examples in terms of how losses can be accounted, i.e. *£10 million per event* or *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.

3.2.6 International dependencies

The CCRA highlights international interdependencies as a knowledge gap excluded from the analysis. Climate change may increase the frequency and magnitude of weather disruptions to production and supply of energy at coastal oil/gas/LNG terminals, not only in the UK but also abroad. Climate impacts may also affect fuel production, primarily through water shortages, such as for biofuels or fossil fuel extraction. Climate impacts constitute one subset of different risks to overall energy security, such as geopolitical instability and fossil fuel scarcity (Watson & Scott 2009).

4 Previous climate risk assessments of the energy sector

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 (Harrison 2008). A series of tools were created, although the majority of these outputs and expertise remains in industry.

4.1 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 1 in bold boxes, Table 2~~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 (joint loading) 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.

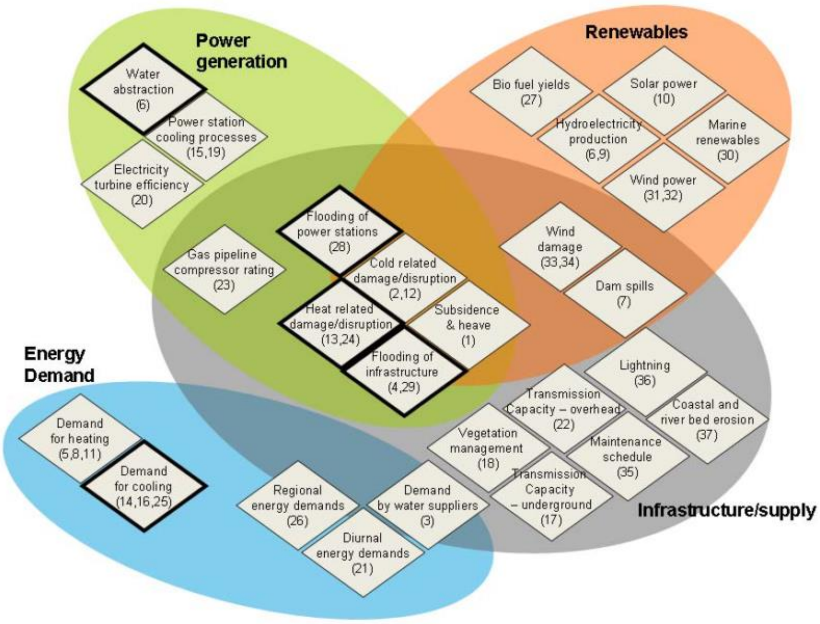

Figure 1. Impacts cluster from the CCRA. Tier 2 impacts in bold boxes. Reproduced from McColl et al. (2012) under Open Government License, Crown Copyright 2012.

Most notably in the context of this study, the impact cluster and Tier 1 risks (Figure 1) appear to not take into account the offshore oil and gas industry, whilst impacts on offshore renewables are explicitly mentioned. 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.

4.2 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. 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~~).

Table 3. Summary of mentions for each climate change impact in the climate change adaptation sections of the National Policy Statements for Energy (DECC 2011c; DECC 2011a; DECC 2009; DECC 2011b). 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			✔	

5 Confidence in the science

~~Here~~ In this section, ~~we make assessment of~~ the confidence of impacts across the subsectors are assessed using an approach used by the Intergovernmental Panel on Climate Change (IPCC) (Mastrandrea et al. 2010). ~~We consider~~ *~~E~~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* i~~a~~s 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		
Evidence / *Agreement*	**Nuclear**	**Coal**	**Oil & gas**	**Nuclear**	**Coal**	**Oil & gas**
Coastal processes	Low / Med	Low / Med	Med / Med	Med / Med	Med / Med	Med / Med
Flooding	Low / Med	Med / Med	Low / Med	High / High	High / High	High / High
Earth subsidence	Low / Med	Low / Med	Med / Med	Med / Med	Med / Med	Med / Med
Wind effects	Low / Med	Low / Med	Med / Low	Med / Med	Med / Med	Med / Med
Snowfall	Low / Med	Low / Med	Low / Med	Med / High	Med / High	Med / High
Drought	Low / Med	Med / Med	Low / Med	Med / Med	Med / Med	Med / Med
Extreme temperatures	Low / Med	Low / Med	Low / Med	Med / High	Med / Med	Med / Med

Based on the literature review, the lack of information about climate change impacts on the extraction and production side of operations, for all sub-sectors, makes it difficult to attribute more than low to medium levels of confidence. Much more information and evidence is available on work that has been undertaken on the electricity generation side, hence the attribution has been medium to high.

6 Future energy systems

This section discusses areas of research requiring further investigation of climate impacts.

6.1 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 hosting various energy systems models could do much to improve accessibility and quality of outputs available for academic scrutiny, in a similar way to the availability of climate modelling outputs. A facility that makes available a set of common infrastructure databases and datasets (such as network grid models), if necessary under license in a controlled environment, could rapidly accelerate the pace of research regarding climate impacts (amongst others) on energy infrastructure systems, as well as associated disruptions and n^{th} order effects. Rigorous investigation of multi-sector infrastructure interdependencies will be difficult without greater availability of infrastructure datasets. The challenge with this is the proprietary information that private companies are often unwilling to release for 'commercial sensitivity' reasons.

6.2 Further investigation into the links between energy and water

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, complex and changing. 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 from imported fuels. In particular, a detailed and rigorous assessment is required for the water demands from projections of domestic shale gas production, even if these are not thought to be substantial (Royal Society & Royal Academy of Engineering 2012; DECC 2014). Some international work addresses these issues, including forward projections. (McMahon 2010; U.S. DOE 2006; World Energy Council 2010; Pan et al. 2012; Francis et al. 2013; Hadian & Madani 2013). Water use from UK electricity production is slightly better understood on a national and regional scale (Schoonbaert 2012; Naughton et al. 2012; Byers et al. 2014; Tran et al. 2014; Environment Agency & Natural Resources Wales 2013; Byers et al. 2015; Gasparino 2012), with the conclusion that rising energy demands, the high water-intensity of CCS generation capacity and the clustering of CCS plants may leave generation capacity vulnerable to droughts or contribute to localised water stress. Studies to date are no more comprehensive than those performed for the US (Jenner & Lamadrid 2013; Clark et al. 2013; Macknick, Sattler, et al. 2012; Macknick, Newmark, et al. 2012; Scanlon et al. 2013; Grubert et al. 2012; U.S. DOE 2006; Torcellini et al. 2003; NETL 2007; NETL 2009; Benjamin K. Sovacool & Sovacool 2009; Benjamin K Sovacool & Sovacool 2009; Sovacool 2000; King et al. 2008), or internationally (World Energy Council 2010; Pan et al. 2012; Francis et al. 2013; Müller et al. 2007). 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; Byers et al. 2015), and other simulation-based and spatially explicit approaches should be investigated (Förster & Lilliestam 2009; van Vliet et al. 2012; van Vliet et al. 2013; Koch & Vögele 2009; Rübbelke & Vögele 2011; Koch et al. 2012).

6.3 Climate impacts on systems, not silos and assets

Most of the impacts on energy infrastructure 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. 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.

Work done by the Infrastructure Transitions Research Consortium has begun to tackle these issues. Recent work has connected telecoms, water and water treatment assets to the electricity network in order to identify "infrastructure criticality hotspots" (ITRC 2014). Whilst many are talking about the need to tackle systemic issues, only few are doing in-depth analysis.

6.4 Climate impacts to new infrastructure systems

The response to climate change will bring new technologies, particularly if the use of coal, oil and gas are to continue in a low-carbon UK. However it is not quite clear what research has been done on climate impacts to future energy systems, mainly centred around carbon capture and storage systems and the 'unconventional' fossil fuels.

- CO_2 pipeline infrastructure – a whole new set of CO_2 pipeline infrastructure is set to develop around existing energy infrastructure. Failures in pipelines could affect operation not just to one power station, but whole clusters of assets using carbon capture facilities.
- Carbon capture and storage facilities – the clustering of power plants and industry connecting to CCS facilities may increase the localised risk of high-impact spatial hazards, such as flooding and drought. Impacts on multiple-connected and spatially-

dependent assets may present disproportionate risks. Conversely, these are also opportunities for coordinated, cost-effective and shared resilience-building and risk-reduction.

- Shale gas production pads and gas distribution networks– the infrastructure that builds up around shale gas production is likely to be semi-permanent or temporary, but should still take into account climate impacts. Flood risk of sites and local gas networks needs to be evaluated, in particular with regards to hydraulic fracturing chemicals and fluids and how they are safely stored. Localised water demands need to be quantified over the principal shale plays, as does the treatment of wastewater and flowback, particularly under drought conditions when effluent dilution may be challenging. The safe storage of hydraulic fracturing chemicals against exposure to high temperatures and flooding should be determined.
- Climate impacts on underground coal gasification (UCG) need to be established, which has until now received less public and academic scrutiny than shale gas exploration. Risks from climate impacts on UCG are likely to be similar to those from shale gas, although this is unclear.
- Small nuclear power reactors (up to 300 MW_e) increase the potential for use of nuclear away from the coast, although water requirements would be approximately the same as for similarly-sized coal powered units.

7 Conclusions

This study has reviewed the literature on climate change impacts on the UK's energy infrastructure for the nuclear, coal, oil and gas sectors. Based on the existing findings of the UK Climate Change Risk Assessment for Energy (McColl et al. 2012) and the National Policy Statements for Energy, there have been no significant changes although gaps in knowledge remain. This work brings new analysis to the topic with suggestions for complementary approaches to enhance subsequent risk assessments, leading to the following conclusions:

- A variety of systemic considerations may be used to broaden the approach of risk assessment of the UK energy system (section 3), taking into account the systemic nature of UK energy supply, over a more traditional asset management approach.
- There is a notable gap in available information on the oil and gas sectors, particularly for upstream activities. Whilst the risks are investigated by the sectors, these have not been covered by the current UK CCRA.
- From the evaluation of 'confidence in the science', overall it is ~~we~~ concluded ~~overall~~ that there is a medium to high level of confidence on the electricity generation side of operations for all sub-sectors, but only a low to medium level of confidence on the extraction and production side.
- There is a case for further research into climate impacts on the future energy systems of the UK, that may use a consistent set of open-source energy scenarios, that investigates systemic risks with energy and other infrastructure sectors, and that considers climate impacts on key technologies of the future, like carbon capture and storage and unconventional fossil fuels.

8 Acknowledgements

Comments from two anonymous reviewers and the editorial office are gratefully acknowledged. This paper is a shortened version of a working paper produced for the *Living with environmental change* (LWEC) programme Infrastructure Report Card (link?).

Comment [EB1]: http://www.lwec.org.uk/infrastructure-climate-change-impacts-report-card

Formatted: Highlight

9 References

Arrieta, F.R.P. & Lora, E.E.S., 2005. Influence of ambient temperature on combined-cycle power-plant performance. *Applied Energy*, 80(3), pp.261–272. Available at: http://www.sciencedirect.com/science/article/pii/S0306261904000601 [Accessed January 31, 2014].

Boonassa, S., Namprakai, P. & Muangnapoh, T., 2006. Performance improvement of the combined cycle power plant by intake air cooling using an absorption chiller. *Energy*, 31(12), pp.2036–2046. Available at: http://www.sciencedirect.com/science/article/pii/S0360544205001842 [Accessed July 31, 2014].

Brown, S., Hanson, S. & Nicholls, R.J., 2013. Implications of sea-level rise and extreme events around Europe: a review of coastal energy infrastructure. *Climatic Change*, 122(1-2), pp.81–95. Available at: http://link.springer.com/10.1007/s10584-013-0996-9 [Accessed July 31, 2014].

Byers, E.A. et al., 2015. Cooling water for Britain's future electricity supply. *Proceedings of the ICE - Energy*, In press. doi: 10.1680/ener.14.00028

Formatted: Highlight

Byers, E.A., Hall, J.W. & Amezaga, J.M., 2014. Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, 25, pp.16–30. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959378014000089 [Accessed May 26, 2014].

Chaudry, M. et al., 2014. Combined gas and electricity network expansion planning. *Applied Energy*, 113, pp.1171–1187. Available at: http://www.sciencedirect.com/science/article/pii/S0306261913007150 [Accessed February 20, 2014].

Chaudry, M. et al., 2012. Modelling UK energy system response to natural gas supply infrastructure failures. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 226(4), pp.501–513. Available at: http://pia.sagepub.com/lookup/doi/10.1177/0957650912442461 [Accessed February 20, 2014].

Chaudry, M., Jenkins, N. & Strbac, G., 2008. Multi-time period combined gas and electricity network optimisation. *Electric Power Systems Research*, 78(7), pp.1265–1279. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378779607002222 [Accessed July 14, 2010].

Clark, C.E., Horner, R.M. & Harto, C.B., 2013. Life cycle water consumption for shale gas and conventional natural gas. *Environmental science & technology*, 47(20), pp.11829–36. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24004382.

Coates, I. & Hall, C., 2009. Chapter 12 Energy. In *The climate change research report 2009*. The Chartered Insurance Institute, pp. 1–33.

Colman, J., 2013. *The effect of ambient air and water temperature on power plant efficiency*. Duke University.

DECC, 2012. *CCS Roadmap*, London, UK: Department of Energy & Climate Change. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48317/4899-the-ccs-roadmap.pdf.

DECC, 2014. *Fracking UK shale : water*, London, UK: Department of Energy & Climate Change. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/277211/Water.pdf.

DECC, 2011a. *National Policy Statement for Fossil Fuel Electricity Generating Infrastructure (EN-2)*, London, UK: Department of Energy and Climate Change.

DECC, 2009. *National Policy Statement for Gas Supply Infrastructure and Gas and Oil Pipelines (EN-4)*, London, UK: Department for Energy & Climate Change.

DECC, 2011b. *National Policy Statement for Nuclear Power Generation (EN-6) Volume I of II*, London, UK: Department of Energy & Climate Change.

DECC, 2011c. *Overarching National Policy Statement for Energy (EN-1)*, London, UK: Department of Energy & Climate Change.

Durmayaz, A. & Sogut, O.S., 2006. Influence of cooling water temperature on the efficiency of a pressurized-water reactor nuclear-power plant. *International Journal of Energy Research*, 30(10), pp.799–810. Available at: http://doi.wiley.com/10.1002/er.1186 [Accessed July 31, 2014].

Environment Agency & Natural Resources Wales, 2013. *Current and future water availability – addendum*, Bristol, UK: Environment Agency, Department for Environment, Food & Rural Affairs. Available at: http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com.

Förster, H. & Lilliestam, J., 2009. Modeling thermoelectric power generation in view of climate change. *Regional Environmental Change*, 10(4), pp.327–338. Available at: http://link.springer.com/10.1007/s10113-009-0104-x [Accessed July 16, 2013].

Francis, S. et al., 2013. *China Coal and Power*, Hong Kong: HSBC Global Research.

Gasparino, U., 2012. Independent Development of Water Use in Scenarios for Future Thermal Power Stations. *Joint Environmental Programme*.

Gerber, A. et al., 2012. A 2020 GB transmission network study using dispersed wind farm power output. *Renewable Energy*, 37(1), pp.124–132.

Grubert, E. a, Beach, F.C. & Webber, M.E., 2012. Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal- and natural gas-fired electricity. *Environmental Research Letters*, 7(4), p.045801. Available at: http://stacks.iop.org/1748-9326/7/i=4/a=045801?key=crossref.83064af27ee58ab087058b090b6cda92 [Accessed January 22, 2014].

Hadian, S. & Madani, K., 2013. The Water Demand of Energy: Implications for Sustainable Energy Policy Development. *Sustainability*, 5(11), pp.4674–4687. Available at: http://www.mdpi.com/2071-1050/5/11/4674/ [Accessed December 23, 2013].

Hammond, G.P. & Waldron, R., 2008. Risk assessment of UK electricity supply in a rapidly evolving energy sector. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 222(7), pp.623–642. Available at: http://pia.sagepub.com/lookup/doi/10.1243/09576509JPE543 [Accessed February 4, 2014].

Harrison, R., 2008. *Supply and generation Final report*, Exeter, UK: Met Office.

Health and Safety Executive, 2005. OSD Technical policy relating to extreme weather hazards. Available at: http://www.hse.gov.uk/Offshore/extremeweather.htm#exev [Accessed April 8, 2015].

Highways Agency, 2011. *Highways Agency Climate Change Risk Assessment*, Dorking, UK: Department for Transport.

Horrocks, L. et al., 2010. *Adapting the ICT Sector to the Impacts of Climate Change*, Department for Environment Food & Rural Affairs.

ITRC, 2014. *ITRC infrastructure criticality hotspot analysis*, Environmental Change Institute, University of Oxford, UK.

Jenner, S. & Lamadrid, A.J., 2013. Shale gas vs. coal: Policy implications from environmental impact comparisons of shale gas, conventional gas, and coal on air, water, and land in the United States. *Energy Policy*, 53(2013), pp.442–453. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421512009755 [Accessed January 26, 2014].

Kim, T.S. et al., 2000. Influence of ambient condition on thermodynamic performance of the humid air turbine cycle. *Energy*, 25(4), pp.313–324. Available at: http://www.sciencedirect.com/science/article/pii/S0360544299000742 [Accessed February 19, 2014].

King, C.W., Holman, A.S. & Webber, M.E., 2008. Thirst for energy. *Nature Geoscience*, 1(5), pp.283–286. Available at: http://www.nature.com/doifinder/10.1038/ngeo195 [Accessed May 29, 2014].

Koch, H. et al., 2012. Trends in water demand and water availability for power plants—scenario analyses for the German capital Berlin. *Climatic Change*, 110(3-4), pp.879–899. Available at: http://link.springer.com/10.1007/s10584-011-0110-0 [Accessed May 10, 2013].

Koch, H. & Vögele, S., 2009. Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecological Economics*, 68(7), pp.2031–2039. Available at: http://www.sciencedirect.com/science/article/pii/S0921800909000639 [Accessed October 24, 2013].

Macknick, J., Newmark, R., et al., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters*, 7(4), p.045802. Available at: http://stacks.iop.org/1748-9326/7/i=4/a=045802?key=crossref.6f4ebd5836ab24141e19d95fd1e65709 [Accessed June 9, 2014].

Macknick, J., Sattler, S., et al., 2012. The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. *Environmental Research Letters*, 7(4), p.045803. Available at: http://stacks.iop.org/1748-9326/7/i=4/a=045803?key=crossref.27e22811cb9df56bbe8f6d32257a70ee [Accessed January 6, 2015].

Marsh, 2013. *Common Causes of Large Losses in the Global Power Industry*, London, UK: Marsh & McLennan Companies.

Marsh, 2011. *The 100 Largest Losses 1972-2011*, London, UK: Marsh Energy Practice.

Mastrandrea, M.D. et al., 2010. *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*, Intergovernmental Panel on Climate Change. Available at: http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

Maulbetsch, J.S. & DiFilippo, M.N., 2006. *Cost and value of water use at combined-cycle power plants*, California Energy Commission,PIER Energy-Related Environmental Research. CEC-500- 2006-034. Available at: http://www.energy.ca.gov/2006publications/.

McColl, L., Angelini, T. & Betts, R., 2012. *Climate Change Risk Assessment for the Energy Sector*, London, UK.

McMahon, J.E., 2010. Water and Energy Interactions. *Annu. Rev. Environ. Resour.*, 36(1). Available at: http://www.annualreviews.org/doi/abs/10.1146/annurev-environ-061110-103827 [Accessed October 7, 2011].

Müller, U., Greis, S. & Rothstein, B., 2007. Impacts on Water Temperatures of Selected German Rivers and on Electricity Production of Thermal Power Plants due to Climate Change 1 Introduction 2 Data and Methodology. In *DKKV/CEDIM: Disaster Reduction* in *Climate Change*. Karlsruhe: Karlsruhe University. Available at: http://www.cedim.de/download/33_Mueller_etal.pdf.

Murphy, J.M. et al., 2009. *UK Climate Projections Science Report: Climate change projections*, Met Office Hadley Centre, Exeter, UK.

Naughton, M., Darton, R.C. & Fung, F., 2012. Could Climate Change Limit Water Availability for Coal-Fired Electricity Generation with Carbon Capture and Storage? A UK Case Study. *Energy & Environment*, 23(2&3), pp.265–282.

NETL, 2007. *Power Plant Water Usage and Loss Study*, National Energy Technology Laboratory: U.S. Department of Energy.

NETL, 2009. *Water Requirements for Existing and Emerging Thermoelectric Plant Technologies*, National Energy Technology Laboratory: U.S. Department of Energy. Available at: http://www.circleofblue.org/waternews/wp-content/uploads/2010/08/Water-Requirements-for-Existing-and-Emerging-Thermoelectric-Technology.pdf.

OGP, 2010. *Structural risk for offshore installations*, London, UK: International Association of Oil & Gas Producers.

Palin, E.J. et al., 2013. Future projections of temperature-related climate change impacts on the railway network of Great Britain. *Climatic Change*, 120(1-2), pp.71–93. Available at: http://link.springer.com/10.1007/s10584-013-0810-8 [Accessed February 11, 2014].

Pan, L. et al., 2012. A supply chain based assessment of water issues in the coal industry in China. *Energy Policy*, 48, pp.93–102. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421512002686 [Accessed January 22, 2014].

Prudhomme, C. et al., 2012. *Future Flows and Groundwater Levels - Final Technical Report*, Centre for Ecology and Hydrology, Wallingford, UK. Available at: http://www.ceh.ac.uk/sci_programmes/water/future flows/documents/futureflowsandgroundwaterlevels_pn9_finalreport_finaloct2012.pdf.

Prudhomme, C. et al., 2013. Future Flows Hydrology: an ensemble of daily river flow and monthly groundwater levels for use for climate change impact assessment across Great Britain. *Earth System Science Data*, 5(1), pp.101–107. Available at: http://www.earth-syst-sci-data.net/5/101/2013/ [Accessed August 27, 2013].

Pyzik, E., Jarzębowski, S. & Miller, A., 2012. Impact of inlet air cooling on gas turbine performance. *Journal of Power ...*, 92(4), pp.249–257. Available at: http://www.papers.itc.pw.edu.pl/index.php/JPT/article/view/314 [Accessed July 31, 2014].

Qadrdan, M., Chaudry, M., Wu, J., et al., 2010. Impact of a large penetration of wind generation on the GB gas network. *Energy Policy*, 38(10), pp.5684–5695. Available at:

http://linkinghub.elsevier.com/retrieve/pii/S0301421510003873 [Accessed February 17, 2014].

Qadrdan, M., Chaudry, M., Ekanayake, J., et al., 2010. Impact of wind variability on GB gas and electricity supply. In *2010 IEEE International Conference on Sustainable Energy Technologies (ICSET)*. IEEE, pp. 1–6. Available at: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5684953 [Accessed February 20, 2014].

Qadrdan, M. et al., 2014. Operating Strategies for a GB Integrated Gas and Electricity Network Considering the Uncertainty in Wind Power Forecasts. *IEEE Transactions on Sustainable Energy*, 5(1), pp.128–138. Available at: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6589136 [Accessed February 20, 2014].

Rees, A. & Sharp, D., 2011. *Drilling in extreme environments*, London, UK: Lloyd's.

Royal Society & Royal Academy of Engineering, 2012. *Shale gas extraction in the UK: a review of hydraulic fracturing*, London, UK. Available at: http://royalsociety.org/policy/projects/shale-gas-extraction.

Rübbelke, D. & Vögele, S., 2011. Impacts of climate change on European critical infrastructures: The case of the power sector. *Environmental Science & Policy*, 14(1), pp.53–63. Available at: http://www.sciencedirect.com/science/article/pii/S1462901110001371 [Accessed December 29, 2014].

Sathaye, J. a. et al., 2013. Estimating impacts of warming temperatures on California's electricity system. *Global Environmental Change*, 23(2), pp.499–511. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959378012001458 [Accessed February 28, 2013].

Scanlon, B.R. et al., 2013. Controls on water use for thermoelectric generation: Case study Texas, U.S. *Environmental Science and Technology*, 47(19), pp.11326–11334. Available at: http://www.ncbi.nlm.nih.gov/pubmed/23937226.

Schoonbaert, B., 2012. *The water-energy nexus in the UK: Assessing the impact of UK energy policy on future water use in thermoelectric power generation*. MSc Thesis, King's College, University of London, UK.

Skea, J., Chaudry, M. & Wang, X., 2012. The role of gas infrastructure in promoting UK energy security. *Energy Policy*, 43, pp.202–213. Available at: http://www.sciencedirect.com/science/article/pii/S0301421511010639 [Accessed February 4, 2014].

Sovacool, B.K., 2000. Running on Empty: The Electricity-Water Nexus and the US Electric Utility Sector. *Energy Law Journal*, 30(1), pp.11–51. Available at: http://aquadoc.typepad.com/files/sovacool_running_on_empty.pdf.

Sovacool, B.K. & Sovacool, K.E., 2009. Identifying future electricity–water tradeoffs in the United States. *Energy Policy*, 37(7), pp.2763–2773. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421509001645 [Accessed March 12, 2012].

Sovacool, B.K. & Sovacool, K.E., 2009. Preventing National Electricity-Water Crisis Areas in the United States. *Columbia Journal of Environmental Law*, 34(2), pp.333–393.

Thornes, J. et al., 2012. *Climate Change Risk Assessment for the Transport Sector*, London, UK: Department for Environment Food & Rural Affairs. Available at: http://randd.defra.gov.uk/Document.aspx?Document=CCRAfortheTransportSector.pdf.

Tol, R.S.J., Klein, R.J.T. & Nicholls, R.J., 2008. Towards Successful Adaptation to Sea-Level Rise along Europe's Coasts. *Journal of Coastal Research*, 242, pp.432–442. Available at: http://www.bioone.org/doi/abs/10.2112/07A-0016.1 [Accessed July 10, 2014].

Torcellini, P., Long, N. & Judkoff, R., 2003. *Consumptive Water Use for U . S . Power Production*, Golden, CO, US: National Renewable Energy Laboratory.

Tran, M. et al., 2014. *National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain*, Environmental Change Institute, University of Oxford, UK. Available at: http://www.itrc.org.uk/.

U.S. DOE, 2006. *Energy Demands on Water Resources*, U.S. Department of Energy: U.S. Department of Energy.

Valdés, M., Rovira, A. & Fernández, J.A., 2006. The Influence of Atmospheric Conditions on the Performance of Combined Cycle Gas Turbine Power Plants. In *Volume 4: Cycle Innovations; Electric Power; Industrial and Cogeneration; Manufacturing Materials and Metallurgy*. ASME, pp. 495–499. Available at: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1590338 [Accessed February 19, 2014].

Van Vliet, M.T.H. et al., 2012. Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, 2(June), pp.1–6. Available at: http://www.nature.com/doifinder/10.1038/nclimate1546 [Accessed January 5, 2015].

Van Vliet, M.T.H., Vögele, S. & Rübbelke, D., 2013. Water constraints on European power supply under climate change: impacts on electricity prices. *Environmental Research Letters*, 8(3), p.035010. Available at: http://stacks.iop.org/1748-9326/8/i=3/a=035010?key=crossref.9f5ad0f67f1b027dab32fb3a4beee790 [Accessed November 13, 2014].

Watson, J. & Scott, A., 2009. New nuclear power in the UK: A strategy for energy security? *Energy Policy*, 37(12), pp.5094–5104. Available at: http://dx.doi.org/10.1016/j.enpol.2009.07.019.

Willis, 2004. *Energy Loss Database Information*, London, UK: Willis Limited.

World Energy Council, 2010. *Water for Energy*, London, UK: World Energy Council.