The Water-Energy Nexus: Quantifying the Impact of Water Availability on Future UK Thermal Power Generation

by

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Abstract

The effects of increasing water and energy demand due to a growing population and climate change pose a growing threat to national infrastructure strategies. There is concern that a future lack of available water will compromise the UK's current energy policy to meet an increasing demand for electricity with more thermal generation. This research asks what impact a lack of available water will have on UK thermal generation by 2050 and aims to quantify this impact in terms of cost, type of generation technology, and cooling method. The future national water demand of the UK's thermal electricity generation for nine generation pathways was modelled. The regional water demand of one pathway; the Energy Technologies Institute's ESME.MC pathway was then modelled. This identified how technology and cooling method combinations drive demand and regionally, where the increase in water demand is likely to be greatest. The ESME.MC pathway was modified to allow the cost and technology implications of a lack of water to be modelled. This research found it is likely that relying on freshwater alone will constrain the levels of thermal generation present by 2050 and increase the cost of the UK energy system by £12.5bn per annum. Relying on sea and estuarine water is a feasible mitigation option but will result in trade-offs with the environmental standards of the UK's waterbodies. It is recommended that when considering these trade-offs the societal and economic benefits of a cost competitive electricity generation system is given due weight. Additionally it is recommended that alternative, less water intensive, renewable energy dominated electricity generation pathways in tandem with financially viable energy storage, continue to receive substantial levels of Government, academic and commercial interest.

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Glossary

BAT	Best Available [cooling] Technique
CAPEX	Capital Expenditure
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
DECC	Department for Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DUKES	Digest of UK Energy Statistics
EA	Environment Agency
ESME	Energy Systems Modelling Environment
ESME.MC	ESME Monte Carlo pathway
ETI	Energy Technologies Institute
Evap	Evaporative Cooling
EW	Estuarine Water
FW	Fresh Water
HLF	High Load Factor (capacity factor $\geq$ 46%)
IGCC	Integrated Gasification Combined Cycle
LLF	Low Load Factor (capacity factor $<$ 46%)
MARKAL	Market Allocation UK energy system model
OPEX	Operational Expenditure
OFWAT	The UK's water services financial regulation authority

OT	Once-through cooling
Q70	Flows which are exceeded 70% of the time
Q70 SW	Water availability scenario assuming Q70 freshwater flows and seawater availability
Q70 SWL	Water availability scenario assuming Q70 freshwater flows and limited seawater availability
Q70 SWN	Water availability scenario assuming Q70 freshwater flows and no seawater availability
Q95	Flows which are exceeded 95% of the time
Q95 SW	Water availability scenario assuming Q95 freshwater flows and seawater availability
Q95 SWL	Water availability scenario assuming Q95 freshwater flows and limited seawater availability
Q95 SWN	Water availability scenario assuming Q95 freshwater flows and no seawater availability
SMR	Small Modular Reactors
SW	Sea Water
Tot	Total Water
UKCP09	2009 UK Climate Projections
UKTM	UK energy systems model, the successor to MARKAL
VOM	Variable Operations and Maintenance
WFD	Water Framework Directive

Chapter 1 - Introduction

1.1 General

It is recognised that adequate provision of infrastructure is fundamental for the prosperity of a nation's economy (Infrastructure and Projects Authority, 2016, Martin-Utrillas et al., 2015). Globally, both the World Bank and the International Monetary Fund have in recent reports stated that with the world economy still recovering from the financial crash of 2008, greater infrastructure investment is required to boost economic growth (IMF, 2016, World Bank Group, 2016). At a national level, a number of studies have made the same case specifically for the UK (Aghion et al., 2016, Coelho and Dellepiane, 2016, Green-Wilkes, 2014).

Different literature sources often refer to different infrastructure sectors, but much of the UK literature and Government policy refers to a relatively narrow range of sectors, most commonly, but not exclusively, energy, transport, communications (ICT), water and waste (Hall et al., 2014, Rhodes, 2016). For over a decade there has been a growing global acknowledgement that infrastructure sectors cannot be considered as isolated and individualistic systems, but rather as a series of interconnected, interdependent networks (Fu et al., 2014, Hunker, 2002, Min et al., 2007, Rinaldi et al., 2001). Figure 1.1 demonstrates in generalised terms the interdependent nature of these infrastructure networks. While the interdependent nature of infrastructure systems provides many benefits in terms of operational efficiency (Chan and Dueñas-Osorio, 2014), it also results in an increased vulnerability, as a failure in one infrastructure system can produce a cascading effect leading to degraded service in another (Brummitt et al., 2012, Huang et al., 2014, Pescaroli and Alexander, 2016). This vulnerability is likely to be exacerbated as the effects of climate change and a rising population put increased pressure on infrastructure and their interdependencies (Kelly et al., 2015, Utne et al., 2011).

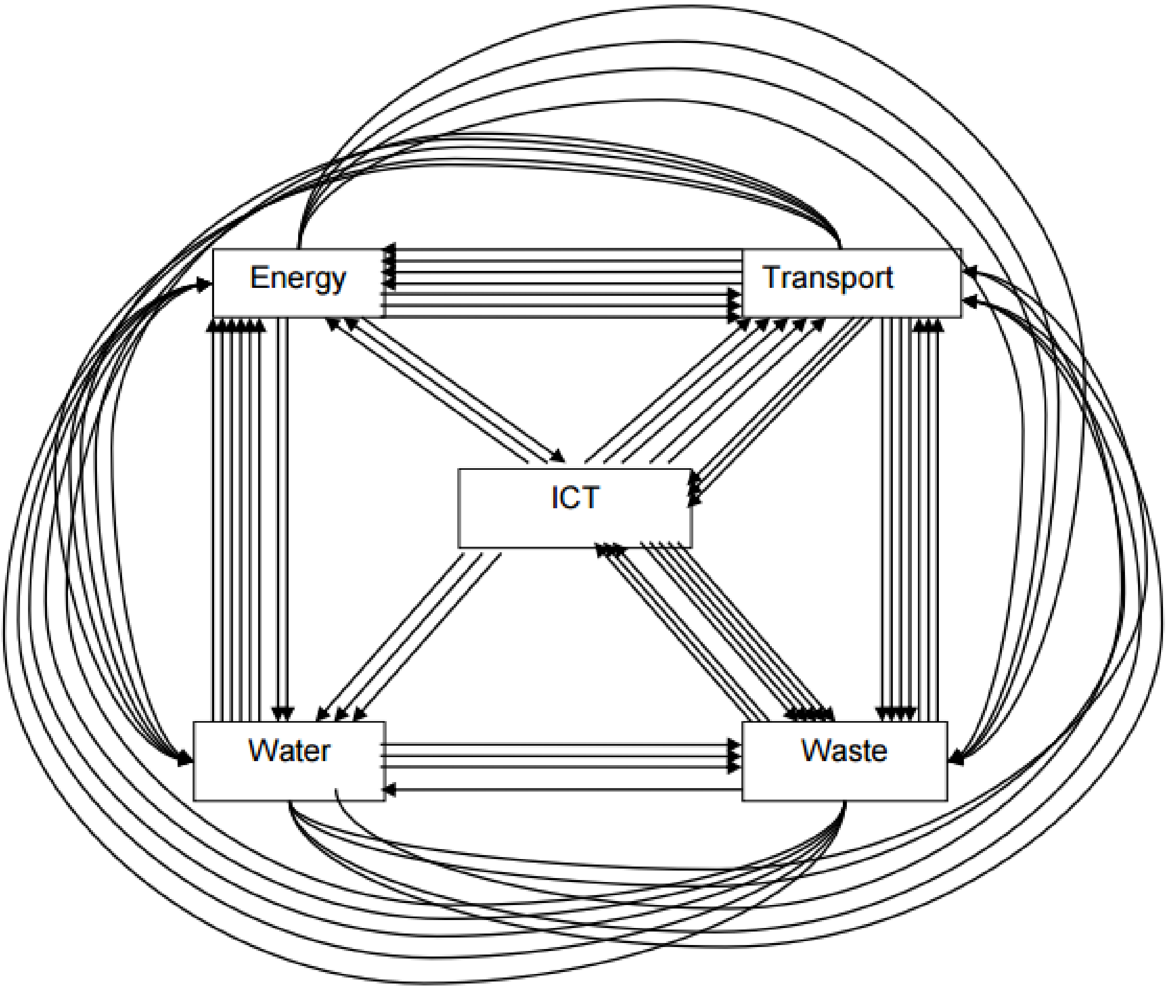

Figure 1.1 Infrastructure Interdependencies (AEA-Ricardo, 2009)

Examples of cascading infrastructure effects include;

1. In October 2012 Hurricane Sandy hit the North-East US causing substantial damage to infrastructure, including widespread power failures. These power failures then in turn caused major damage to communication (wireless and internet) infrastructure. Oil and gas assets were also forced to shut down due to power failure (Comes and Van de Walle, 2014, Hasan and Foliente, 2015).
2. In November 2009 the UK and Ireland suffered a number of flooding events, with the county of Cumbria one of the most badly affected areas. In one instance a bridge was

destroyed, which not only provided a transport route but also carried a number of fibre optic communication cables, which served some 40,000 customers including police services. Therefore the initial damage to transport infrastructure led to damage to communications infrastructure, which in turn compounded the disruption caused to the transport sector (Bissell, 2010, Fu et al., 2014, URS, 2010).

1.2 The Water-Energy Nexus

Water and energy infrastructure sectors provide an example of two highly interdependent networks. Figure 1.2 illustrates some of the interdependencies between these networks which include; water[1] for fossil fuel extraction and cooling power plants, and energy for water purification and pumping (Siddiqi et al., 2013). An example of the adverse impacts which can result from the interdependence of the water and energy sectors is provided by the 2003 power blackout which occurred in the North-East and Mid-West US as well as Ontario, Canada. Due to a software fault, power was lost across these areas which shut down water treatment plants and pumping stations, this resulted in raw sewage contaminating public water supplies, which led to approximately 8 million people being advised to boil water before drinking (Hasan and Foliente, 2015, Wilbanks and Fernandez, 2014).

[1] This thesis adopts the terminology that the term water when used applies jointly to mean freshwater, seawater, and estuarine water.

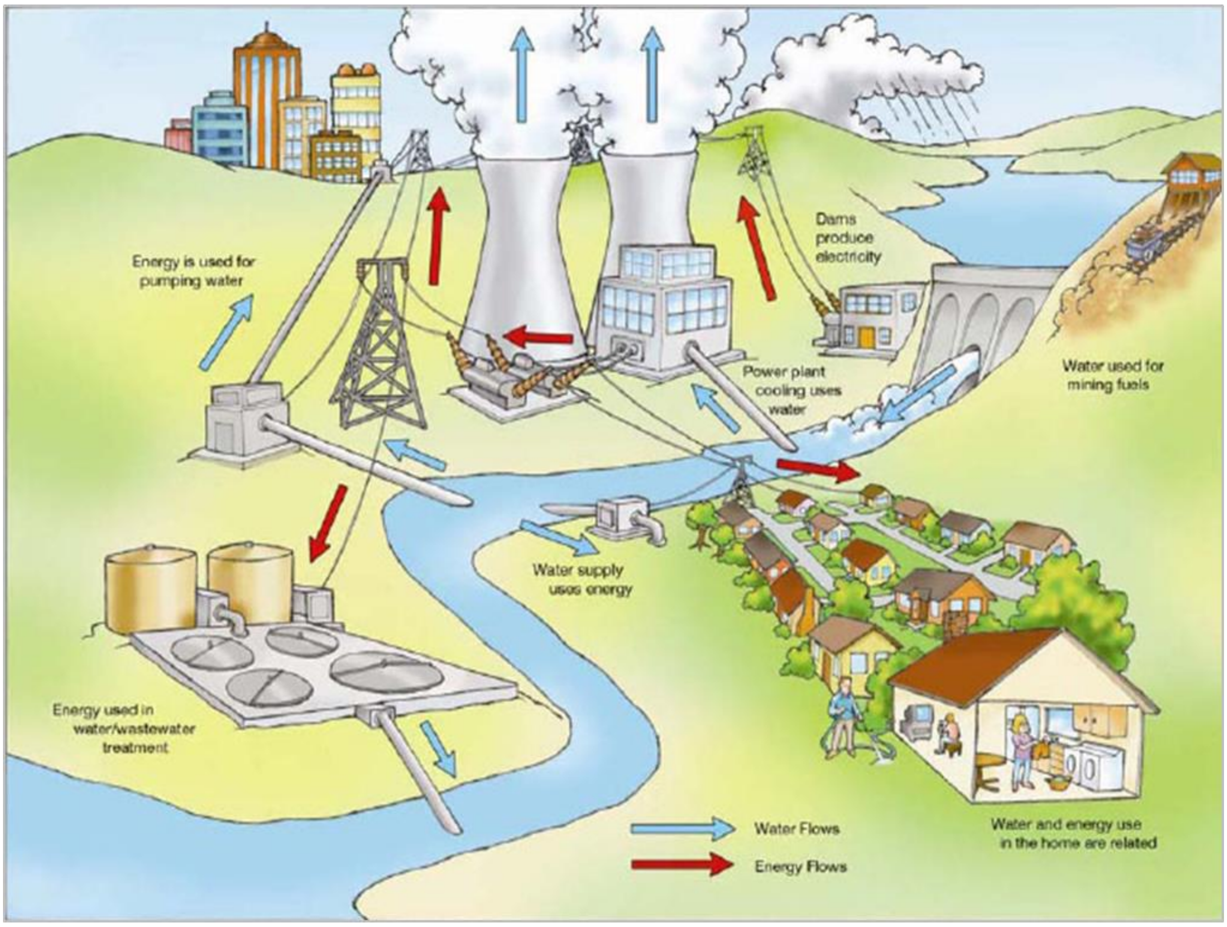

Figure 1.2 Water and Energy Interdependencies (NREL, 2015)

Despite the previous example, sudden, catastrophic events, are not the only, or necessarily even the most significant pressure, that results from water and energy interdependence. A report from the United Nations identified freshwater and energy as being critical to human well-being and sustainable socio-economic development (UNESCO, 2014). The importance of water and energy interdependencies in global affairs is that energy availability is the driver of global wealth, this in turn makes it a precursor of the world population's economic wellbeing. However thermal energy production depends on the availability of large amounts of water, predominantly for cooling (UN WWAP, 2015), and many countries already find the required levels of freshwater are unavailable during the hot/dry season. For instance, over the last decade, several heat-waves have led to low river flows, which have forced thermal power stations across central and southern Europe to reduce their load, in some cases leading to increased energy prices and power cuts (Eisenreich, 2005, Fink et al., 2004, Koch and Vögele, 2009, Olsson, 2013). The effects of climate change and a growing population are predicted to further reduce freshwater availability in the future (Miletto, 2015, Wong and Johnston, 2014). Conversely it has been estimated that for many countries electricity demand accounts for up to 40% of the total operating cost of their water and wastewater utilities (UN WWAP, 2015, van den berg and Danilenko, 2011).

In order for the UK to meet its future energy demand this suggests the case for a more detailed understanding of the interdependencies that exist between the UK water and energy networks, from now on referred to as the water-energy nexus, and how their interdependency may threaten them individually. The interdependencies between water and energy are often considered alongside their interdependencies with the food and agriculture sectors; the water-food-energy nexus (Allan et al., 2015, Smajgl et al., 2016). Whilst it is acknowledged that this is an important research area, this research will concentrate on the water-energy nexus only.

There is a growing concern that the lack of availability of cooling water for thermal power stations will compromise the UK's ability to meet its increasing future demand for a secure and affordable supply of electricity (Byers et al., 2014, Byers et al., 2015, Schoonbaert, 2012, The Royal Academy of Engineering et al., 2011). Of particular note, the Committee on Climate Change (CCC), an independent body established to advise the UK Government (the Government) on preparing for climate change, produced an evidence report to inform the UK's second climate change risk assessment. This report identified, with a high level of confidence, that lack of freshwater available for abstraction for a number of sectors including thermal energy generation presented a high risk to the UK by the 2050's (CCC, 2016).

For the UK, as is the case globally, this is again largely due a rising population (Environment Agency, 2013b), and the effects of climate change (Charlton and Arnell, 2011). Alongside this, increasingly stringent environmental regulations governing the abstraction process will decrease the volumes of all water sources available to UK power stations (Kelly, 2014). This can increasingly call in to question the ability of UK thermal power stations to deliver their planned contribution. Particularly as it is predicted that the growth in UK electricity demand will rise from 359TWh in 2013 (MacLeay et al., 2014), to a possible 610 TWh by 2050 (DECC, 2013a, HM Government, 2011a), and the expectation is a large proportion of this growth will come from an expansion of thermal generation (DECC, 2015a, HM Government, 2011a, White et al., 2016).

1.3 Research Question, Aim and Objectives

The water-energy nexus is a broad, multifaceted subject, therefore any research project within this topic needs to define its scope. To help focus the scope a research question to be answered by this thesis was developed. As there are already concerns regarding whether there will be enough water by 2050 for the suggested levels of thermal generation in the UK this thesis asks; what impact will a lack of available water have on UK thermal generation by 2050, in terms of physical make-up and associated costs?

With this in mind this thesis identifies future availability of water and its possible impact on future UK electricity generation policy out to 2050 as its subject area. Within this subject a number of system boundaries are set. The electricity system is defined as being all UK infrastructure that contributes to the UK's generation and supply of electricity. The energy system is defined as being the electricity system plus all UK infrastructure that facilitates transport or contributes to the generation and supply of heat. Thermal generation refers to all generation of electricity where thermal energy is converted into electricity. Although the water system is often defined as being all infrastructure that contributes to the supply of freshwater this research does not focus specifically on the water system but rather on water resource which is defined as Fresh, Estuarine and Sea water. Freshwater is defined as groundwater and all non-tidal surface water including rivers. Estuarine water is defined as tidal water (determined by tidal limits) which has not yet reached the sea.

As discussed above (section **1.2**) food and agriculture systems are not considered in this research. This alongside a lack of any detailed consideration of the water system places some limitations on this research, particularly in regards to competition for water resource and the energy demand of the water system. However it was felt that a relatively narrow scope would lead to a more detailed analysis that concentrated specifically on the research question rather than a broader, but potentially more dilute analysis. Additionally some consideration is given to competition of water resource where appropriate (section **6.2.1**.)

While the UK has generally recognised the importance of the interdependencies between infrastructure networks (HM Treasury, 2011), it has been relatively slow in translating this into any significant academic effort in respect of its water-energy nexus. This is particularly so when compared to other nations (Gu et al., 2014, Stillwell et al., 2011), although it may be argued that the nexus poses less threat in the UK than is the case of many other countries. Nevertheless, this thesis will show that there are significant constraints on development options and therefore policy directions, posed to the future UK electricity sector by its water-energy nexus and, in particular, in respect of the UK's future water availability.

Based on this and the research question, the aim of this thesis is; to quantify the impact of future water availability on the UK thermal generation power station fleet by 2050, in terms of cost, type of generation technology, and cooling method chosen.

To achieve this the following objectives will need to be met:

1. Identify the key water constraints to UK thermal generation and determine the role water availability plays as a constraining factor. Also consider the current mitigation and adaptation options.
2. Determine water demands of different thermal electricity generation and cooling method combinations which are applicable to the UK.
3. Review and develop an existing water demand framework to model the future national water demand of the UK electricity sector. Downscale these results to the regional level to identify regions most likely to be constrained by water availability.
4. Develop a range of regional water availability scenarios to allow the modelling of future water availability alongside water demand. Determine the costs of different thermal electricity generation and cooling method combinations.
5. Model future water availability alongside the water demand, and cost of, thermal electricity generation and cooling method combinations, allowing the impact of future water availability on the UK thermal generation power station fleet to be quantified and discussed.

1.4 Thesis Structure

To answer the research question and achieve the aim and objectives set out, the remaining chapters of this thesis are structured in the following way:

Chapter 2 – Literature Review

An initial summary of infrastructure interdependencies is presented, followed by a more detailed examination of the current literature on the water-energy nexus, where the implications of future water resource availability on current UK thermal generation policy are discussed. The uncertainty of current climate change modelling, and the challenges this presents when considering the future freshwater resource available to power stations is also presented. The key findings of this review were published as a journal paper in the Water and Environment Journal which is included as **Appendix A.1**.

Chapter 3 – The Energy Technologies Institute (ETI) and the Energy Systems Modelling Environment (ESME)

The Energy Technologies Institute (ETI) have developed the Energy Systems Modelling Environment (ESME), a least cost optimised, UK energy system model. ESME is the main tool used in this research to meet the stated thesis aim and objectives. This chapter explains the ETI's involvement with this research, and why ESME was selected above other UK energy system models. It gives an overview of the ESME model, including its background and how it operates.

Chapter 4 - Future UK National Water Demand Modelling

To identify the risks associated with the water demand of specific electricity generation technologies, the unconstrained national water demands of proposed electricity generation pathway scenarios are modelled. To do this a framework for modelling future water demand of the generation options is introduced. A methodology for applying this framework to proposed UK electricity generation pathways, including those of the ESME model, is then produced. Water abstraction and consumption figures relevant to UK power station generation technology and cooling methods combinations are prepared. A validation of the modelling framework, and the UK abstraction and consumption figures used is undertaken. The modelled national water demands of the pathways selected in 2030 and 2050, and the historic 2010 demand, are presented, compared and the implications discussed. The UK abstraction and consumption figures obtained are compared to those based on U.S. power stations, which were used previously for a similar UK study. The results of this chapter formed the first part of a two-part submission to Energy Policy which is currently under review, the title page including the abstract are included as **Appendix A.2**.

Chapter 5 – Future UK Regional Water Demand Modelling

To bring the unconstrained national UK water demands of Chapter 4 to the more relevant regional level, the modelling framework used in Chapter 4 was modified. Now by applying the UK abstraction and consumption figures to the ESME.MC pathway, and using the modified framework, unconstrained UK regional water demands were attributed to the ESME.MC's regional generation pathway. The results produced are compared to the national results, and conclusions are drawn as to the regional results practical relevance, which then leads onto Chapter 6's interest in regional water availability. The results found in this chapter were presented at the WASET 18th International Conference on Water, Energy and Environmental Management, Spain. The conference paper is included as **Appendix A.4**.

Chapter 6 – Constraining the ESME.MC Pathway by Water Availability

A methodology was devised to enable the ESME.MC pathway's cost optimising process to select at the UK regional level, those thermal generation technologies and associated cooling methods required on the basis of their relative cost, while recognising the availability of preset levels of freshwater and, sea and estuarine water. Here the objective was to explore for the UK the change in generation technologies and commercial advantage, if any, that coastal cooling provides relative to inland cooling given any lack of freshwater availability. The results of this chapter formed the second part of a two-part submission to Energy Policy which is currently under review, the title page including abstract are included as (**Appendix A.3**)

Chapter 7 – Discussion of Results

The results produced in this thesis and their limitations are discussed at length. In particular, the chosen generation technology and associated cost implications water availability has on the global competitiveness of future UK thermal generation. A discussion as to the trade-offs policymakers will have to make when deciding how to best mitigate some of the negative implications is also undertaken.

Chapter 8 – Conclusions and Recommendations for Further Work

Conclusions are made from the work undertaken in this thesis and related back to the original aim and objectives. A number of areas where further work may be of benefit are then proposed.

Chapter 2 - Literature Review

2.1 Infrastructure Interdependencies

Infrastructure is a broad term often used as a catch-all covering many services and sectors required for an economy to function. A number of studies have tried to provide a definition of infrastructure (Miles, 2015, Moteff and Parfomak, 2004), however Snieska and Simkunaite (2015) suggest that there is not yet a generally accepted one. This would seem to be confirmed by the Government who in a recent briefing paper used two definitions of infrastructure: *"[the] economic arteries and veins; roads, ports, railways, airports, power lines, pipes and wires that enable people, goods, commodities, water, energy and information to move about efficiently*" and then "*the physical assets underpinning the UK's networks for transport, energy generation and distribution, electronic communications, solid waste management, water distribution and waste water treatment*" (Rhodes, 2016). From the viewpoint of this thesis it is important to note that under both infrastructure definitions water and energy assets are named. For this thesis the definition of infrastructure that will be used, which again covers energy and water assets, is that of the UK Infrastructure Transitions Research Consortium, that is "*A collection of technological and human organisational structures that come together to form interdependent networks that provide reliable flows of goods and services leading to economic productivity and human wellbeing*" (Pant and Hall, 2012).

Infrastructure is becoming increasingly interconnected due to the need to improve efficiency, and monitor and control infrastructure processes (Taft and Becker-Dippmann, 2015). This leads to an increase in infrastructure interdependencies. Rinaldi et al. (2001) was the first to present a conceptual framework for considering these interdependencies. Rinaldi et al. (2001) defines an infrastructure dependency as '*a connection between two infrastructures through which the state of one infrastructure is influenced by the state of the other*'. It defines an interdependency as '*a bidirectional relationship between two infrastructures through which the state of each infrastructure is influenced by the state of the other*'. Whilst much of the 'interdependence' work since is based upon Rinaldi et al. (2001), the definition of infrastructure interdependencies is now often generalised to include infrastructure dependencies (Pant and Hall, 2012).

The global challenges of a rising population and climate change is driving international interest, both commercial and academic, in infrastructure interdependencies and how they will be impacted by these challenges (Booth, 2012, Kelly et al., 2015, Lienert and Lochner, 2012, Utne et al., 2011, Wilbanks et al., 2015). Much of the work focuses on improving the resilience of infrastructure to extreme events, driven by climate change, and other factors, which increasingly now includes terrorism (Chopra and Khanna, 2015, O'Rourke, 2007, Ouyang and Wang, 2015, Varga and Harris, 2014). Some recent studies also consider other aspects of infrastructure interdependence such as the their application to novel business models and how they can be used to create added value (Bouch et al., 2015, Rosenberg and Carhart, 2013).

The Government does recognise the importance of the interdependencies between infrastructure networks (HM Treasury, 2011, HM Treasury, 2013, Infrastructure and Projects Authority, 2016), and recognises that understanding the complex relationships that constitute infrastructure interdependencies is vital to quantifying the future risks, including cascading failures, they could inflict on critical UK infrastructure systems (DEFRA, 2012, Pescaroli and Alexander, 2016). A further advantage of this process is that gaining a better understanding of infrastructure interdependencies can uncover opportunities to improve operational efficiency (Frontier Economics, 2012)

This has led to a significant and increasing body of academic literature on UK infrastructure interdependencies (Kelly et al., 2015, Metz et al., 2016, Sircar et al., 2013, Tran et al., 2014). However, there has been relatively little research within a UK context concentrating on the interdependencies between the water and energy infrastructure networks, the water – energy nexus, and how they may impact each other. This is in contrast to many other nations and international organisations, including the USA and United Nations, who now recognise the importance of the water-energy nexus (Bhaduri and Liebe, 2013, Gu et al., 2014, Stillwell et al., 2010, UNESCO, 2014, Vilanova and Balestieri, 2015). Indeed the growing importance of the water-energy nexus is evidenced by the inclusion for discussion of the subject 'The Water-Energy Nexus' in the United Nations Conference on Sustainable Development in Rio de Janeiro (United Nations, 2012), there have also been several other UN-backed initiatives with a water-energy nexus focus since (Endo et al., 2015).

2.2 The Water Energy Nexus and Thermal Power Generation

As discussed in section **1.2**, energy availability is a prerequisite of the world population's economic wellbeing, but thermal energy production depends on the availability of large amounts of water. International Energy Agency (2012) suggests the global water use for energy production in 2010, represents some 15% of the world's total yearly freshwater withdrawals, second only to agriculture. Worldwide, many thermal power stations are already unable to withdraw the water they require during the hot/dry season. This is a situation made worse by the increasing effects of climate change and population growth (Miletto, 2015, Wong and Johnston, 2014). International Energy Agency (2012) predicts annual world energy demand will grow by 56% from 2010 to 2035, with fossil fuels and nuclear generation continuing to be the major providers. Under current policies it is claimed this growth will increase the global energy water withdrawal by 36% by 2035 (International Energy Agency, 2012).

Thermal power stations require water for many purposes (e.g. flue gas desulphurisation, dust removal, boiler feed-water) (Delgado and Herzog, 2012, Gerdes and Nichols, 2009), but the main need is for cooling the exhaust heat from the generators. Byers et al. (2014) estimates this use to be as much as 90% of total water abstracted. When water availability is not a concern, once-through cooling (Figure 2.1) is used and large amounts of water are abstracted to cool the exhaust heat and then discharged back into the water body. This is acknowledged as the Best Available [cooling] Technique (BAT) (European Commission, 2001). While a reduction in water withdrawal for fossil fuel and nuclear power plants is possible by using alternative cooling systems, including recycled evaporative cooling water options (Figure 2.2); air options (Figure 2.3); as well as evaporative and air cooled hybrid systems, these all incur higher capital costs and losses in plant efficiency. This is particularly so when ambient temperatures are high. Another trade-off required when deploying less water intensive cooling methods is that while they reduce withdrawal demand they incur greater water consumption. This, in water stressed areas, reduces the water available to other downstream users. The advantage water has over air for cooling is its high density and thermal capacity make it a much more efficient and less costly cooling medium (Turnpenny et al., 2010). The choice of cooling method therefore depends on balancing water availability, against the additional cost and loss of generating efficiency of using the less water intensive alternative cooling methods (Cooling Tower Solutions, 2012).

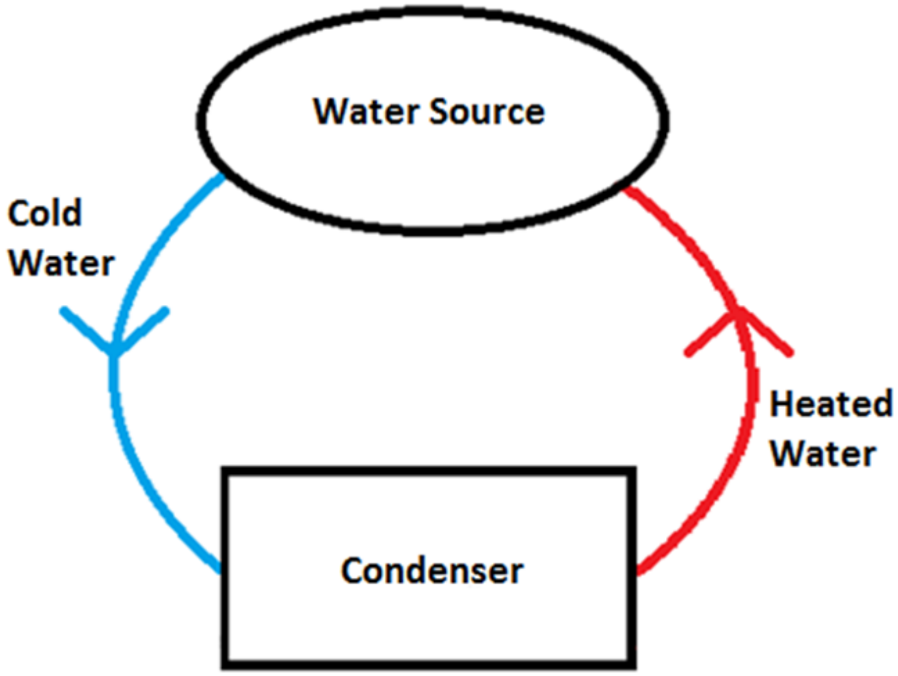

Figure 2.1 Once-through Cooling Schematic

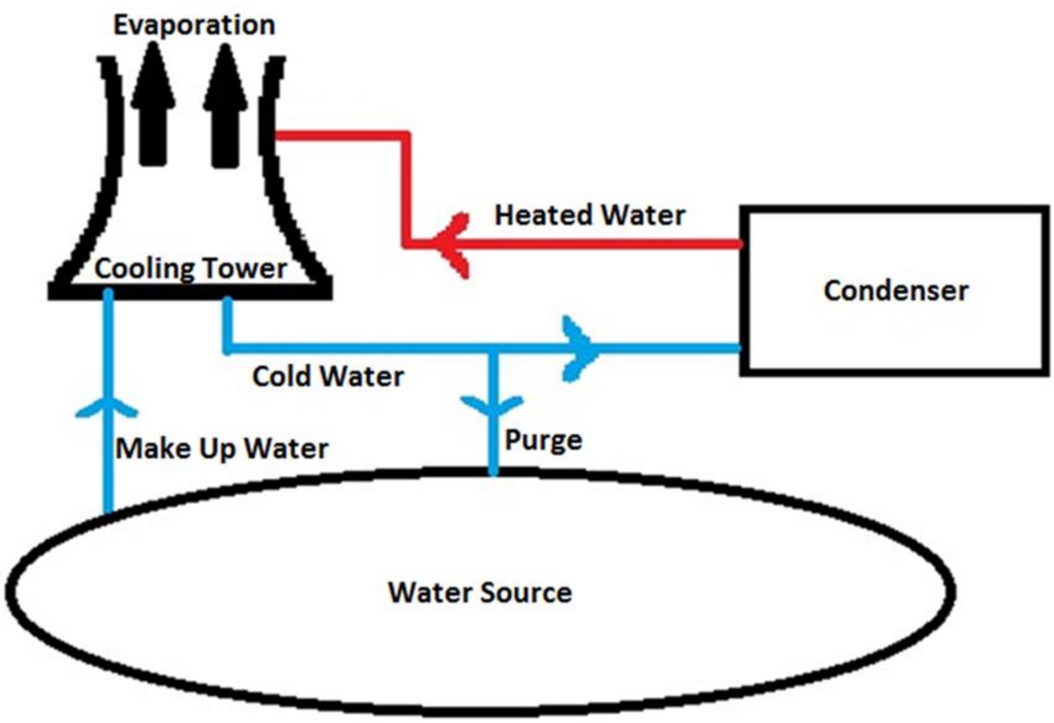

Figure 2.2 Evaporative Cooling Schematic

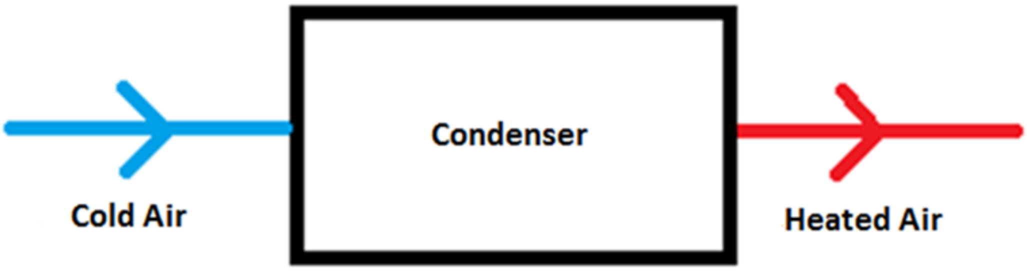

Figure 2.3 Direct Air Cooling Schematic

Another alternative cooling medium to freshwater for power stations is the use of seawater (and estuarine water). Seawater comprises 96.5% of the world's potential combined power station cooling water resource (Lal, 2015). For countries with large coastlines like Japan, Korea, Australia, and the UK, the use of seawater as a suitable, abundant and secure source of power station cooling water has been proved (International Energy Agency, 2012). Despite its availability some countries do not always see seawater as being the means of resolving their energy policy's otherwise increasing demand for freshwater cooling, and accept the inefficiency penalties. The arguments against seawater can be that:

1. The 'physics' of cooling mean that, due to its salinity, seawater is a less efficient cooling medium than freshwater (Turnpenny et al., 2010).
2. Coastal generation can be remote from demand centres.
3. The arguments for protecting the marine environment are judged to outweigh the arguments for limiting the use of freshwater (Energy UK, 2014).

Thermal power stations obtain their water from adjacent rivers, estuaries and the sea. For the purpose of this thesis, groundwater, and all non-tidal surface water including rivers are regarded as being freshwater. Over the past decade, thermal power stations in mainland Europe and in the USA that obtain freshwater from rivers, have experienced increasing difficulty in abstracting the water they require because of more frequent low flow rates. To compensate for reduced freshwater availability, generation loads have had to be reduced, or generation stopped altogether (Bartos and Chester, 2015, Förster and Lilliestam, 2010, Paskal, 2010, Tweed, 2013). Based on spatial analogues, which is the method of studying regions that currently have a climate similar to a study area in the future (Horvath et al., 2009), it is likely that the predicted increase in ambient air and water temperature, as well as the reduction in summer precipitation due to climate change, will in future expose the UK to similar problems.

2.2.1 Water Abstraction and Consumption Requirements of Thermal Power Generation

There was little specific data available regarding the abstraction and consumption needs of the different technology/ancillary systems of the UK's electricity generation fleet. However, US figures published by the National Renewable Energy Laboratory (NREL) (Table 2.1), provide a starting point for the water demand of thermal power stations (Macknick et al., 2011). Schoonbaert (2012) compared the NREL figures with the limited UK data available and concluded that whilst the abstraction values for the UK tended to be higher, the consumption values were lower. Neither Byers et al. (2014) nor Schoonbaert (2012) were able to obtain enough UK specific water abstraction or consumption data, on which to base their research.

Table 2.1 Water Withdrawal and Consumption by Fuel and Cooling Type (Macknick et al., 2011)

Fuel Type	Cooling	Technology	Number of Samples (Abstraction, Consumption)	Abstraction (L/MWh)			Consumption (L/MWh)		
				Median	Min	Max	Median	Min	Max
Natural Gas	Once-through	CCGT	2,3	43,078	28,391	75,708	379	76	379
		Steam	1,2	132,489	37,854	227,125	908	360	1,102
	Evaporative	CCGT	6,5	958	568	1,071	750	492	1,136
		CCGT + CCS	2,1	1,843	1,878	1,915	1,431	1,431	1,431
		Steam	2,4	4,554	3,596	5,527	3,127	2,506	4,429
	Air	CCGT	2,2	8	0	15	8	0	15
Coal	Once-through	Generic	4,4	137,600	75,708	189,271	946	379	1,200
		Subcritical	3,3	102,539	102,380	102,634	428	269	522
		Supercritical	3,3	85,512	85,365	85,592	390	242	469
	Evaporative	Generic	4,5	3,804	1,893	4,542	2,601	1,817	4,164
		Subcritical	7,6	2,010	1,753	2,567	1,783	1,491	2,514
		Subcritical + CCS	2,1	4,834	4,633	5,031	3,566	3,566	3,566
		Supercritical	7,6	2,305	2,203	2,532	1,866	1,734	2,249
		Supercritical + CCS	2,1	4,251	4,156	4,346	3,202	3,202	3,202
		IGCC	11,7	1,476	1,355	2,290	1,408	1,204	1,662
		IGCC + CCS	6,3	2,218	1,813	2,567	2,044	1,976	2,112
Biomass	Once-through	Steam	1,1	132,489	75,708	189,271	1,136	1,136	1,136
	Evaporative	Steam	2,4	3,324	1,893	5,527	2,093	1,817	3,653
		Biogas	-,1	N/A	N/A	N/A	890	890	890
	Air	Biogas	-,1	132	132	132	N/A	N/A	N/A
Nuclear	Once-through	Generic	4,4	167,883	94,635	227,125	1,018	379	1,514
	Evaporative	Generic	4,4	4,168	3,028	9,842	2,544	2,199	3,199

Assuming the NREL figures are indicative of the UK they attribute an order of relative water demand for different electricity generation technology and cooling method combinations. They show for abstraction, for example, a Natural Gas Combined Cycle Gas Turbine (CCGT) power station's water demand with BAT, once-through cooling is 43,078Litre/Megawatt hour; with the less water intensive evaporative cooling this is reduced to 958L/MWh, and, virtually eliminated by air cooling. For water consumption the position changes, the volume lost with the once-through method is 379L/MWh; with evaporative cooling 750L/MWh are lost; with air cooling the water loss again remains negligible. The deployment of carbon capture and storage (CCS) to abate carbon emissions is shown to require a noteworthy increase in a thermal power station’s water demand; approximately double the non-CCS equivalent which is in accord with other studies (Byers et al., 2016, Cormos et al., 2013, Koornneef et al., 2012, Zhai and Rubin, 2011)

The major reduction in water demand by thermal power stations achieved in changing from water to air cooling appears to provide a panacea for any future freshwater shortages. However, the change from once-through to alternative cooling options incurs cost and efficiency penalties (Table 2.2). A loss in power station efficiency of up to 10-11% (for air cooling relative to once-through) reported by Byers et al. (2014) and World Nuclear Association (2013) is significant when compared to distribution losses which are typically around 7% (MacLeay et al., 2016). Mills et al. (2012) put the cost penalty for new 500MW evaporative and dry cooled thermal power stations in terms of average annualised capital and operational cost, in the region of £1.3 - £2.8Million and £6.3 - £11.9Million above that of BAT once-through cooling, respectively. With total annualised costs of a 500MW thermal power station likely to be in the region of £200-£400Million, these penalties are noteworthy (DECC, 2013b).

Thermal power stations pay these efficiency penalties by increasing their fossil fuel burn, thereby also increasing their CO_2 emissions. With a higher ambient temperature dependent penalty clause, without greater certainty on future summer ambient temperatures, adapting to future freshwater shortages by trying to factor in the less/no water cooling alternatives could be found to be a convoluted process.

Table 2.2 Power Station Cooling Technologies

	Cooling Technology		
	Once-through	**Evaporative**	**Air**
Advantages	Lowest cost option both in terms of capital and operational cost (RWE npower, 2005). Relatively low water consumption.	Significantly lower water abstraction compared to once-through cooling.	Negligible/no water abstraction or consumption required.
Disadvantages	High water abstraction, so much so that in the UK direct cooling is only used where stations are near to an estuary or the sea. Discharges large volumes of warmed water back into water bodies.	More costly than once-through cooling and tends to have a reduction in generation efficiency, especially when ambient temperature is high (Turnpenny et al., 2010). It also has a comparatively high level of water consumption.	Most costly cooling technology, also has the greatest reduction in generation efficiency, especially when ambient temperature is high (Carney, 2011, Turnpenny et al., 2010).

2.3 UK Water and Energy Policy

With the literature clearly identifying risks to thermal generation from a future lack of available water, and with this thesis focus on the UK, the question arises as to how is UK energy and water policy proposing to manage this threat. The UK energy system is in a state of transition, ageing energy infrastructure, including the current power generation fleet, needs to be replaced in a way that provides an energy system that is secure, affordable and decarbonised. There are many organisations involved in this process and there is a wealth of literature on the subject, much of which records the convoluted process this has become (Ginige et al., 2012, Ngar-yin Mah and Hills, 2014, Poortinga et al., 2014).

One casualty is the water- energy nexus; with societal, environmental and electricity generation policy arguments being made more on the basis of the immediate environmental concern, rather than the more distant consequences for secure and affordable generation. The UK energy transition is not just about replacing outdated plant, there is also a need to increase generation, potentially by as much as 250TWh/annum from 2013 to 2050. The UK's current approach sees this growth coming largely from an expansion of thermal generation (DECC, 2015a, HM Government, 2011a), which requires more cooling water when, particularly in future summers, the best predictions suggest there will be less (Environment Agency, 2011, Environment Agency, 2013b, Wade et al., 2013, Watts et al., 2015).

2.3.1 UK Water Over-abstraction

The Government first addressed the shortage of freshwater through a series of publications, the foremost being the ‘Water for Life’ White Paper (DEFRA, 2011). Precipitated by Cave (2009) the need for the white paper was confirmed by two further studies. Firstly, the Environment Agency (2011) argued that due to over-abstraction, the majority of the UK’s freshwater water-bodies no longer had fully functioning ecosystems. Secondly, OFWAT and Environment Agency (2011) warned there would be increasingly less freshwater to meet the greater demand of an increased population that would put even more pressure, on even more ecosystems. This led to the Government committing to introduce *“a reformed water abstraction regime resilient to the challenges of climate change and population growth and which will better protect the environment”* (DEFRA, 2011).

The DEFRA (2011) approach to protecting UK ecosystems from over-abstraction was set out in the Government White Paper “The Natural Choice” (HM Government, 2011b). OFWAT (the UK’s water services financial regulation authority) with the task of initiating the reform required, also identified that seawater abstraction and discharge was an issue stating “*changes in seawater temperature could adversely affect maritime biodiversity*” (OFWAT, 2011). The Environment Agency (2011) over-abstraction case was based on its Catchment Abstraction Management Strategy (CAMS) that gauged for each UK water catchment how much water, after protecting the environment, was available for abstraction. On this basis Environment Agency (2011) concluded additional abstraction of freshwater for cooling water could not be relied upon in the future for large areas of England and Wales. The environmental flow for catchment protection is legislated by the EU Water Framework Directive (WFD) (Directive 2000/60/EC) and Habitats Directive (Council Directive 92/43/ECC), and is assessed using Environmental Flow Indicators (EFI), (Collins et al., 2012, Morris et al., 2014).

OFWAT and Environment Agency (2011) accepted the problem of over-abstraction and the resultant future reduced freshwater availability case. The primary reason for the over-abstraction was that abstraction licences were issued believing there was surplus water which with time had now proved incorrect. Hence, both the Water Resources Act 1991 (HM Government, 1991), and the Water Act 2003 (HM Government, 2003), had allowed the issuing of unsustainable abstraction licenses. The conclusion of OFWAT and Environment Agency (2011) was that reforming abstraction will inevitably reduce the volumes licensed for abstraction. However, it was accepted that despite less summer rainfall and higher summer temperatures, thermal power generation would need more cooling water. The solution offered was that energy generators should invest more in technology that does not require water for cooling. However, this takes no account of the higher costs and additional emissions penalties incurred when using alternatives to once-through cooling for power stations (DeNooyer et al., 2016, Turnpenny et al., 2010).

This advice is also contrary to the opinion that the use of saline (sea and estuarine) water for power station cooling water would resolve any lack of freshwater issues (section **2.3.2**). DEFRA's (Department for Environment, Food & Rural Affairs) instructions to OFWAT on tackling over-abstraction were succinct (DEFRA, 2013a). OFWAT should achieve the reform through its regulatory functions with the management of ecosystems being consistent with their environmental wellbeing as prescribed by HM Government (2011b). Ultimately, the environmental argument was that the damage to the UK's ecosystem was neither being recognised, nor being attributed. The societal case was that this damage would eventually have to be acknowledged and would then subsequently increase household and business energy charges. Environment Agency (2013c) suggested restoring sustainable abstraction should be based on the EA's EFI strategy, and in future water abstraction licences should not be regarded as being inviolate. The detail as to how the UK Government proposed to meet its commitment to reform the water abstraction management system in England and Wales was set out in a consultation paper (DEFRA, 2013b).

2.3.2 Water Abstraction of the UK Electricity Sector

DEFRA (2011) acknowledged, when it came to licensed abstraction, electricity generation is unique in being the largest abstractor. It accepted the new UK infrastructure rebuild necessary to meet an increased generation demand, and new legally-binding emission targets all suggested the demand for water would increase. The position of electricity generators would therefore be assessed as a study undertaken by the Government, the Environment Agency (EA) and the power sector. This study's publication (Environment Agency, 2013b), coincided with the abstraction reform consultation (DEFRA, 2013b). After considering four UKCP09 Regional Climate Model simulations applied to future electricity demand, the view was that power stations would in future rely on "*saline/tidal*" water so that there would be no lack of freshwater cooling impact. A concurrent paper (Environment Agency, 2013d), appeared equally positive on coastal generation by deciding any linking of EFI freshwater flow restrictions could threaten the UK's ability to meet generation demand. This paper also recognised coastal generation had other advantages that would promote investor confidence. They were:

1. Large quantities of cooling water resource available.

2. Large water bodies with their high thermal capacities are capable of receiving the necessary high levels of cooling water discharge.

3. In the case of seawater, relative to freshwater and estuary abstraction, complying with regulatory requirements of coastal discharge is more easily managed.

2.3.3 Coastal v Freshwater Water Sources for UK Power Stations

However, the reality of UK coastal generation is not straightforward. An examination of recent nuclear energy policy provides a good, but not isolated, example. Similarly, the case of the CCGT power station at Pembroke provides another relevant example (Lewis, 2015) (section **2.3.4**). A Strategic Siting Assessment consultation to find suitable sites in England and Wales for new nuclear infrastructure, taking a wide range of planning constraints into account, was launched by the Department for Business Enterprise and Regulatory Reform (BERR, 2008). All sites found to be suitable were at coastal or estuarine locations, yet with some 7,000 miles of coastline, DECC (2011a) finally confirmed only eight suitable sites were found. The Government accepted these eight sites were the only possibilities which were subsequently listed by the UK's Overarching National Policy Statement for Energy (EN-1) (DECC, 2011b). This now allows decisions taken by the Infrastructure Planning Commission on these sites to recognise national strategic interest.

Poor implementation of energy policies have at times provoked public opposition to a wide-range of energy matters; particularly nuclear power generation. For example, the Government consultation (DTI, 2007), intended to promote nuclear power, was when publically challenged, judged by a High Court ruling to be procedurally "*misleading*", "*seriously flawed*", and "*manifestly inadequate and unfair*" (Warburton, 2009). This effectively undermined the UK Government's authority to now set any energy policy without microscopic scrutiny (Ngar-yin Mah and Hills, 2014). Coastal generation, given its association with nuclear infrastructure, thus becomes a casualty.

Leading UK electricity generators, in view of the new legislative and regulatory thinking, initiated The Joint Environmental Programme (JEP) to consider the future water demand of the electricity sector by 2050, along with possible environmental implications (Gasparino, 2012). The study found there was such uncertainty over the makeup of any future UK generation fleet, and the type and amount of water that will be available, that no firm conclusion could be reached. Their view was if the Government's preference remained thermal generation, provided the right investment opportunities are created, the Government could either opt to use saline water instead of freshwater for cooling, or adopt less freshwater intensive cooling methods.

Energy UK's (the trade association for the UK energy industry) response to the abstraction reform consultation (DEFRA, 2013b), was more forthcoming, but there was scepticism over Government policy (Energy UK, 2014). A concern expressed was that although there was likely to be less freshwater available, because of increasing environmental pressures at coastal sites, the generators' expectation was that water-dependant thermal power stations would still be expected to operate on English rivers for decades to come. The level of protection being considered by DEFRA for the environment was also queried. The challenge was the disproportionate priority being given to protecting the ecological status of water bodies, in contrast to that given to the wider societal need for energy by the population. The concept of power stations being required to use less water intensive cooling methods was questioned. It was in direct contradiction with the EU Directive on Industrial Emissions 2010/75/EU that acknowledged once-through cooling to be the BAT cooling method (European Commission, 2001). As a consequence the increased efficiency compared to other cooling methods provided more electricity per unit of fuel employed thereby reducing greenhouse gas emissions and generation costs. The Government's argument for reforming freshwater water abstraction is that the eventual ongoing ecosystem damage will lead to increases in future household and business energy costs. There is, however, no thought given to the additional costs that will inevitably be incurred, by households and businesses, by limiting the cooling water available to thermal power stations. This will be considered in greater detail later in this thesis (section **6.4**).

2.3.4 UK Environmental Regulation Impact on Thermal Generation Cooling

There has been a sea-change in the regard ecosystems, and the environment, are entitled to over the last few decades, which in part drove the issues discussed above. For example, under the EU Habitats Directive power stations are required to demonstrate that activities such as abstraction, and discharge, do not have an unacceptably adverse impact upon protected Natura 2000 sites (Environment Agency, 2012, Morris et al., 2014). Natura 2000 sites were developed as a result of the EU Habitats Directive (along with the EU Birds Directive), and are a series of ecologically important areas which are protected to conserve Europe's rare species and habitats (Joint Nature Conservation Committee, 2016). They are broken down into Special Areas of Conservation and Special Protection Areas.

The European Commission (2016b) claims Natura 2000 sites are not strict reserves from which all human activity should be excluded. Nevertheless, Energy UK stated in evidence to the UK Government's Science and Technology Committee, that planning permission for some thermal power stations had been complicated, or made controversial, due to the perceived adverse impact they would have on Natura 2000 sites (HM Government, 2013). These perceived impacts include the effects of thermal discharge, and chemical treatment of cooling water systems, which will be most severe under the once-through cooling regime.

With Natura 2000 sites covering over 18% of the EU's land mass, and 6% of its marine territory (European Commission, 2016b), they clearly have the potential to disrupt the development of new power stations across Europe, particularly those wishing to use once-through cooling.

The WFD was adopted by the European Union (EU) in 2000, and commits all member states to achieve good ecological status of freshwater, transitional (estuarine), and coastal water bodies by 2015 (Collins et al., 2012). The WFD also has a number of daughter directives, including the Environmental Quality Standard Directive, which lays down environmental quality standards with the aim of achieving a good chemical status in surface waters (European Environment Agency, 2016).

The WFD places emphasis on aquatic ecology when making management decisions (Hering et al., 2010), and recognises the environment as a critical user of water, almost on par with human activities (White and Howe, 2003). In the case of freshwater bodies abstraction licenses are now being monitored to avoid flows becoming reduced to levels that damage their ecology. Some non-coastal thermal power stations have "*hands-off*" conditions incorporated into their abstraction licenses that limit, and sometimes stop, freshwater abstraction during periods of low flow (Environment Agency, 2013c).

The temperature of a thermal power station's discharged cooling water is another determinant used by the WFD to classify the ecological wellbeing of the recipient water body. While lack of water resource does not apply to estuarine and seawater abstraction they are not absolved from complying with the WFD's ecological temperature specifications. The WFD requires that a thermal power station's discharge temperature should not cause recipient cold water bodies (that do not support cyprinids) to exceed 23^{o}C; for warm water bodies (that do support cyprinids) to exceed 28^{o}C (WFD UK TAG, 2008). In continental Europe where the problems of water shortages and climate change are that much greater, complying with WFD temperature requirements, as with low river flows, has caused reduced generation, and power cuts. Such disruptions increase the cost paid by customers for their electricity (Eisenreich, 2005, Fink et al., 2004, Koch and Vögele, 2009, Olsson, 2013).

Thermal power stations, when abstracting water, can bring aquatic fauna onto the screens intended to stop debris entering and damaging a power station's generation system (Turnpenny et al., 2010, Shepherd et al., 2016). From an ecological standpoint the extent of fauna impact can seriously affect an area's species population (Greenwood, 2008), and damage its attributed WFD ecological status. Whilst the volume of water abstracted by those thermal power stations which use water from estuaries and the sea are not constrained by low flow thresholds they still have to adhere to the WFD discharge temperature standards and fauna impacts. Both have the potential to restrict the UK from mitigating and adapting to a future shortage of inland freshwater by finding a once-through cooling water solution for thermal power stations at the coast.

A further example of how environmental regulations are pushing thermal power stations inland, where they must then rely on a scarce freshwater resource is shown by Figure 2.4. It shows a number of environmental designations for the UK (excluding Northern Ireland), within 5 miles of the coast, which to varying degrees can hinder the siting of a thermal power station. Only national designations are shown; some are missing due to the relevant datasets not being publicly available. Nevertheless it can be seen that the vast majority of the UK's coastline has an additional level of environmental protection above that which applies to the UK as a whole.

Figure 2.4 UK Coastal Environmental Designations; data taken from (Natural England, 2016, Scottish Natural Heritage, 2014)

An interesting case study which gives context to the impact these environmental regulations can have on thermal power stations is the 2000MW CCGT power station at Pembroke, which uses once-through cooling taken from the mouth of the estuary at Milford Haven. The European Commission has stated that it is having a damaging effect on the nearby ecosystem due to the cooling method employed, resulting in an environmental quality standard and the EU Habitats Directive being breached (European Commission, 2014a). This case is still (in 2016) ongoing, although, if the European Commission decides to pursue infringement action this will likely result in RWE Npower (the operator of the station), having to modify the power stations cooling processes, or even shut the station all together (Lewis, 2015). However, as the case is against the Government for providing the required permissions, it is likely that any costs incurred by this action will ultimately have to be covered by the Government, not RWE Npower.

As this section shows, many of the environmental regulations governing thermal power stations are EU directives. On 23rd June 2016 the UK public voted in a referendum to leave the EU; there is great uncertainty to the implications of this, but if the UK leaves these directives may no longer apply, and environmental regulations may be lowered (Travers, 2016). However, if the UK wishes to remain in the single market then it may still have to adhere to many of the EU's environmental policies, as in the example of Norway (Dhingra and Sampson, 2016). In addition, environmental regulation was not an area that was high on the political agenda during the lead up to the referendum, nor is it an area where the UK has in the past regularly voted against EU policy (Hix et al., 2016). Therefore it would appear reasonably likely that general UK environmental regulations will not substantially change, although there may still be specific environmental exemptions for power stations. None of this is guaranteed, but as the bulk of this thesis research considers a range of pathways and scenarios it makes relatively little difference to the validity of the results found, although it does add uncertainty as to exactly where the future water demand will lie within the range of results found.

2.4 Water Resource for UK Thermal Power Generation

For the UK it is clear that there will be less freshwater available in the future for power stations, but the question has to be asked exactly how much will be available? In 2008, the EA acknowledged that in England and Wales 15% of river catchments were over-abstracted at low flows and an additional 35% of catchments had no additional freshwater available for abstraction (Environment Agency, 2008). There is no underlying data available, but the EA provide an associated map for catchments in England and Wales showing the annual percentage of time that different areas currently have freshwater available for additional abstraction (Environment Agency, 2013c). To illustrate the affect this already has on the energy sector, the location and cooling methods of the thermal power stations in England and Wales in 2010, with an installed capacity greater than 150MW (including the then under construction West Burton and Pembroke stations), were superimposed on this map (Figure 2.5), with the data being obtained from a number of sources (Byers et al., 2014, MacLeay et al., 2011, MacLeay et al., 2013, Schoonbaert, 2012).

The result shows the only thermal power stations in England and Wales deploying the most efficient/least cost once-through cooling method (38% of total UK capacity) are those situated on an estuary, or at the coast. For the remaining inland power stations, it is noted cooling water abstraction is already limited to the less water intensive, more inefficient, more costly and greater carbon emitting evaporative, hybrid and air cooling methods.

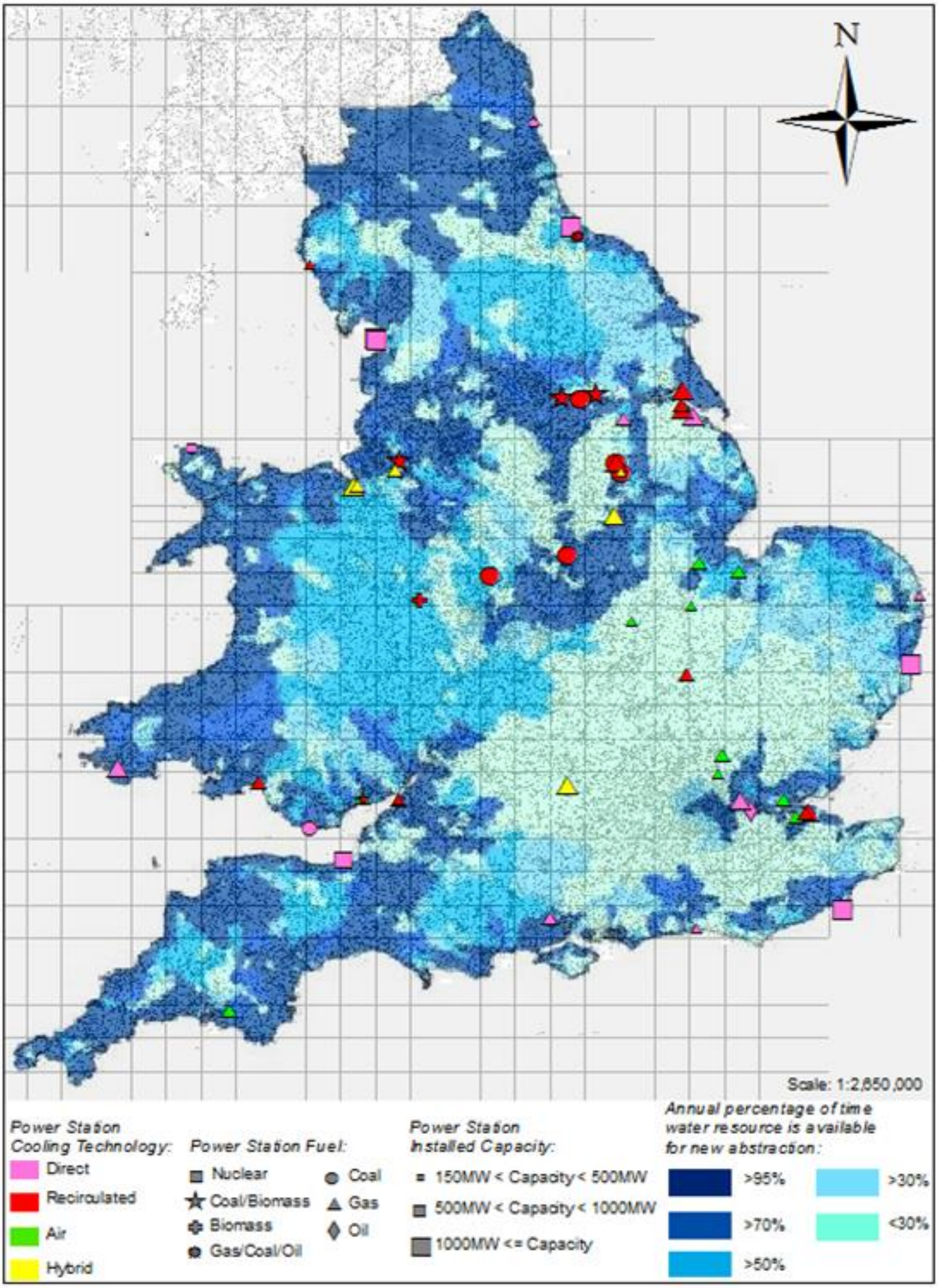

Figure 2.5 UK Thermal Power Stations and Freshwater Abstraction Availability; data taken from (Byers et al., 2014, Environment Agency, 2013c, MacLeay et al., 2011, MacLeay et al., 2013, Schoonbaert, 2012)

The Environment Agency prepared sixteen outcomes that modelled 2050 freshwater profiles (Figure 2.6), that compared the likely total freshwater demand for all purposes, and the likely availability of freshwater under Q70 summer flow conditions, defined as "the long-term average flow which is exceeded 70 per cent of the time" (Environment Agency, 2011). The sixteen outcomes shown in Figure 2.6 represent four climate change scenarios applied to two different freshwater demand scenarios, which are then in turn applied to two levels of environmental standard. The climate change scenarios are based on UKCP09 and denoted as A, C, G, and J, with scenarios A and C showing relatively mild reductions in freshwater flow due to climate change and scenarios G and J showing more significant reductions. The two demand scenarios are classified as "sustainable behaviour" which foresees a reduction in current freshwater demand of approximately 15% by 2050, and "uncontrolled demands" which foresees an increase in freshwater demand of approximately 35%. The two levels of environmental standard used are "fixed at current levels" and "reduces in proportion to climate change impacts", the latter standard is less severe as it allows the flow of freshwater which must be maintained for environmental protection to reduce as the net flow of freshwater also reduces.

To obtain a comparison between 2010 and 2050, the thermal power stations used in Figure 2.5 were superimposed onto the Environment Agency's scenario map G: uncontrolled demands and fixed environmental protection, to produce Figure 2.7. This worst case scenario was chosen as it acknowledges the suggestion that the climate change projections used by the Environment Agency (based on UKCP09), for various reasons, have a tendency to underestimate the effect of climate change (Brown and Castellazzi, 2015, Brysse et al., 2013, Cavan, 2011, Cowtan and Way, 2014, Frigg et al., 2013).

Fundamentally, Figure 2.7 shows there will be less freshwater available for cooling water abstraction in 2050 than in 2010. By 2050 any inland thermal power station, unlike 2010, is now in a freshwater environment where, under summer flows, the majority of catchment areas of England and Wales are unable to meet their freshwater demand, whilst satisfying environmental need. A further concern is that the lack of summer freshwater will likely coincide with an increase in ambient summer water temperatures, which can only increase the inefficiency penalties that have to be paid when using the less water intensive cooling methods.

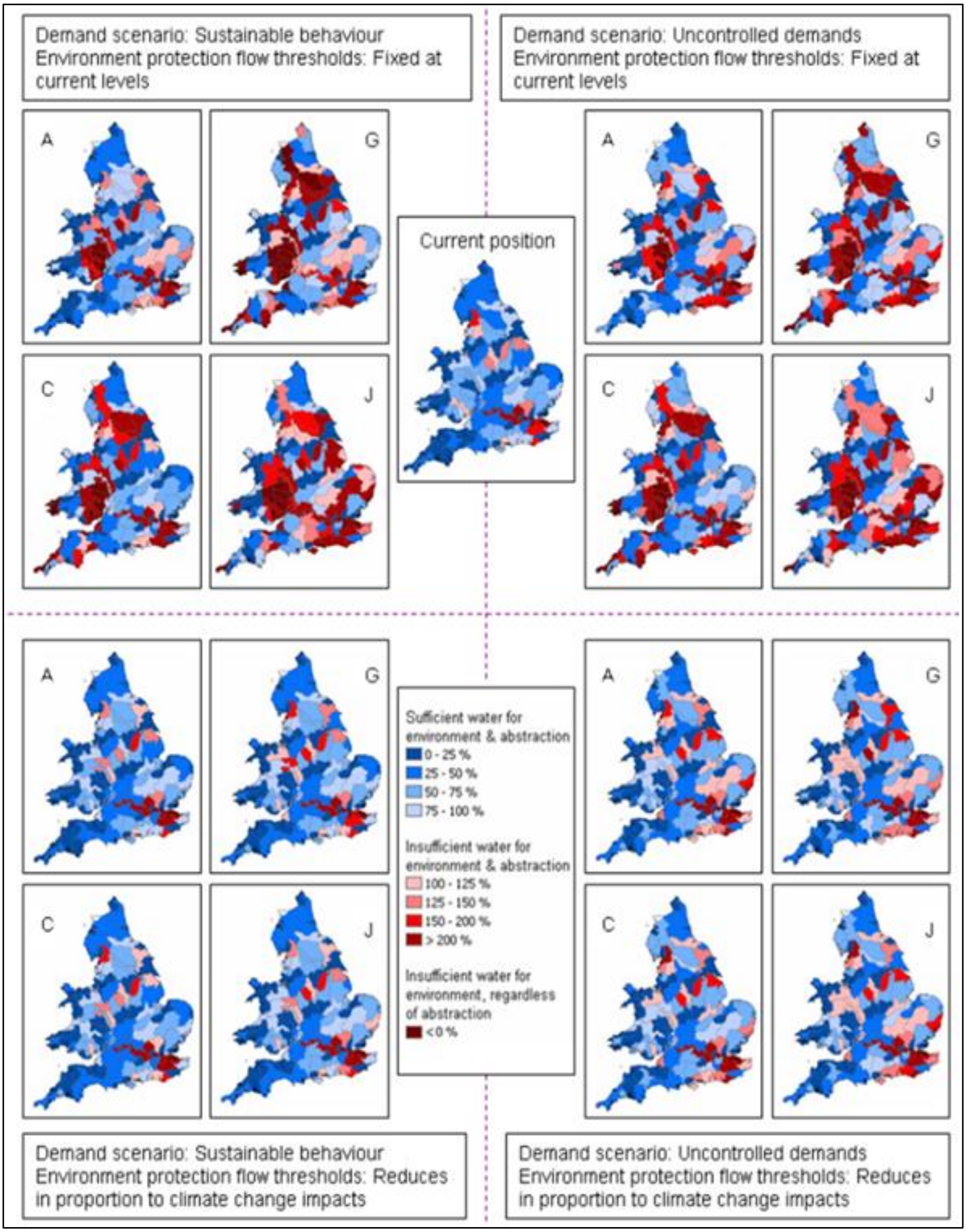

Figure 2.6 2050 Freshwater Supply Relative to Freshwater Demand Scenarios; data taken from (Environment Agency, 2011)

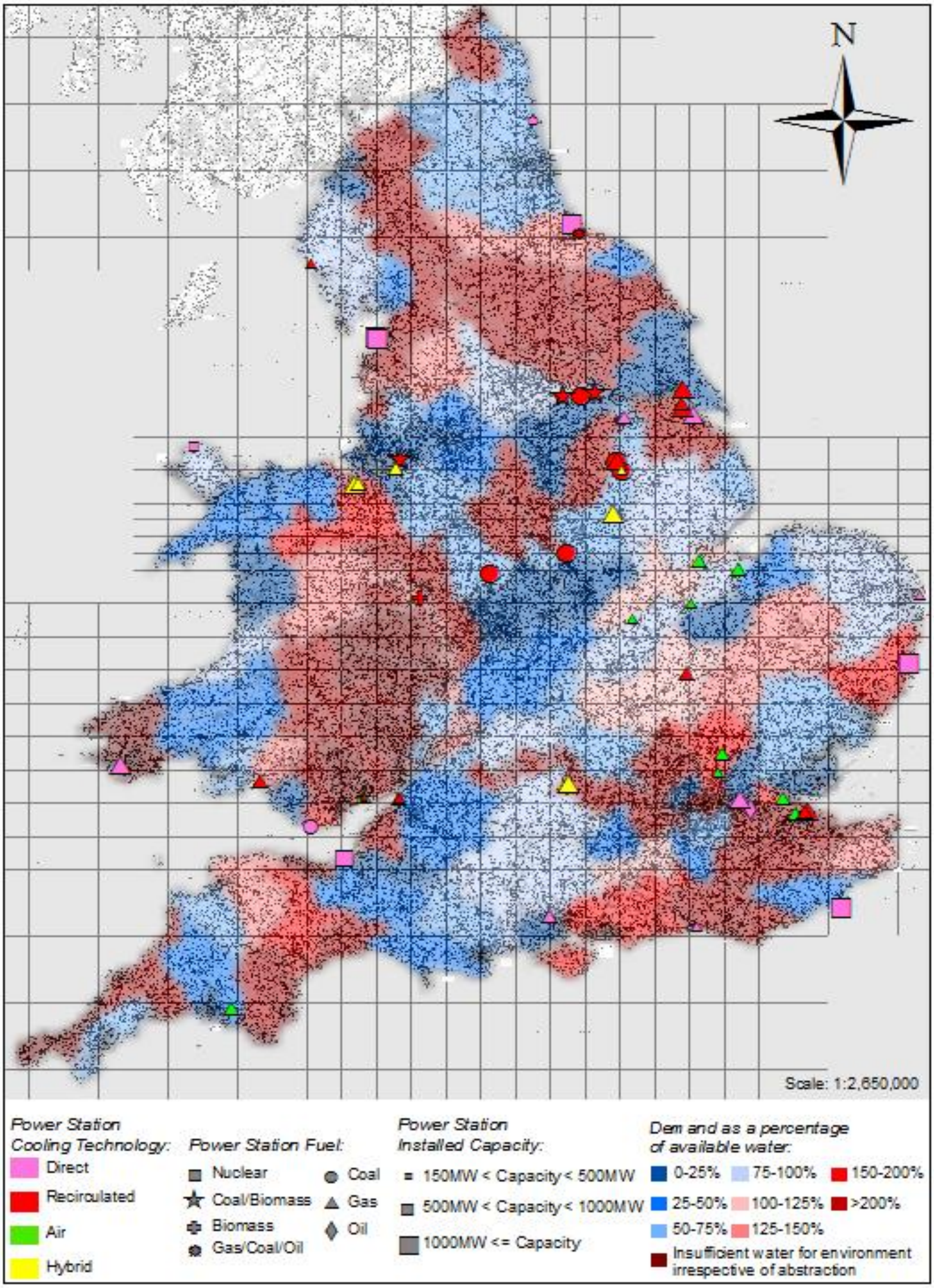

Figure 2.7 2050 Freshwater Supply Relative to Freshwater Demand, Worst Case Demand; data taken from (Byers et al., 2014, Environment Agency, 2011, MacLeay et al., 2011, MacLeay et al., 2013, Schoonbaert, 2012)

Linnerud et al. (2011) report a rise in ambient cooling water temperature of 1^{o}C can lead to a drop in power output of 0.15-0.5%. However, as will be discussed later (section **2.6**), the extent of this increase in ambient temperature is uncertain. This should therefore also be taken into account when deciding the form and location of the UK's 2050 thermal power generation infrastructure.

Overall, the past century has witnessed global and UK outputs of the power sector rise dramatically (Davies et al., 2013a), and this growth has come predominantly from an expansion of thermal power generation. For the UK the first half of the twenty-first century will see this growth in generation continue; from 359TWh in 2013 (MacLeay et al., 2014), to a possible 610TWh by 2050 (DECC, 2013a). With the government's enthusiasm for shale gas (White et al., 2016), and the opportunity it provides to reduce carbon emissions by switching coal fired generation capacity to gas; along with an adoption of CCS; additional biomass and nuclear power stations (DECC, 2015a), thermal power generation would seem the obvious, if most questionable, means of providing this increase. Any attempt to do this by investing in inland thermal power generation, in tandem with less available freshwater, would almost certainly be committing to an increase in the proportion of the UK's generating capacity that requires the less efficient, alternative cooling methods. This generation would be subject to the unknown cost and carbon emission consequences that are governed by the vagaries of uncertain ambient summer temperatures. Byers et al. (2014), Tran et al. (2014) and Schoonbaert (2012) all researched water requirements for thermal power stations in England and Wales under a number of pathways to 2050, and concluded that a lack of freshwater resource will if not mitigated, constrain UK power generation.

2.4.1 Alternative Water Sources

Despite the potential environmental and ecological regulatory requirements identified, a solution that has already been noted would be to move all, or a far greater proportion, of the UK's thermal power stations to coastal, or estuarine locations. In the UK, with no load location being more than 70 miles from the coast, and with some 7,000 miles of coastline in England and Wales alone, this should not be dismissed as a potential solution (Frost, 2010, Haran, 2003). To increase the adoption of sea/estuarine water for thermal power station generation there are, besides the environmental and policy hurdles to be cleared (section **2.3**), the more engineering-focussed issues shown by Table 2.3 to be considered. Although here the UK's long learning curve of coastal nuclear generation since 1956 is of inestimable value (DECC, 2012a).

Table 2.3 Effects and Consequences of Seawater Cooling

Effect	Consequence
Increased scaling, corrosion and abrasion due to the slightly alkaline nature of salt water	Can lead to increased costs as more expensive corrosion-resistant materials are required (Maulbetsch and DiFilippo, 2008).
Sedimentation	Sedimentation can be a problem for all thermal power stations which use some form of wet cooling; it can reduce abstraction capacity and cause damage to the pumping system (Mahgoub, 2013). However, macrotidal estuaries such as the Humber, Trent, Ouse, and Severn are particularly vulnerable to sedimentation (Mitchell and Uncles, 2013).
Reduced vapour pressure and specific heat of salt water	More water is required per KWh generated resulting in a larger cooling tower, if evaporative cooling is being employed (Turnpenny et al., 2010).
Concentration of salts if evaporative cooling is used	There is the potential for salts to become concentrated in the makeup water, this can damage the condenser so more makeup water is required than for a freshwater cooling system (Maulbetsch and DiFilippo, 2008), this will result in additional cost.
Salt drift	Drift is water which is blown out of the cooling towers, and if the system uses saltwater then there is the potential for the drift to cause damage to any nearby sensitive equipment such as transformers and switch gear, this can however be mitigated by sensible design (Nelson, 1986). There is also the potential for salt drift to damage surrounding vegetation (TRC Environmental Corporation, 2009), although very small drift levels are achievable (Nelson, 1986).
Rising Sea Levels	This increases the risk of flooding to coastal power stations, particularly nuclear plants with longer lifetimes (The Royal Academy of Engineering et al., 2011). Although less likely to be significant a further potential impact of rising sea levels is coastal erosion (British Geological Survey, 2012, Kopytko and Perkins, 2011).

Globally, countries that do not have such a sea, or estuarine water solution are looking at a number of non-traditional water sources for power station use, particularly as cooling water. They include treated public wastewater, water from mining processes, and water from ash settling ponds at coal-fired power plants (Chien, 2009). Of these water sources public wastewater is currently the most likely possibility due to its wide availability; (Li et al., 2011, Vidic et al., 2009). At present there are three UK thermal power stations which use (at least some) wastewater (Schoonbaert, 2012), and this comparatively small take-up may be as a result of some as yet unresolved issues associated with this technology. These include an increased level of scaling and biofouling (Safari et al., 2013), health concerns related to bacteria, and viruses, that may be present in the cooling tower drift (Cooper, 2012), and the additional energy (180-780kWh/ML) required to treat the wastewater (Stillwell et al., 2010). The economic incentive to solve these issues will come from the rising marginal cost of water, as it is appreciated freshwater is a raw material that is increasingly becoming more valuable.

2.5 The Water-Energy Nexus and its Implications on Non-thermal UK Electricity Generation

This research focuses on thermal electricity generation, however, in the process of this review, a number of interdependencies between non-thermal aspects of UK electricity generation (renewable energy) and water infrastructure networks which could result in adverse impacts to the energy sector were identified. For completeness these interdependencies are discussed here.

Future lack of resource has the potential to constrain electricity generation from renewable energy sources which use water directly. Indeed a study of the Elbe river basin by Koch et al. (2014) found that generation from hydroelectric schemes would decline by approximately 13% between 2010 and 2050. However, water was only used directly to generate 2.6% of the UK's electricity in 2014, through 'run of river' hydroelectric schemes (1.7%), and pumped hydroelectric storage (0.9%) (MacLeay et al., 2015). This is only a small percentage of the UK's current electricity generation, and whilst the UK's stated ambitions to reduce GHG emissions by 80% by 2050, and increase renewable energy uptake, have the potential to increase the electricity production of these technologies in the future, it is likely to be limited. The Government appear to confirm this; neither approach is identified as being one of the technologies thought capable of providing 90% of the renewable energy required by 2020 (DECC, 2011c). Furthermore, it is generally felt that there are few remaining suitable sites for pumped storage on any significant scale (Energy Research Partnership, 2011), although Gimeno-Gutiérrez and Lacal-Arántegui (2015) suggest there is realisable potential to double the installed capacity of pumped storage. Even then pumped storage would provide a small percentage of the UK's electricity generation, and would only go a small way to meeting the near 10 fold increase in grid connected electricity storage it is suggested will be needed by 2050 (Goater, 2015).

Similarly, wave and tidal devices also require a dynamic water resource. Whilst the electricity generated by these technologies is currently negligible, it does have the potential to become more significant in the future (DECC, 2011c, Wright, 2016). However, as these devices are located in coastal, or estuarine waters, resource availability is not considered to be a constraint, although the environmental impact of these technologies still needs to be taken into account, and may provide a constraint to development (Frid et al., 2012, Magagna and Uihlein, 2015, Uihlein and Magagna, 2016).

Bioenergy is also likely to play a key role in the UK's future energy mix (DECC, 2011c, DECC, 2012b, HM Government, 2010, Sinclair et al., 2015). While some of this may be for thermal electricity generation, much of it will be for heat and transport. However, the biomass required to produce bioenergy requires a significant amount of freshwater for growth, the exact levels will depend amongst other variables, on the crop type and climate. No UK data is available regarding the freshwater footprint for a given quantity of bioenergy, although a study in the Netherlands (which has a similar climate to the UK) showed that $24m^3$ of freshwater were required per GJ of bioenergy produced (Gerbens-Leenes et al., 2009). This translates to a freshwater requirement of 86,400L/MWh, and is additional to any water required by the thermal generation cooling process. This is likely to put significant pressure on UK freshwater resources which may already be in short supply. One alternative would be to import any biomass the UK requires for energy generation.

2.6 Climate Change

One of the first references to modern Climate Change in academic literature was in 1975 when Wallace Broecker used the term Global Warming in his paper "*Climatic Change: Are We on the Brink of a Pronounced Global Warming?*" (Broecker, 1975). Today climate change is regarded as posing an irreversible, and dangerous long term threat to the global community (IPCC, 2014), and is considered by many to be the biggest global health threat of the 21st century (Wang and Horton, 2015). The EU alone is to spend at least 20% of its budget for 2014-2020 on climate change related action (European Commission, 2016a), and there is already an enormous body of research on the subject.

With regard to the water-energy nexus and water resource, the primary interest is on how climate change will impact the availability of freshwater. However, the uncertainty over the extent of the change in future summer ambient temperatures, and precipitation levels, presents a fundamental problem for deciding how to adequately mitigate, and adapt to its consequences. Higher temperature is the pervasive manifestation of climate change (Rohde et al., 2013), and for the UK the likely increases are made available via the probabilistic 2009 UK Climate Projections (UKCP09). Acknowledging the anthropogenic generator is carbon dioxide emissions, UKCP09 provides temperature projections for the 2050's under Low, Medium, and High Emission scenarios (UK Climate Projections, 2014). As an example the 10% - 90% probabilistic temperature range for the North and South of the UK are shown in Table 2.4. Even with the probabilistic range of temperatures within each scenario, UK Climate Projections (2014) makes it clear that no one scenario should be favoured. Subsequently their usefulness in quanitfying the impact of, and developing appropriate mitigation and adaptation strategies to, the water-energy nexus, becomes blurred by the range of possibilities. Additionally there are suggestions that the UKCP09 projections tend to underestimate the effect of climate change (Brown and Castellazzi, 2015, Brysse et al., 2013, Cavan, 2011, Cowtan and Way, 2014, Frigg et al., 2013).

Table 2.4 UKCP09 Projected 2050 Temperature Rise Ranges; data taken from (UK Climate Projections, 2014)

Region	Emissions Scenario	10% Probability Level (*temperature rise very unlikely to be less than)* °C	90% Probability Level *(temperature rise very unlikely to be greater than)* °C
South of UK (*London, S.E England, S.W England regions*)	**Low**	1.0	3.6
	Medium	1.2	4.0
	High	1.4	4.4
North of UK (*Scotland East, Scotland West, Scotland South, N.E England, N.W England regions)*	**Low**	0.8	2.9
	Medium	0.8	3.1
	High	0.9	3.5

A number of studies question the approach taken by UKCP09 which adds further uncertainty to the results produced. Murphy et al. (2010) and Street et al. (2009) accept that the decision by UKCP09 to characterise climate change using an ensemble of several global climate models provides a more robust basis for UK climate change assessments than previous attempts. Both papers, however, point out the method has its limitations. Fundamental challenges still remain in developing a spatially coherent framework to combine different climate models into one probabilistic assessment. Combining global climate models to provide future data in a regional climate probabilistic format is also questioned by Christensen et al. (2010). That study's conclusion was the value of ensemble model weighting has not been demonstrated, and remains highly controversial. At the time UKCP09 was in progress, Fowler and Kilsby (2007) argued while probabilistic methods appear to offer a more robust way of assessing climate change impacts more research is needed. Furthermore industry often finds probabilistic forecasts of climate change hard to understand and therefore difficult to use (Dilling and Lemos, 2011).

In his book '*A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*', Edwards (2010) went further and argued against obtaining regional climate outcomes by first making global data, and then using increasingly sophisticated computer models to analyse, and reanalyse results derived from many sources. Preferably he argues, to produce regional climate models (RCM) one should reverse the process and start with regionally focused national weather records. Muerth et al. (2013) and Foley (2010) both found RCMs obtained by global downsizing simulations can be interpreted in many different ways, and they are often adjusted by reference to local historic climatology. This again leads to increased uncertainty.

When it comes to climate model uncertainty, Maslin and Austin (2012) make the point that improving our understanding of complex climate processes is likely to produce wider, rather than smaller ranges of uncertainty in predictions. This is because climate models are not reality, and by their very nature cannot capture all the factors involved in a natural system. This uncertainty therefore makes it difficult to accurately quantify the impact climate change will have on available freshwater resource. If there is to be inevitable, and enduring uncertainty as to what extent the UK energy system can, or cannot, rely on the availability of freshwater during the summer; and uncertainty over the cost and efficiency penalties that will have to be paid by the use of the less water intensive cooling methods, then any future use of freshwater for cooling should be approached with caution.

2.7 Literature Review Discussion

For policymakers charged with finding a mitigation and adaptation strategy to protect the UK energy system from a future lack of available water resource, finding a solution is complicated. There is a growing demand for the protection of freshwater ecosystems from over abstraction. Future freshwater availability is unknown, and is characterised by the wide range of scenarios obtained using climate projections modelled by the Environment Agency, that it is accepted are subject to a wide range of uncertainty. Maslin and Austin (2012) argued a reduction in the uncertainty that pervades anthropogenic warming and climate change is unlikely. From the policymaker's perspective, it is therefore prudent to consider how thermal power stations would cope if there were no available freshwater.

To obtain the essential, abundant and secure source of water required by nuclear stations since 1956, 36 nuclear reactors at 13 different coastal or estuarine locations have been built (DECC, 2012a). Currently 15 coastal/estuarine reactors generate about 21% of the UK's electricity (World Nuclear Association, 2016). Indeed, in almost 60 years of operation no reactor has suffered from a physical lack of its primary water resource. Placing a higher proportion of the UK's thermal power generation capacity at the coast is already, albeit implicitly, a government considered option; it is the UK's high nuclear pathway (DECC, 2013a, HM Government, 2011a). Minimising freshwater abstraction for energy generation by placing non-nuclear thermal power stations at the coast has been adopted by Japan, Korea and Australia (International Energy Agency, 2012).

While more coastal generation could resolve any scarcity of freshwater, this review has highlighted that high levels of estuarine and seawater abstraction do have associated environmental issues. Environmental regulation including the WFD concerns itself with, and monitors, the temperature of all cooling water discharges, including those at estuarine and seawater locations. Historically, some nuclear power stations in the UK have been required to reduce their operational load to comply with temperature standards (EDF Energy PLC, 2011). Ginige et al. (2012) also considered potential nuclear developments on the Severn estuary, and found impingement and entrainment of fauna could have a significant impact on the estuaries marine ecology.

Coastal location was also the interest of a UK Government Strategic Siting Assessment, which concluded there were only 8 sites potentially suitable for the development of nuclear power stations, all of which were situated at coastal or estuarine locations (DECC, 2011a). If cooling water discharges and ecological damage are to be a consideration of coastal generation, then the height at which environmental regulatory hurdles are set, along with the emphasis given to other environmental considerations, will be factors that decide how many future thermal power stations can be situated at the coast.

This review also highlighted that there is already no inland thermal power generation, with a capacity greater than 150MW (Figure 2.5), that uses the most effective once-through cooling process; instead it is the less water demanding evaporative, hybrid, or air cooling systems, that have been adopted. It is reasonable to assume, if in the future there is less freshwater available (Environment Agency, 2011), and an increase in thermal generation is required, this form of cooling for any inland thermal power generation would remain the norm, with most likely a greater preponderance of air cooling. The consequence of this will have to be acknowledged by the energy pathway models that invariably optimise for minimal cost and low carbon emissions. With efficiency loses in the order of 10-11% suggested, this becomes a significant commercial factor further complicated by the uncertainly over the UK's future summer temperatures. Currently committing to any long-term evaporative, hybrid or air cooling strategy as a means of enabling any additional future inland thermal generation, should be regarded as a questionable decision.

A third solution to the issues surrounding available cooling water, outside of the water-energy nexus, is an increased adoption of certain renewable energy technologies. Renewable energy technologies such as wind and solar photovoltaic generation require no water during the operational phase. The large scale uptake of renewable energy technologies has many barriers, both technical, financial and in some instances political (Kandpal and Broman, 2014, Yaqoot et al., 2016). Overall, it is felt that when trading-off the advantages of, and the barriers to renewable energy, it will be important to fully recognise the benefits these technologies may make in mitigating any lack of available water resource for thermal generation. Never the less thermal generation still plays an important role in the UK's current approach to its future energy strategy (DECC, 2015a, HM Government, 2011a).

There are numerous other approaches that could make a contribution to resolving any future shortage of freshwater the UK may experience, such as a reduction in leakage in the water supply system or the use of desalination plants to produce potable water (Loftus and March, 2016, Venkatesh et al., 2014). Improved agricultural practices is seen as another worthwhile opportunity (Finley and Seiber, 2014), for while it makes only a modest demand on total freshwater availability (1% of UK abstraction), it is a demand that has to be met when there is least freshwater available (dry, hot summers). This is when pressure on the public water supply system, and the environment, is at its highest (DEFRA, 2008). Such possibilities for mitigating future UK shortages of freshwater are important, but are not applications directly relevant to the thermal generation of electricity, and so have not been considered further in this thesis.

2.8 Literature Review Conclusion

This chapter has reviewed the literature on the subject of the UK water-energy nexus. It had the aim of identifying how a range of subject publications approach the way in which a future lack of available water resource may impact a future UK thermal power generation fleet. It highlights the fact that the future water resource available to the UK generation fleet is likely to be greatly reduced. This is not only due to the effect of climate change, and a rising population on freshwater resources, but also due to the need to maintain the environmental well-being of the UK's fresh, sea and estuarine water resources.

A number of options for mitigating the impact of a lack of future water resources on thermal power generation were identified. These ranged from continuing the shift from once-through cooling to the less water intensive alternative cooling methods, to a greater use of the UK's estuarine and seawater resources. The use of other freshwater saving possibilities was also identified, but not developed. The environmental barriers associated with the cooling method and water source options were identified and discussed. The suggestion is the future lack of freshwater will help crystallise the trade-offs that have to be made. In this respect more work is needed to quantify the monetary and environmental trade-offs that have to be made. This is particularly so when one of the key determinants, the exact impact climate change will have, remains so uncertain. The intention is to give further consideration to these trade-offs in the course of this thesis.

Chapter 3 - The Energy Technologies Institute (ETI) and the Energy Systems Modelling Environment (ESME)

3.1 UK Energy System Models

To achieve the aim and objectives of this thesis it was recognised that a tool capable of modelling the UK energy system would be required. There is a wide range of models available which broadly can be broken down into two categories; top-down and bottom-up models. Top-down models consider aggregate behaviour using historic economic trends, whereas bottom-up models tend to focus on the system or sectoral level allowing specific technical opportunities to be considered (UKERC, 2011). As water demand of thermal generation is dictated by specific technical choices, e.g. fuel type and cooling method it was felt that a bottom-up model would be most appropriate for this thesis.

Bottom-up models tend to be simulation or optimisation models. Simulation models simulate the performance of a system given an in-depth specification of its properties whilst optimisation models look to optimise a specific property of a system, often its cost (Heaton, 2014). There are disadvantages to both types of model; simulation models can often be complex and lack transparency around the performance assumptions made. On the other hand optimisation models are normally data intense and tend to assume a least-cost solution which is not always favourable (Hall and Buckley, 2016). As there would be a need to modify any model used to include assumptions regarding the water requirements of thermal generation technologies, it was felt that starting with a model whose operational assumptions were inherently opaque should be avoided. Furthermore with the clear need for energy supply to be affordable (section **2.3**) optimising for least cost was not felt to be inappropriate, therefore only optimisation models were considered.

There are a number of UK energy system optimisation models but UKTM (the successor to UK MARKAL) and the Energy Technologies Institute's (ETI) Energy System Modelling

Environment (ESME) are arguably the most important UK-focussed models. Both are whole system, least cost optimised, UK energy system models and both have had their strategic importance to the UK confirmed by their use by both the Department of Energy and Climate Change (DECC) and the CCC (CCC, 2013, CCC, 2015, Heaton, 2014, HM Government, 2011a). However, UKTM unlike ESME does not have a Monte Carlo option for dealing with uncertainty that besides providing an averaged result, also shows the range of possibilities that constitute this result. Furthermore ESME has a regional functionality that UKTM lacks. When considering the analysis to be undertaken in this thesis being able to disaggregate national water demand and availability, both of which vary regionally, to region levels is a fundamental advantage. The sensitivity analysis the Monte Carlo approach allows to be carried out is also extremely useful in identifying the range of uncertainty that policymakers have to consider when taking decisions. Therefore it is the ESME model which will be used in this thesis to consider, identify, and quantify, any impacts reduced availability of cooling water could have on UK thermal generation by 2050.

It is, however, acknowledged that the different modelling biases of other UK energy models, may have contributions to make when deciding the 'best' make-up of a future UK electricity system that will face water availability constraints. Section 8.2.6 will therefore consider this and recommend further research along these lines. Ultimately, however, irrespective of whatever UK energy system modelling tool is used, the validity of the output obtained will always depend on the legitimacy of the modelling data being used.

3.2 The ETI

The ETI is a collaboration between industry and the public sector. It was formed in 2007 to accelerate the development of new energy technologies for the UK's transition to a low carbon economy (Heaton, 2014). The ETI's members are: BP, Caterpillar, EDF Energy, Rolls-Royce, Shell, Engineering and Physical Sciences Research Council, Department for Business, Energy and Industrial Strategy, and Innovate UK (ETI, 2016a). The ETI's main role is to provide targeted investment to build knowledge, and develop and demonstrate projects across the energy sector to promote affordable, secure, and sustainable technologies. The aim is to help the UK achieve its long term emissions reduction targets as well as delivering nearer term benefits (ETI, 2015a). The ETI has a number of diverse technology programmes spread across the energy sector to help it undertake this role, but one essential tool which underpins much of its decision making, is the ETI's Energy Systems Modelling Environment (ESME) energy system modelling tool.

3.3 Energy Systems Modelling Environment (ESME)

The ETI's internationally peer reviewed Energy System Modelling Environment (ESME) models the UK energy system to 2050. It was initially developed in 2007, as a tool to help the ETI identify and design investments in technology development, and innovation programmes that meet the ETI's objective of accelerating the development of new energy technologies for the UK's transition to a low carbon economy (Heaton, 2014). ESME has since become a powerful energy system model for the UK, and is employed by the ETI, its members, and academic institutions.

Due to its use in supporting the ETI's investment decisions, ESME is a design tool rather than a forecasting tool. ESME adopts a least-cost optimisation approach, and works with annualised costs averaged over the whole lifetime of a technology. Annualised capital costs are calculated assuming a discount rate of 8%, which represents the commercial cost of borrowing money. A commercial rate is assumed as ESME assumes that investments made in energy infrastructure will be made by the private sector A second discount rate of 3.5% is used for all net present value calculations in ESME, including the calculation of future total energy system costs (ETI, 2016). This second discount rate is used for calculations which compare costs that occur in different years and reflects the "time preference rate", that is the general preference of society to receive benefits sooner rather than later. A value of 3.5% is chosen as this is recommended by the UK Treasury to convert all future costs and benefits to present values (Office for National Statistics, 2013). ESME employs this cost optimisation approach to modelling the UK energy system while still adhering to a number of specified targets and constraints. These targets and constraints include emission reduction targets, resource availability, technology build rate, and meeting the projected energy demand. ESME is only constrained by CO_2 emissions rather than all greenhouse gas emissions (GHG), although the expected pathway of all GHG emissions are taken into account when determining the levels of CO_2 allowed (Heaton, 2014).

When modelling the future UK energy system, ESME adopts a whole system scope which includes all the major flows of energy: electricity generation, fuel production, energy use for heating, industrial energy use and the transportation of people and freight. A range of technology options are available encompassing all the energy flows above, including power stations, vehicle and heater type, each with a number of input parameters such as available resources, fuel prices and technology costs (ETI, 2016c). This energy system is described in five, or 10 year time steps, from 2015 to show the progression to 2050. ESME also provides a historic view of the energy system in 2010 which acts as a baseline for the model. A generalised flow chart of the ESME model is provided in Figure 3.1.

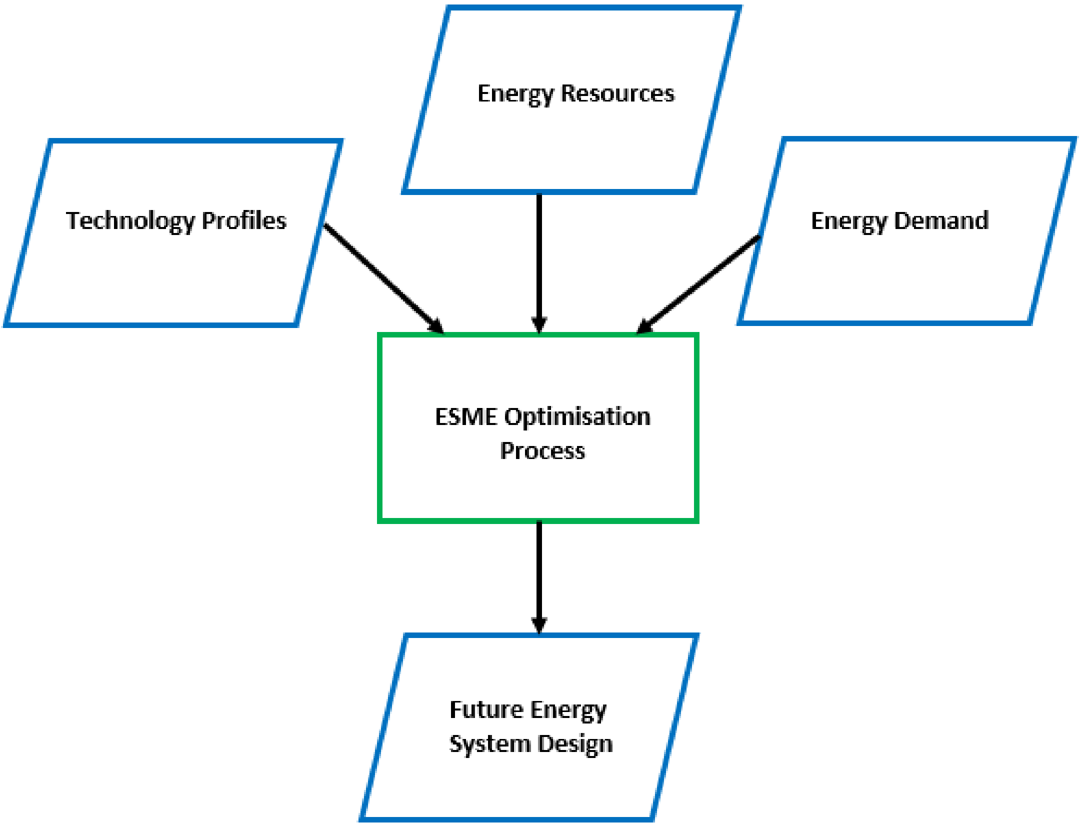

Figure 3.1 ESME Flow Chart

ESME can also define demands and resources at the UK regional level. This broadly shows the physical location of future energy infrastructure options (HM Government, 2011a), and allows variations in resource supply and demand across the UK to be better accounted for (UCL, 2014). The regions modelled by ESME are shown by Figure 3.2.

Figure 3.2 ESME Regions

3.3.1 Monte Carlo Approach

Any model has inherent uncertainties, particularly one as complex and broad as ESME. While it is impossible to entirely remove these uncertainties, ESME uses the Monte Carlo technique to manage and quantify them. Rather than producing a single model run, ESME produces hundreds, or even thousands of runs, known as simulations, where the input parameters (e.g.

energy resources, fuel prices and technology costs) vary for each simulation according to the probabilistic distribution of the considered parameter, as developed by the ETI in consultation with industry experts. As well as showing the individual model results, a final result is produced by finding the mean average of the results across an ensemble of simulations.

This approach allows a range of possible future energy systems to be considered. From this technologies can be identified that initially appear to have little chance of contributing to the future energy system, as well as those which appear highly likely to contribute, and those which may contribute depending on how the input parameters change in the future.

3.3.2 ESME Pathways

For this thesis, Version 4.0 of ESME, released in August 2015 will be used (ETI, 2016b). When ESME is perturbed using a standard probabilistic distribution for each input parameter using the Monte Carlo approach, the final results are (in this analysis) referred to as the ESME.MC pathway; ESME's standard outcome. It represents ESME's best design of the future make-up of the UK energy system, it focuses on achieving the UK's 2050 CO_2 emission reduction and energy generation targets at the least-cost. While ESME models the whole UK energy system, this thesis will focus on its modelling of the future UK electricity generation system to 2050 under the ESME.MC pathway, alongside, for the first time, any water constraints that are identified. Figure 3.3 shows the electricity generation profile of the ESME.MC pathway and is taken directly from the ESME model (ETI, 2015). It can be seen that to meet future demand it primarily relies on the use of nuclear and CCGT + CCS power stations, supported by renewables

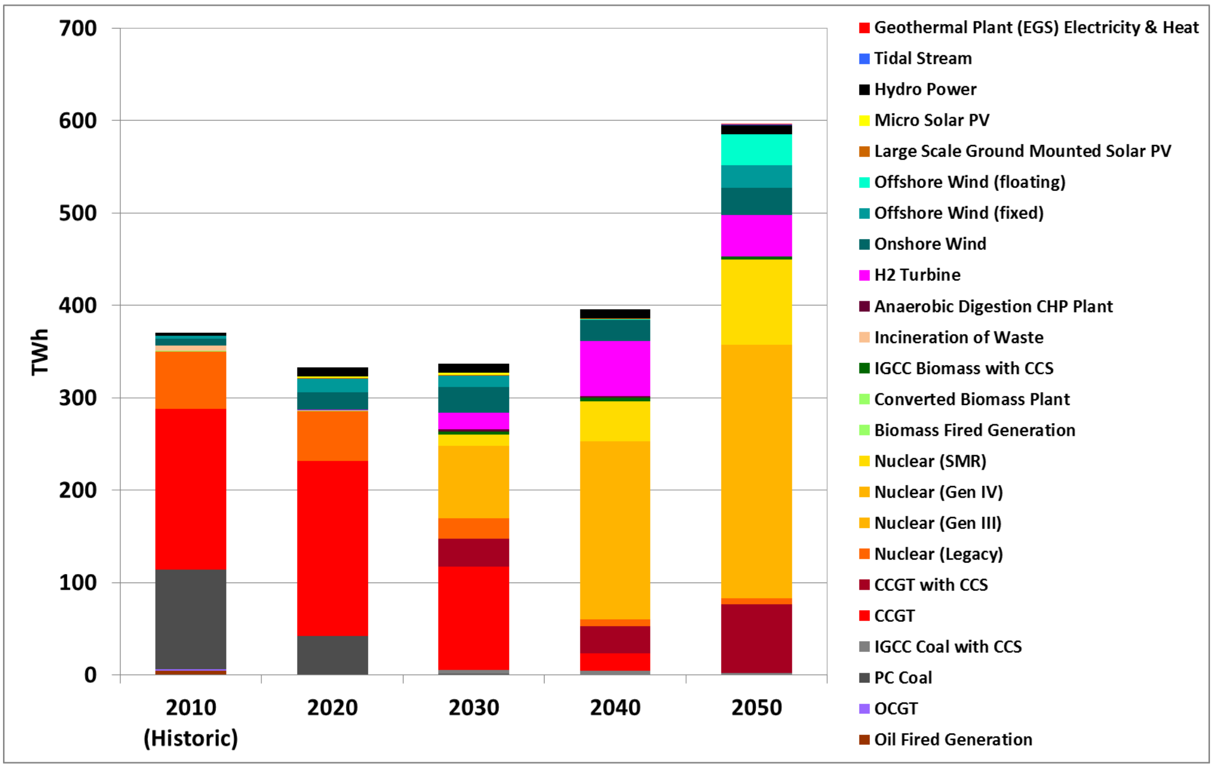

Figure 3.3 Monte Carlo Pathway Electricity Generation per Annum (ETI, 2015)

This research will predominantly consider the ESME.MC pathway as it represents ESME's best design of the future UK energy system and its Monte Carlo approach allows some consideration to be given to the uncertainty a single sets of results hides (section **5.1**). However ESME can also be perturbed in a deterministic way where just a single run is undertaken allowing 'what-if?' scenarios to be tested. The ETI has two such published scenarios, they are, the 'Clockwork' pathway, and the 'Patchwork' pathway. For completeness these will also receive initial consideration. The Clockwork pathway assumes that well-coordinated, long term national investment allows new energy infrastructure to be installed like clockwork. It favours additional nuclear generation to meet baseload, and unabated gas generation continues to play a role for meeting peak demand into the 2030's until it is gradually replaced by hydrogen fired turbines. CCGT + CCS plants and renewable energy, particularly onshore and offshore wind, are also expected to contribute to the generation mix (Milne and Heaton, 2015), Figure 3.4. This pathway resembles the ESME.MC pathway, nevertheless it is a recognised and distinct ESME pathway.

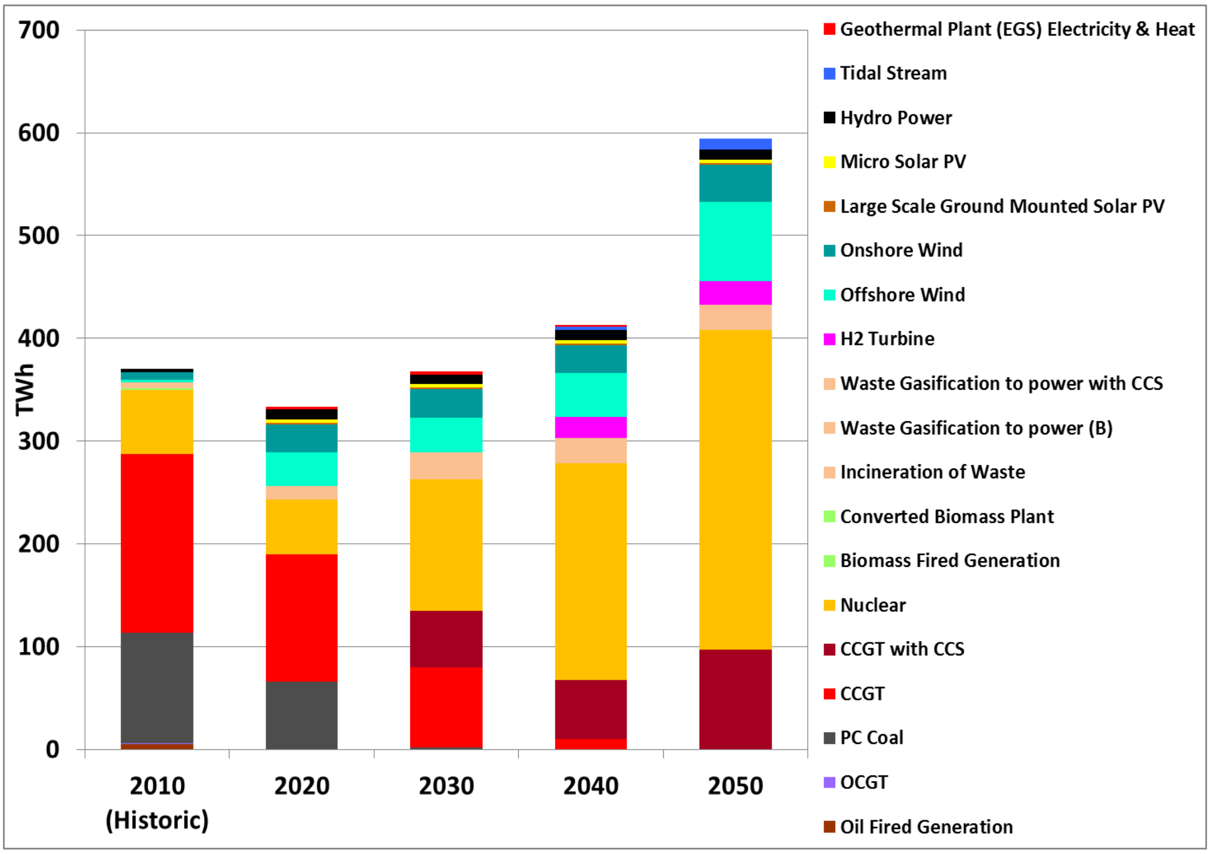

Figure 3.4 Clockwork Pathway Electricity Generation per Annum (Milne and Heaton, 2015)

The Patchwork pathway sees central government taking less of a leading role and envisages a patchwork of distinct energy strategies developing at the regional level. Decarbonisation is achieved by the adoption of ad hoc renewable energy technologies, particularly offshore wind, although onshore wind, solar PV, hydro power and marine renewable energy all have a role to play by 2050. Nuclear and CCGT + CCS generation are still present in the energy mix but on smaller scales than in the Clockwork pathway (Milne and Heaton, 2015), Figure 3.5.

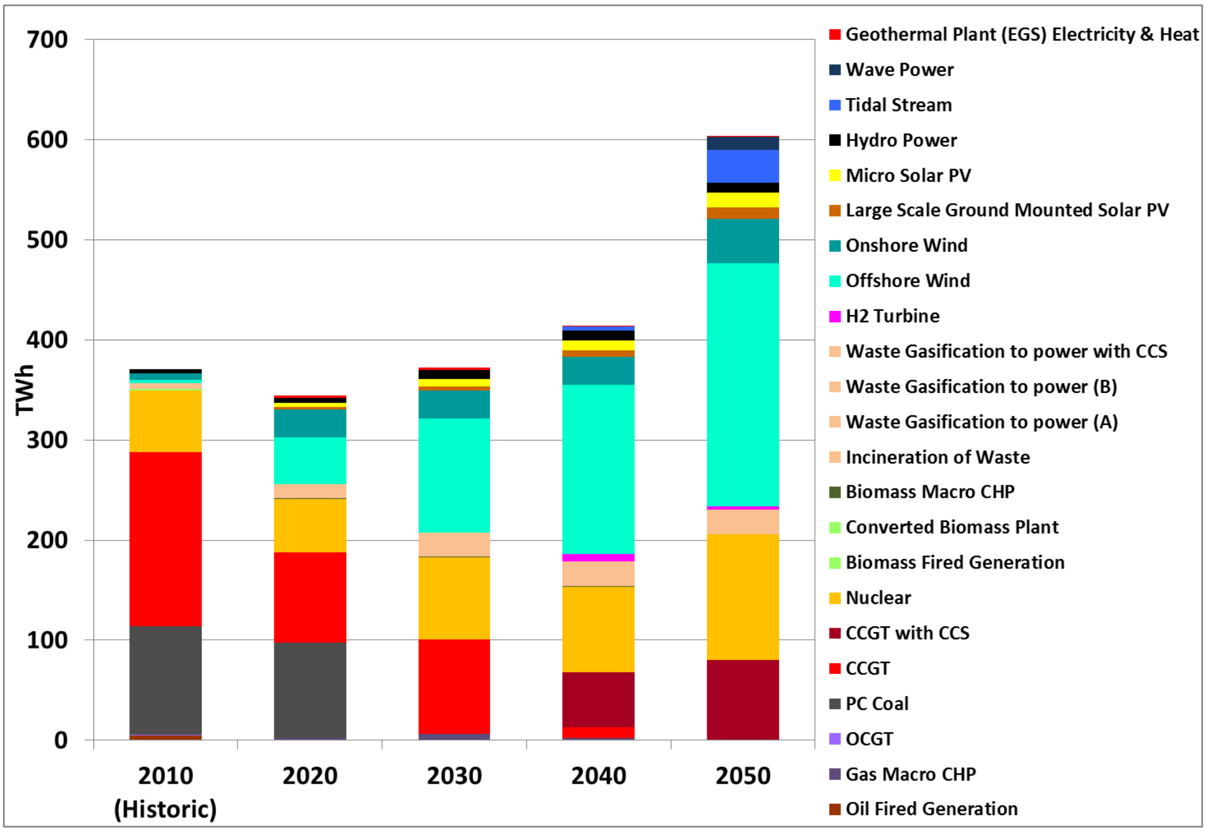

Figure 3.5 Patchwork Pathway Electricity Generation per Annum (Milne and Heaton, 2015)

Whilst the ESME.MC and Clockwork pathways are relatively similar the Patchwork pathway is noticeably different. The ESME.MC and Clockwork pathways both essentially envisage a centralised future UK energy system with nuclear and CCGT+CCS generation meeting the majority of demand by 2050. Whereas the Patchwork pathway foresees a more decentralised future UK energy system where renewable energy generation meets the majority of demand. From this perspective analysing the Patchwork pathway provides an interesting contrast to the other two ESME pathways. On the other hand it must be recognised that the Patchwork pathway is considered by the ESME model to be a more expensive option, largely due to the need to balance an energy system with a large amount of intermittent generation, and is therefore only selected when ESME is run in a more deterministic scenario-driven mode.

Chapter 4 – Future UK National Water Demand Modelling

4.1 Introduction

To achieve the ultimate aim of this study it will become necessary to constrain the water available to the ESME.MC pathway at the regional level. However, first, consideration will be given to the unconstrained future national water demand at 2030 and 2050 of the UK electricity sector, relative to 2010, using the three ESME pathways. This will identify the relative magnitude of increase in cooling water demand from 2010, through 2030, to 2050 by these UK electricity sector pathways, while also establishing a water demand profile by proposed generation technology.

This is not the first study to consider the water demand of future electricity generation systems. Feeley et al. (2008) and Macknick et al. (2012) analysed the future freshwater demand of electricity generation in the USA and found that despite a greater demand for freshwater, abstraction may have to decrease due to lack of resource, while actual consumption is likely to go up. This would be particularly true if there is a large adoption of Coal + CCS and nuclear generation with evaporative cooling. In Spain, Carrillo and Frei (2009) modelled future water demand of total energy generation (electricity, transport, domestic, agriculture and industrial sectors) and found that by 2030 water abstraction for electricity generation may rise, with consumption likely to increase. The International Energy Agency projected global future water demand of energy generation to 2035. Their forecast is that both water abstraction and consumption will increase, and in the case of consumption it could be a significant increase in the region of 85% (International Energy Agency, 2012).

For the UK, a number of studies have modelled the water demand of the future electricity sector to 2050 (Byers et al., 2014, Schoonbaert, 2012, Tran et al., 2014). Schoonbaert (2012) focussed on England and Wales, whereas Tran et al. (2014) and Byers et al. (2014) modelled the whole of the UK, including Northern Ireland. All three studies came to broadly similar conclusions; future UK water demand is uncertain but any significant uptake of thermal generation technologies is likely to increase water demand, with CCS technologies particularly likely to increase freshwater abstraction and consumption, whilst nuclear technologies are likely to result in a significant increase in sea and estuarine water abstraction demand.

Byers et al. (2014) produced a model framework to quantify the future operational water requirements of electricity generation networks in terms of their water abstraction and consumption; per generation technology, per cooling method, per time-frame. It also distinguished between the source of cooling water with the options being freshwater, estuarine and sea water. Byers et al. (2014) used this method to model the water demands of six possible future electricity pathways, (section **4.2)**.

Tran et al. (2014) used the same approach as Byers et al. (2014) but considered regional water demand, albeit only for freshwater, whereas Byers et al. (2014) only considered the national water demand. However, neither Byers et al. (2014), Tran et al. (2014) nor Schoonbaert (2012), considered the water demand of the ESME model's electricity pathways. All three of these studies, with no UK data available, used water abstraction and consumption figures largely based on a study carried out by the USA's NREL (Table 2.1) (Macknick et al., 2011). This project has been given access to specific UK water abstraction and consumption figures compiled by the JEP, and provided through the EA, (section **4.3.2.3**). For the remainder of this thesis these figures are referred to as the UK abstraction and consumption figures.

The primary intention of this chapter, is to apply the UK abstraction and consumption figures to the Byers et al. (2014) framework to quantify the unconstrained national water demands at

2030 and 2050 of the three ESME pathways, relative to 2010. This will be the first step in reconciling the suggested future water demand of UK thermal power generation, with suggested future water availability.

4.2 Carbon Plan Pathways

The analysis carried out by Byers et al. (2014) using the NREL abstraction and consumption figures (Table 2.1) modelled the water demands of six possible future electricity pathways by 2050, four taken directly from the UK Government's Carbon Plan (HM Government, 2011a), (High Nuclear, High Renewables, High CCS, UK MARKAL 3.26), and two modified versions of the Carbon Plan pathways (CCS+ and UKM+), defined in Table 4.1. Here the opportunity will be taken to update the water demands of the six pathways analysed by Byers et al. (2014) with the UK abstraction and consumption figures.

Table 4.1 Carbon Plan Pathways

High Nuclear	A low uptake of energy efficiency measures and CCS not being commercially viable lead to a large adoption of nuclear generation.
High Renewables	Increased uptake of renewable energy due to reduction in cost as well as increased use of energy efficiency measures, result in a generation mix of wind, solar, marine and back-up gas generation.
High CCS	CCS proves to be commercially viable resulting in a large uptake of CCS generation, largely driven by natural gas imports and exploitation of shale gas. Also assumes negative emissions through biomass CCS.
UK MARKAL 3.26	Least-cost optimised model results in a large uptake of energy efficiency measures and subsequent reduction in demand as well as a balanced generation mix including renewable energy, CCS and nuclear.
CCS+	Similar to High CCS with nuclear now replaced with further coal CCS, biomass and renewable energy.
UKM+	Similar to UK MARKAL 3.26 but with an increased energy demand met by a balanced generation mix of renewable energy, CCS and nuclear.

4.3 Methodology

4.3.1 General Methodology

An in-depth description of the Byers et al. (2014) model framework, and the assumptions it makes are described in that paper and will not be repeated here. However, an overview of the framework's principles is necessary, as is an explanation of the additional assumptions and modifications that are made in this chapter (section **4.3.2**). The model framework designates a generation pathway by its year (t) and an annual generation output given in TWh, of each individual pathway technology (g), represented by a matrix **G** with dimensions (n_t x n_g). The framework then requires the distribution of cooling water source (w) (freshwater, estuarine, seawater) and the distribution of cooling method used (m) (once-through, evaporative, hybrid, air cooling), for each generation technology, for each time period to be identified. This defines a **4-D** array **S** with dimensions (n_w x n_m x n_g x n_t). Known water abstraction and consumption figures per generation technology, per cooling method, can then be introduced and are represented by matrices **A** and **C** respectively, with dimensions (n_g x n_m), and given in ML/TWh. For this paper matrices **A** and **C** are populated by the UK abstraction and consumption figures.

Element-wise multiplication of the arrays **GSA** and **GSC** gives total water abstraction and consumption results for each water source and cooling method combination, per generation technology for the year in question: ($Atotal_{w,m,g,t} = G_{t,g} A_{g,m} S_{w,m,g,t}$, $Ctotal_{w,m,g,t} = G_{t,g} C_{g,m} S_{w,m,g,t}$); summation of the relevant combinations will allow total water abstraction and consumption of any given pathway generation technology, for any time period, to be calculated ($Atotal_{w,g,t} = \sum_{m=1}^{n_m} Atotal_{w,m,g,t}$, $Atotal_{g,t} = \sum_{w=1}^{n_w} Atotal_{w,g,t}$, $Ctotal_{w,g,t} = \sum_{m=1}^{n_m} Ctotal_{w,m,g,t}$, $Ctotal_{g,t} = \sum_{w=1}^{n_w} Ctotal_{w,g,t}$). Similarly, summation of all combinations would produce the total pathway water abstraction and consumption for any given time period ($Atotal_t = \sum_{g=1}^{n_g} Atotal_{g,t}$, $Ctotal_t = \sum_{g=1}^{n_g} Ctotal_{g,t}$).

4.3.2 Applying the Model Framework

4.3.2.1 Generation Technologies

The pathways considered each give their projected generation by technology for 2030 and 2050. For 2010, generation by technology was taken from the Digest of UK Energy Statistics

(DUKES) (MacLeay et al., 2011). The thermal generation technologies considered by this analysis are those present in 2010, or those the ESME model and Carbon Plan pathways chosen, include in their thermal generation portfolios, namely, nuclear (includes all large scale nuclear power plant variants), nuclear small modular reactors (SMR), gas (CCGT), coal (includes incineration of waste and biomass, as well as a number of coal power plant variants, but all assumed to be sub-critical), CCGT + CCS, coal + CCS, waste gasification and waste gasification CCS. Oil represents only 1.3% of all thermal generation in 2010 (MacLeay et al., 2011); the ESME and Carbon Plan pathways predict by 2050 oil will have been phased out, the ESME.MC pathway also identifies geothermal technology as providing 0.25% of the UK's energy by 2050. On the basis of their small take-up both of these technologies have been omitted from this study. ESME identifies three gas generating technologies; CCGT, CHP plants fired by gas produced by anaerobic digestion, and hydrogen fired turbines. After email consultation with the ETI gas team (Gammer, 2015), it was agreed that the water use of these technologies would be similar; they are therefore treated as one technology, namely CCGT.

The pathways modelled choose Coal + CCS generation that uses either a super-critical system with post-combustion carbon capture, or an integrated gasification combined cycle (IGCC) system with pre-combustion carbon capture, or in some instances, a combination of both. For the purpose of this chapter they are principally treated as one technology referred to as coal + CCS, except for the abstraction and consumption figures where there is a noticeable difference. Here, the coal CCS abstraction and consumption figures used for each pathway are weighted according to the ratio of each coal CCS technology adopted by that pathway. Nuclear SMR power stations are a new technology, being smaller than traditional nuclear power stations it is assumed for modelling purposes that there will be fewer siting constraints (Middleton, 2015); for this reason they are classed as a separate technology.

4.3.2.2 Distribution Array

To produce the cooling method and water source array **S** for 2010, which defines how the cooling methods and water sources are distributed for a given generation technology for 2010, DUKES was first used to find the installed capacity of nuclear, CCGT, and coal/biomass power stations in the UK for 2010 > 15MW (MacLeay et al., 2011). Neither DUKES, nor any official source, provides cooling water method and water source information by power station for UK thermal generation. This was a problem Schoonbaert (2012), Byers et al. (2014) and Tran et al. (2014) also had to resolve. This was achieved for those studies by consulting satellite imagery, online records, site visits, and contacting generation companies. Their results were revisited and, with only minor changes, produced Table 4.2. **Appendix B** shows the raw power station data obtained. In the absence of specific power station generation information, the cooling method and water source distributions were attributed relatively by using power station installed capacity. Whilst this may introduce a level of error into the results produced, a validation of the methodology being used will be carried out to confirm the scale of any error is acceptable.

Table 4.2 also shows the cooling method and water source distribution for technologies not yet operational in the UK but predicted to be by 2050; they are waste gasification, nuclear SMR, CCGT + CCS, coal + CCS and waste Gasification + CCS. The assumptions made for these distributions are shown as a footnote to Table 4.2.

Table 4.2 Distribution of Cooling Method and Water Source

			Cooling Method			
Generation Technology	**2010 Installed Capacity (MW)**	**Water Source**	**Once-through (%)**	**Evaporative (%)**	**Hybrid (%)**	**Air (%)[a]**
Nuclear	10,125	Freshwater	0	0	0	0
		Estuarine Water	15.84	0	0	0
		Seawater	84.16	0	0	0
		Air	0	0	0	0
Nuclear SMR[b]	N/A	Freshwater	0	17	0	0
		Estuarine Water	0	41	0	0
		Seawater	42	0	0	0
		Air	0	0	0	0
CCGT (including H2 Turbines and Anaerobic Digestion)	32,169	Freshwater	0.48	11.91	5.19	0
		Estuarine Water	20.56	13.28	19.62	0
		Seawater	5.58	0	0	0
		Air	0	0	0	23.38
Waste Gasification[c]	N/A	Freshwater	0	68.07	0	0
		Estuarine Water	0	0	0	0
		Seawater	0	0	0	0
		Air	0	0	0	31.93
Coal (including Biomass)	28,971	Freshwater	0	34.50	0	0
		Estuarine Water	18.32	34.00	1.38	0
		Seawater	11.25	0	0	0
		Air	0	0	0	0.55
CCGT CCS[d]	N/A	Freshwater	0.48	11.91	5.19	0
		Estuarine Water	20.56	13.28	19.62	0
		Seawater	5.58	0	0	0
		Air	0	0	0	23.38
Coal CCS[e]	N/A	Freshwater	0	34.50	0.00	0
		Estuarine Water	18.32	34.00	1.38	0
		Seawater	11.25	0	0	0
		Air	0	0	0	0.55
Waste Gasification CCS[e]	N/A	Freshwater	0	34.50	0	0
		Estuarine Water	18.32	34.00	1.38	0
		Seawater	11.25	0	0	0
		Air	0	0	0	0.55

[a]Air cooling requires negligible volumes of water; this was assumed to be freshwater due to air cooling's use when water is scarce.
[b]Nuclear SMR distribution based on discussion with the ETI and informed by Middleton (2015).
[c]Waste gasification distribution calculated from all operational and consented sites as well as those in the planning process.
[d]CCGT CCS distribution the same as CCGT.
[e]Waste gasification CCS distribution the same as coal CCS which in turn is the same as coal.

It was decided when it came to determining the water demands of the ESME and Carbon Plan pathways for 2030 and 2050, that it would again be the 2010 distributions shown by Table 4.2 that would be used, effectively assuming a 'business-as-usual' situation. Regarding the 2030 and 2050 cooling method and water source distribution, both Byers et al. (2014) and Chapter 2 of this thesis found that one of two possible options, or a combination of both from 2010 would be likely to apply. Either, greater use of the less water intensive cooling methods that incur higher costs and CO_2 emissions, or a greater adoption of estuarine and seawater sources with the caveat that environmental and ecological regulation could constrain this solution.

With such uncertainty it was reasoned that any UK national comparison of water demands of the study's selected pathways at 2030 and 2050, relative to 2010, can only identify a generalised overview of the magnitude of potential national water demand issues. In reality, the availability of freshwater and seawater resource, as well as the demand for power, as already noted, varies significantly regionally (Mitchell and McDonald, 2015), and it is therefore at this level of detail that the real issues will lie. On this basis applying the 2010 national cooling distribution array relatively to 2030 and 2050, serves this chapter's comparison methodology purpose.

4.3.2.3 Abstraction and Consumption Figures

This chapter uses the abstraction and consumption figures for UK power stations, compiled by the JEP and made available by the EA. The JEP is made up of eight of the UK's leading electricity generators (RWE npower, Eon, Drax Power, Scottish and Southern Energy, EDF Energy, International Power, Eggborough Power, Scottish Power) (Gasparino, 2012). The JEP has a research and development objective to understand and expand the knowledge of the environmental science and impacts, related to the generation of fossil fuel electricity. A specific interest is to better understand the water use of UK power stations.

Macknick et al. (2011) discusses at length the wide ranging variability found in the published data, when attempting to consolidate the literature of water use by various electricity generation technologies in the United States. That study's research objective was to obtain figures that could "*be incorporated into energy-economic models to estimate generation-related water use under different projected electricity portfolio scenarios*". It was found that despite significant differences in the methodologies used to compile the data based on generation technology, it invariably resulted in wide-ranging high and low values for water abstraction and consumption. However, compiling the data by the cooling method employed invariably produced significantly different, and more definitive, water demand magnitudes. The conclusion was that water use needs of thermal power stations should be categorised by cooling method rather than generation technology.

With regard to the UK abstraction and consumption figures compiled by the JEP, these were based upon the Resource Efficiency Physical Index Data for 2010, and the data previously prepared for the DG Environment Blueprint. The Combustion Industry Sector Group, and the UK Water Working Group were also consulted to help improve the quality of the data. The water use figures provided were in the form of lower and upper limits, for abstraction and consumption for various generation technology and cooling method combinations. The CCS water rates provided were based on Parsons Brinckerhoff (2012). In the case of coal and coal + CCS technologies, the load factor at which they are run can make a significant difference to their water demands, subsequently values for High Load Factors (HLF, capacity factor $\geq$ 46%) and Low Load Factors (LLF, capacity factor $<$ 46%) were given. The data provided is acknowledged to be wide ranging with some omissions, but with no other UK specific data available, it was felt to be adequate, subject to the validation process not identifying large errors (section **4.4**). The variability present in the UK's abstraction and consumption data supports the view of Macknick et al. (2011) that variability in power station water abstraction and consumption data would inevitably be found, irrespective of the country the data relates to.

The UK abstraction and consumption figures shown (Tables 4.3a and 4.3b) are those required in 2010 or by either the ESME model, or Carbon Plan pathways. Some are for yet-to-be-developed technologies. The abstraction and consumption figures shown are the mid-points of the ranges of the data provided. With the wide-ranges present this was an arbitrary, although logical decision, but will also be judged by the validation process. The values in standard font are the abstraction and consumption figures which are the calculated mid-points of the JEP data. The values in bold are the calculated figures for those technology and cooling method combinations not in the JEP data provided. These unknowns were derived by finding the Ratio (Table 4.3a; Table 4.3b) between the provided cooling methods, and then applying these ratios to the known figure(s) of a generation technology and cooling method(s) combination to find the unknown(s). When viewed in the context of the Macknick et al. (2011) conclusion, that for the United States water use of thermal power stations could be categorised by cooling method, the evidence of the available UK abstraction and consumption figures finds this is also so for the UK.

Table 4.3a Abstraction Figures (x10^{3}ML/TWh)

Cooling Method	Nuclear	Nuclear SMR	CCGT	Coal (HLF)	Coal (LLF)	Waste Gasification	CCGT + CCS	Coal IGCC + CCS (HLF)	Coal CCS post-combustion (HLF)	Waste Gasification + CCS	Ratio
OT	172.85	**172.85**	79.85	160.90	217.75	**138.61**	141.35	**191.83**	259.05	**191.83**	N/A
Evap	7.00	**7.00**	**2.33**	3.85	5.25	**4.05**	**4.13**	5.60	**7.56**	**5.60**	0.03
Hybrid	**4.35**	**4.35**	1.45	**2.39**	**3.27**	**2.52**	**2.57**	**3.48**	**4.70**	**3.48**	0.62
Air	**0.45**	**0.45**	0.15	**0.25**	**0.34**	**0.26**	**0.27**	**0.36**	**0.49**	**0.36**	0.10

OT: Once-through Cooling, Evap: Evaporative Cooling

Table 4.3b Consumption Figures (x10^{3}ML/TWh)

Cooling Method	Nuclear	Nuclear SMR	CCGT	Coal (HLF)	Coal (LLF)	Waste Gasification	CCGT + CCS	Coal IGCC + CCS (HLF)	Coal CCS post-combustion (HLF)	Waste Gasification + CCS	Ratio
OT	0.15	**0.15**	0.10	0.15	0.30	**0.16**	0.10	**0.18**	0.15	**0.18**	N/A
Evap	3.00	**3.00**	**0.96**	1.20	1.55	**1.55**	**0.96**	1.75	**1.44**	**1.75**	9.58
Hybrid	**1.88**	**1.88**	0.60	**0.75**	**0.97**	**0.97**	**0.60**	**1.10**	**0.90**	**1.10**	0.63
Air	**0.47**	**0.47**	0.15	**0.19**	**0.24**	**0.24**	**0.15**	**0.27**	**0.23**	**0.27**	0.25

OT: Once-through Cooling, Evap: Evaporative Cooling

Waste gasification is a relatively new technology (Lightowlers, 2012, Persson and Münster, 2016), and there are no 'live' abstraction and consumption figures available, however the JEP and EA do provide a value for Integrated Gasification Combined Cycle Coal + CCS, for evaporative cooling. Discussion with the ETI gas team confirmed in the absence of an actual value, this would be a reasonable value to use for evaporative waste gasification with CCS (Gammer, 2015). This now allowed values to be calculated for the other cooling methods in the same way as for any other omitted data. For waste gasification without CCS with once-through cooling, abstraction and consumption figures were obtained by finding the ratio between non-CCS technologies and their CCS equivalents; (CCGT + Coal(HLF)) ÷ (CCGT+CCS + Coal IGCC+CCS (HLF)[2]), and multiplying the now calculated Waste gasification + CCS with once-through cooling abstraction and consumption figures by this result (0.72 and 0.89 respectively). This now enabled the remaining waste gasification abstraction and consumption figures to be found.

Nuclear SMR is also a relatively new technology and also has no available abstraction and consumption data; however it is still a nuclear fission based process. So for the purpose of this paper it was assumed that the abstraction and consumption figures would be the same as those for traditional nuclear generation.

4.4 Validation

To confirm the methodology employed, and the assumptions made, do not produce unacceptable inaccuracies when modelling pathway water demands, a validation of the results obtained was carried out. The EA receives data annually showing the water abstracted from

[2] Waste gasification is only selected by ESME, all coal CCS selected by ESME is IGCC pre-combustion; therefore for consistency IGCC pre-combustion was used for this calculation rather than coal post-combustion.

freshwater and estuarine (not seawater) sources for power stations in England and Wales; figures for Scotland and Northern Ireland were not available which this thesis will recognise. This data for the years 2006-2010 was obtained with the main interest being 2010, the year for which the UK abstraction and consumption figures obtained apply. This is another data source that does not associate power stations with cooling technologies, but this was a problem resolved when preparing Table 4.2. Not all the EA data sent could be used as in some instances it was incomplete. The original data provided by the EA was for thirty England and Wales power stations (35,820MW). The twenty-three power stations used had a total generating capacity of 29,215MW, Table 4.4. This is a 42% sample of the English and Welsh total installed thermal generating capacity of 70,040MW in 2010 (MacLeay et al., 2011).

Table 4.4 Power Stations Used in Validation Process

Power Station	Installed Capacity (MW)	Fuel Type	Water Source	Cooling Method
Little Barford	714	CCGT	FW	Evaporative
Glanford Brigg	260	CCGT	FW	Evaporative
Medway	688	CCGT	EW	Evaporative
Roosecote	229	CCGT	EW	Open loop
South Humber Bank	1,285	CCGT	EW	Open loop
Killingholme A	665	CCGT	EW	Hybrid
Killingholme B	900	CCGT	EW	Hybrid
Great Yarmouth	420	CCGT	EW	Open loop
Barking	1,000	CCGT	EW	Open loop
Keadby	710	CCGT	EW	Open loop
Ironbridge	940	Coal	FW	Evaporative
Eggborough	1,960	Coal	FW	Evaporative
Ratcliffe	1,960	Coal	FW	Evaporative
Rugeley	1,006	Coal	FW	Evaporative
Drax	3,870	Coal	EW	Evaporative
Kingsnorth	1,940	Coal	EW	Open loop
Cottam	2,008	Coal	EW	Evaporative
West Burton	2,012	Coal	EW	Evaporative
Ferrybridge C	1,960	Coal/Biomass	FW	Evaporative
Fiddler’s Ferry	1,961	Coal/Biomass	EW	Evaporative
Tilbury B	1,063	Biomass	EW	Open loop
Hartlepool	1,180	Nuclear	EW	Open loop
Oldbury	434	Nuclear	EW	Open loop

FW: Freshwater
EW: Estuarine water

When matching generation technologies with water demand the question arises whether for 2010 the correct choice for coal was coal low load factor, or coal high load factor. This has a profound effect on water demand. In an exchange of correspondence with the EA, their opinion was that with the large number of operational mode influences that a generating plant has to respond to on a daily basis, with the information available there could be no definitive answer (Brierley, 2014). In line with this opinion it was decided to show the validation with both the coal LLF and coal HLF values. The results obtained for the years 2006 – 2010 are shown, Table 4.5.

Table 4.5 Validation Results; Percentage Error between Modelled Results and EA Validation Data

Validation using Coal HLF				Validation using Coal LLF			
	Freshwater (% error)	**Estuarine Water (% error)**	**Freshwater +Estuarine Water (% error)**		**Freshwater (% error)**	**Estuarine Water (% error)**	**Freshwater +Estuarine Water (% error)**
2010	-3.01	3.39	3.23	**2010**	28.80	17.08	17.37
2009	3.52	14.90	14.62	**2009**	37.26	29.06	29.26
2008	23.57	-6.16	-5.58	**2008**	64.10	7.40	8.51
2007	2.12	-0.16	-0.10	**2007**	36.15	15.11	15.66
2006	12.98	19.65	19.46	**2006**	51.37	38.67	39.03
Avg.	7.83	6.32	6.33	**Avg.**	43.53	21.47	21.97

Table 4.5 shows the closest correlation for the years tested is for coal HLF, with the error for 2010, for which the UK abstraction and consumption figures relate, being just 3.23%. When considering the HLF result over the whole validation period it is felt that whilst the error varies significantly, with the large changes in operational mode known to occur this could be expected. This result validated the methodology’s use of the UK abstraction and consumption figures to attribute ‘relative’ 2010 national water demands to 2030 and 2050. For the 2030 and 2050 pathways both the ESME and Carbon Plan pathways provide their load factor for coal and coal + CCS technologies; for the ESME pathways it is LLF, for the Carbon Plan pathways it is HLF (DECC, 2013a). Their respective factors have been used.

4.5 Results

4.5.1 ESME and Carbon Plan Pathways 2030 and 2050 National Water Demand

With thermal generation being the favoured means of electricity generation, the current preferred technologies are nuclear and fossil fuels + CCS, supported by renewables. For the UK the water demands this incurs at 2030 and 2050 for the electricity generation pathways studied in this chapter, relative to 2010, are shown by Figures 4.1-4.8. Regarding these figures the methodology's total water demand refers to all water sources, but it is predominantly sea and estuarine water due to their association with the large take-up of once-through cooling, especially in the case of nuclear.

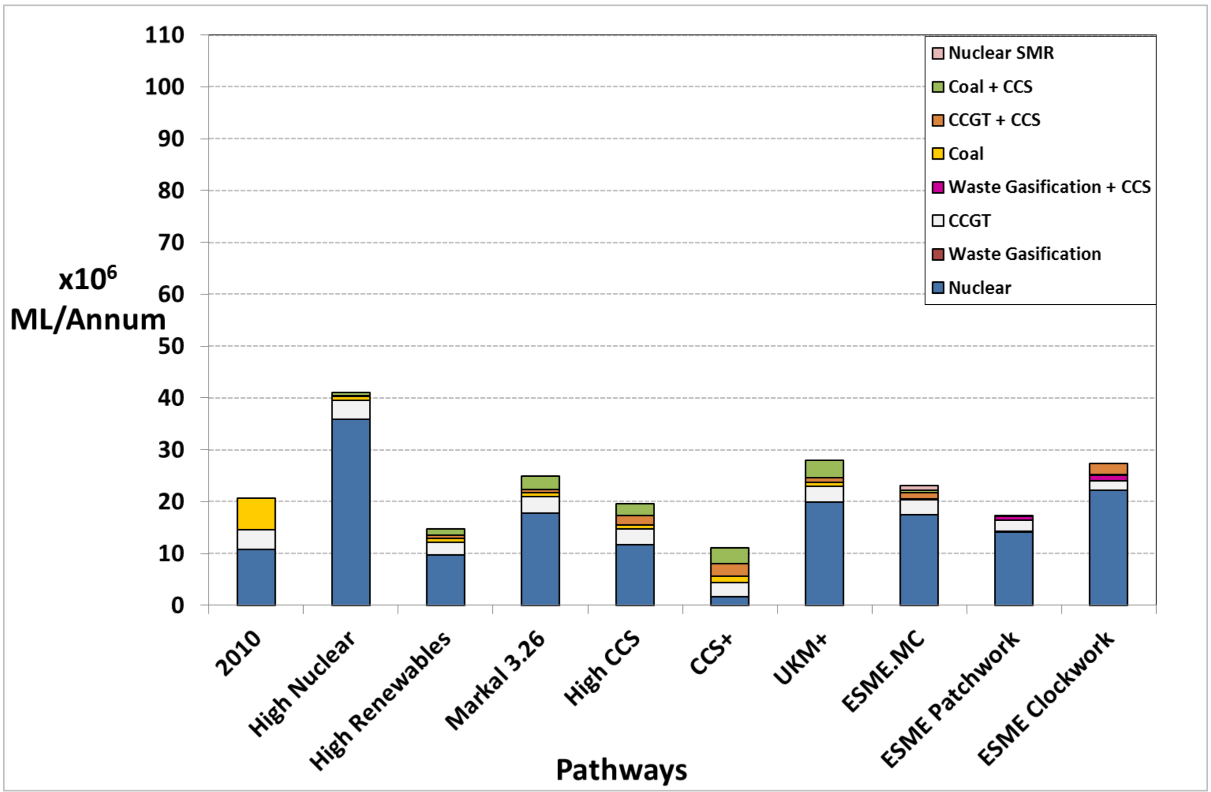

Figure 4.1 2030 Total Water Abstraction

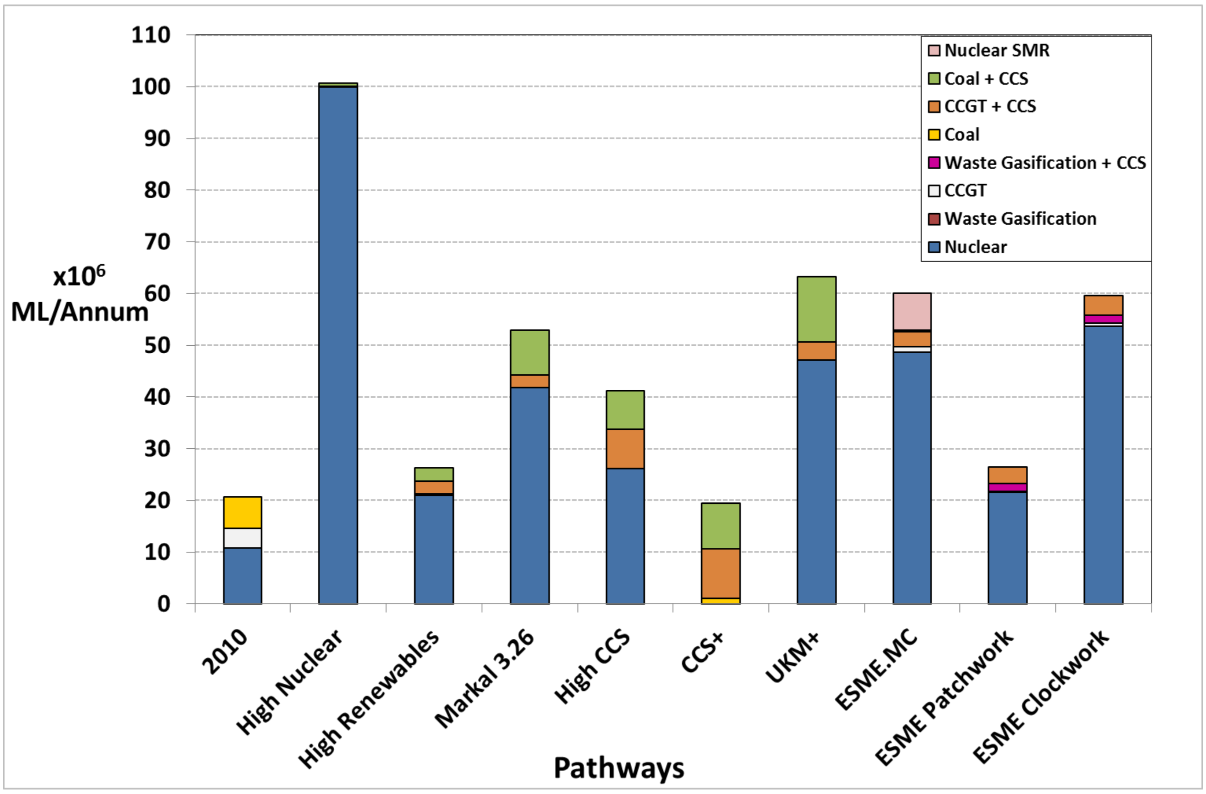

Figure 4.2 2050 Total Water Abstraction

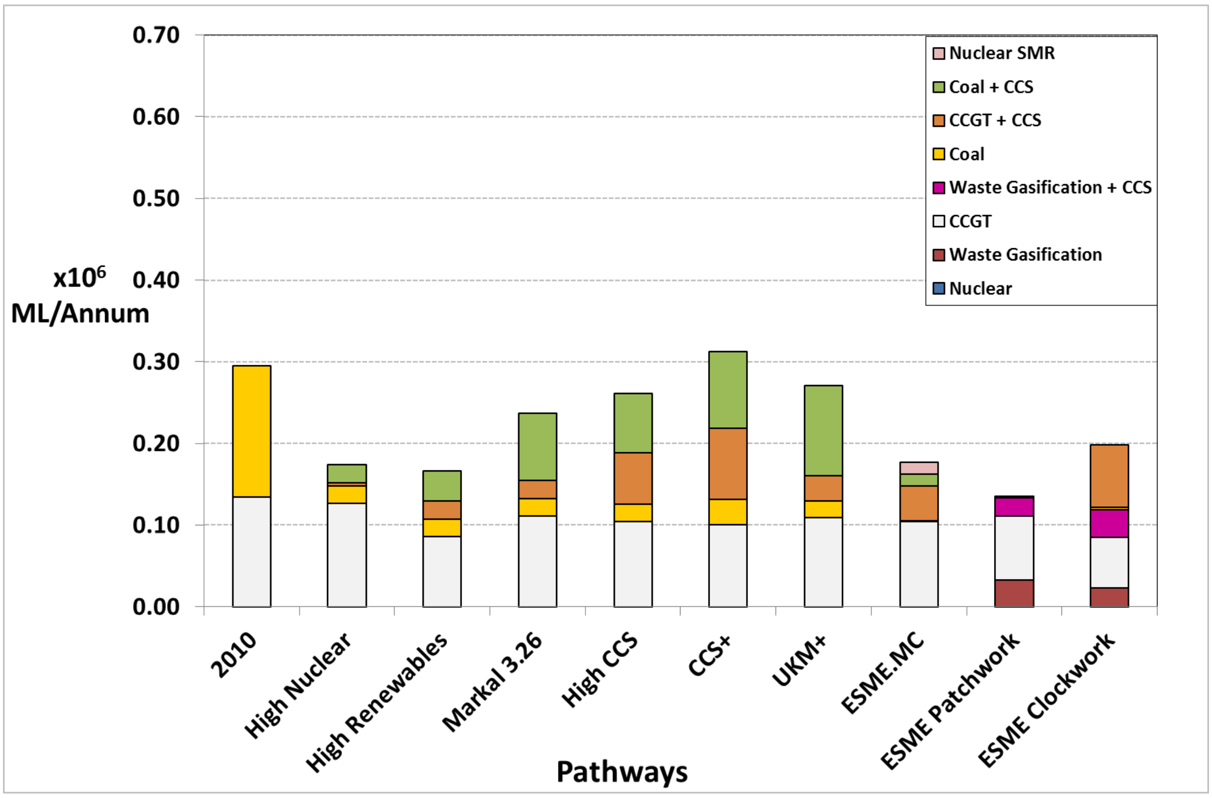

Figure 4.3 2030 Freshwater Abstraction

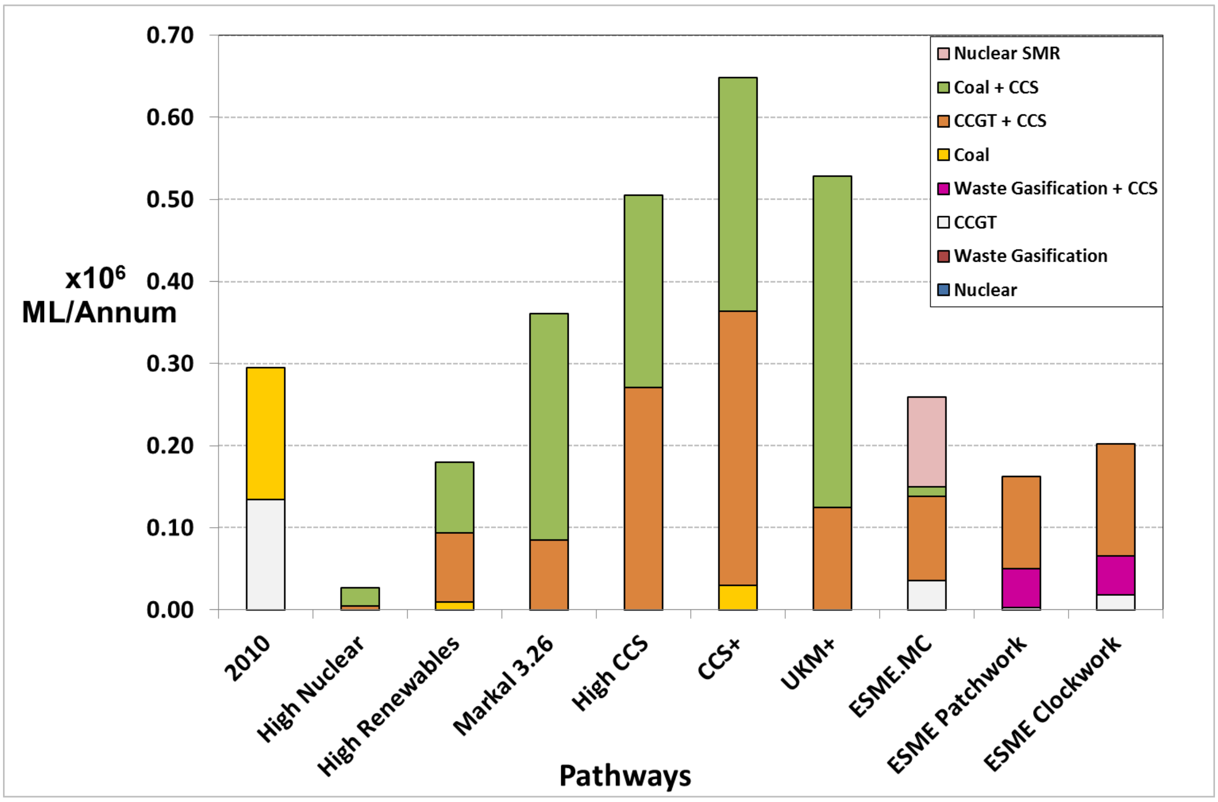

Figure 4.4 2050 Freshwater Abstraction

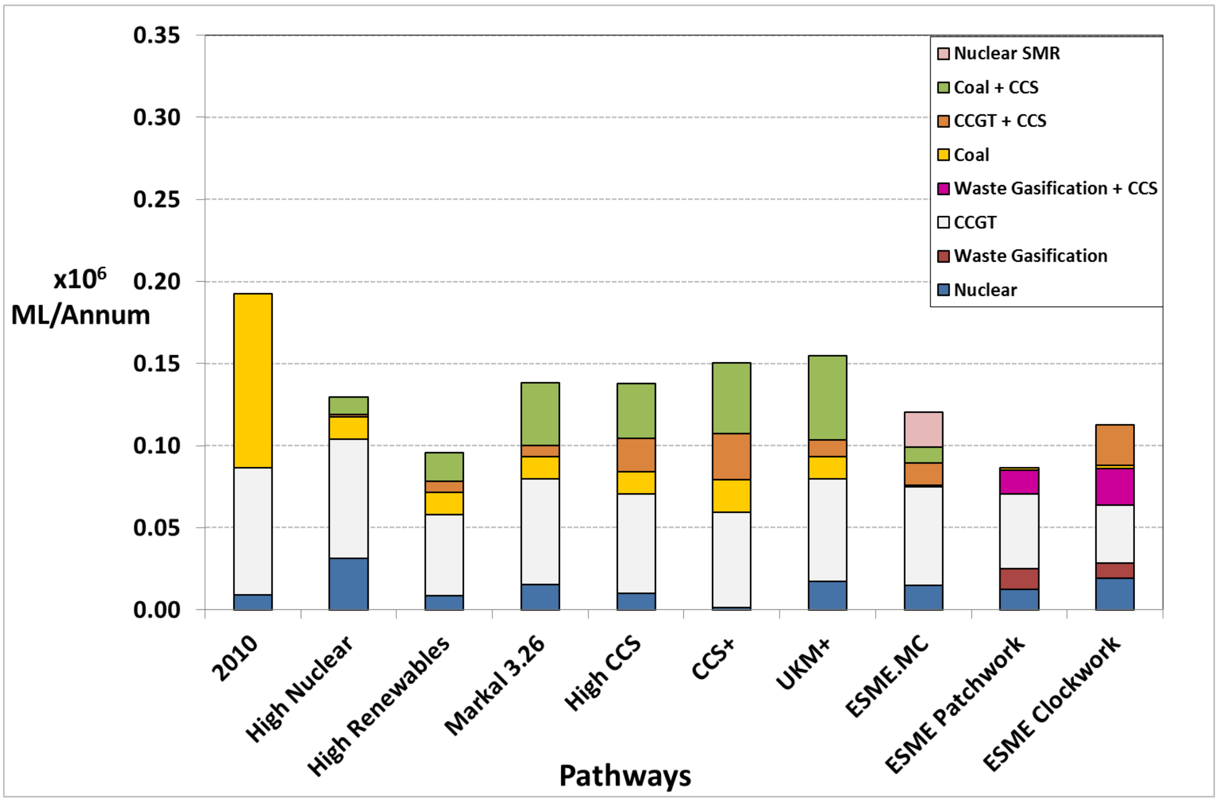

Figure 4.5 2030 Total Water Consumption

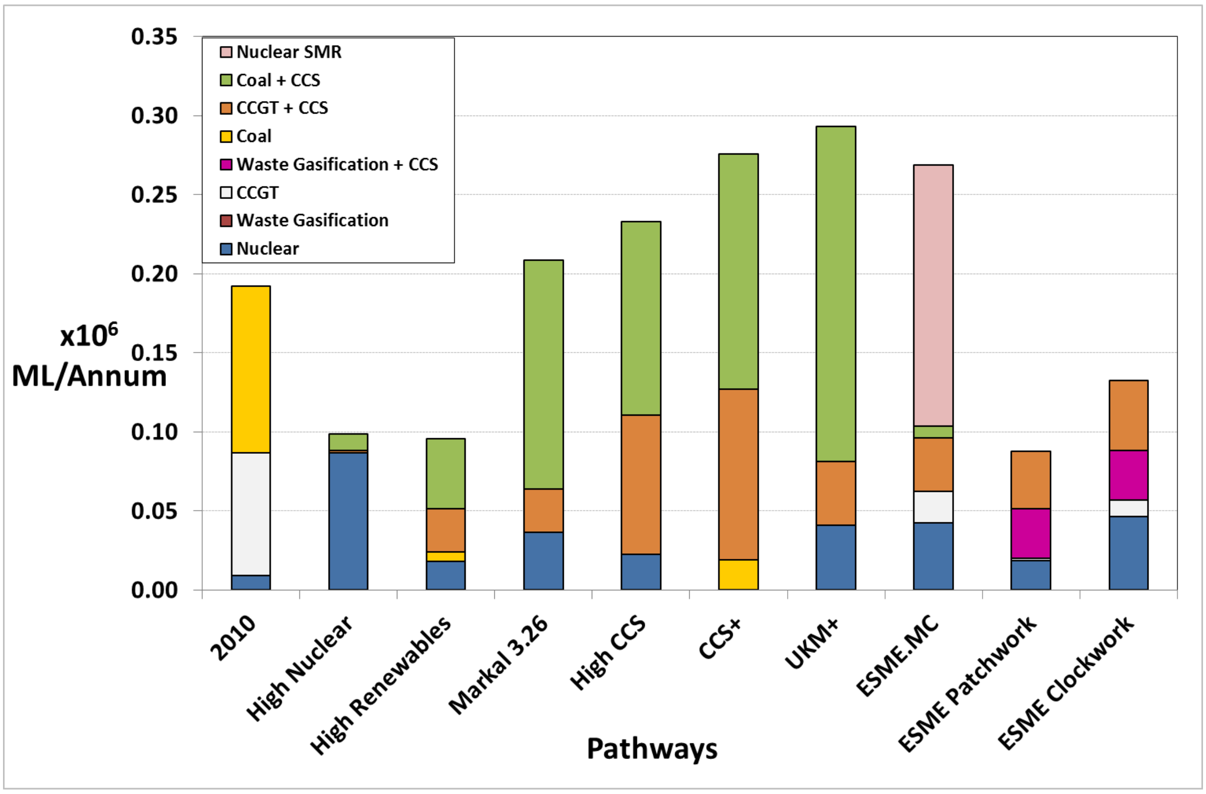

Figure 4.6 2050 Total Water Consumption

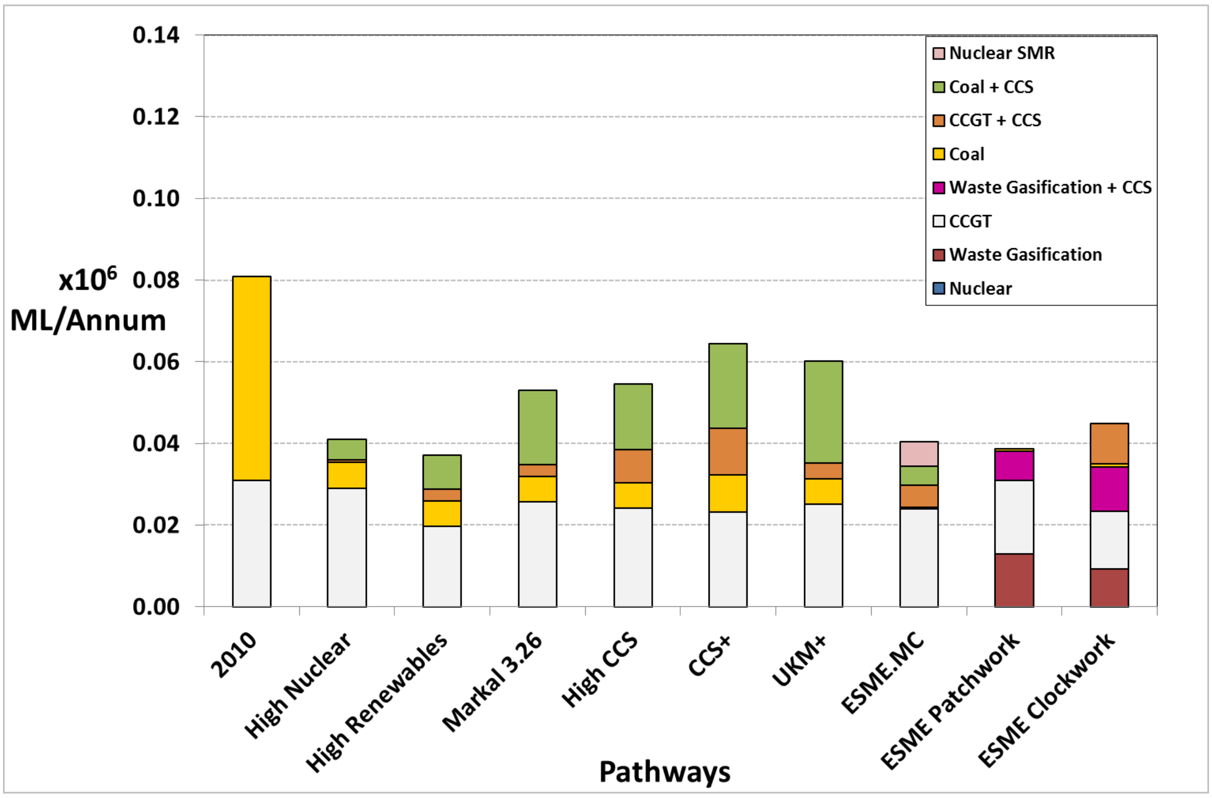

Figure 4.7 2030 Freshwater Consumption

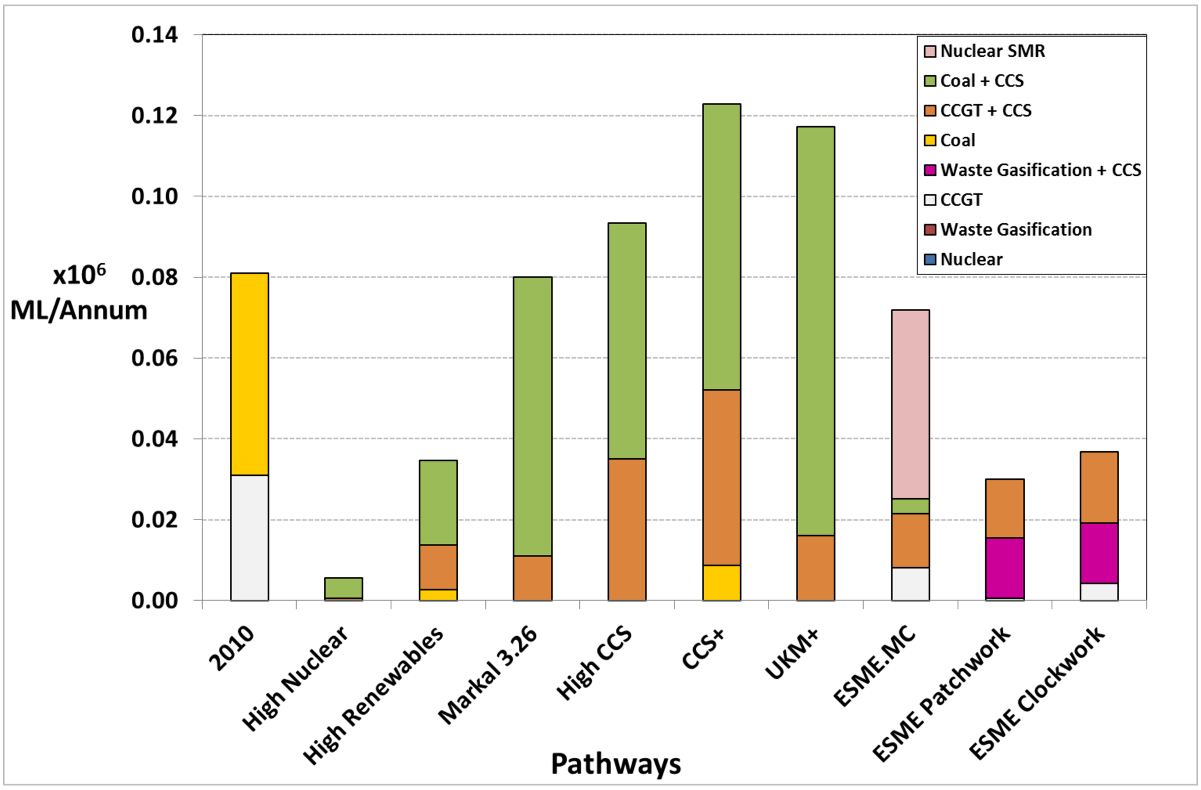

Figure 4.8 2050 Freshwater Consumption

Interpreting Figures 4.1-4.8, knowing at 2050 there will be no physical shortage of estuarine and seawater, but there will be a serious shortage of UK freshwater, the figures clearly identify potential issues. It is noticeable that the ESME.MC and Clockwork pathways are total water intensive while the Carbon Plan thermal generation pathways are on balance more freshwater intensive. As would be expected the Carbon Plan's High Renewables and the ESME Patchwork pathways have lower water demands. This underlines the success high renewable pathways have in avoiding a need for large volumes of water in 2030 and 2050. In this context it should, however, be noted that even high renewable pathways have water demands that will have to be met.

4.5.2 Sensitivity Analysis

The ESME.MC pathway with its Monte Carlo approach to uncertainty (section **3.2.1**) rather than producing a single result produces a range of possibilities known as simulations, normally 100. The inputs of each simulation are from probabilistic ranges reflecting a parameter's future range of uncertainty over the form a future UK energy system could take (Heaton, 2014). These individual simulations are then averaged to provide the mean average ESME.MC electricity generation results of Figure 3.3, from which its corresponding water demands in Figures 4.1-4.8 were calculated using this chapter's methodology. The spread of the simulations is indicative of the level of uncertainty that an averaged result, and indeed the results produced using the other non Monte Carlo pathways, hides. In order to know this level of uncertainty, a sensitivity analysis was carried out. This was achieved by applying this chapter's methodology to each of the ESME.MC pathway's simulations, and showing the water demand results for 2030 and 2050 in a box and whiskers form, Figures 4.9-4.12. In this case the extremes shown are the highest and lowest water demands found.

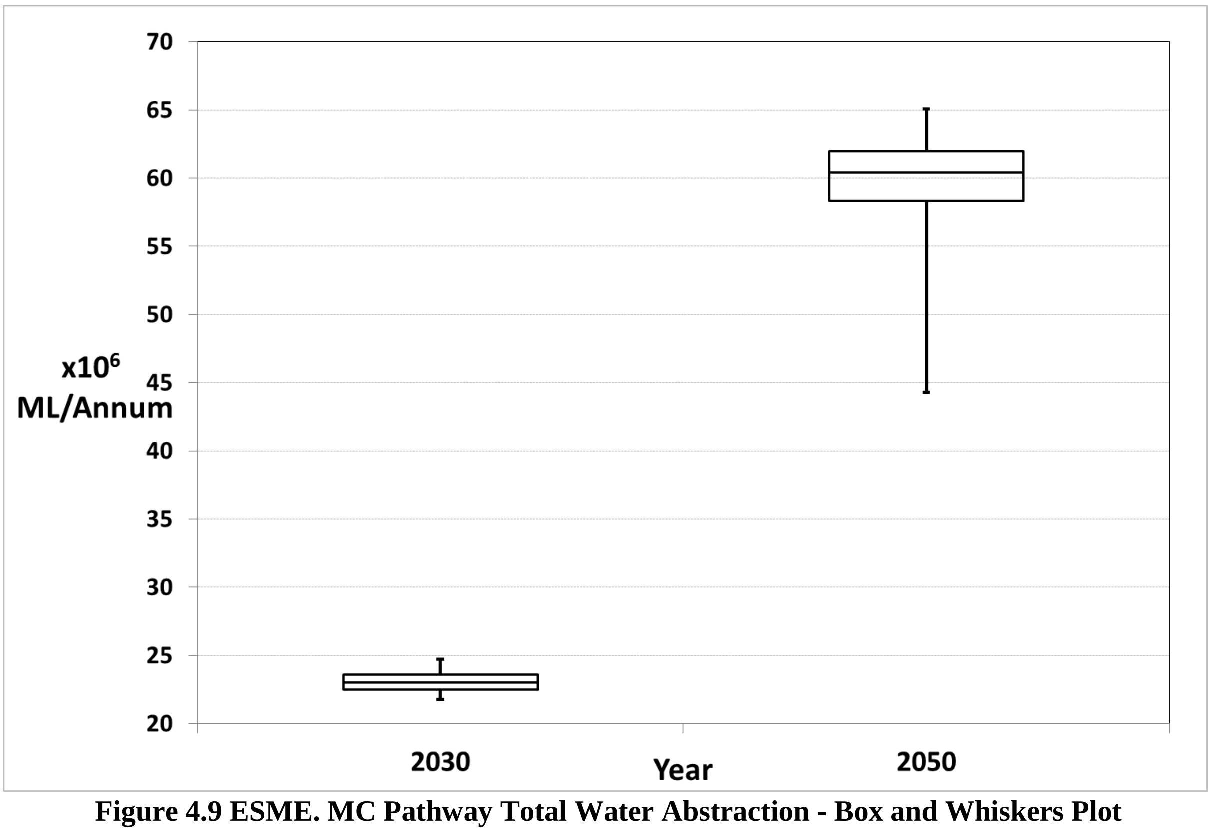

Figure 4.9 ESME. MC Pathway Total Water Abstraction - Box and Whiskers Plot

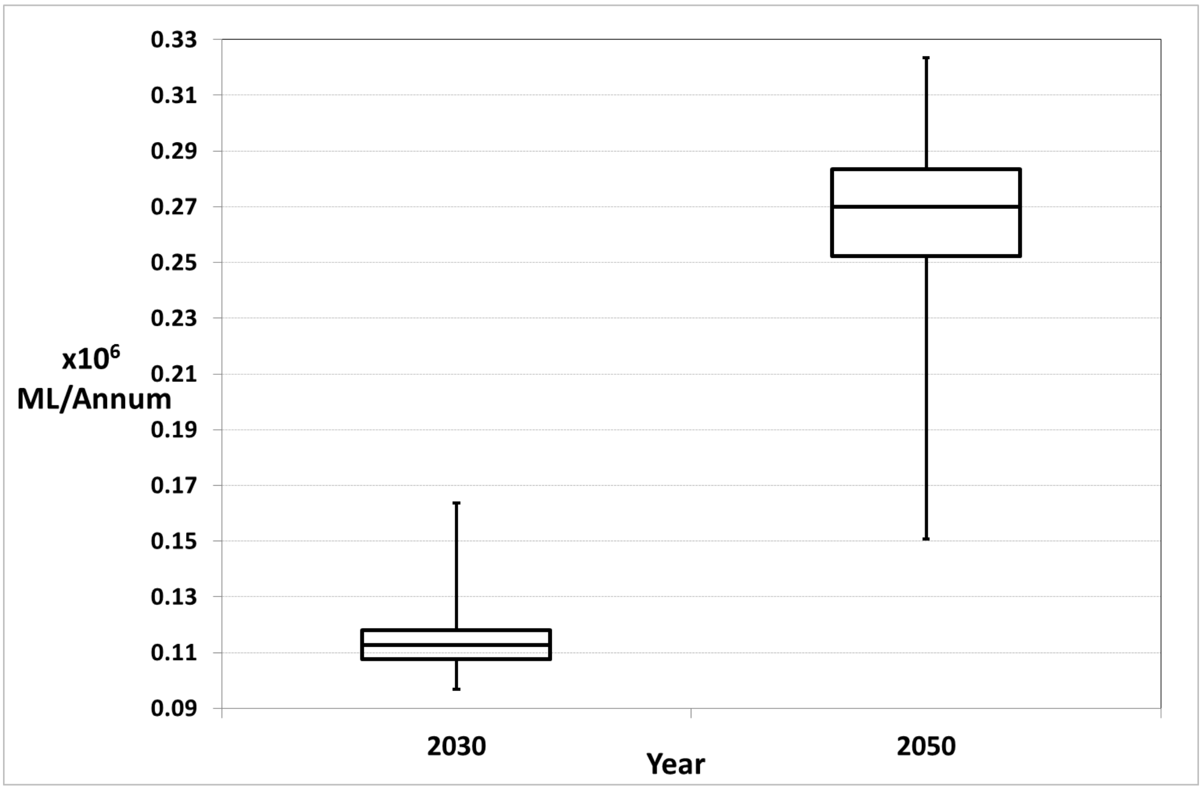

Figure 4.10 ESME.MC Pathway Total Water Consumption - Box and Whiskers Plot

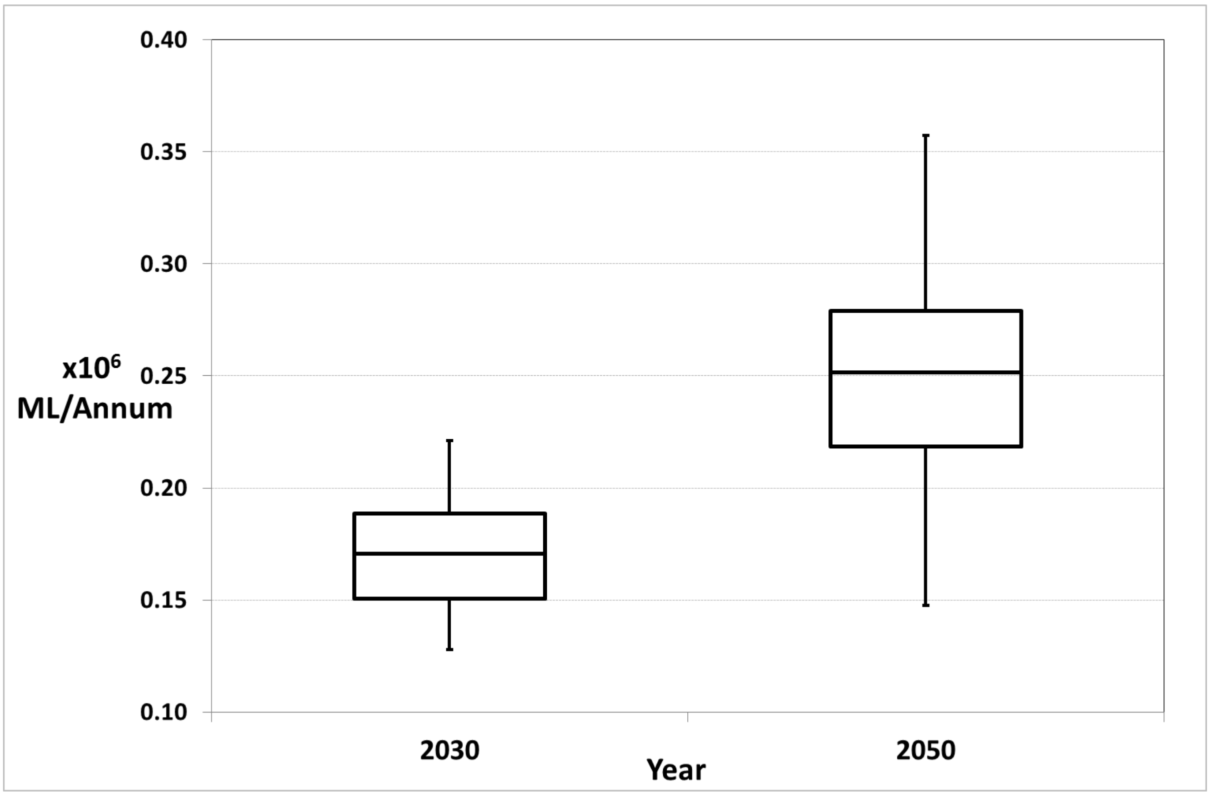

Figure 4.11 ESME.MC Pathway Freshwater Abstraction - Box and Whiskers Plot

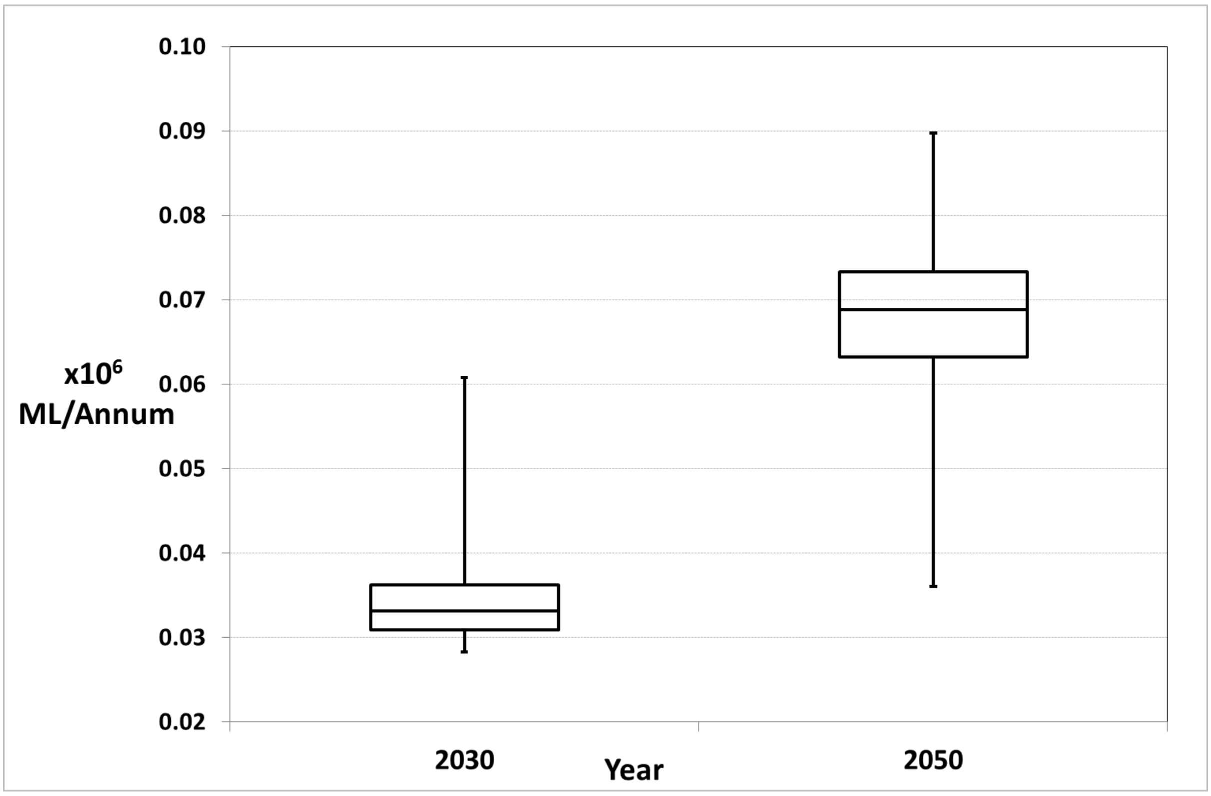

Figure 4.12 ESME.MC Pathway Freshwater Consumption - Box and Whiskers Plot

Figures 4.9-4.12 show that the simulations are spread more widely for 2050 than 2030, which is not unexpected given the greater uncertainty at the longer timeframe. With the exception of freshwater abstraction, the distribution of all the other 2050 datasets is negatively skewed, whilst all 2030 datasets and 2050 freshwater abstraction are positively skewed. For the ESME.MC pathway, the mean result is more likely to be an overestimate of those datasets with a positive skew, and an underestimate of those with a negative skew.

Table 4.6 shows how the first and third quartile of each dataset varies from the median. With the exception of the third quartiles of the 2050 and 2030 freshwater abstraction datasets (<14%), all are within 10% of the median, with the majority <7%. Table 4.6 then shows that the difference between the ESME.MC modelled mean average generation water demands of Figures 4.1-4.8, and the median values of the data shown in Figures 4.9-4.12, are in even closer agreement. This confirms that using the ESME.MC pathway's Monte Carlo approach of producing an average generation result from numerous simulations, does provide a water demand that is representative of the individual simulations.

Table 4.7 compares the range of water demand results produced for the ESME.MC pathway's 100 simulations, with the water demands of the other pathways calculated in section **4.5.1**. It can be seen that with the exception of 2030 freshwater consumption, the first and third quartiles of the ESME.MC dataset always fits within the range of water demands presented by the other pathways. In the majority of instances the maximum and minimum of the ESME.MC data also fits within this water demand range, and as these are the extremes of the dataset, some variation away from this range is to be expected, and does not represent the ESME.MC dataset as a whole. Table 4.6 showed that the bulk of the ESME.MC simulations have water demands that are relatively tightly spread. Table 4.7 now shows that even towards the extremes of this dataset, the vast majority of water demands which could relate to the ESME.MC pathway, are within the range of demands covered by the other pathways considered in this chapter.

Table 4.6 Percentage Differences from the Median

	2030 Total Water Abstraction	2050 Total Water Abstraction	2030 Total Water Consumption	2050 Total Water Consumption	2030 Freshwater Abstraction	2050 Freshwater Abstraction	2030 Freshwater Consumption	2050 Freshwater Consumption
% Difference Between Median and Q1	-2.48	-3.44	-4.40	-6.55	-11.82	-13.16	-6.58	-8.26
% Difference Between Median and Q3	2.34	2.58	4.64	5.02	10.45	10.97	9.58	6.39
% Difference Between Median and ESME MC Average Value	-0.10	-0.73	2.00	-2.01	-0.47	0.52	4.90	-1.75

Table 4.7 Water Demands of ESME.MC Simulations Compared to Other Pathways (x10^6 ML/Annum)

	2030				2050			
	Total Water Abstraction	**Total Water Consumption**	**Freshwater Abstraction**	**Freshwater Consumption**	**Total Water Abstraction**	**Total Water Consumption**	**Freshwater Abstraction**	**Freshwater Consumption**
ESME.MC Minimum	21.77	0.10	0.13	0.03	44.27	0.15	0.15	0.04
ESME.MC Q1	22.47	0.11	0.15	0.03	58.34	0.25	0.22	0.06
ESME.MC Median	23.04	0.11	0.17	0.03	60.42	0.27	0.25	0.07
ESME.MC Q3	23.58	0.12	0.19	0.04	61.98	0.28	0.28	0.07
EMSE.MC Maximum	24.75	0.16	0.22	0.06	65.05	0.32	0.36	0.09
2010	20.58	0.19	0.29	0.08	20.58	0.19	0.29	0.08
High Nuclear	41.07	0.13	0.17	0.04	100.70	0.10	0.03	0.01
High Renewables	14.72	0.10	0.17	0.04	26.34	0.10	0.18	0.03
Markal 3.26	24.98	0.14	0.24	0.05	52.88	0.21	0.36	0.08
High CCS	19.54	0.14	0.26	0.05	41.14	0.23	0.50	0.09
CCS+	11.03	0.15	0.31	0.06	19.49	0.28	0.65	0.12
UKM+	28.03	0.15	0.27	0.06	63.23	0.29	0.53	0.12
ESME Patchwork	17.22	0.09	0.14	0.04	26.38	0.09	0.16	0.03
ESME Clockwork	27.30	0.11	0.20	0.04	59.59	0.13	0.20	0.04

4.5.3 Comparison of USA and UK Abstraction and Consumption Figures

The previous studies (Byers et al., 2014, Schoonbaert, 2012, Tran et al., 2014), that looked at how the scarcity of cooling water may compromise future UK thermal electricity generation, in the absence of UK data were carried out principally using the United States' NREL data (Macknick et al., 2011). With UK abstraction and consumption figures now being available a comparison with the NREL figures used is appropriate, Tables 4.8a and 4.8b achieve this. The water demands for thermal generation with air cooling is negligible and so was not included. The hybrid figures were calculated assuming a 0.65:0.35 ratio between evaporative and air cooling as in Byers et al. (2014). Table 4.8a finds for abstraction, the NREL figures for the once-through, evaporative and hybrid cooling processes underestimate the UK demand and, with the exception of nuclear generation, the difference is significant. Table 4.8b shows for water consumption in most instances the opposite is found to be the case with the relative differences, while being large, relating to much lower levels of demand.

Table 4.8a Comparison of USA and UK Abstraction Figures (x10^3ML/TWh)

	Nuclear			CCGT			CCGT+CCS			Coal (HLF)			Coal + CCS Post-combustion (HLF)		
	OT	Evap	Hybrid	OT	Evap	Hybrid	OT	Evap	Hybrid	OT	Evap	Hybrid	OT	Evap	Hybrid
NREL	164	3.88	2.52	47.6	0.93	0.59	90	1.82	1.19	118	2.11	1.33	220	4.29	2.79
UK	173	7	4.45	79.85	2.22	1.45	141	4.13	2.57	161	3.85	2.39	259	7.56	4.7

OT: Once-through Cooling, Evap: Evaporative Cooling

Table 4.8b Comparison of USA and UK Consumption Figures (x10^3ML/TWh)

	Nuclear			CCGT			CCGT+CCS			Coal (HLF)			Coal+CCS Post-combustion (HLF)		
	OT	Evap	Hybrid	OT	Evap	Hybrid	OT	Evap	Hybrid	OT	Evap	Hybrid	OT	Evap	Hybrid
NREL	1.27	2.66	1.71	0.38	0.72	0.47	0.9	1.36	0.88	0.78	1.77	1.17	2.1	3.22	2
UK	0.15	3.06	1.88	0.1	0.96	0.6	0.1	0.96	0.6	0.15	1.2	0.75	0.15	1.44	0.9

OT: Once-through Cooling, Evap: Evaporative Cooling

4.6 Discussion

The aim of this chapter was to attribute a cooling water demand to the UK's predicted 2030 and 2050 thermal electricity generation relative to 2010, and to consider the implications of the results obtained with respect to the water likely to be available. The future water demands obtained were found to be heavily pathway dependent, but with the significant increase in the 2050 electricity demand, not surprisingly the majority of pathways showed a corresponding significant increase in their total and/or freshwater demands.

This increase has to be judged bearing in mind that for the years to 2050 it is forecast that there will be less inland freshwater available (Environment Agency, 2011, Environment Agency, 2013b, Wade et al., 2013, Watts et al., 2015), with a policy to build more thermal generation infrastructure to meet the increase in electricity demand. Should policymakers fail to recognise this thermal generation is water intensive, and therefore low cost generation depends on substantial levels of water being available for the BAT cooling. Then this would increase the UK's cost of electricity generation, thereby implicitly reducing the UK's global commercial competiveness. Already for the UK there is no inland thermal generation with a capacity greater than 150MW that can operate with its optimum cooling water (**2.4 Water Resource for UK Thermal Power Generation**). This chapter found the increased water demands in 2030 and 2050, relative to 2010, are significant and policymakers need to factor this into their policy decisions.

In this respect this chapter's findings, especially for 2050 underline why this is important. The Carbon Plan's thermal generation pathways are far more dependent on freshwater than are those of ESME, with the Carbon Plan's High Nuclear pathway being the exception. This is predominantly due to a reliance on CCGT, or fossil fuels with CCS. These stations are often seen to be placed inland and to use freshwater. Here they will have to rely on the less abstraction intensive, but more consumptive, and more costly evaporative and hybrid cooling methods, as well as air cooling. Conversely, the ESME.MC and Clockwork pathways, with their cost optimising goals favour coastal nuclear generation using the abstraction intensive, but least-consumptive once-through cooling, as does the Carbon Plan's high nuclear pathway. This results in high total water, but low freshwater demand. If large volumes of sea and estuarine water were not available at the coast then the scarcity of freshwater (Naughton et al., 2012), will present policymakers with a major nuclear feasibility rethink, that is, if cost of generation is still to remain a consideration.

While there will be scarcity issues for any 2030 and 2050 thermal generation policy that envisages employing freshwater cooling, in so far as sea and estuarine water abstraction is concerned its physical availability cannot be a limiting factor. Nevertheless, there are issues that could be limiting. Environmental and ecological regulation (including The WFD and EU Habitats Directive) is limiting new coastal nuclear site availability. Historically, UK nuclear power stations have been required to reduce their load to comply with thermal discharge temperature standards (EDF Energy PLC, 2011). Additionally it has already been noted in section **2.8** that nuclear development could result in significant impact on marine ecology (Ginige et al., 2012). Despite an extensive study, the Government with 7,000 miles of England and Wales coastline, have only identified eight potential coastal sites suitable for the development of nuclear power (DECC, 2011a).

In this context while nuclear generation often raises public safety concerns there are other serious issues that should be considered such as the more general barriers to coastal generation of habitat, environmental protection, and planning objections such as visual pollution which cover much of the UK's coastline (Boyle, 2015, Energy UK, 2014). These have the capacity to restrict any form of coastal thermal generation, everywhere. This has ominous connotations for any 2050 progressive energy policy that has to satisfy the high water intensity demands of the envisaged nuclear, or fossil fuel + CCS generation, with little, or no freshwater available, restricted access to sea and estuarine water resources, and with an affordable and secure electricity supply ambition.

Although both the ESME Patchwork, and the Carbon Plan's High Renewable pathway's generation output at 2030 and 2050 is of the same order as for the ESME.MC and Clockwork pathways, their relative water demands (Figures 4.1 -4.8) show they are far less dependent on water. To this extent they provide an alternative solution to any lack of required freshwater. However, their Achilles' heel is at 2050 they need support from fossil fuel + CCS generation, both as complimentary generation, and to provide base load. Any approach that allied the provision of this high water intensity fossil fuel + CCS generation with freshwater, would have to factor-in a high level of expensive air cooling. This would quickly lead to questions about the realisability of these crucially important renewable pathways

4.7 Chapter Conclusion

This chapter aims to provide an estimate of the increase in the UK national water demand, relative to 2010, of thermal electricity generation at 2030, and then at 2050. A methodology was developed and applied that looked at cooling methods, and cooling water demand trends of UK thermal power stations in 2010. Using these trends, it then attributed a total and freshwater demand to the 2030 and 2050 ESME model, and Carbon Plan generation pathways.

It found that while water demand is very pathway dependent, relative to 2010 values, the total water abstraction demand has increased for the majority of pathways considered by 2030, with a further significant increase in demand by 2050. For total water consumption, as well as freshwater abstraction and consumption, demand had dropped by 2030 for all the pathways, with the exception of freshwater abstraction under the CCS+ pathway. Although by 2050, many pathway water demands were now greater than their 2010 values. Broadly, those pathways which foresee a large role for thermal generation in the future, rather than those which rely more heavily on energy efficiency measures and renewable energy technologies, were the ones found to have the significantly greater water demands.

However, when it comes to the 2030 and 2050 generation water demands this chapter simply provides a first order assessment of thermal generation water demand issues, when in reality electricity generation, and water availability issues will be regionally specific. Identifying the UK regional water demand issues, and then trying to attribute cost consequences to them using the ESME.MC's UK regional modelling capability, will be the task of Chapters 5 and 6.

Chapter 5 - UK Regional Water Demand Modelling

5.1 Introduction

Chapter 4 modelled the unconstrained national water demands of a number of future electricity generation pathway scenarios, some sympathetic to the UK's current policy to meet much of its future electricity demand with additional thermal generation, whilst still adhering to its emission reduction targets. This identified a number of related water availability issues that have the potential to limit the thermal electricity generation output this policy foresees. They ranged from the threat of a reduction in future freshwater availability for cooling purposes, to environmental and ecological regulation limiting the deployment of coastal generation which could, as an alternative, make use of the UK's abundant estuarine and seawater resource. Furthermore these issues would be made that more exacting, by the UK's hope to increase the use of the more water intensive CCS thermal generation technologies in order to comply with future emission targets.

While comparative present and future national UK electricity thermal generation water demand results are of interest, the demand for power varies significantly from UK region to region, as does water demand, as does water availability. So for policymakers national figures are of limited practical use. To provide the level of detail required on these matters, it becomes necessary to now bring the national water demand modelling of Chapter 4 to the UK regional level.

The Carbon Plan pathways modelled in Chapter 4 cannot disaggregate their national generation projections to a regional scale, which is a prerequisite for quantifying the UK's regional water demands. This does not apply to the identified national electricity generation demands of the three selected ESME pathways (section **3.2.2**), where the disaggregated regional generation projections for 2030 and 2050 are known.

When considering the use of these three pathways, it was shown in Chapter 4, that in the case of the Patchwork pathway, due to its large uptake of non-water requiring renewables, its water demands in 2050 were less than in 2010. This was with the exception of total water abstraction which had a relatively small increase. This low water demand may initially seem to make the Patchwork pathway an interesting candidate for further study as a potential option for adapting to constrained water availability. However as discussed in section **3.3.2** its high level of intermittent renewable energy generation makes it a costly option. It was therefore considered that it would not be informative to include the Patchwork pathway in this regional study. As described in section **3.2.2**, the generation make-up of the Clockwork pathway is very similar to that of the ESME.MC pathway and, as such the water demands of both would be similar. This was generally confirmed in Chapter 4. It was therefore decided for this regional study to proceed with just the ESME.MC regional pathway for 2030 and 2050. The thermal generation by technology, for each region, according to the ESME.MC pathway for 2030 and 2050 is shown by Figures 5.1a – 5.1b Taking this decision was reinforced by the fact that the ESME.MC pathway represents the ESME models' best design of the future UK energy system, and it has been shown to be in accord with current UK energy policy. The greater depth of information that the Monte Carlo facility can make available should also broaden the width of the information obtained.

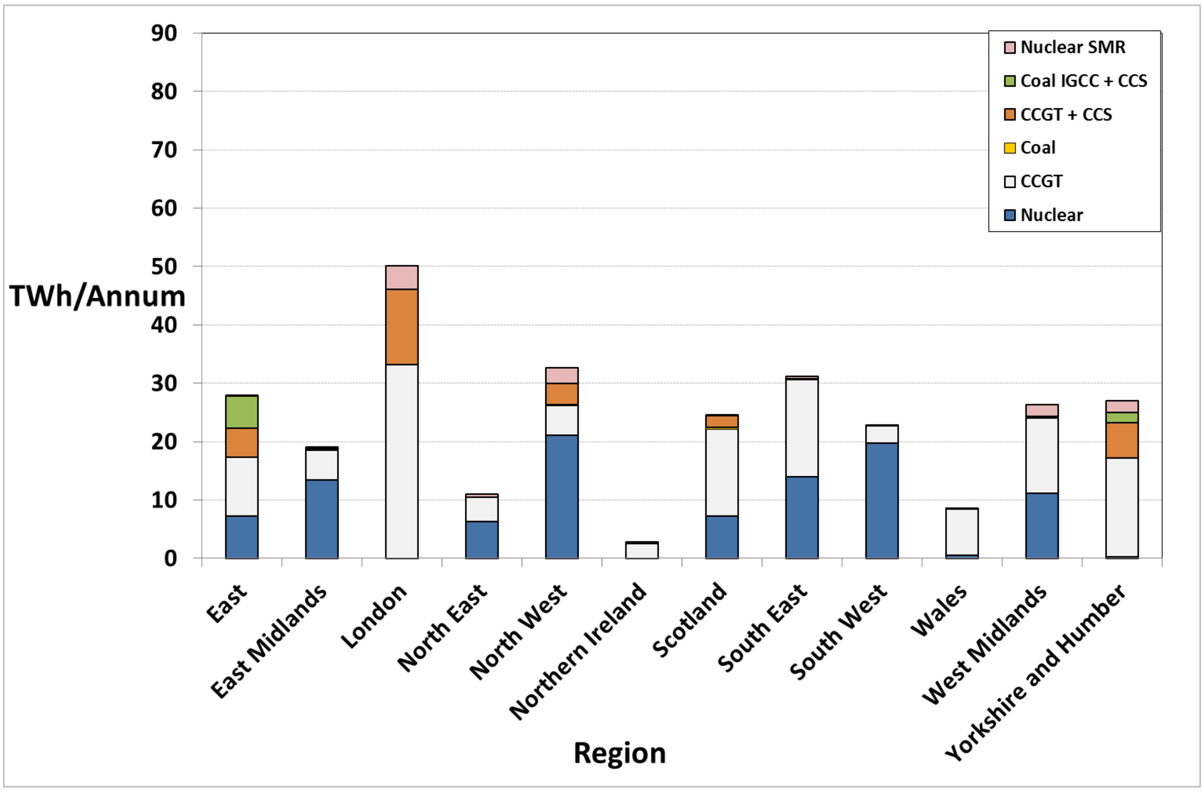

Figure 5.1a ESME.MC Pathway Regional Thermal Generation by Technology – 2030

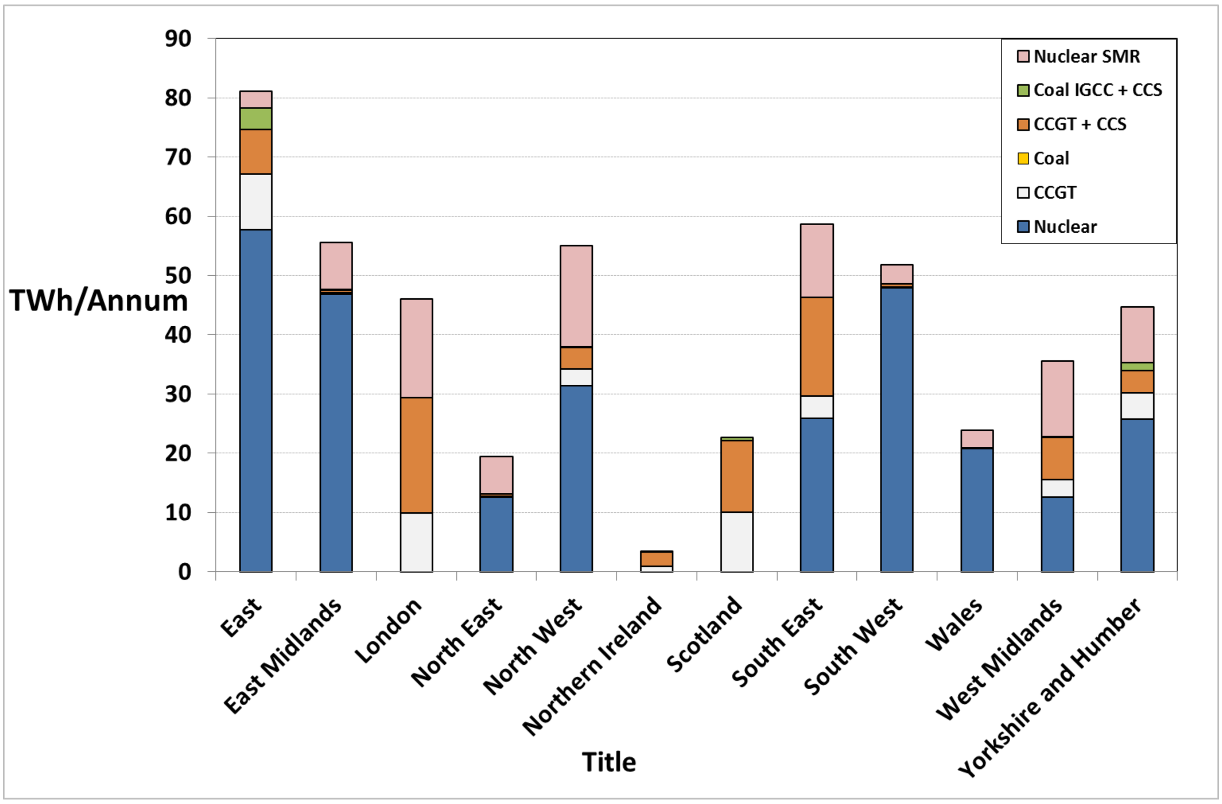

Figure 5.1b ESME.MC Pathway Regional Thermal Generation by Technology – 2050

At a regional level, future water demand for the UK electricity sector has only been previously attempted by the Infrastructure Transitions Research Consortium (Tran et al., 2014), but not using the ESME.MC model. Furthermore, Tran et al. (2014) primarily used the USA's NREL water abstraction and consumption figures (section **4.1**), which as shown in section **4.5.3,** were found to be significantly different from the UK figures**.** Using the ESME.MC pathway's regional generation at 2030 and 2050, and the UK abstraction and consumption figures, the associated UK 2030 and 2050 regional abstraction and consumption demands were found.

5.2 Methodology

The model framework used to find the regional water demands is broadly similar to that developed by Byers et al. (2014), and described in section **4.3**. However, further modifications were necessary to allow the framework to model the water demand of the ESME.MC pathway at a regional level.

5.2.1 Modification of Model Framework

5.2.1.1 Regional Generation

The twelve UK regions represented by the ESME.MC pathway comprise the nine English Government Office Regions (Office for National Statistics, 2015), and Scotland, Wales and Northern Ireland (Figure 3.2). To account for the water demand of each region's generation pathway the original generation array **G** (section **4.3.1**) now becomes $\mathbf{G_{region.}}$. This creates twelve ESME.MC regional generation pathway arrays for 2030 and 2050, each of which is populated with the corresponding thermal generation values for a single region, shown in Figures 5.1a-5.1b. As with the analysis in Chapter 4, the 2010 water demand was modelled to provide a baseline, but this time at a regional level. MacLeay et al. (2011) provides national generation figures per technology for 2010. To proceed, the assumption was made that for each technology in 2010, the proportion of its generation located in any given region would be the same as the proportion of its installed capacity which was located in the same region. This was found when producing **Appendix B** (**4.3.2.2 Distribution Array**).

5.2.1.2 Abstraction and Consumption Figures

It was deemed unlikely that the UK abstraction and consumption figures for each generation technology would vary significantly from region to region. As such the figures used were the same UK abstraction and consumption figures used for the national modelling undertaken in Chapter 4, therefore arrays **A** and **C** remained the same as those in section **4.3.2.3**.

5.2.1.3 Cooling Method and Water Source Distribution

For the array **S**; which defines cooling method and water source distribution, a similar approach was taken as for generation. Instead of a single array **S**, there now became 12 x $\mathbf{S_{region}}$ arrays representing the generation technology's cooling method and water source distribution for each region. It was recognised that the distribution of water source and cooling method may vary from region to region. Reflecting this in a manner that produced credible outcomes of regional water demands at 2030 and 2050 presented a challenge for this modelling analysis. In acknowledging this it was realised that this chapter's objective was not to just predict what the future regional water demands of the power sector would be. It was also to identify what additional risks these future regional water demands, under the ESME.MC pathway, may pose, and to identify those regions where there were in the future, potential serious issues that could threaten the UK's energy policy intentions.

Therefore, it was decided that as for the national analysis in Chapter 4, the 'business-as-usual' 2010 cooling method and water source distributions, could again be used to determine the relative change in the ESME.MC regional generation pathways' cooling water demand from 2010 to 2030, and then to 2050. To apply this business-as-usual approach the $\mathbf{S_{region}}$ arrays were populated with the respective regional water source and cooling method distributions that applied in 2010 using the methods described in section **4.3.2.2**. For the CCS technologies not in operation in 2010, it was assumed the distribution would be as per their respective non-CCS technologies.

There were a number of instances where this approach could not be applied. Nuclear SMR is a new technology, which being smaller than traditional nuclear power stations, it is assumed would have less rigorous siting constraints (Middleton, 2015). For this reason, and for this study, they are therefore classed as a separate technology. As a new technology no current siting history exists, therefore as in section **4.3.2.2**, the cooling method and water source distribution assumed by this study is based on discussions held with the ETI's nuclear team and informed by Middleton (2015). By 2050 coal, or its CCS equivalent, is projected to be present in the South West when neither were present in 2010. To ensure water sources which are available in that region are being used, the distribution of a generation technology which was present in the South West in 2010 was chosen, in this case CCGT. For nuclear generation any region that does not have nuclear generation in 2010, but is projected to in 2030, or 2050, is assumed to use seawater with once-through cooling, as does the majority of nuclear generation on the national scale.

The exception to this is the West Midlands. The West Midlands is expected by 2050 to have a level of large scale nuclear generation. Traditionally nuclear generation is sited on the coast and uses once-through cooling. For the West Midlands, with only freshwater available, it will be assumed this generation will instead use evaporative cooling using freshwater as the coolant, as air and hybrid cooling are ruled out by DECC due to cost and efficiency penalties (DECC, 2011a, World Nuclear Association, 2013). All the regional distributions produced using the Methodology's assumptions are shown by Table 5.1.

5.2.2 Validation

The validation data used in Chapter 4 (**4.4 Validation**) was not sufficiently comprehensive to use at the regional level. The regional generation figures used in this chapter's methodology were produced by the ESME.MC pathway, which had been subject to an international peer review, so these could be viewed with a level of confidence (Heaton, 2014). However with no authoritative UK regional power station water use data available, a validation of the regional water demand results produced could not be carried out. As already noted, Tran et al. (2014) did undertake a similar study, and calculated the UK power sector's regional freshwater demand for a number of generation trajectories to 2050. However the regions and trajectories used are not directly comparable with the ESME.MC pathway and only a summary of the results is publicly available, so it was not possible to use this study for validation purposes. Nevertheless the general model framework used is the same as that in Chapter 4 which was successfully validated. Therefore the underlying principles of the framework used in this chapter's methodology have been demonstrated to be sound and further validation was not felt to be required.

Table 5.1 Regional Distribution of Cooling Method and Water Source

		Nuclear %				CCGT and CCGT CCS %				Nuclear SMR %				Coal, Biomass and Coal CCS %			
		OT	**Evap**	**Hybrid**	**Air**	**OT**	**Evap**	**Hybrid**	**Air**	**OT**	**Evap**	**Hybrid**	**Air**	**OT**	**Evap**	**Hybrid**	**Air**
East:	**FW**	0	0	0	0	0	18	0	0	0	17	0	0	0	0	0	0
	EW	0	0	0	0	11	0	0	0	0	41	0	0	93	0	0	0
	SW	100	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	71	0	0	0	0	0	0	0	7
				Total:	100			**Total:**	100			**Total:**	100			**Total:**	100
E.Mids:	**FW**	0	0	0	0	0	40	0	0	0	17	0	0	0	33	0	0
	EW	0	0	0	0	0	26	8	0	0	41	0	0	0	67	0	0
	SW	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	26	0	0	0	0	0	0	0	0
				Total:	0			**Total:**	100			**Total:**	100			**Total:**	100
London:	**FW**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EW	0	0	0	0	71	0	0	0	0	100	0	0	0	0	0	0
	SW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	29	0	0	0	0	0	0	0	100
				Total:	0			**Total:**	100			**Total:**	100			**Total:**	100
N. East	**FW**	0	0	0	0	0	2	0	0	0	17	0	0	0	80	0	0
	EW	100	0	0	0	0	98	0	0	0	41	0	0	0	0	20	0
	SW	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Total:	100			**Total:**	100			**Total:**	100			**Total:**	100
N. West	**FW**	0	0	0	0	0	65	18	0	0	17	0	0	0	0	0	0
	EW	0	0	0	0	17	0	0	0	0	41	0	0	0	100	0	0
	SW	100	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Total:	100			**Total:**	100							**Total:**	100
N. Ireland	**FW**	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0
	EW	0	0	0	0	40	0	0	0	0	41	0	0	0	0	0	0
	SW	0	0	0	0	60	0	0	0	42	0	0	0	100	0	0	0
	Air	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Total:	0			**Total:**	100			**Total:**	100			**Total:**	100

Table 5.1 Regional Distribution of Cooling Method and Water Source cont.

		Nuclear %				CCGT and CCGT CCS %				Nuclear SMR %				Coal, Biomass and Coal CCS %			
		OT	**Evap**	**Hybrid**	**Air**	**OT**	**Evap**	**Hybrid**	**Air**	**OT**	**Evap**	**Hybrid**	**Air**	**OT**	**Evap**	**Hybrid**	**Air**
Scotland	**EW**	0	0	0	0	0	0	0	0	0	41	0	0	66	0	0	0
	SW	100	0	0	0	100	0	0	0	42	0	0	0	33	0	0	0
	Air	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
				Total:	100			**Total:**	100			**Total:**	100			**Total:**	100
S.East	**FW**	0	0	0	0	1	0	31	0	0	17	0	0	0	51	0	0
	EW	0	0	0	0	37	15	0	0	0	41	0	0	49	0	0	0
	SW	100	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0
				Total:	100			**Total:**	100			**Total:**	100			**Total:**	100
S.West	**FW**	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0
	EW	33	0	0	0	28	0	41	0	0	41	0	0	28	0	41	0
	SW	67	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	30
				Total:	100			**Total:**	100			**Total:**	100			**Total:**	100
W.Mids	**FW**	0	100	0	0	0	100	0	0	0	100	0	0	0	100	0	0
	EW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Total:	100			**Total:**	100			**Total:**	100			**Total:**	100
Wales	**FW**	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0
	EW	0	0	0	0	0	14	51	0	0	41	0	0	0	0	19	0
	SW	100	0	0	0	0	0	0	0	42	0	0	0	81	0	0	0
	Air	0	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0
				Total:	100			**Total:**	100			**Total:**	100			**Total:**	100
York + Hum	**FW**	0	0	0	0	2	4	0	0	0	17	0	0	0	50	0	0
	EW	0	0	0	0	31	19	44	0	0	41	0	0	0	50	0	0
	SW	100	0	0	0	0	0	0	0	42	0	0	0	0	0	0	0
	Air	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Total:	100			**Total:**	100			**Total:**	100			**Total:**	100

OT: Once-through Cooling, Evap: Evaporative Cooling, FW: Freshwater, EW: Estuarine Water, SW: Seawater

5.3 Results

Using this chapters methodology, regional abstraction and consumption values by water source for the ESME.MC pathway in 2030 and 2050, as well as the 2010 baseline, were produced and are shown by Table 5.2. The major change Table 5.2 finds when applying the adapted methodology to the ESME.MC pathway, is the large increase there is in the total water abstraction (fresh, estuarine and seawater) needed from 2010 through to 2050, which increases from 21,079 to 59,111 $x10^3$ML/annum. However, of this increase 58,726$x10^3$ML/ Annum is sea, or estuarine water. For freshwater abstraction the change is a relatively modest one, from 298 to 385$x10^3$ML/annum. The volume of sea and estuarine water consumed is not a factor, due to abundant resource, but total water consumption rises from 188 to 327$x10^3$ML/annum. The change in freshwater consumption from 2010 to 2050 is from 79 to 135$x10^3$ML/annum. The ESME.MC pathway is therefore defined by its high sea and estuarine water, low freshwater demand. This increase in sea and estuarine water demand results from the ESME.MC pathways large adoption of thermal, particularly, nuclear generation. A similar order of increase can therefore be reasonably expected to apply to the UK's future energy policy, which foresees a generation portfolio similar to the ESME.MC pathway (section **2.3**).

The results shown in Table 5.2 are presented proportionally by Figures 5.2-5.9. For total water abstraction the regions with highest demand at 2030 are the North West, South West and London; at 2050 the East, South West and East Midlands. For freshwater abstraction the high demand regions at 2030 and 2050 are the same being the West Midlands, Yorkshire and Humber, South East and North West, with the West Midlands being by far the greatest. For freshwater consumption in 2030 and 2050, it is the same regions with high demand, with the East additionally having relatively high demand.

Table 5.2 Regional Abstraction and Consumption, (x10^3 ML/Annum)

	2010 Abstraction				2010 Consumption				2030 Abstraction				2030 Consumption				2050 Abstraction				2050 Consumption			
Regions	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**
East	12	888	1,258	2,158	6	1	1	8	10	1,134	1,272	2,416	4	1	1	7	15	862	10,182	11,060	6	4	9	19
E.Mids	50	78	0	128	18	26	0	44	6	5	2,340	2,351	2	2	2	7	11	39	8,098	8,147	4	16	7	28
London	0	438	0	439	0	1	0	1	2	3,212	0	3,215	2	15	0	17	2	2,636	0	2,637	1	52	0	53
N.E.	4	1,262	0	1,266	1	3	0	4	1	1,098	36	1,135	0	5	0	6	8	2,198	457	2,662	3	10	0	14
N.W	12	126	2,503	2,641	5	10	2	17	24	164	3,845	4,033	8	4	3	15	37	174	6,794	7,005	13	21	6	41
N.I.	0	292	878	1,170	0	0	1	1	0	89	151	240	0	0	0	0	0	164	273	436	0	0	0	0
Scotland	0	1,539	3,549	5,088	0	1	3	5	0	60	2,762	2,822	0	0	3	3	0	77	2,542	2,619	0	0	2	2
S.E.	64	2,045	1,099	3,208	15	6	1	22	22	510	2,442	2,974	4	4	2	10	57	1,032	5,371	6,461	11	19	5	34
S.W.	1	829	923	1,752	1	5	1	6	0	1,193	2,279	3,472	0	2	2	4	4	2,769	5,784	8,557	2	6	5	13
Wales	1	24	2,083	2,108	1	10	2	13	0	8	104	113	0	3	0	4	3	8	3,804	3,816	1	4	3	8
W.Mids	31	0	0	31	10	0	0	10	123	0	0	123	52	0	0	52	214	0	0	214	86	0	0	86
York & Hum	121	968	0	1,090	21	36	0	57	34	720	188	943	4	15	0	19	34	316	5,147	5,496	6	17	4	27
Totals	298	8,488	12,293	21,079	79	98	11	188	223	8,194	15,419	23,837	77	52	14	142	385	10,275	48,451	59,111	135	150	42	327

FW: Freshwater, EW: Estuarine Water, SW: Seawater, Tot: Total Water

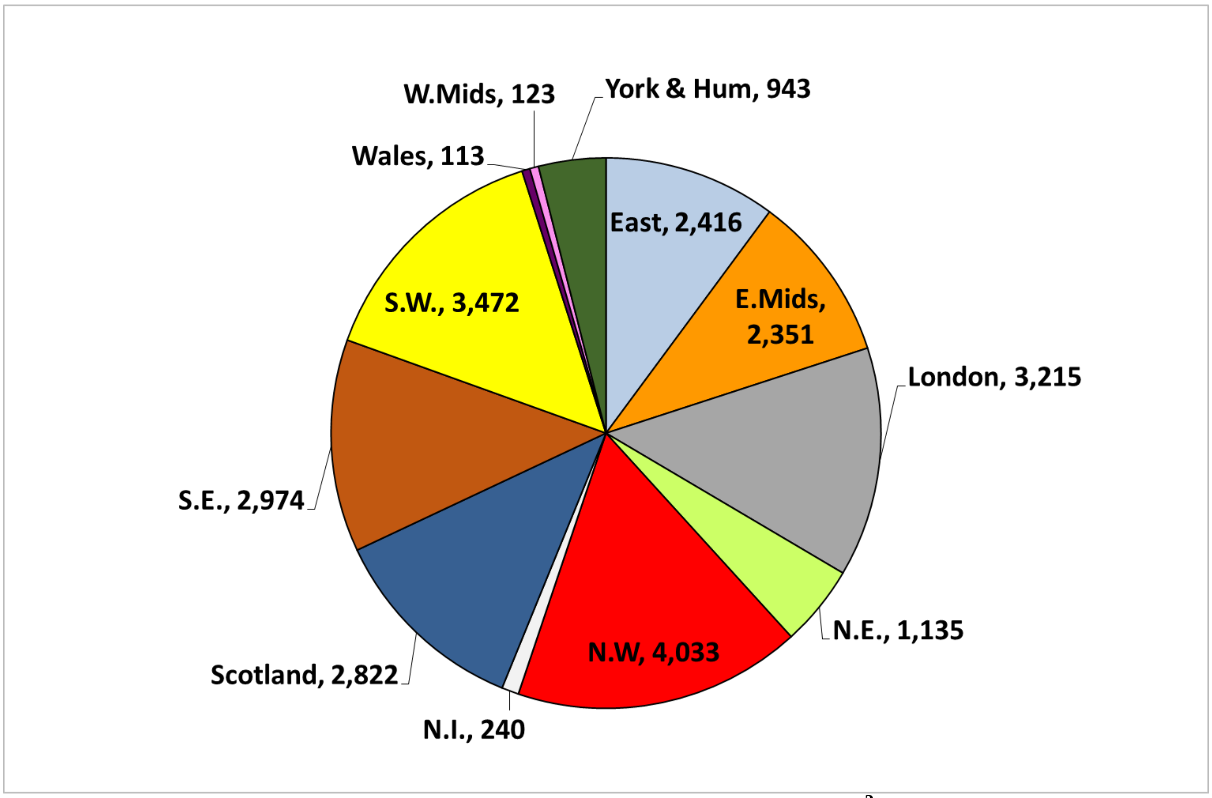

Figure 5.2 2030 Regional Total Water Abstraction (x10^3 ML/Annum)

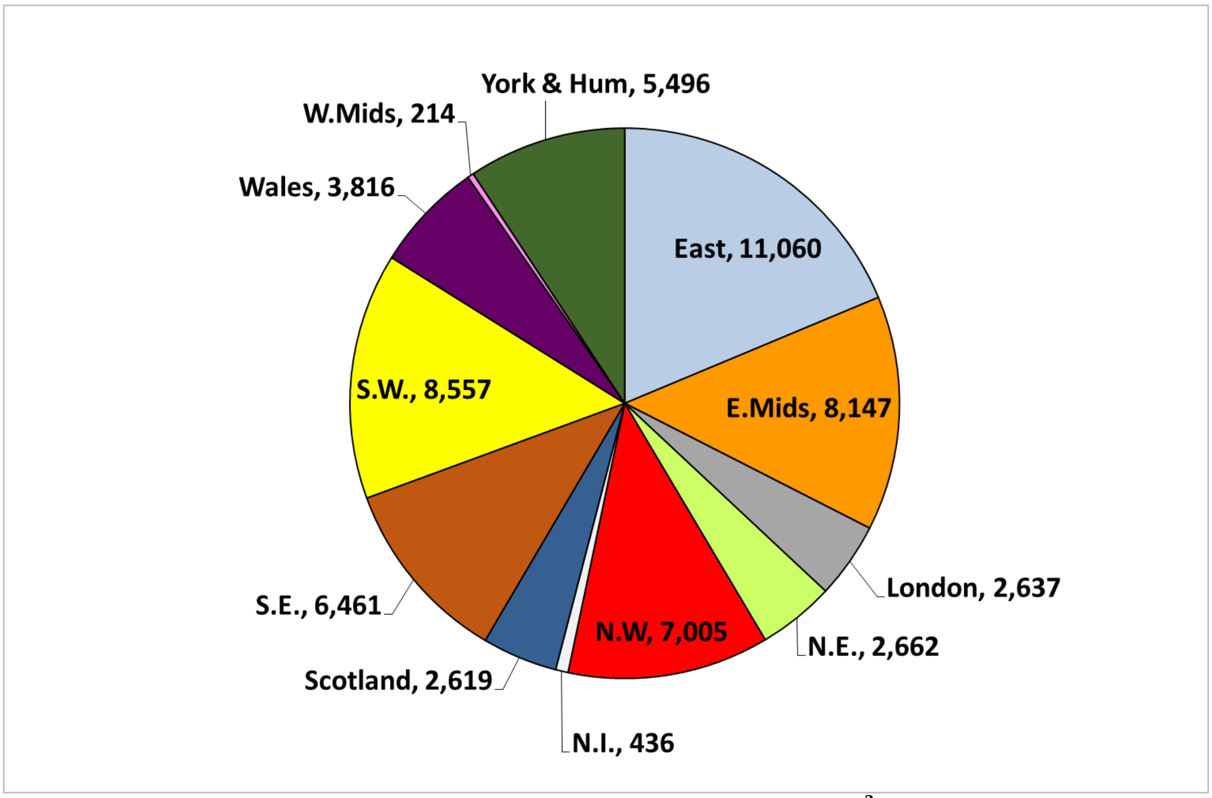

Figure 5.3 2050 Regional Total Water Abstraction (x10^3 ML/Annum)

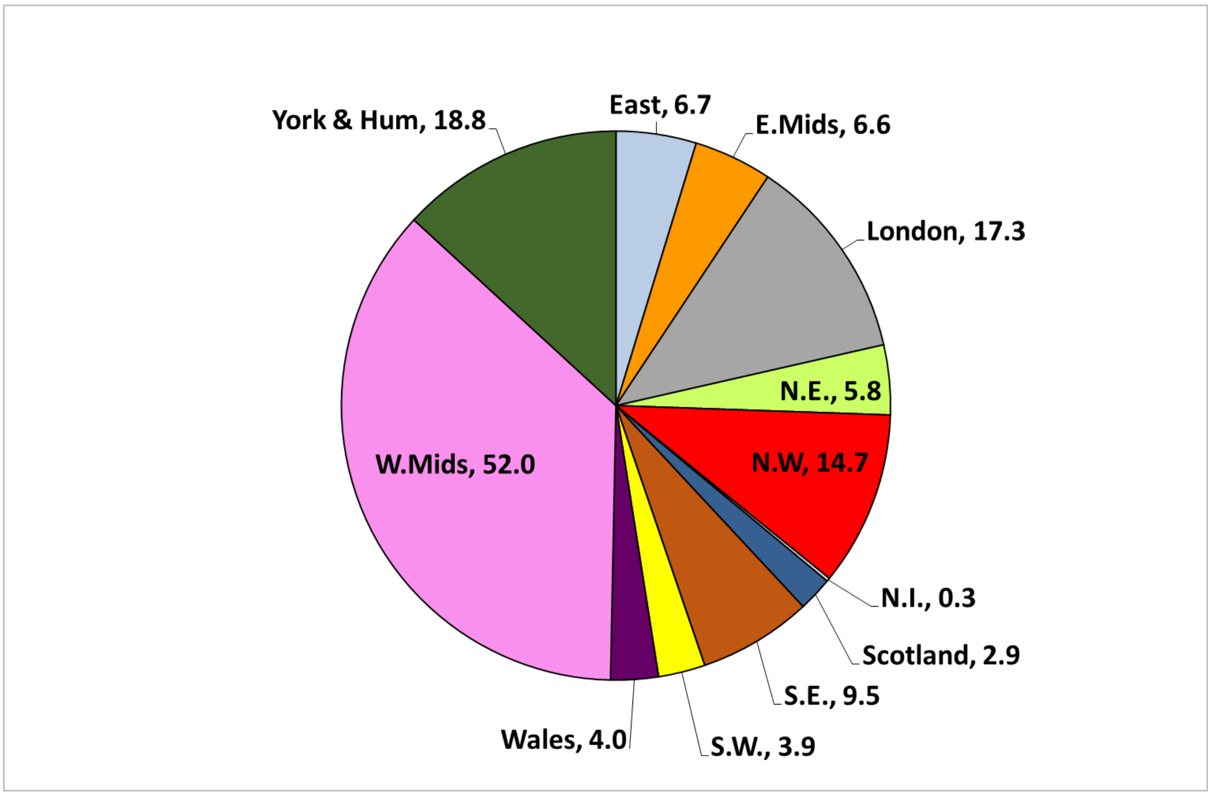

Figure 5.4 2030 Regional Total Water Consumption (x10^3 ML/Annum)

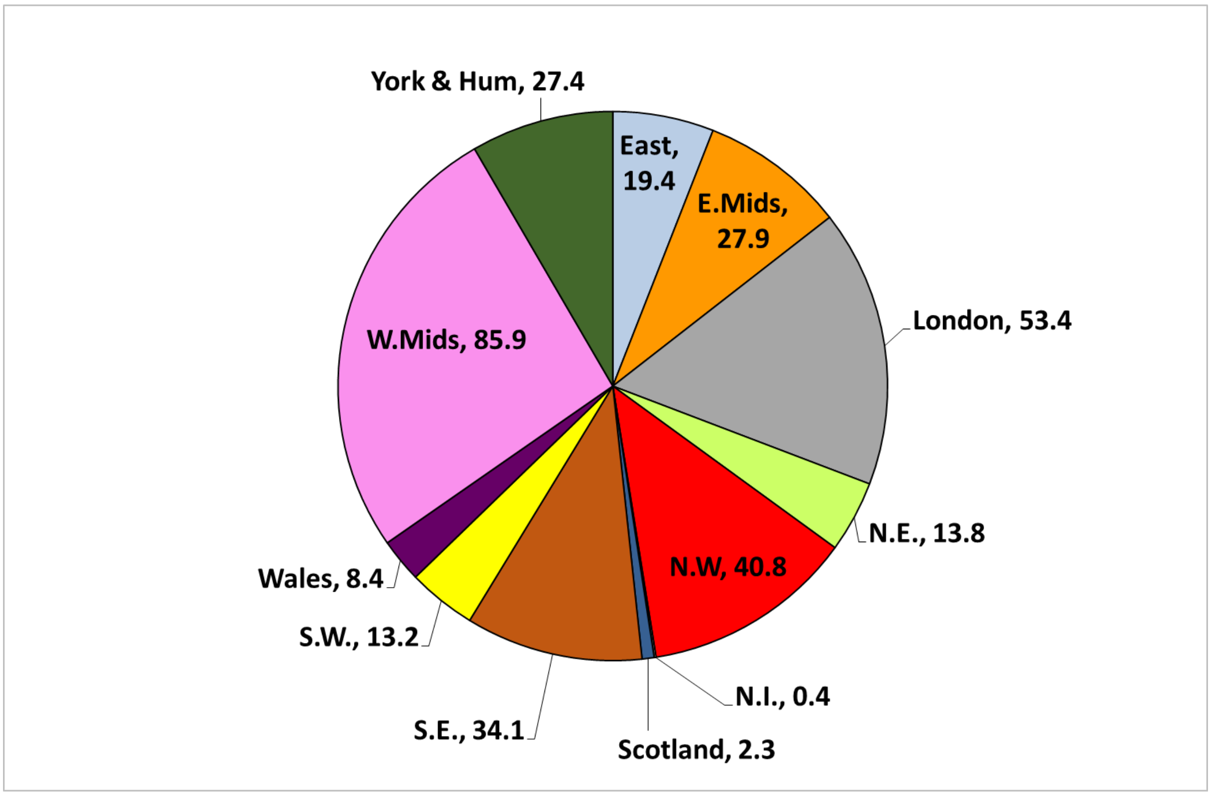

Figure 5.5 2050 Regional Total Water Consumption (x10^3 ML/Annum)

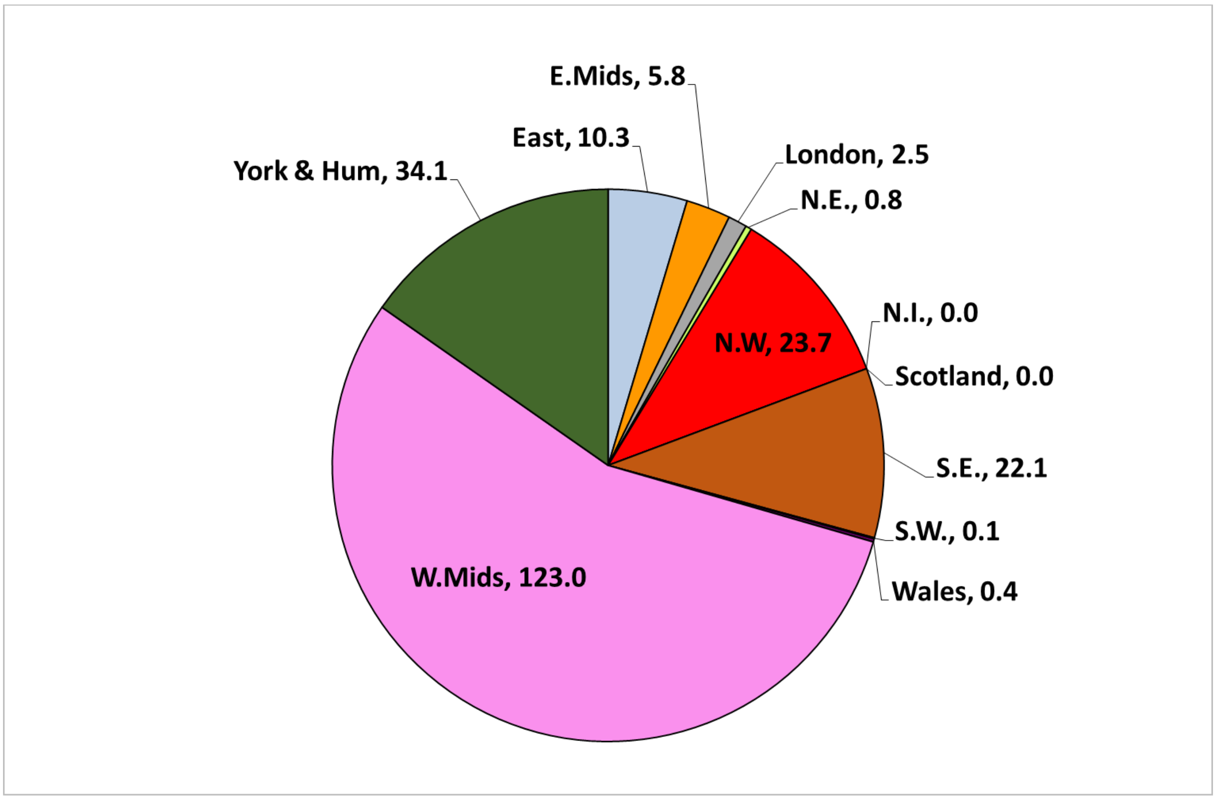

Figure 5.6 2030 Regional Freshwater Abstraction (x10^3 ML/Annum)

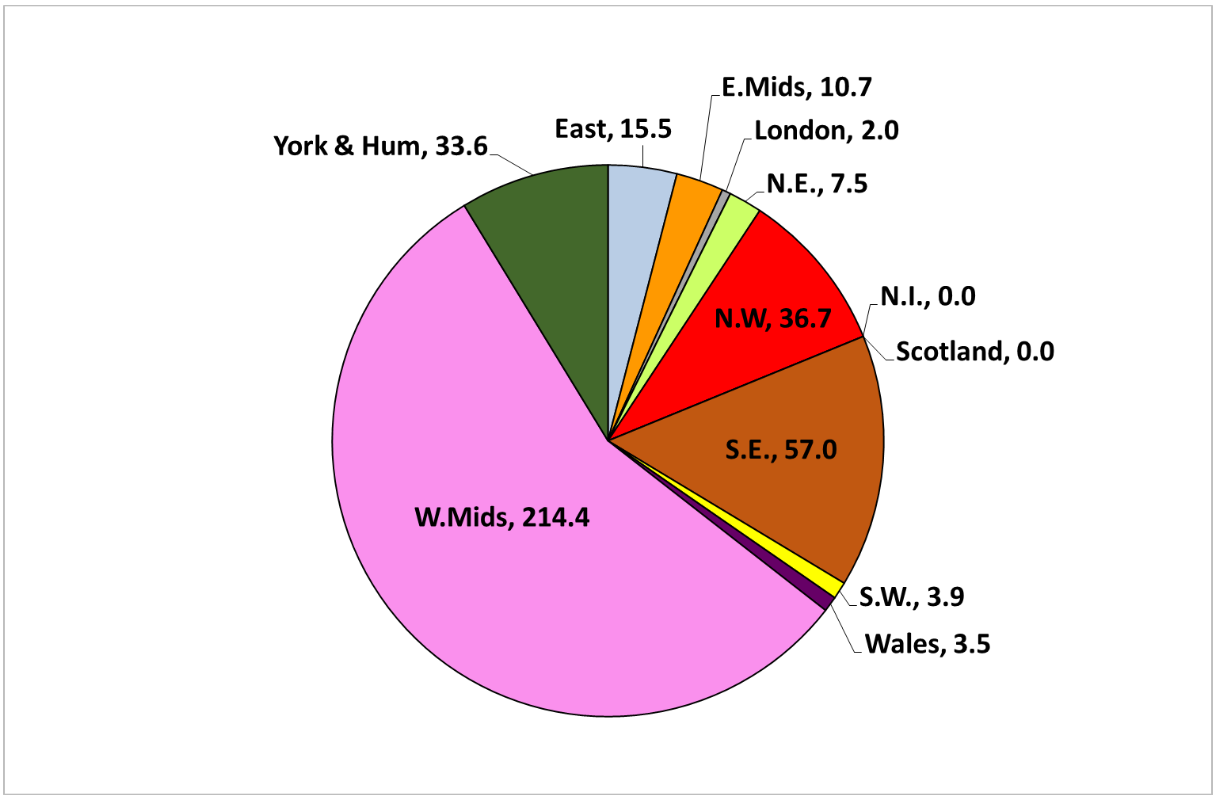

Figure 5.7 2050 Regional Freshwater Abstraction (x10^3 ML/Annum)

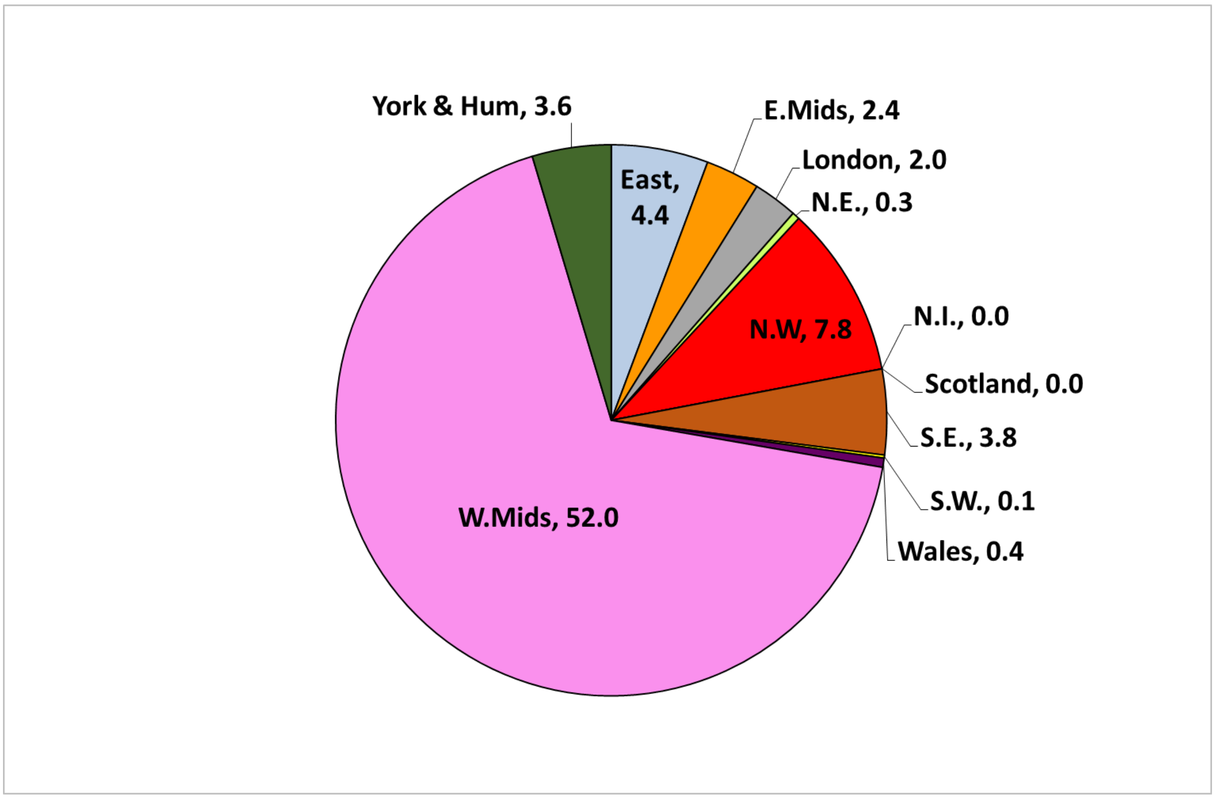

Figure 5.8 2030 Regional Freshwater Consumption (x10^3 ML/Annum)

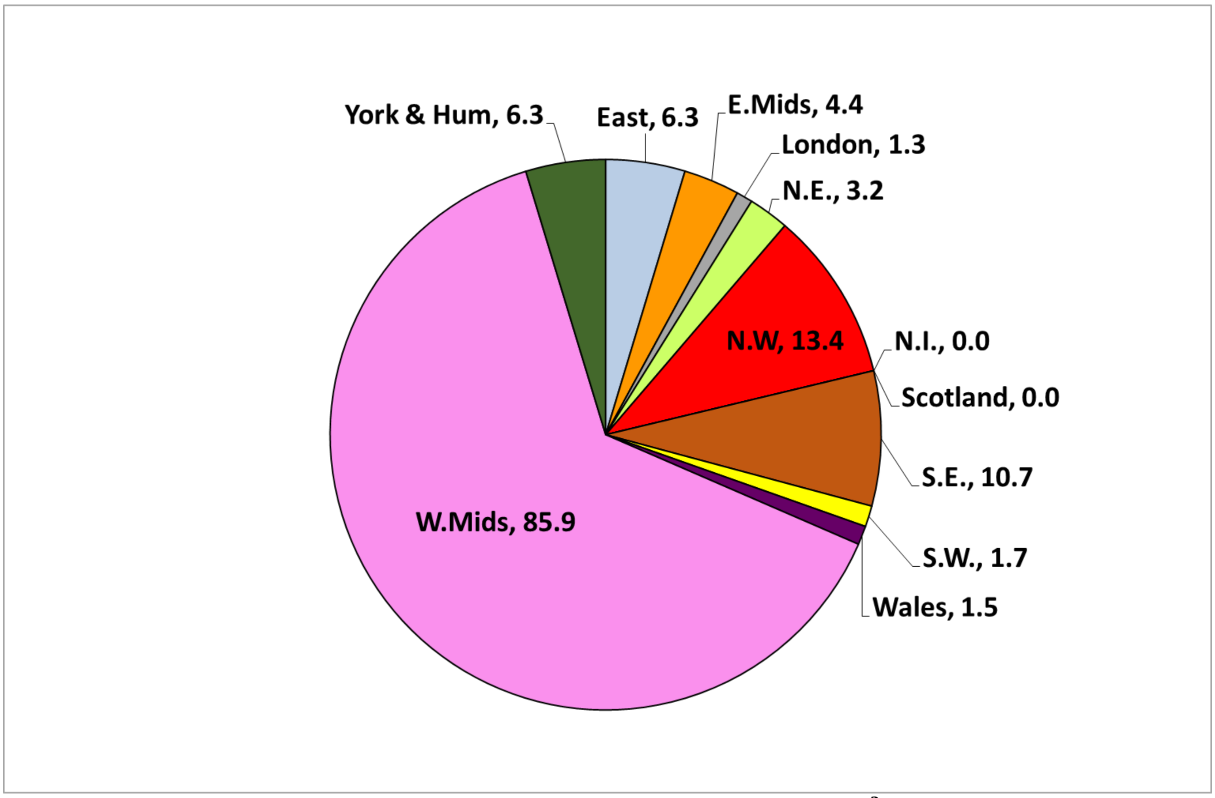

Figure 5.9 2050 Regional Freshwater Consumption (x10^3 ML/Annum)

5.3.1 Results by Generation Technology

Figures 5.10-5.13 expand on both Table 5.2 and Figures 5.2-5.9 by now showing the 2010, 2030 and 2050 comparative total and freshwater abstraction and consumption, broken down by technology for each region, and time period.

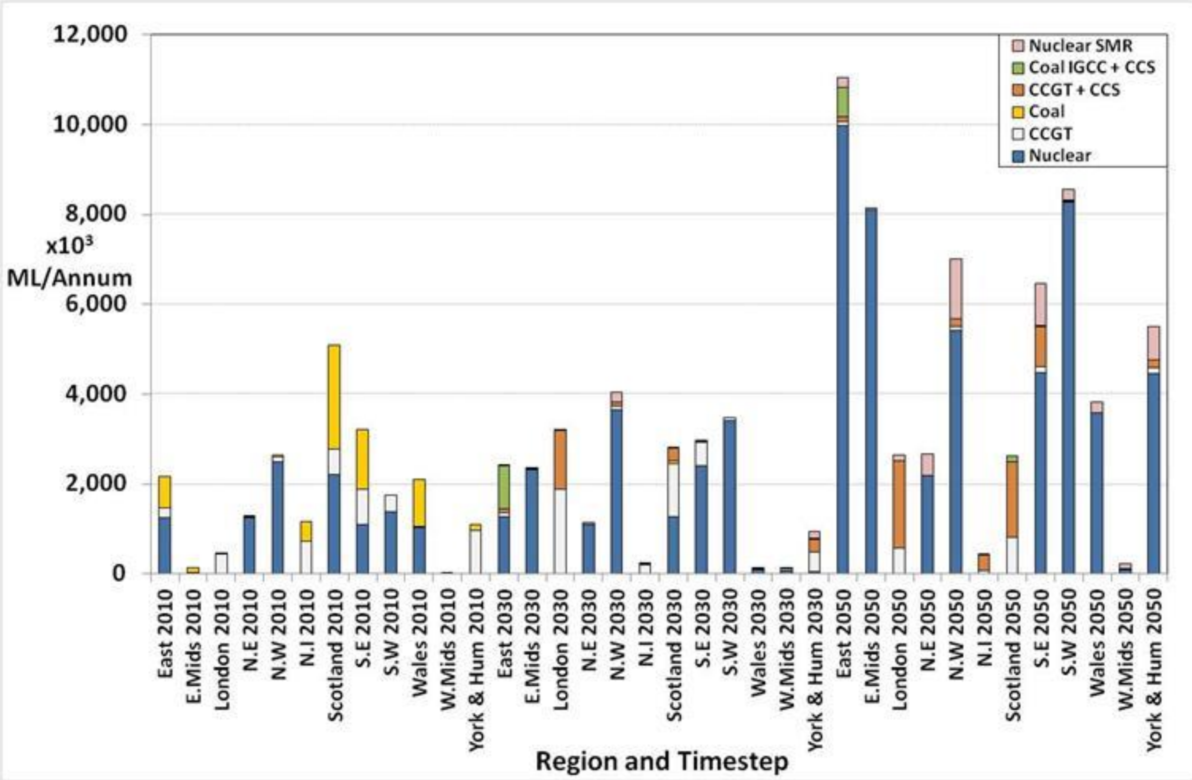

Figure 5.10 Total Water Abstraction by Generation Technology (x10^3 ML/Annum)

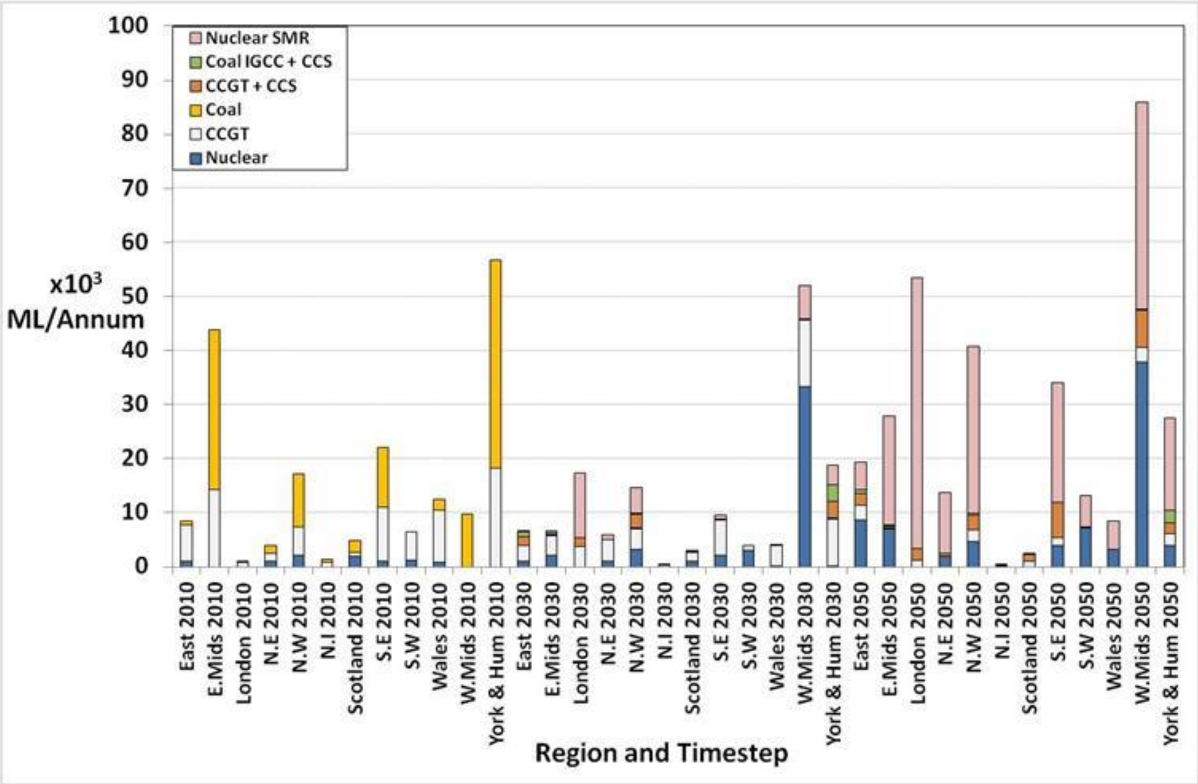

Figure 5.11 Total Water Consumption by Generation Technology (x10^3 ML/Annum)

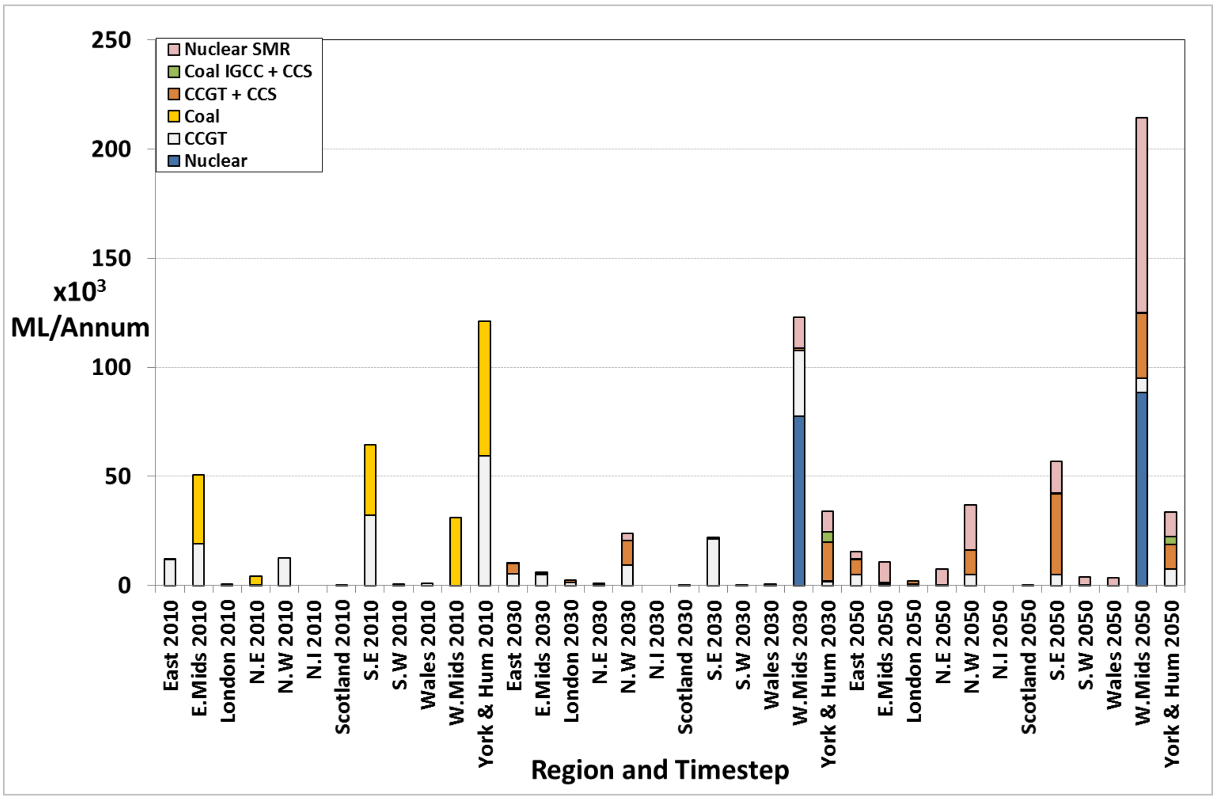

Figure 5.12 Freshwater Abstraction by Generation Technology (x10^3 ML/Annum)

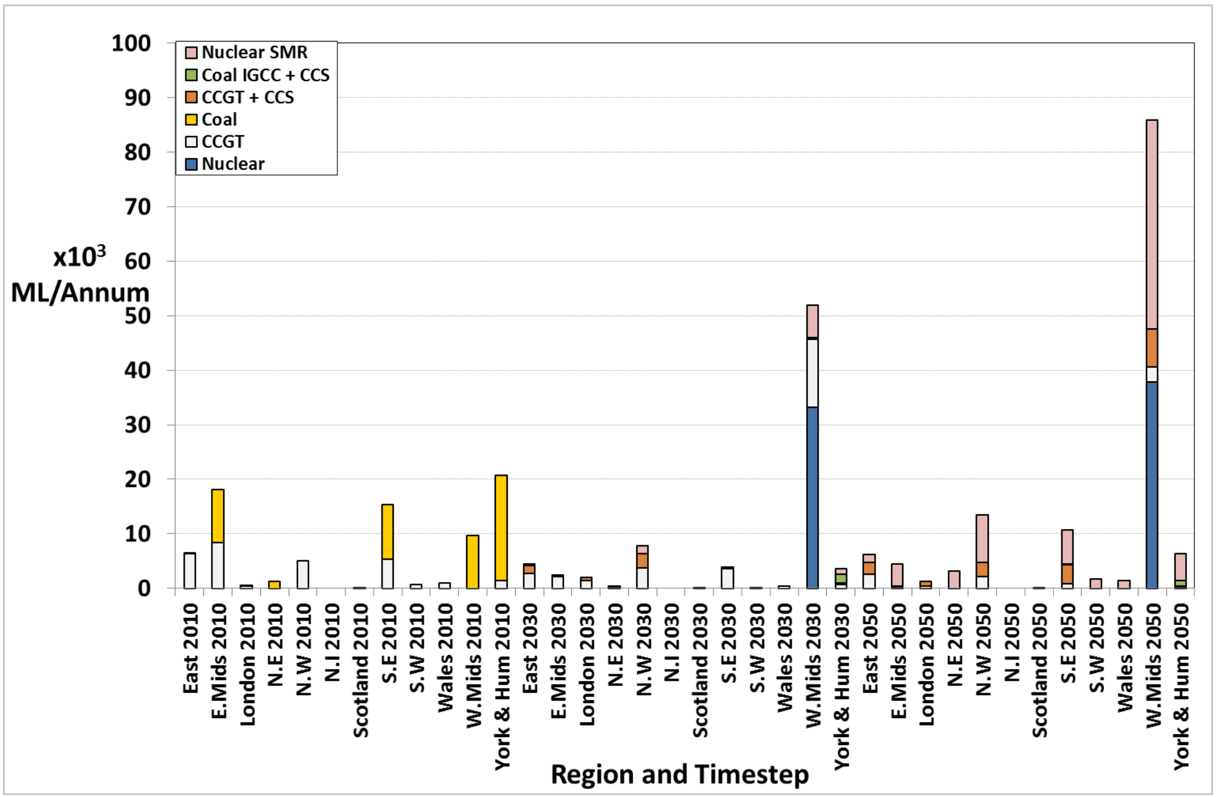

Figure 5.13 Freshwater Consumption by Generation Technology (x10^3 ML/Annum)

Figure 5.10 finds that the large increase in the ESME.MC pathway's total water abstraction from 2010 to 2050, and particularly from 2030 to 2050, is as a result of the methodology extending the 2010 preference for nuclear with estuarine and seawater once-through cooling to the 2030 and 2050 regional generation. Of the regions with (relatively) high total water abstraction the only ones that do not have significant nuclear generation are London, and Scotland (only in 2050) where there is a high adoption of CCGT and CCGT + CCS, as well as nuclear SMR in London.

In terms of generation technologies, total water consumption (Figure 5.11), is more complex with a matrix of generation technologies being deployed around the regions that decide their total consumption demand, although by 2050 nuclear SMR is seen to be the main technology driving consumption demand. This regional consumption increases significantly from 2030 to 2050. This is mainly due to the large increase in nuclear SMR which for all regions, but especially London and the West Midlands, is assumed by the methodology, to adopt a high level of evaporative cooling, which is the most consumptive of all the cooling methods.

Figure 5.12 shows the technologies that make-up the regional freshwater abstraction demand, and identifies CCGT + CCS and nuclear SMR as the main abstractors. These are, after large scale nuclear, favoured by the ESME.MC pathway with its low CO_2, least cost optimised interest. The exception to nuclear at the coast is the West Midlands, which despite being landlocked has some nuclear generation with freshwater evaporative cooling. This, in addition to the inclusion of nuclear SMR and CCGT + CCS generation, is the reason for the extremely high growth in freshwater abstraction demand found in the West Midlands. The freshwater consumption (Figure 5.13) across the regions goes in tandem with freshwater abstraction, and for similar reasons is seen to exhibit from 2010 to 2050 a similar high level of growth in demand for the West Midlands.

5.3.2 Comparison of the National and Regional Modelling

Summing the total water demands of all the regions determined in this chapter gives the water demand of the UK. These UK summed regional water demands are compared to those calculated for the ESME.MC Pathway in the national analysis undertaken in Chapter 4 (section **4.5**), the results are shown in Table 5.3. On first reflection it may be expected that the total summed water demand of the regional analysis would equate to that of the national. As can be seen in Table 5.3 this is not the case. For the regional analysis, the general trend of total water abstraction and consumption from 2010, through to 2030 and 2050, is the same as that of the national analysis. However, for freshwater abstraction and consumption, the regional analysis, unlike the national analysis, sees a rise by 2050 relative to 2010 values.

The regional analysis is not simply a disaggregated version of the national analysis, but rather it adds an extra layer of detail that subsequently can lead to a different projection of the national water demand. Specifically, the three water sources modelled (freshwater, estuarine and seawater) are all available on a UK-wide scale, however they are not all present within each region, for example there is only freshwater present in the West Midlands, and in London there is no seawater. This is duly reflected in the regional water resource and cooling method distribution shown in Table 5.1.

Although the regional distribution is calculated from exactly the same data as the national distribution, the ESME.MC pathway forecasts in the future different levels of generation in each region, therefore the averaged distribution of all the regions combined is skewed towards the distribution of those regions with the most generation, and away from the national distribution used in Chapter 4. This should not be the case for 2010, as this is the same year the distribution was calculated for, and therefore corresponds to the regional generation. It can be seen this is the case as the error for 2010 is significantly smaller than that for 2030 and 2050. Any remaining error, although small, is due to the fact that because of a lack of data, regional generation was calculated from installed capacity per power station rather than electricity generated (section **4.3.2.2**).

This demonstrates the potential error incurred by applying national assumptions to something as dependent on regional variables as future water demand of power stations. Nevertheless, as Table 5.3 shows, the national assumptions did provide a reasonable first order approximation of future water demand in most cases. The greatest errors (2030 and 2050 freshwater consumption and 2050 freshwater abstraction), are largely due to the ESME.MC pathway placing nuclear and nuclear SMR generation, which under the national distribution used predominantly sea and estuarine water, in the West Midlands which only has access to freshwater.

Table 5.3 National and Regional Water Demand Comparison

	2010 Abstraction				2010 Consumption				2030 Abstraction				2030 Consumption				2050 Abstraction				2050 Consumption			
	FW	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**	**FW**	**EW**	**SW**	**Tot**
National	295	8,312	11,978	20,585	81	101	11	192	177	6,270	16,581	23,028	41	66	15	121	259	11,172	48,552	59,983	72	155	42	269
Regional	298	8,488	12,293	21,079	79	98	11	188	223	8,194	15,419	23,837	77	52	14	142	385	10,275	48,451	59,111	135	150	42	327
Δ Regional - National (%)	1	2	3	2	-3	-3	3	-2	26	31	-7	4	90	-21	-5	18	48	-8	-0.2	-1	87	-3	-0.1	22

FW: Freshwater, EW: Estuarine Water, SW: Seawater, Tot: Total Water

5.4 Discussion

Regarding future UK freshwater abstraction and consumption, as Figures 5.6 – 5.9 illustrate, for some regions high levels of demand are predicted by the ESME.MC pathway, particularly for the West Midlands, but also for Yorkshire and Humber, North West and the South East. This makes the likely lack of freshwater a potential risk in these regions. Although the results are not directly comparable, a related study produced similar results; finding high regional freshwater abstraction and consumption for a number of regions, particularly when CCS technologies are present including in Yorkshire and Humber (Tran et al., 2014). It is felt these findings lend additional support to this chapters results. This is further underlined by areas in the West Midlands and the South East being already classified by DEFRA as being water-stressed (DEFRA, 2008). The Environment Agency have also produced a number of 2050 UK regional scenarios for freshwater that express demand as a percentage of supply. The South East, Yorkshire and Humber, North West and the West Midlands, are all identified as being regions with areas where 2050 demand is expected to exceed availability of supply during summer flows (Figure 2.6) (Environment Agency, 2011). For both total and freshwater consumption, the respective levels of abstraction are always substantially greater, therefore it is the abstraction that will be the limiting factor.

It is clear from the results obtained that in general the high regional total water abstraction of the ESME.MC pathway is, as it was in Chapter 4's national analysis, a result of the high uptake of nuclear which relies on sea and estuarine water, with resource availability therefore not an issue. This unreservedly permits the use of the abstraction intensive, BAT, once-through cooling method. Whilst water resource is not a concern there are the serious environmental and ecological regulation impediments that were discussed at length in Chapter 2, that do have ominous connotations. Such regulation clearly undermines the Government's declared wish to reduce regulatory and planning barriers for low carbon generation (Eadson, 2016, HM Government, 2011a). Effectively, it limits the use of ESME.MC type pathways (high coastal thermal generation uptake), from providing the UK with a means of circumventing any future lack of inland regional freshwater, by taking advantage of an abundant physical, alternative coastal cooling water resource.

The ESME.MC pathway considers nuclear generation to be particularly desirable due it its low carbon, and, in the context of an entire energy system, commercially attractive low cost credentials, when placed at the coast and able to deploy the BAT once-through cooling method. This water demand results obtained find that if nuclear, and the UK's also favoured fossil fuel + CCS thermal generation (DECC, 2015a, HM Government, 2011a), cannot satisfy their cooling water needs at the coast, then inland thermal generation will have major cost, and additional CO_2 emissions penalties to pay. With an affordable electricity generation objective there is then for the UK an at the coast/inland generation cost dichotomy, further confused by just what this unknown cost differential will be.

Regional abstraction and consumption demands of future electricity generation scenarios can now, with UK abstraction and consumption figures available, be determined with a greater order of confidence. However the results obtained here simply underline the potential problems the increased demand for cooling water creates, as identified by the previous studies (Byers et al., 2014, Schoonbaert, 2012, Tran et al., 2014). Without greater clarity as to regional water availability, and the impacts of climate change, then the real, water demand/ water available, mismatch issues will still remain unknown. Despite the limitations of this regional analysis, it has shown the future reliance of most regions on sea and estuarine water under the ESME.MC pathway, although the West Midlands is the key exception. This adds further weight to the claim; "*Future electricity generation [will] have minimal impact on the* *overall picture of future water availability because of the significant reliance of the industry on saline/tidal waters*" (Environment Agency, 2013b) (section **2.3.2**). Although this will only be the case if the UK adopts this approach.

5.5 Chapter Conclusion

This chapter expands upon the national water demand analysis of Chapter 4, by now modelling the regional water demands of the projected regional thermal electricity generation for the UK at 2030, and then 2050. This is again relative to 2010 and now using the ESME.MC regional pathways option. On this basis it was found that the regions with the highest 2030 total water demands were the North West, South West and London; at 2050 the East, South West and East Midlands. For freshwater abstraction the regions with the highest demand at both 2030, and 2050, were the West Midlands, Yorkshire and Humber, South East and the North West. The region with the far greatest freshwater demand was identified as being the West Midlands. The regions with the highest freshwater consumption demand for both 2030, and 2050, coincide with the freshwater abstraction result, but now with the addition of the East region. Total water consumption, given the abundant nature of sea and estuarine resource, is considered not to be an issue. Even for freshwater consumption, with abstraction being that much greater, the abstraction demand is seen to be the future limiting factor. These results, and their possible implications, have been considered and recorded.

This regional study also found any attempt to bring the water intensive nuclear, and fossil fuel + CCS generation infrastructure inland, given the expected shortage of freshwater for cooling, would result in a reliance on the less water intensive cooling methods. This will introduce as yet unknown, ongoing, reduced efficiency costs and greater CO_2 emissions penalties. This, it is suggested, could be mitigated by the adoption of a policy that sees a greater use of coastal generation. However, this option is found to be made more difficult by an increase in coastal environmental and ecological regulation. Having identified this inland increased generation cost versus more coastal environment regulation conundrum, Chapter 6 will now consider this in greater detail.

Chapter 6 - Constraining the ESME.MC Pathway by Water Availability

6.1 Introduction

Up to this point this thesis has concentrated on modelling the future water demand of the UK electricity sector, both at the national and regional level, with no quantitative consideration of the actual water resources that may in the future be available. This has provided an important comparative insight into how the water demand of UK thermal power stations would in accord with different policy options increase to the 2050 timeline. It has identified how individual technology and cooling method combinations drive demand, and for the regions, where the increase in water demand is likely to be a problem. However, a consideration of the actual regional water resource likely to be available is required to assess the extent of any problem, and the cost implications this will have on the ESME.MC pathways cost optimised choice of generation technology and cooling method. To achieve this it becomes necessary to now be able to match projected regional water demands, with projected regional water resource availability.

Previous chapters have already noted that not only is there likely to be less freshwater available in the future, but that due to environmental and ecological regulation, sea and estuarine water may be limited in the extent they can be considered to be an alternative cooling water resource. As pointed out in section **5.4** for the UK it is water abstraction, rather than consumption, that is more likely to be the limiting factor in the future for obtaining water for thermal power stations. For this chapter a methodology will therefore be developed to adapt the ESME.MC pathway to now explore how the future availability of freshwater and seawater for abstraction by thermal power stations, impacts the projected generation costs and technology mix of the UK energy system.

6.2 Methodology

To do this a number of additional datasets were required, produced, and then built into the ESME.MC pathway. These additional datasets allowed the ESME.MC pathway to produce its cost-optimised, low carbon, best design of the future UK energy system, whilst taking into account the nature of future available water resource and the relative costs of the generating technology and cooling method combinations possible. The following datasets were prepared and built into the ESME.MC pathway:

1. Future 2030 and 2050 regional freshwater available for cooling at Q70 and Q95 flows (freshwater flows which are exceeded 70% and 95% of the time respectively), shown in Table 6.1 (Environment Agency, 2013a).
2. Cooling water scenarios to be tested, Table 6.2
3. 2030 and 2050 regional seawater available for cooling, Table 6.3.
4. Cooling water abstraction demands for generation technologies and cooling methods, Table 6.4.
5. Freshwater/seawater capital expenditure (capex) and operational expenditure (opex) costs of generation technologies and cooling methods, Tables 6.5 and 6.6, (Maulbetsch and Stallings, 2012).

6.2.1 Regional Freshwater Available for Cooling

Future freshwater availability is based on the Case for Change Refresh 2013 CAMS Results (Environment Agency, 2013a). The EA provided the Q70 and Q95 freshwater flows available for abstraction, leaving the required volume for the environment, in 2012, as well as projections for 2050, for the 117 catchments in England and Wales. As described in section **3.2**, ESME uses 2010 as its baseline for the UK Energy System. The assumption was therefore made that the 2012 figures provided by the EA could reasonably be used for 2010.

The freshwater figures provided were in the form of ML/day, and were converted to ML/annum as the ESME.MC pathway recognises available resource in a yearly format.

Although Q70 and Q95 flows would not persist for a whole year, these represent the periods when thermal generation is most vulnerable to a lack of freshwater; usually the summer months. Without feasible methods of storing very large quantities of water, it is these periods that will dictate the cooling methods available to thermal power stations in the future. It is therefore felt that using these figures on a whole-year basis was reasonable.

Using GIS it was possible to allocate each catchment's 2010 and 2050 figures to its corresponding region(s), with the percentage of each catchment that falls in a region(s) known. For each catchment, the assumption was made that the water transferred to a region is proportional to the area of the catchment which lies in that region. This provided a means of finding each region's total 2010 and 2050 freshwater available for abstraction. As discussed in section **1.3** competition for freshwater from other sectors including food and agriculture had to be taken into account. To do this the percentage of total regional freshwater available which could be allocated to the energy sector, excluding hydropower, was found by using DEFRA's regional freshwater abstractions by sector estimations for 2000-2013 (DEFRA, 2016). The amount of freshwater allocated at Q70 and Q95 for electricity generation in each region, was then obtained by multiplying each region's total available freshwater by the percentage of freshwater used by the electricity sector in that region on average from 2000-2013. It is acknowledged that using sector estimations for 2000-2013 may introduce errors when considering 2030 and 2050. However, with no other data available and within the broader context of the inherent uncertainty present when modelling into the future, it was felt this assumption was appropriate.

For 2050 the EA CAMs' data provided 60 different Q70 and Q95 freshwater availability scenarios for each of the 117 catchments. For each of the ten regions of England and Wales this then provided, using the process just described, 60 sets of Q70 and Q95 scenario results of freshwater available to thermal generation. For each scenario the complimenting regional values were individually totalled to give sixty national values which were then sorted into ascending order. This produced a range of values from which, high, medium and low values of Q70 and Q95 regional freshwater availability for England and Wales were found. This provided the triangular distribution of 2050 regional freshwater availability used by the ESME.MC pathway's Monte Carlo approach for creating the 2050 Q70 and Q95 freshwater available for thermal generation. The ESME.MC pathway determined the 2030 values by interpolation from the 2010 and 2050 figures. The freshwater values used in 2030 and 2050 along with the 2010 baseline values are shown in Table 6.1.

Freshwater data for Scotland and Northern Ireland was not available. However the Regional distribution of cooling method and water source produced in section **5.2.1.3**, showed that in 2010 all existing thermal generation in both countries used only sea and estuarine water for cooling, with the exception of 1% of coal generation in Scotland which used air cooling. Therefore in the absence of any data, this chapter assumes this reliance on sea and estuarine water will remain the case in 2030 and 2050.

Table 6.1 Freshwater Availability Implemented in ESME: 2010, 2030 and 2050 (ML/Annum)

Fresh Water Availability 2010						
	Q70			**Q95**		
Regions	**Baseline Values**			**Baseline Values**		
E.Mids	172,908			144,984		
East	5,371			4,411		
London	1,845			1,414		
N.East	67,541			53,184		
N.West	1,270			936		
S.East	17,326			12,522		
S.West	1,115			710		
Wales	9,615			6,574		
W.Mids	109,538			92,868		
York & Hum	114,228			82,943		
Fresh Water Availability 2030						
	Q70			**Q95**		
Regions	**Low**	**Median**	**High**	**Low**	**Median**	**High**
E.Mids	137,116	160,286	182,418	122,512	139,620	160,425
East	4,259	4,979	5,666	3,727	4,248	4,881
London	1,463	1,710	1,946	1,195	1,362	1,565
N.East	53,560	62,610	71,256	44,940	51,216	58,848
N.West	1,007	1,178	1,340	791	902	1,036
S.East	13,740	16,061	18,279	10,581	12,059	13,856
S.West	884	1,034	1,176	600	684	786
Wales	7,624	8,913	10,144	5,555	6,331	7,275
W.Mids	86,863	101,541	115,562	78,474	89,432	102,759
York & Hum	90,583	105,890	120,511	70,086	79,874	91,776
Fresh Water Availability 2050						
	Q70			**Q95**		
Regions	**Low**	**Median**	**High**	**Low**	**Median**	**High**
E.Mids	101,324	147,664	191,928	100,039	134,256	175,866
East	3,147	4,587	5,961	3,044	4,085	5,350
London	1,081	1,575	2,047	976	1,310	1,716
N.East	39,579	57,680	74,970	36,697	49,248	64,512
N.West	744	1,085	1,410	646	867	1,136
S.East	10,153	14,796	19,232	8,640	11,596	15,190
S.West	653	952	1,238	490	658	862
Wales	5,634	8,211	10,672	4,536	6,088	7,975
W.Mids	64,189	93,545	121,587	64,079	85,996	112,649
York & Hum	66,938	97,551	126,794	57,230	76,805	100,609

6.2.2 Scenarios Tested

In contrast to freshwater, estuarine and seawater resources are both abundant and therefore this chapter now uses seawater to refer to both sea and estuarine water, unless explicitly stated otherwise. Seawater potentially provides an abundant cooling water resource, but environmental and other siting issues could limit its availability. Understanding how limiting the use of seawater in this way affects the cost of UK thermal generation is explored by adopting an arbitrary range of three seawater scenarios, under both the Q70 and Q95 freshwater conditions. This results in there being six scenarios for the ESME.MC pathway to model (Table 6.2). The basis of the seawater scenarios is that at SW all the seawater needed by the pathways thermal generation to support once-through cooling is available; at SWL, half the amount of SW seawater is made available; for SWN, no seawater is available so the reliance is solely on the Q70 or Q95 freshwater available. The volumes of seawater made available per annum for each scenario are shown by Table 6.3. For the SW scenarios there was no fixed limit on the seawater available but Table 6.3 shows the volumes of seawater that the ESME.MC pathway actually chose. As seawater is abundant it was assumed for all scenarios that any seawater cooling would use the once-through cooling method. The assumption therefore was for all regions with a coastline, the cooling water available would be the allotted regional seawater plus the Q70, or Q95 regional freshwater.

There were three exceptions. Firstly, the West Midlands has no coastline so the only cooling water available is its 2030 and 2050, Q70 or Q95 freshwater volumes. Secondly, although under this methodology London has access to seawater, the water available is actually estuarine, which in this case may not be able to support the volume of thermal discharge, produced by once-through cooling during the summer months (Turnpenny et al., 2010). The methodology therefore limits the use of seawater in the London region to just evaporative cooling. Finally seawater is always available in Scotland and Northern Ireland, which is in line with the cooling method and water source distributions of their thermal generation in 2010 (section **6.2.1**). There was potential for this to bias the other regions, for example by allowing ESME to place all of the UK's thermal generation in Scotland and Northern Ireland.

To ensure this did was not the case the volume of seawater allowed in Scotland and Northern Ireland, under all scenarios, was fixed at the volume selected when seawater was unconstrained for Q70 and Q95 freshwater flows respectively.

Table 6.2 Scenarios Tested

Scenario	Assumption
Q70 SW	Seawater is available at each region's required once-through cooling demand. Freshwater also available at Q70 flows.
Q95 SW	Seawater is available at each regions required once-through cooling demand. Freshwater also available at Q95 flows.
Q70 SWL	Seawater is available but constrained at half the level of each region's SW scenario. Freshwater also available at Q70 flows.
Q95 SWL	Seawater is available but constrained at half the level of each region's SW scenario. Freshwater also available at each Q95 flows.
Q70 SWN	Freshwater is available at Q70 flows. Seawater is unavailable.
Q95 SWN	Freshwater is available at Q95 flows. Seawater is unavailable.

Table 6.3 Regional Seawater Available for Cooling Implemented in ESME; 2030 and 2050 (ML/Annum)

	Q70 SW	Q95 SW	Q70 SWL	Q95 SWL	Q70 SWN	Q95 SWN
2030						
East	7,573,353	7,505,118	3,786,677	3,752,559	0	0
E.Mids	5,127,339	5,171,618	2,563,670	2,585,809	0	0
London	28,568	28,625	14,284	14,312	0	0
N.East	1,491,682	1,502,333	745,841	751,167	0	0
N.West	5,857,963	5,834,226	2,928,982	2,917,113	0	0
N.Ireland[a]	252,836	252,290	252,836	252,290	252,836	252,290
Scotland[a]	2,880,396	2,890,865	2,880,396	2,890,865	2,880,396	2,890,865
S.East	6,446,364	6,483,695	3,223,182	3,241,848	0	0
S.West	3,357,868	3,379,498	1,678,934	1,689,749	0	0
Wales	865,128	872,258	432,564	436,129	0	0
W.Midlands	0	0	0	0	0	0
York & Hum	4,473,841	4,459,038	2,236,920	2,229,519	0	0
2050						
	Q70 SW	**Q95 SW**	**Q70 SWL**	**Q95 SWL**	**Q70 SWN**	**Q95 SWN**
East	16,228,326	16,156,386	8,114,163	8,078,193	0	0
E.Mids	10,448,926	10,474,345	5,224,463	5,237,172	0	0
London	165,957	168,783	82,978	84,392	0	0
N.East	3,503,040	3,523,790	1,751,520	1,761,895	0	0
N.West	10,850,261	10,881,004	5,425,131	5,440,502	0	0
N.Ireland[a]	495,476	493,692	495,476	493,692	495,476	493,692
Scotland[a]	3,141,271	3,129,959	3,141,271	3,129,959	3,141,271	3,129,959
S.East	10,454,238	10,535,260	5,227,119	5,267,630	0	0
S.West	9,374,460	9,414,982	4,687,230	4,707,491	0	0
Wales	4,346,649	4,356,946	2,173,325	2,178,473	0	0
W.Midlands	0	0	0	0	0	0
York & Hum	9,127,676	9,150,895	4,563,838	4,575,447	0	0

[a] Seawater was always available in Scotland and Northern Ireland; to ensure this did not bias the other regions, the volume of seawater allowed in all scenarios was fixed at the volume selected when seawater was unconstrained, for Q70 and Q95 freshwater flows respectively

6.2.3 Cooling Methods

The costs and water demands of the four cooling methods being considered (once-through, evaporative, hybrid, air) were built into the ESME.MC pathway, and made available to each generation technology on the basis of the cooling water available and ESME's cost optimised process. The water required for abstraction by each combination of generation technology and cooling method is shown by Table 6.4. The figures used are those developed in section **4.3.2.3**, with additional input provided by the ETI for H_2 turbines, which are treated as their own technology rather than being categorised as CCGT. This was due to a request from the ETI to allow for the water demand of the H_2 production and corresponding CCS process to also be taken into account. It can be seen in Table 6.4 that the difference between the water demand, per unit generated, for H_2 turbines and CCGT generation, both with and without CCS is minimal.

The costs of the relevant thermal generation technologies and cooling methods are shown in Table 6.5 and Table 6.6 respectively, for completeness the cost of renewable generation technologies are also shown in Table 6.5. The thermal generation technology capital costs used by the ESME.MC pathway assume once-through cooling is employed. The additional capital cost of the alternative cooling methods were derived using data taken from Maulbetsch and Stallings (2012), with all other technology costs, including renewables, already built into the ESME.MC pathway by the ETI. The means of adjusting the operational cost of thermal generation technologies when using the alternative cooling methods was according to their relative efficiencies. This was interpreted as also requiring the installed capacity, and hence total capital cost, to be proportionately increased to still meet the required design load. Relative to once-through cooling the difference allowed in efficiency, and, therefore increase in operational costs are, as shown in Table 6.6; Evaporative +4%, Hybrid +6.5%, Air +10%

(Byers et al., 2014, World Nuclear Association, 2013). Cooling with seawater incurs an additional capital charge due to a corrosion factor of around 35-50% (Maulbetsch and DiFilippo, 2008). This was recognised by increasing the once-through and evaporative seawater cooling capex costs by 45%. The relative fuel costs used by the ESME.MC pathway are shown for completeness in Table 6.7. In the case of nuclear generation only once-through and evaporative cooling are made available, as air and hybrid cooling are ruled out by DECC due to cost and efficiency penalties (DECC, 2011a, World Nuclear Association, 2013).

Table 6.4 Water Abstraction Demand of Generation and Cooling Method Combinations ($x10^3$ ML/TWh)

Cooling Method	Nuclear	CCGT	Coal (HLF)	Coal (LLF)	CCGT + CCS	Coal IGCC + CCS (HLF)	Coal CCS Post-combustion (HLF)	H_2 Turbine	H_2 Production + CCS Process
OT	172.85	79.85	160.90	217.75	141.35	191.83	259.05	78.11	64.66
Evap	7.00	2.33	3.85	5.25	4.13	5.60	7.56	2.28	1.89
Hybrid	4.35	1.45	2.39	3.27	2.57	3.48	4.70	1.42	1.17
Air	0.45	0.15	0.25	0.34	0.27	0.36	0.49	0.15	0.12

OT: Once-through Cooling, Evap: Evaporative Cooling

Table 6.5 Generation Technology Capex and Opex Costs

Technology	2030 capex Annualised (£/KW installed)	2050 capex Annualised (£/KW installed)	2030 Annualised Fixed OPEX (£/KW)	2050 Annualised Fixed OPEX (£/KW)	2030 Non-fuel Annualised Variable OPEX (£/KWh)	2050 Non-fuel Annualised Variable OPEX (£/KWh)
Anaerobic Digestion CHP Plant	157	145	68	68	0	0
Biomass Fired Generation	172	159	74	69	0.0012	0.0012
CCGT	61	56	27	28	0	0
CCGT + CCS	133	113	52	52	0.0004	0.0004
H2 Plant (Biomass Gasification + CCS)	111	91	72	40	0.0055	0.0030
H2 Plant (Coal Gasification + CCS)	79	65	26	26	0.0005	0.0005
H2 Plant (SMR + CCS)	52	46	25	25	0.0010	0.0010
H2 Turbine	60	55	30	30	0	0
IGCC Biomass + CCS	308	273	183	183	0.0019	0.0019
IGCC Coal	166	142	80	80	0.0007	0.0007
IGCC Coal + CCS	223	183	100	100	0.0011	0.0011
Incineration of Waste	153	141	257	257	0	0
Nuclear (Gen III)	341	303	68	68	0.0050	0.0050

Table 6.5 Generation Technology Capex and Opex Costs cont.

Technology	2030 capex Annualised (£/KW installed)	2050 capex Annualised (£/KW installed)	2030 Annualised Fixed OPEX (£/KW)	2050 Annualised Fixed OPEX (£/KW)	2030 Non-fuel Annualised Variable OPEX (£/KWh)	2050 Non-fuel Annualised Variable OPEX (£/KWh)
Nuclear (Gen IV)	409	364	68	68	0.0060	0.0060
Nuclear (Legacy)	N/A	N/A	68	68	0.0050	0.0050
Nuclear (SMR)	432	432	113	105	0.0050	0.0050
PC Coal	150	138	71	71	0.0012	0.0012
PC Coal + CCS	266	227	113	113	0.0036	0.0036
Offshore Wind Fixed	248	165	68	50	0	0
Offshore Wind Floating	235	139	67	49	0	0
Onshore Wind	151	138	18	18	0	0
Large Scale Ground Mounted Solar PV	103	70	33	15	0	0
Micro Solar PV	201	93	33	15	0	0
Wave Power	321	242	67	53	0	0
Tidal Stream	283	220	64	57	0	0
Hydro Power	151	151	0	0	0.0200	0.0200

Table 6.6 Cooling Method Capex and Opex Costs

Technology	2030 capex Annualised (£/KW/L installed)	2050 capex Annualised (£/KW/L installed)	2030 Increase in Annualised Fixed OPEX (£/KW)	2050 Increase in Annualised Fixed OPEX (£/KW)	2030 Increase in Non-fuel Annualised Variable OPEX (£/KWh)	2050 Increase Non-fuel Annualised Variable OPEX (£/KWh)
Once-through Cooling	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]
Once-through Cooling Sea	0.007	0.007	N/A[a]	N/A[a]	N/A[a]	N/A[a]
Evaporative Cooling	1.034	1.034	4%	4%	4%	4%
Evaporative Cooling Sea	1.507	1.507	4%	4%	4%	4%
Hybrid Cooling	2.539	2.539	6.5%	6.5%	6.5%	6.5%
Air Cooling	29.090	29.090	10%	10%	10%	10%

[a] Cost built into generation technology

Table 6.7 ESME Fuel Costs

Technology	2030 Resource Costs (£/KWh)	2050 Resource Costs (£/KWh)
Biomass (Imported)	0.0234	0.0252
Biomass (UK)	0.0180	0.0180
Coal	0.0100	0.0107
Waste	0.0108	0.0108
Gas	0.0256	0.0273
Uranium	0.0025	0.0034

6.3 Results

6.3.1 General

As well as the scenarios being tested, the equivalent ESME.MC standard result (i.e. the ESME.MC pathway without any water consideration) is included, and for the remainder of this chapter is referred to as the Standard Scenario. Table 6.8 summarises the changes in installed capacity and electricity generation between the scenarios, and shows that the results for the ESME Standard and the SW scenarios are invariably alike for both years. It also shows the equivalent Q70 and Q95 figures are similar and move in tandem. This is because even at Q70 there is not enough freshwater to support any meaningful level of generation, so the additional Q95 constraint makes little difference. Therefore although the Q95 results are shown, in the interest of readability only the Q70 results will be discussed.

Table 6.8 Electricity Installed Capacity and Generation Summary

	ESME Standard	Q70 SW	Q95 SW	Q70 SWL	Q95 SWL	Q70 SWN	Q95 SWN
				2030			
Thermal Installed Capacity (GW)	52.70 1%[a]	52.17	52.29	52.12 0%	52.07 0%	53.79 3%	53.76 2.8%
Non-thermal Installed Capacity (GW)	30.11 0%	30.35	30.22	33.31 10%	33.57 11%	36.67 21%	37.01 22.04%
Total Installed Capacity (GW)	**82.82 0%**	**82.51**	**82.51**	**85.43 4%**	**85.63 3.8%**	**90.47 9.6%**	**90.77 10%**
Thermal Generation (TWh)	283.82 0%	283.16	283.77	268.74 -5%	265.99 -6.3%	257.73 -9%	256.92 -9.5%
Non-thermal Generation (TWh)	53.05 0%	53.56	53.27	60.19 12%	60.80 14%	67.91 27%	68.72 29%
Total Generation (TWh)	**336.87 0%**	**336.72**	**337.04**	**328.93 -2%**	**326.79 -3%**	**325.64 -3%**	**325.64 - 3%**
				2050			
Thermal Installed Capacity (GW)	82.59 1%	81.69	81.90	72.90 -10%	72.79 -11%	70.26 -14%	70.22 -14%
Non-thermal Installed Capacity (GW)	41.43 -2%	42.26	42.54	66.09 56%	66.84 57%	95.29 125%	96.42 166%
Total Installed Capacity (GW)	**124.02 0%**	**123.95**	**124.44**	**138.99 12%**	**139.63 12%**	**165.55 34%**	**166.65 34%**
Thermal Generation (TWh)	497.15 1.3%	490.35	491.14	395.67 -19%	393.05 -20%	308.45 -37%	306.13 -38%
Non-thermal Generation (TWh)	99.91 -2%	102.32	103.39	186.18 81%	188.84 83%	288.03 181%	291.82 182%
Total Generation (TWh)	**597.07 1%**	**592.67**	**594.54**	**581.85 -2%**	**581.90 -2%**	**596.48 1%**	**597.95 1%**

[a] Percentages show the change in installed capacity from the corresponding SW scenario.

6.3.2 ESME Electricity Generation Technology Installed Capacity

Table 6.8 finds for 2030 and 2050, the response to the decreasing availability of seawater is to reduce thermal, and increase non-thermal installed capacity. This is because the ESME cost optimising approach is trying to avoid the extra cost of the less water intensive cooling methods. The increase in non-thermal capacity is in the form of intermittent renewable technologies. As the seawater decreases, Table 6.8 also shows there is an increase in total installed capacity due to the extra reserve provision needed to cover this added intermittency. The change from thermal to non-thermal installed capacity for both 2030 and 2050 is found to be less significant from the SW to SWL scenario, than from the SWL to SWN, with 2050 changes being distinctly greater than their 2030 equivalents.

Tables 6.9 and 6.10 show the installed electricity generation capacities in 2030 and 2050 by technology, by scenario. The reduction in thermal capacity as the seawater available is reduced, is now clearly identified as being due to a loss of nuclear capacity, with the increase in non-thermal capacity being mainly due to an increase in onshore wind, offshore wind fixed and offshore wind floating. With this reduction in nuclear capacity and the requirement to decarbonise, the provision of base load can be seen to come from an increase in the installed capacities of IGCC coal + CCS, CCGT + CCS, IGCC biomass + CCS and, in 2050, H_2 turbines.

Table 6.9 Electricity Generation Installed Capacity 2030

	Installed Capacity 2030 (GW)						
Generation Technology	**ESME.MC Standard**	**Q70 SW**	**Q95 SW**	**Q70 SWL**	**Q95 SWL**	**Q70 SWN**	**Q95 SWN**
Oil Fired Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas Macro CHP	0.0	0.0	0.0	0.1	0.2	0.4	0.6
OCGT	1.5	1.5	1.5	1.5	1.5	1.5	1.5
PC Coal	2.0	2.0	2.0	2.0	2.0	2.0	2.0
IGCC Coal + CCS	0.4	0.4	0.4	0.2	0.3	2.1	2.3
CCGT	25.1	24.6	24.7	27.1	27.2	26.5	26.5
CCGT + CCS	3.9	3.6	3.8	3.2	3.1	8.0	8.4
Nuclear (Legacy)	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Nuclear (Gen III)	10.0	10.0	10.0	10.0	10.0	5.7	4.9
Nuclear (Gen IV)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear (SMR)	1.9	1.9	1.9	1.8	1.7	0.9	0.7
Biomass Fired Generation	0.1	0.1	0.1	0.1	0.1	0.1	0.1
IGCC Biomass + CCS	0.5	0.5	0.5	1.0	1.1	1.7	1.9
Incineration of Waste	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Anaerobic Digestion CHP Plant	0.3	0.4	0.4	0.5	0.5	0.5	0.6
H2 Turbine	2.9	3.1	3.0	0.6	0.4	0.3	0.3
Onshore Wind	12.0	12.2	12.1	15.2	15.4	18.4	18.7
Offshore Wind (fixed)	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Offshore Wind (floating)	0.0	0.0	0.0	0.1	0.1	0.1	0.2
Large Scale Ground Mounted Solar PV	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Micro Solar PV	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Hydro Power	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Tidal Stream	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wave Power	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal Plant (EGS) Electricity & Heat	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6.10 Electricity Generation Installed Capacity 2050

	Installed Capacity 2050 (GW)						
Generation Technology	**ESME.MC Standard**	**Q70 SW**	**Q95 SW**	**Q70 SWL**	**Q95 SWL**	**Q70 SWN**	**Q95 SWN**
Oil Fired Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas Macro CHP	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCGT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PC Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IGCC Coal + CCS	0.4	0.4	0.4	0.3	0.4	4.7	4.9
CCGT	0.1	0.3	0.2	1.7	1.8	1.3	1.1
CCGT + CCS	19.2	16.8	17.4	19.7	20.0	34.2	34.7
Nuclear (Legacy)	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Nuclear (Gen III)	34.8	33.8	33.7	27.1	26.7	5.9	5.1
Nuclear (Gen IV)	0.4	0.5	0.5	0.0	0.0	0.0	0.0
Nuclear (SMR)	15.7	16.2	16.4	11.7	11.4	2.0	1.7
Biomass Fired Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IGCC Biomass + CCS	0.7	0.8	0.7	2.7	2.9	5.0	5.0
Incineration of Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Anaerobic Digestion CHP Plant	0.0	1.4	1.4	1.5	1.5	1.5	1.5
H2 Turbine	10.1	10.4	10.1	7.1	6.9	14.5	15.0
Onshore Wind	12.6	13.0	13.0	18.4	18.5	19.5	19.5
Offshore Wind (fixed)	7.1	7.4	7.5	15.1	15.2	20.4	20.6
Offshore Wind (floating)	8.9	8.9	9.1	16.6	16.9	30.3	30.9
Large Scale Ground Mounted Solar PV	0.0	0.0	0.0	0.8	0.8	4.8	4.8
Micro Solar PV	0.0	0.0	0.0	0.0	0.0	0.5	0.5
Hydro Power	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Tidal Stream	0.1	0.1	0.1	0.6	0.6	1.7	1.8
Wave Power	0.0	0.0	0.0	0.4	0.3	2.0	2.0
Geothermal Plant (EGS) Electricity & Heat	0.1	0.2	0.2	1.7	1.7	3.6	3.6

6.3.3 ESME Electricity Generation

The outcomes for the electricity generated at 2030 and 2050 are provided by Tables 6.11 and 6.12. As would be expected, the changes across the scenarios are compatible with, and for the same reasons as, the changes in installed capacity, and so to an extent are only shown for completeness. However, the generation results, along with the percentage changes in Table 6.8, do clearly underline the increased magnitude of the challenge UK energy policy has to accommodate in the period from 2030 to 2050, than for the current 2010 to 2030 period.

Table 6.11 Electricity Generation 2030

	Generation 2030 (TWh)						
Generation Technology	**ESME.MC Standard**	**Q70 SW**	**Q95 SW**	**Q70 SWL**	**Q95 SWL**	**Q70 SWN**	**Q95 SWN**
Oil Fired Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas Macro CHP	0.0	0.0	0.0	0.2	0.4	1.5	2.1
OCGT	0.2	0.2	0.2	0.2	0.2	0.3	0.3
PC Coal	0.7	0.8	0.7	0.4	0.3	0.3	0.3
IGCC Coal + CCS	3.2	2.9	2.8	1.6	2.2	14.1	15.1
CCGT	112.9	112.5	112.7	120.3	119.5	116.1	116.7
CCGT + CCS	28.6	26.3	27.7	22.6	21.1	53.6	56.1
Nuclear (Legacy)	22.1	22.1	22.1	22.1	22.1	7.7	7.6
Nuclear (Gen III)	78.9	78.9	78.9	77.4	77.6	42.8	36.8
Nuclear (Gen IV)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear (SMR)	12.2	12.1	12.1	10.7	10.3	5.3	4.4
Biomass Fired Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IGCC Biomass + CCS	3.4	3.9	3.7	6.8	7.1	11.2	12.6
Incineration of Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Anaerobic Digestion CHP Plant	2.4	2.6	2.6	3.4	3.5	3.6	3.7
H2 Turbine	19.1	20.8	20.1	3.0	1.6	1.2	1.1
Onshore Wind	28.1	28.6	28.3	35.0	35.5	42.4	43.1
Offshore Wind (fixed)	12.2	12.2	12.2	12.2	12.2	12.3	12.3
Offshore Wind (floating)	0.1	0.1	0.1	0.3	0.3	0.5	0.6
Large Scale Ground Mounted Solar PV	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Micro Solar PV	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Hydro Power	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Tidal Stream	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wave Power	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geothermal Plant (EGS) Electricity & Heat	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6.12 Electricity Generation 2050

	Generation 2050						
Generation Technology	**ESME.MC Standard**	**Q70 SW**	**Q95 SW**	**Q70 SWL**	**Q95 SWL**	**Q70 SWN**	**Q95 SWN**
Oil Fired Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas Macro CHP				0.0	0.0	0.0	0.0
OCGT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PC Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IGCC Coal + CCS	1.6	1.5	1.4	1.0	1.4	25.5	26.8
CCGT	0.0	0.0	0.0	0.3	0.3	0.2	0.2
CCGT + CCS	72.8	63.6	65.9	74.0	75.5	167.8	171.7
Nuclear (Legacy)	7.1	7.2	7.2	6.4	6.4	0.2	0.2
Nuclear (Gen III)	272.4	264.1	263.8	205.6	202.7	42.0	36.6
Nuclear (Gen IV)	3.4	3.8	3.9	0.1	0.2		
Nuclear (SMR)	91.4	92.8	94.0	64.1	62.4	11.3	9.1
Biomass Fired Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IGCC Biomass + CCS	4.7	5.2	4.7	17.3	18.8	32.9	32.7
Incineration of Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Anaerobic Digestion CHP Plant	0.0	5.6	5.6	5.6	5.6	5.4	5.3
H2 Turbine	43.8	46.5	44.6	21.2	19.8	23.2	23.5
Onshore Wind	29.4	30.4	30.4	42.3	42.6	44.7	44.8
Offshore Wind (fixed)	24.6	25.9	26.2	52.2	52.7	70.3	71.0
Offshore Wind (floating)	34.7	34.8	35.6	64.7	66.0	117.5	119.8
Large Scale Ground Mounted Solar PV	0.0	0.0	0.0	0.7	0.8	4.5	4.6
Micro Solar PV	0.0	0.0	0.0	0.0	0.0	0.5	0.5
Hydro Power	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Tidal Stream	0.4	0.2	0.2	2.1	2.2	5.8	6.0
Wave Power	0.0	0.0	0.0	1.2	1.2	6.7	6.9
Geothermal Plant (EGS) Electricity & Heat	1.0	1.2	1.2	13.1	13.6	28.3	28.3

6.3.4 Regional Generation by Technology and Cooling Method

In this revised water-conscious version of the ESME.MC pathway, generating costs are now a function of the technologies and cooling methods ESME chooses, and depend on the amounts of regional seawater and freshwater available. The way in which constraining the seawater available under Q70 and Q95 flows determines the total regional generation, and the cooling methods selected for each generation technology in each region for 2030, is shown by Figures 6.1, and then 6.2-6.7; for 2050 it is shown by Figures 6.8, and then 6.9-6.14. Again the Q95 results are similar, and although shown are not discussed further.

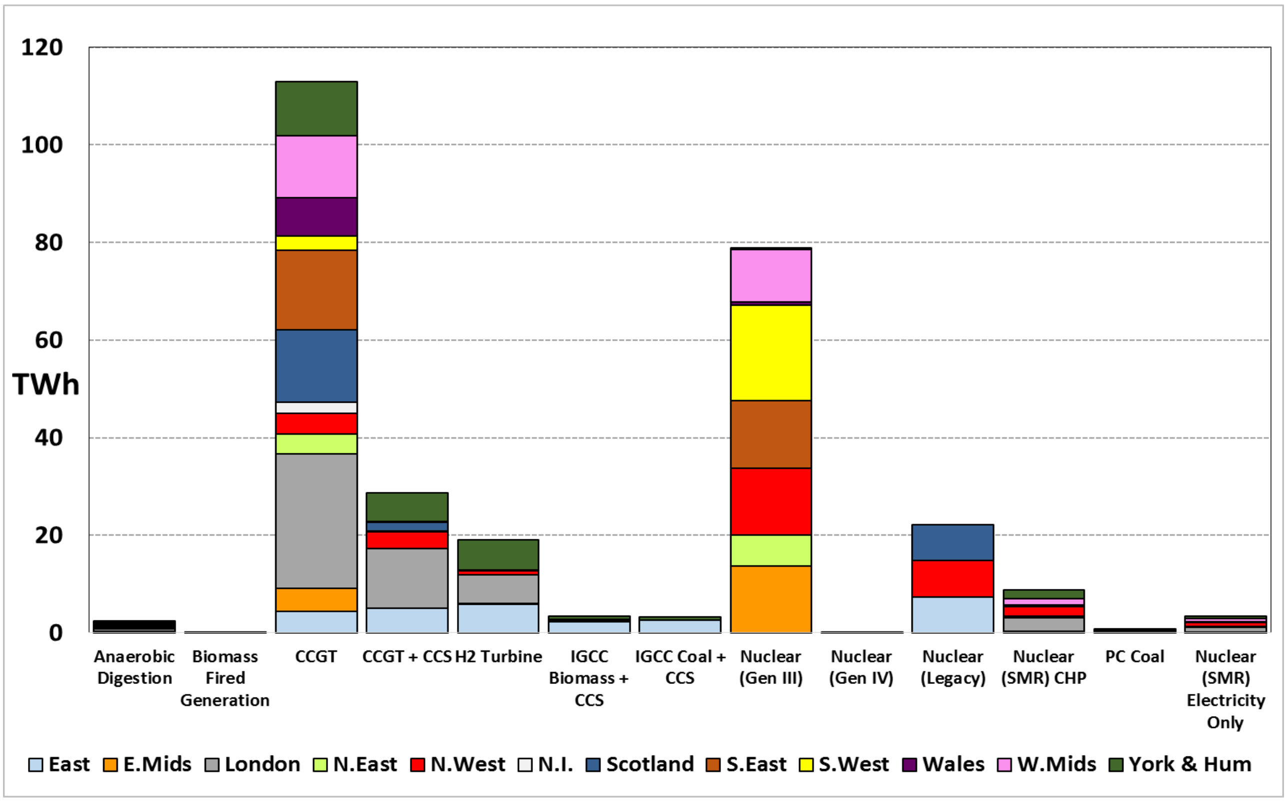

Figure 6.1 Regional Generation ESME.MC Standard 2030

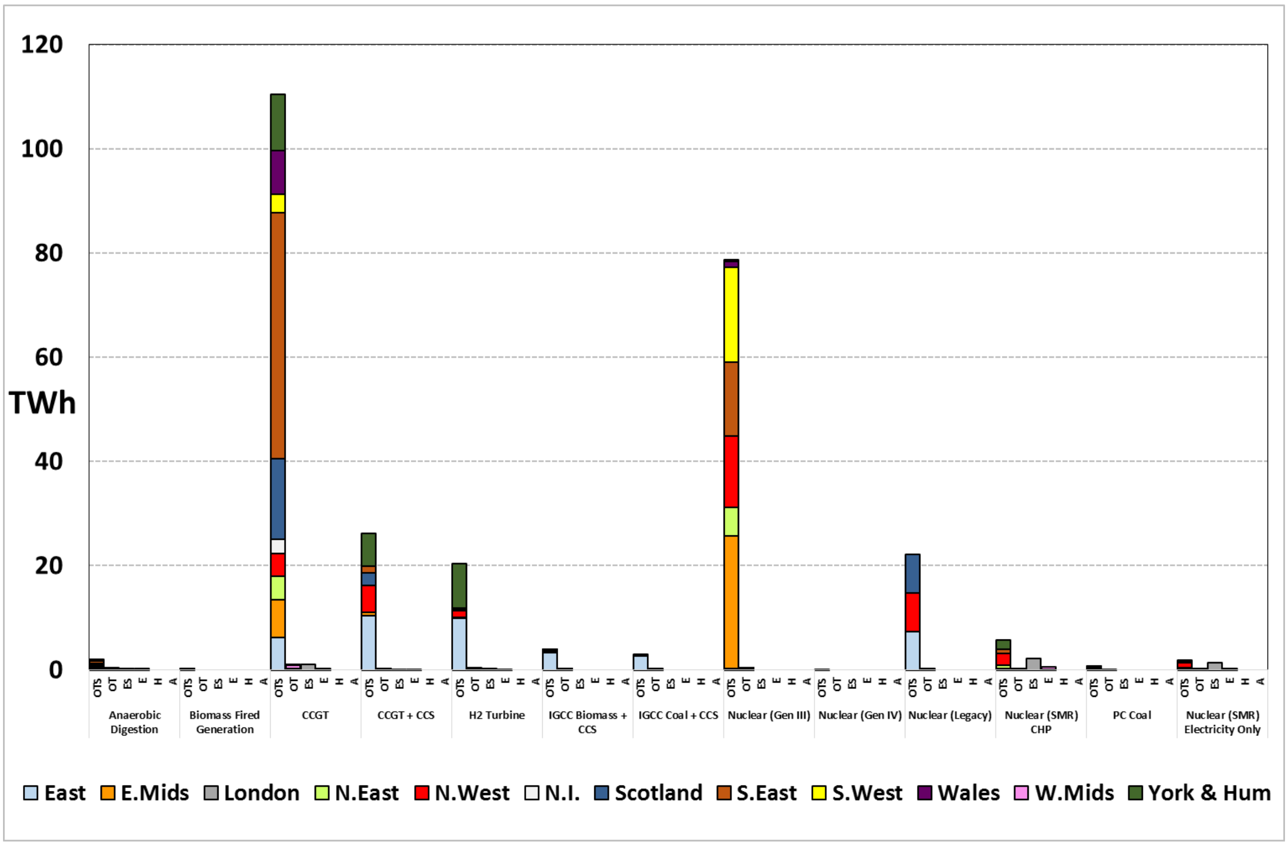

Figure 6.2 Regional Generation by Technology and Cooling Method 2030 Q70 SW

Cooling method abbreviations: OTS – Once-through cooling seawater, OT – Once-through cooling, ES – Evaporative Cooling Sea E – Evaporative cooling, H – Hybrid cooling, A – Air cooling (applies for Figures 6.6-6.11 and 6.13-6.18).

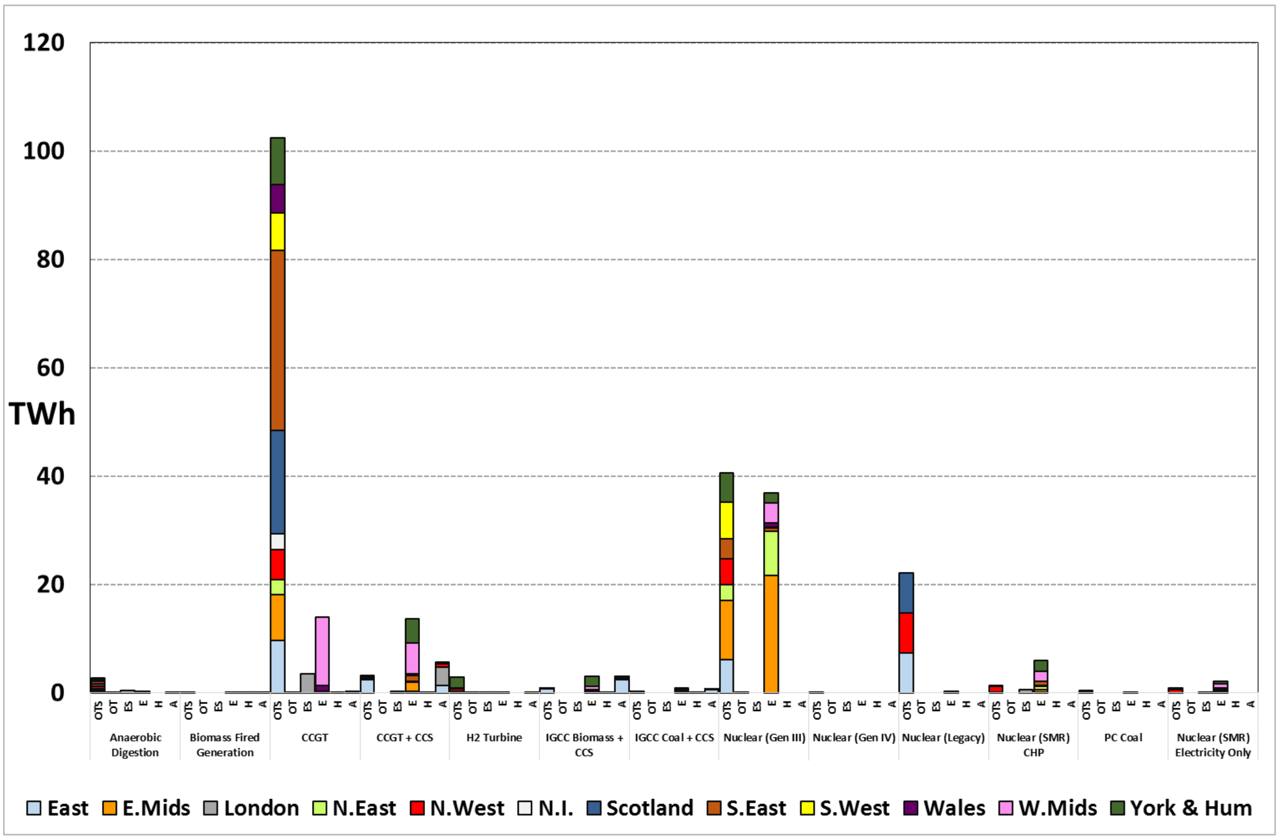

Figure 6.3 Regional Generation by Technology and Cooling Method 2030 Q70 SWL

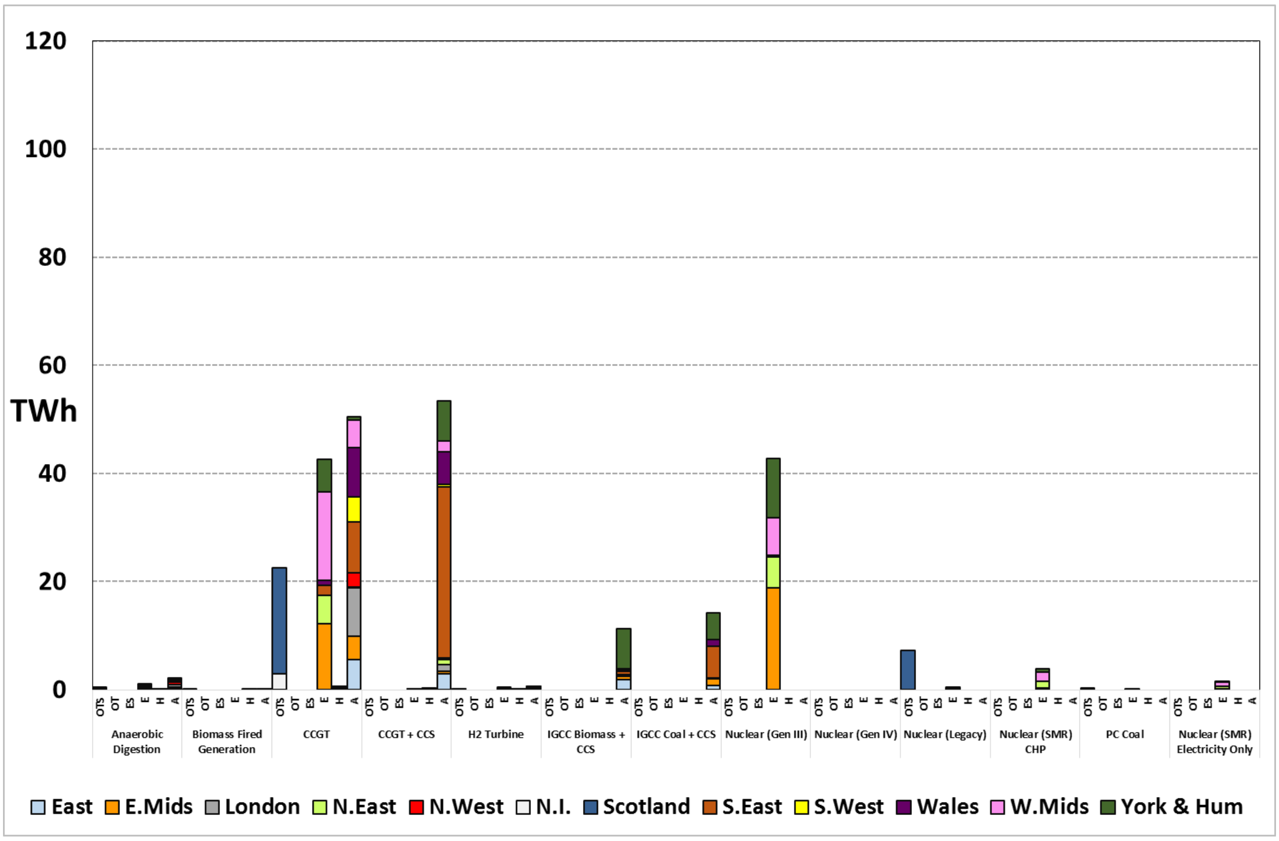

Figure 6.4 Regional Generation by Technology and Cooling Method 2030 Q70 SWN

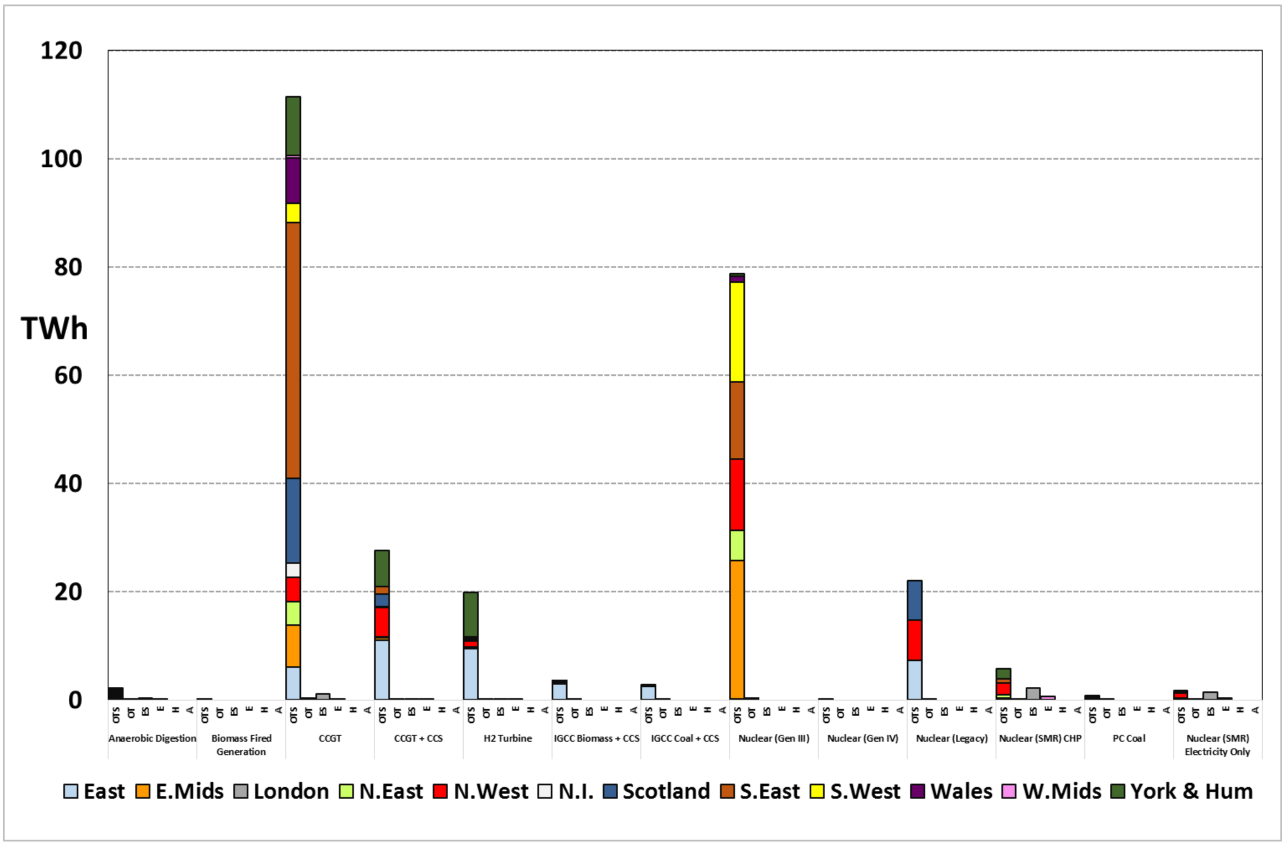

Figure 6.5 Regional Generation by Technology and Cooling Method 2030 Q95 SW

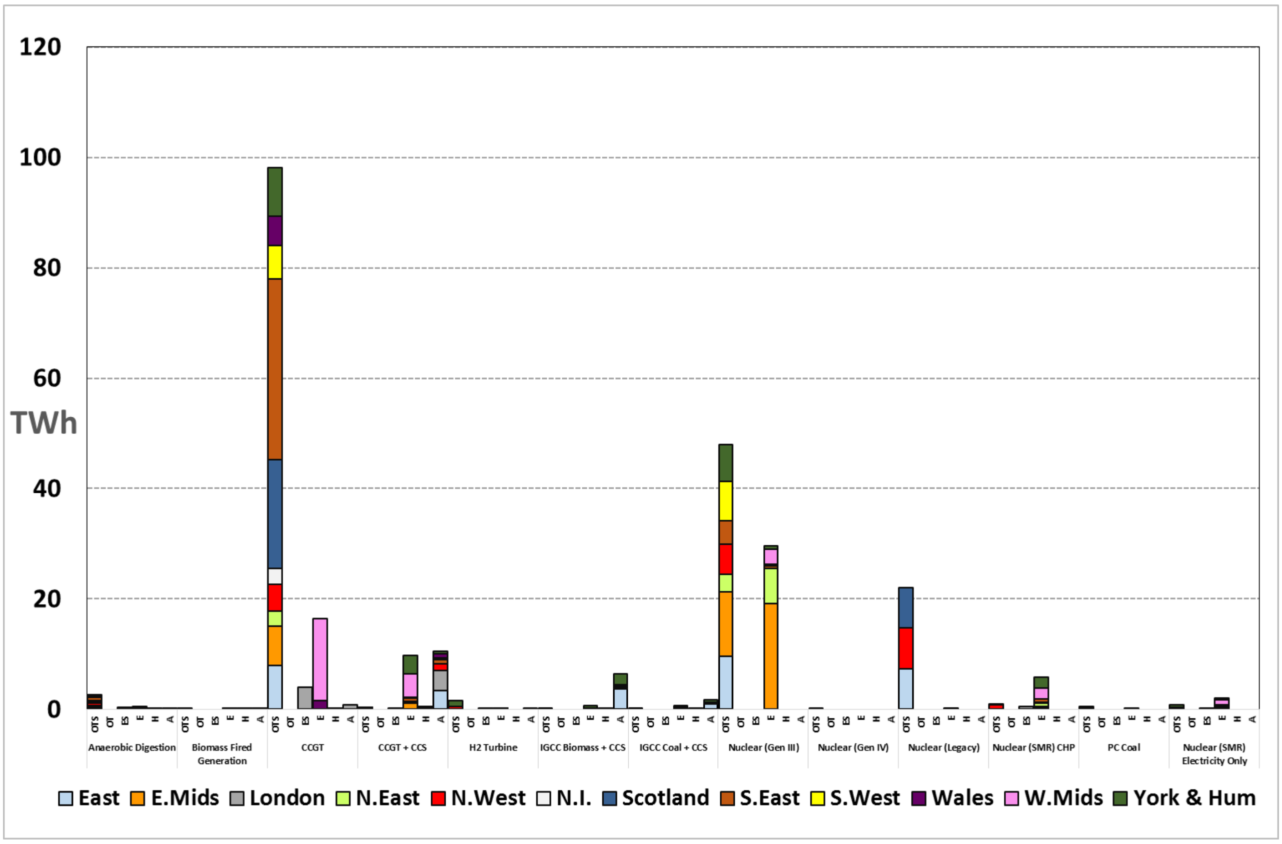

Figure 6.6 Regional Generation by Technology and Cooling Method 2030 Q95 SWL

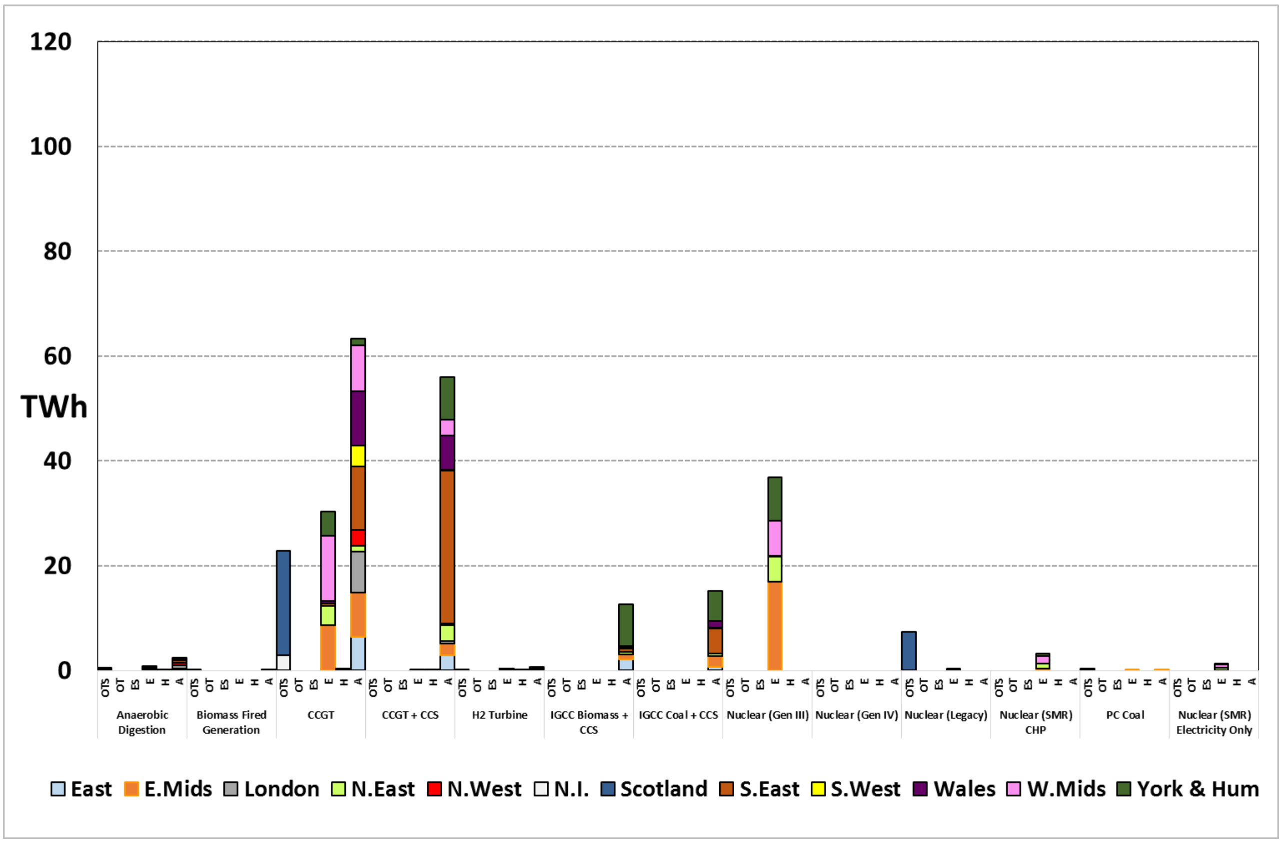

Figure 6.7 Regional Generation by Technology and Cooling Method 2030 Q95 SWN

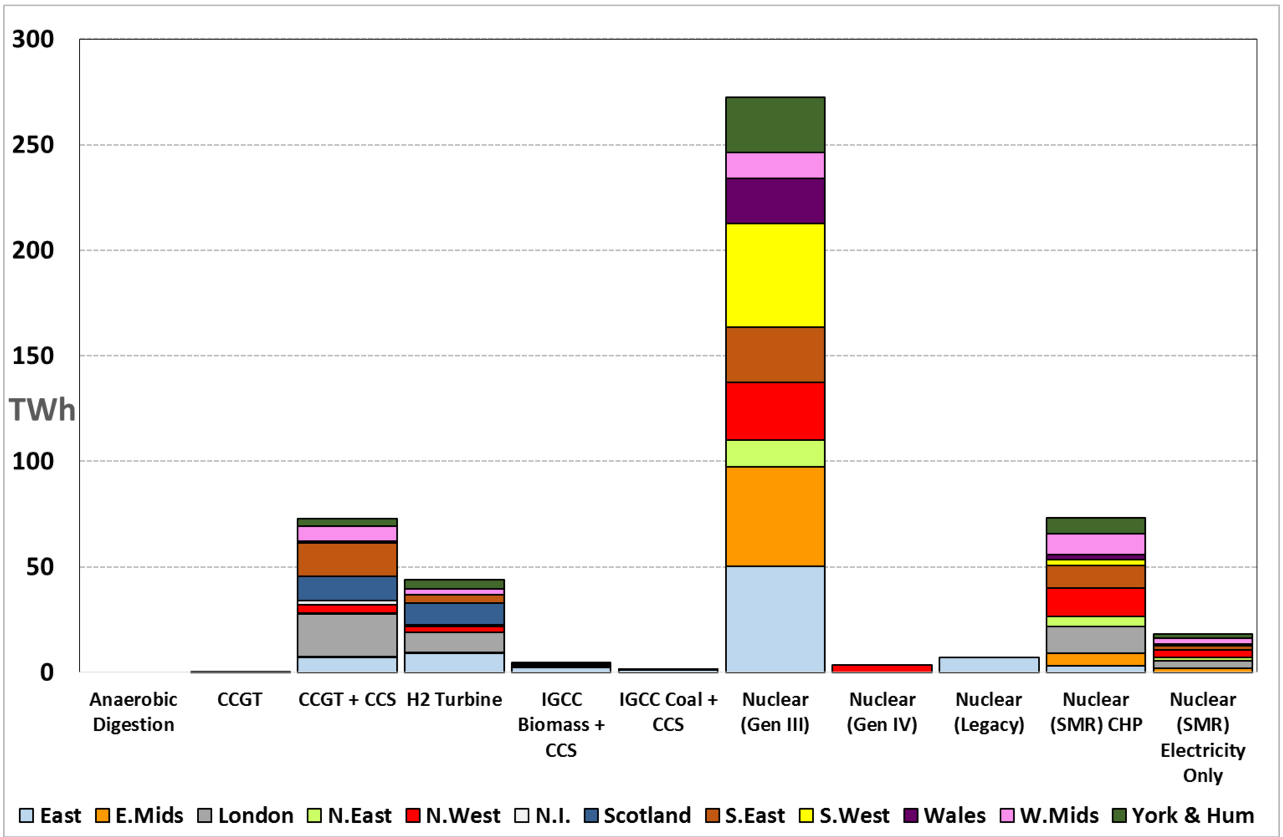

Figure 6.8 Regional Generation ESME.MC Standard 2050

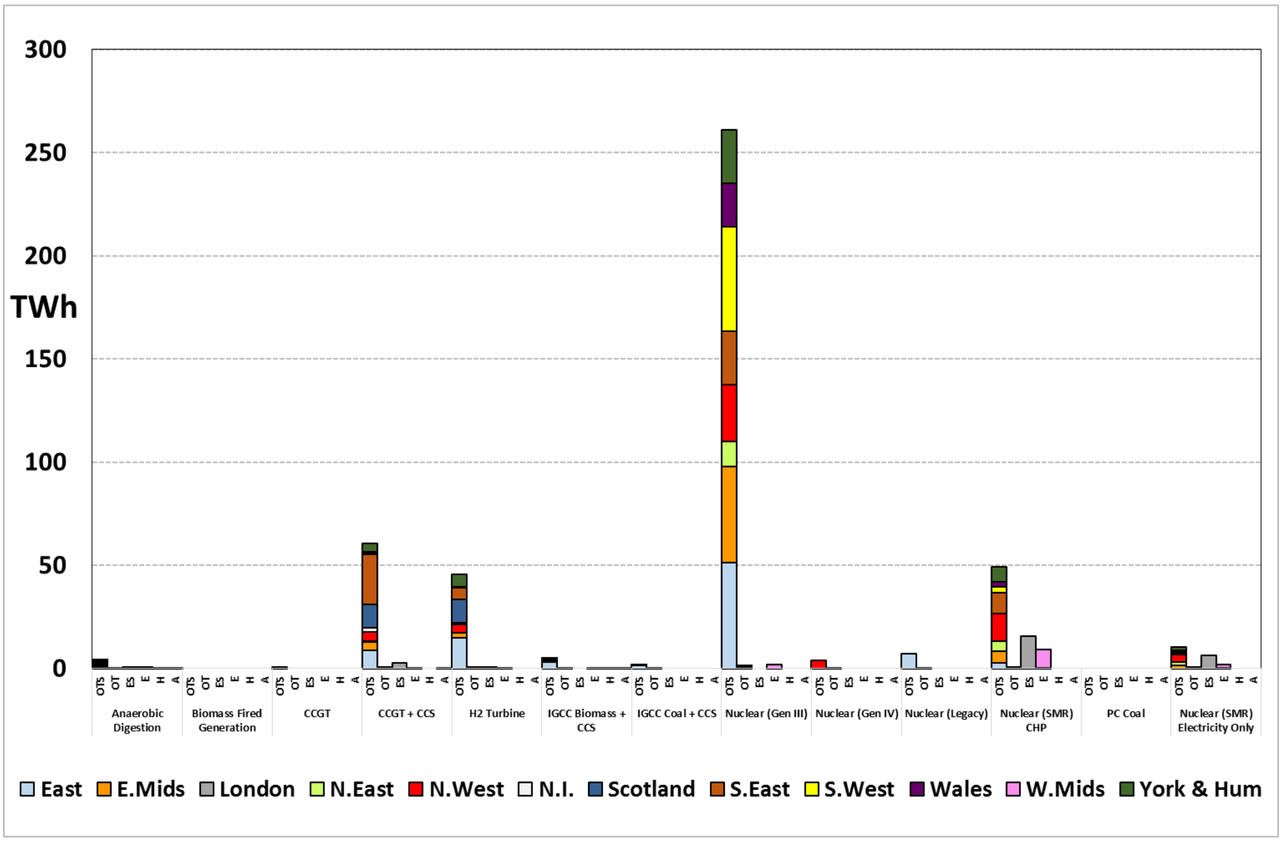

Figure 6.9 Regional Generation by Technology and Cooling Method 2050 Q70 SW

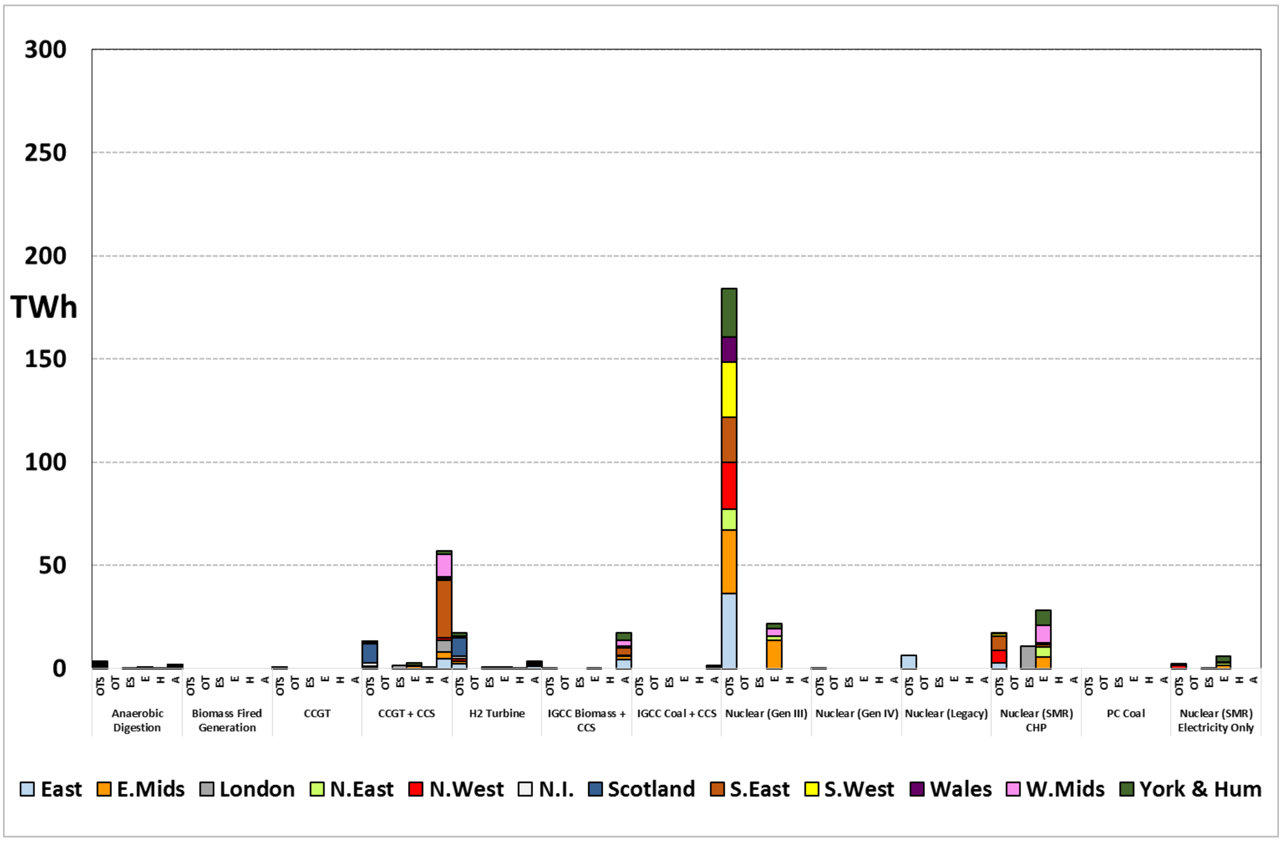

Figure 6.10 Regional Generation by Technology and Cooling Method 2050 Q70 SWL

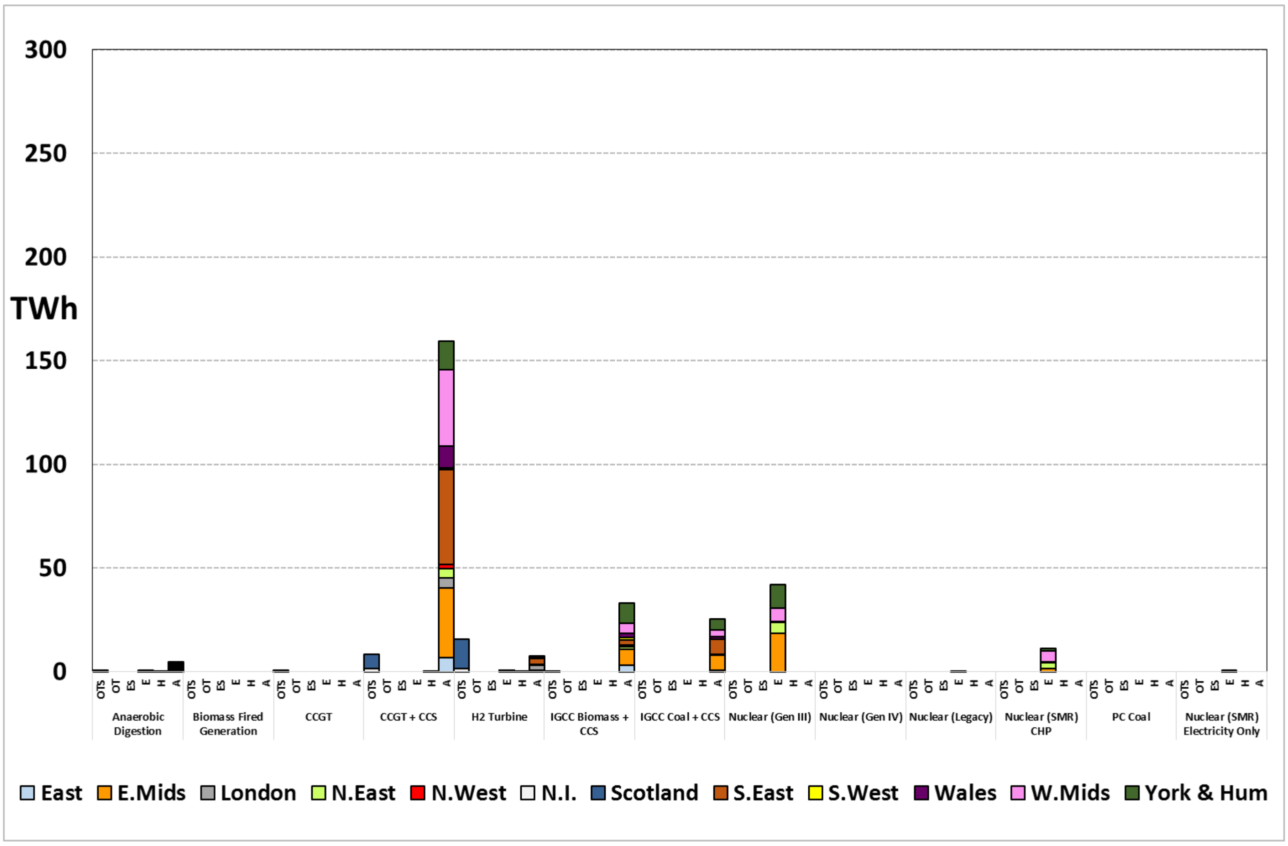

Figure 6.11 Regional Generation by Technology and Cooling Method 2050 Q70 SWN

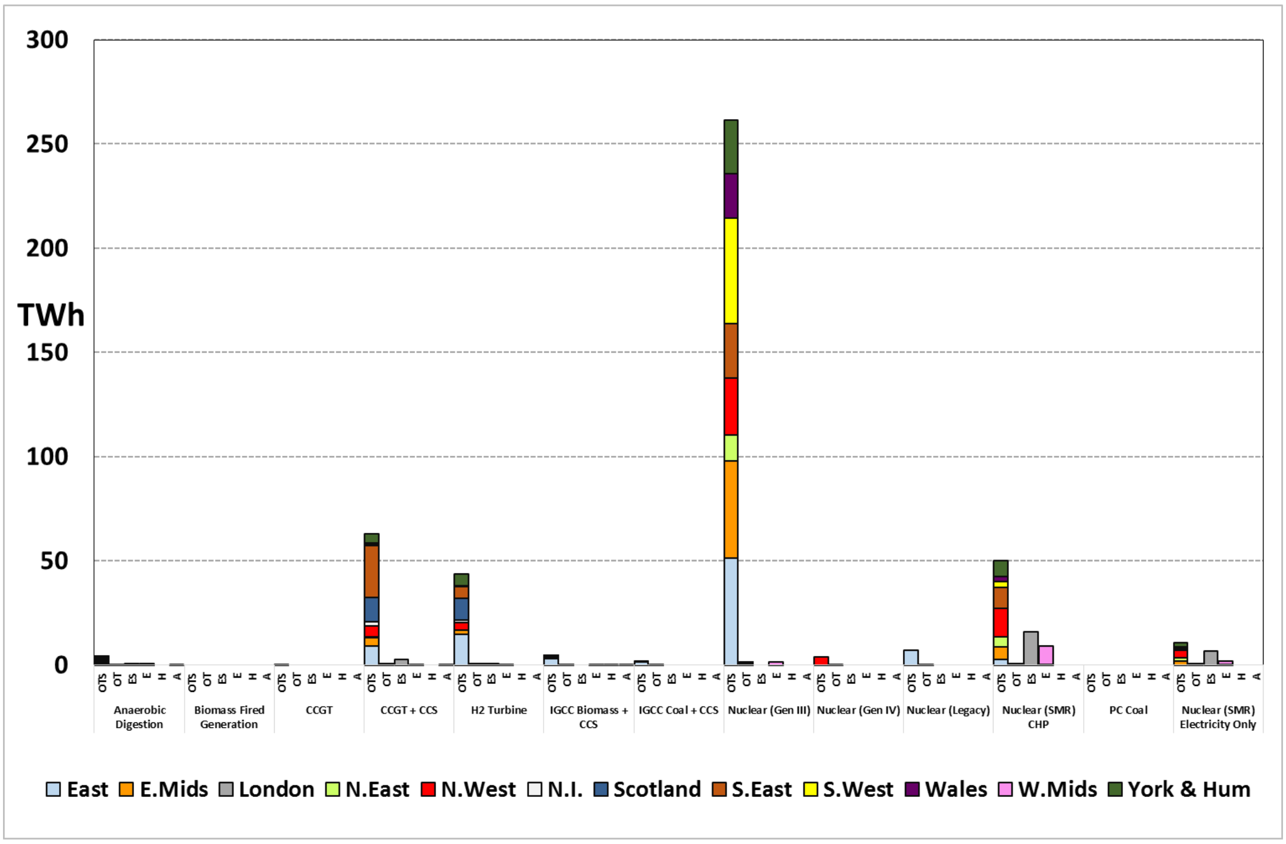

Figure 6.12 Regional Generation by Technology and Cooling Method 2050 Q95 SW

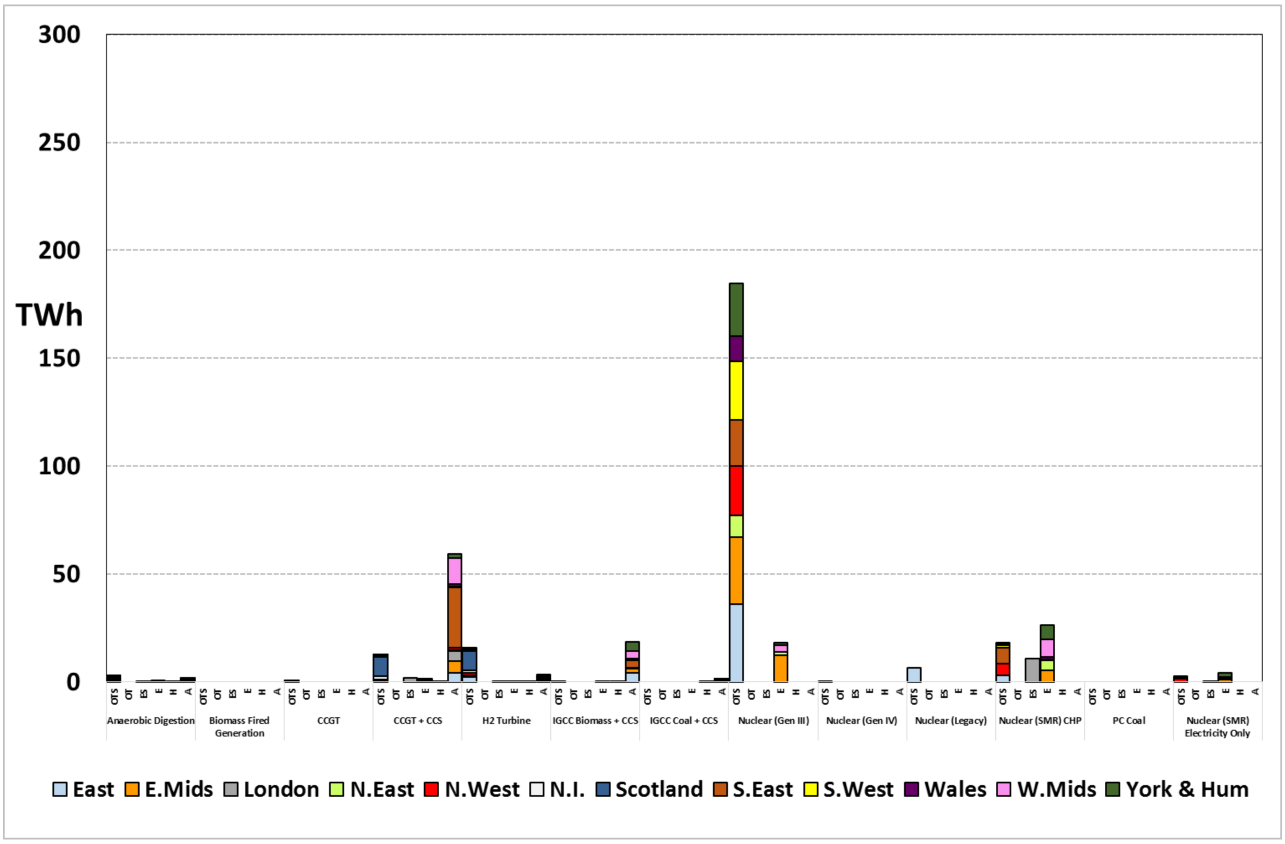

Figure 6.13 Regional Generation by Technology and Cooling Method 2050 Q95 SWL

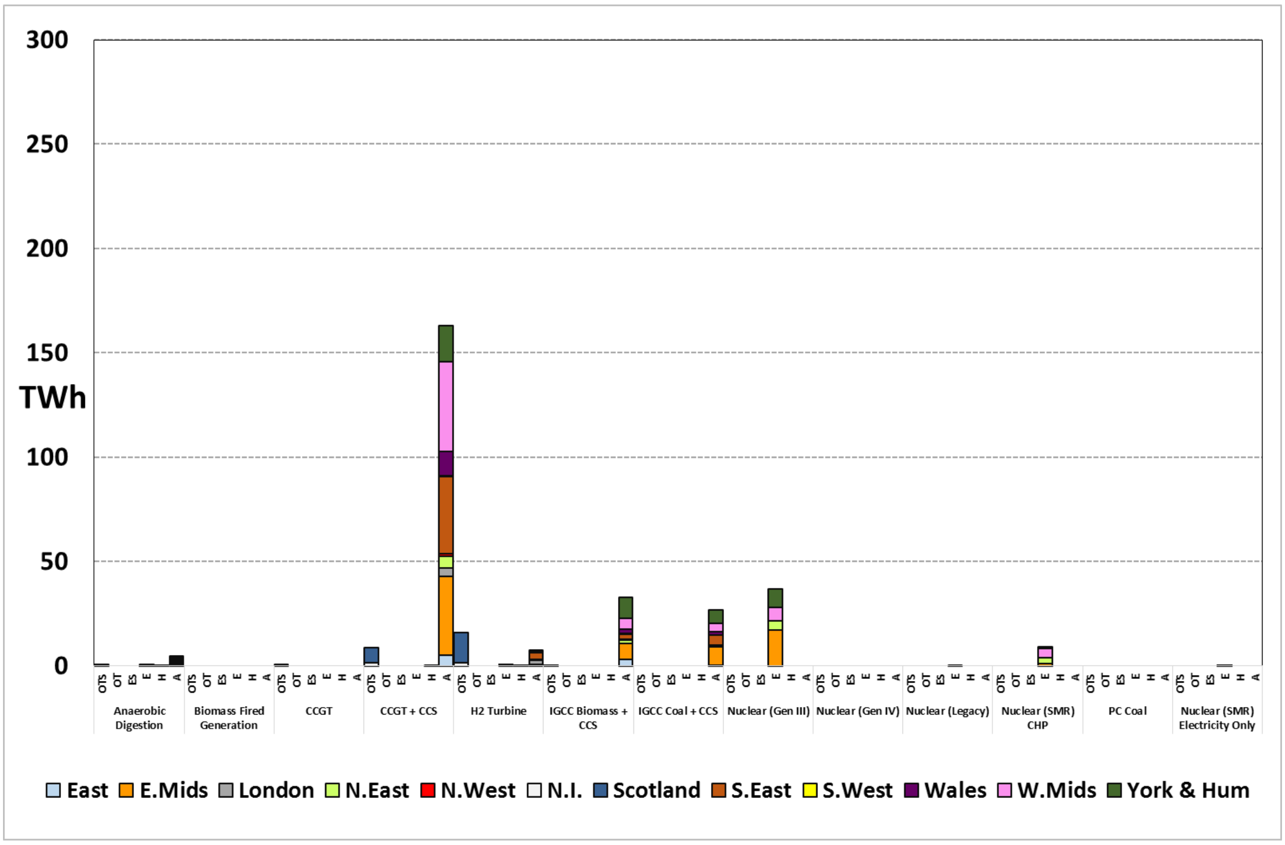

Figure 6.14 Regional Generation by Technology and Cooling Method 2050 Q95 SWN

As per the methodology for 2030 and 2050, both Q70 SW scenarios (Figs 6.2 and 6.9) confirm that with the exception of the West Midlands and London, all thermal generation does use once-through cooling. As the West Midlands is limited to Q70 freshwater, and London is limited to Q70 freshwater or evaporative cooling with sea water, neither region can be a major generator. This is because ESME calculates for the Q70 SW scenario it will be cheaper to ‘import’ electricity from neighbouring regions, rather than the West Midlands and London resorting to their own more costly cooling methods. This effect is in general reduced as the move to SWL, and particularly SWN, increases the generation costs of all regions.

For Q70 SWL at 2030 (Fig 6.3) there is still sufficient seawater to support the majority of nuclear generation but now, in addition to once-through, evaporative cooling becomes necessary and explains the relative low loss of thermal generation. However, this is not the case for Q70 SWL at 2050 (Fig 6.10), for while seawater is still available there is now relatively less freshwater and, far more demand to support. The result is a significant reduction in thermal generation. At Q70 SWN even at 2030 (Fig 6.4), for England and Wales no once-through cooling is now possible, so while the loss in thermal generation can be seen again to be limited by the use of the alternative cooling methods, it is still significant. For Q70 SWN at 2050 (Fig 6.11) the amount of Q70 freshwater available is so little, that 37% of the original thermal generation is now lost (Table 6.8).

The results also show that as the nuclear generation is lost at both 2030 and 2050, the fossil fuel + CCS generation required to provide base load and cover the intermittency of the wind generation that replaces nuclear, is seen to increase. This generation, as with any thermal generation chosen, is seen to increasingly have to select the less water intensive, more costly evaporative, hybrid and air cooling methods as seawater is reduced from the SW to SWN scenarios.

6.3.5 Annualised Cost Differences of Limiting the Seawater Available for Cooling

For 2030 and 2050 the cost consequences of limiting seawater are shown by Tables 6.13 and 6.14. They show for each year the itemised annualised costs of that part of ESME's total energy system which is attributable to the electricity system for each scenario. Table 6.15 for discussion purposes summarises the results obtained. Again only the Q70 results are discussed. At 2030 the increase in cost attributed to constraining seawater is at Q70 SWL £0.67bn (1.56%); and at Q70 SWN £3.63bn (8.48%): for 2050 at Q70 SWL £1.75bn (2.95%); at Q70 SWN, £7.61bn (12.8%). Looking at the reasons for the increases for 2030, it is attributable to the increase in Resource cost which is consistent with the reduction in generation efficiency that the loss of seawater, and the increased uptake of the less water intensive cooling methods introduces. At 2050, the total increase in cost is now partly attributed to Resource, but the greater need to distribute electricity more, caused partly by the greater uptake of intermittent renewables, incurs a greater Transmission Investment cost. An increase in Fixed Technology Operational costs is offset by a reduction in Technology VOM.

Table 6.13 Annualised Electricity System Costs 2030 (£bn)

2030 Annualised Costs (£bn)	Scenarios						
	ESME.MC Standard	**Q70 SW**	**Q95 SW**	**Q70 SWL**	**Q95 SWL**	**Q70 SWN**	**Q95 SWN**
Resource	26.88	26.87	26.89	27.49	27.56	30.47	30.86
Storage Fixed	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Storage Investment	0.20	0.23	0.23	0.16	0.16	0.01	0.01
Storage VOM	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fixed Technology Operational Costs	3.51	3.51	3.51	3.49	3.50	3.70	3.70
Technology Investment	10.81	10.87	10.87	11.06	11.07	11.02	10.88
Technology Retrofit	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Technology VOM	0.85	0.85	0.85	0.83	0.83	0.58	0.55
Transmission Flow	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transmission Investment	0.46	0.49	0.49	0.47	0.46	0.68	0.71
Total Cost	**42.74**	**42.85**	**42.85**	**43.52**	**43.60**	**46.48**	**46.74**

Table 6.14 Annualised Electricity System Costs 2050 (£bn)

2050 Annualised Costs (£bn)	Scenarios						
	ESME.MC Standard	**Q70 SW**	**Q95 SW**	**Q70 SWL**	**Q95 SWL**	**Q70 SWN**	**Q95 SWN**
Resource	18.22	18.20	18.02	17.90	17.94	21.82	22.01
Storage Fixed	0.02	0.02	0.02	0.02	0.02	0.03	0.03
Storage Investment	0.07	0.07	0.07	0.10	0.10	0.05	0.05
Storage VOM	0.01	0.02	0.02	0.02	0.02	0.01	0.02
Fixed Technology Operational Costs	7.90	7.93	7.94	8.47	8.51	9.67	9.70
Technology Investment	27.87	28.10	28.26	28.91	28.90	28.46	28.39
Technology Retrofit	0.45	0.41	0.42	0.43	0.44	0.13	0.13
Technology VOM	2.64	2.63	2.63	2.09	2.06	0.88	0.84
Transmission Flow	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transmission Investment	2.02	2.06	2.08	3.24	3.30	5.99	6.14
Total Cost	**59.21**	**59.44**	**59.44**	**61.20**	**61.30**	**67.05**	**67.31**

Table 6.15 Difference in Electricity System Cost between Scenarios

	2050		2050
Difference Q70 SW Total Cost and Q70 SWL Total Cost (£bn)	1.75	**Difference Q95 SW Total Cost and Q95 SWL Total Cost (£bn)**	1.86
% Difference	2.95	**% Difference**	3.13
Difference Q70 SW Total Cost and Q70 SWN Total Cost (£bn)	7.61	**Difference Q95 SW Total Cost and Q95 SWN Total Cost (£bn)**	7.87
% Difference	12.8	**% Difference**	13.2

Constraining seawater for thermal electricity generation also has the potential to bring additional cost consequences to the UK's total energy system, which is the price that ultimately has to be paid. With the figures available, the opportunity was taken to process and present the annualised total energy system costs for 2030 and 2050 for information as Table 6.16 and Table 6.17; with the summary shown in Table 6.18. Comparing the Electricity System and Total Energy System cost, it is seen both are of a similar form but it is the Electricity System that is seen to carry the bulk of any cost increase across the scenarios.

Table 6.16 Annualised Total Energy System Costs 2030 (£bn)

2030 Annualised Costs (£bn)	Scenarios						
	ESME.MC Standard	**Q70 SW**	**Q95 SW**	**Q70 SWL**	**Q95 SWL**	**Q70 SWN**	**Q95 SWN**
Resource	59.68	59.65	59.65	60.16	60.24	63.02	63.42
Storage Fixed	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Storage Investment	0.78	0.81	0.79	0.76	0.76	0.61	0.61
Storage VOM	0.12	0.12	0.12	0.11	0.11	0.12	0.11
Fixed Technology Operational Costs	27.72	27.71	27.73	27.79	27.79	28.08	28.10
Technology Investment	146.09	146.12	146.23	146.53	146.54	147.02	146.91
Technology Retrofit	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Technology VOM	0.85	0.85	0.85	0.83	0.83	0.58	0.55
Transmission Flow	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transmission Investment	0.46	0.49	0.49	0.47	0.46	0.68	0.71
Total Cost	**235.72**	**235.75**	**235.87**	**236.64**	**236.75**	**240.13**	**240.42**

Table 6.17 Annualised Total Energy System Costs 2050 (£bn)

2050 Annualised Costs (£bn)	Scenarios						
	ESME.MC Standard	Q70 SW	Q95 SW	Q70 SWL	Q95 SWL	Q70 SWN	Q95 SWN
Resource	46.82	46.79	46.46	46.39	46.42	49.62	49.77
Storage Fixed	0.02	0.02	0.02	0.02	0.02	0.03	0.03
Storage Investment	1.95	1.95	1.95	1.94	1.93	1.83	1.83
Storage VOM	0.36	0.36	0.36	0.37	0.36	0.34	0.34
Fixed Technology Operational Costs	35.24	35.11	35.16	35.65	35.69	37.05	37.08
Technology Investment	209.99	210.11	211.16	212.59	212.66	216.08	216.21
Technology Retrofit	5.15	5.03	5.08	5.22	5.23	4.74	4.74
Technology VOM	2.64	2.63	2.63	2.09	2.06	0.88	0.84
Transmission Flow	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transmission Investment	2.02	2.06	2.08	3.24	3.30	5.99	6.14
Total Cost	**304.19**	**304.07**	**304.89**	**307.51**	**307.68**	**316.57**	**316.99**

Table 6.18 Difference in Total Energy System Cost between Scenarios

	2050		2050
Difference Q70 SW Total Cost and Q70 SWL Total Cost (£bn)	3.44	**Difference Q95 SW Total Cost and Q95 SWL Total Cost (£bn)**	2.79
% Difference	1.13	**% Difference**	0.92
Difference Q70 SW Total Cost and Q70 SWN Total Cost (£bn)	12.49	**Difference Q95 SW Total Cost and Q95 SWN Total Cost (£bn)**	12.10
% Difference	4.11	**% Difference**	3.97

6.3.6 Sensitivity Analysis

The Monte Carlo approach employed by the ESME.MC pathway means that for each input parameter a result is produced for each of the 100 simulations. This chapter's methodology uses the averaged results of these simulations, but in the case of cost it is appropriate to show the range of the results obtained for each of the scenarios considered. Figures 6.15 and 6.16 show the range of electricity system costs produced by the ESME.MC pathway for 2030 and 2050. The extremes shown are the highest and lowest costs found. Equivalent figures for the Total Energy System were found to show a similar trend and are included as Figures 6.17 and 6.18.

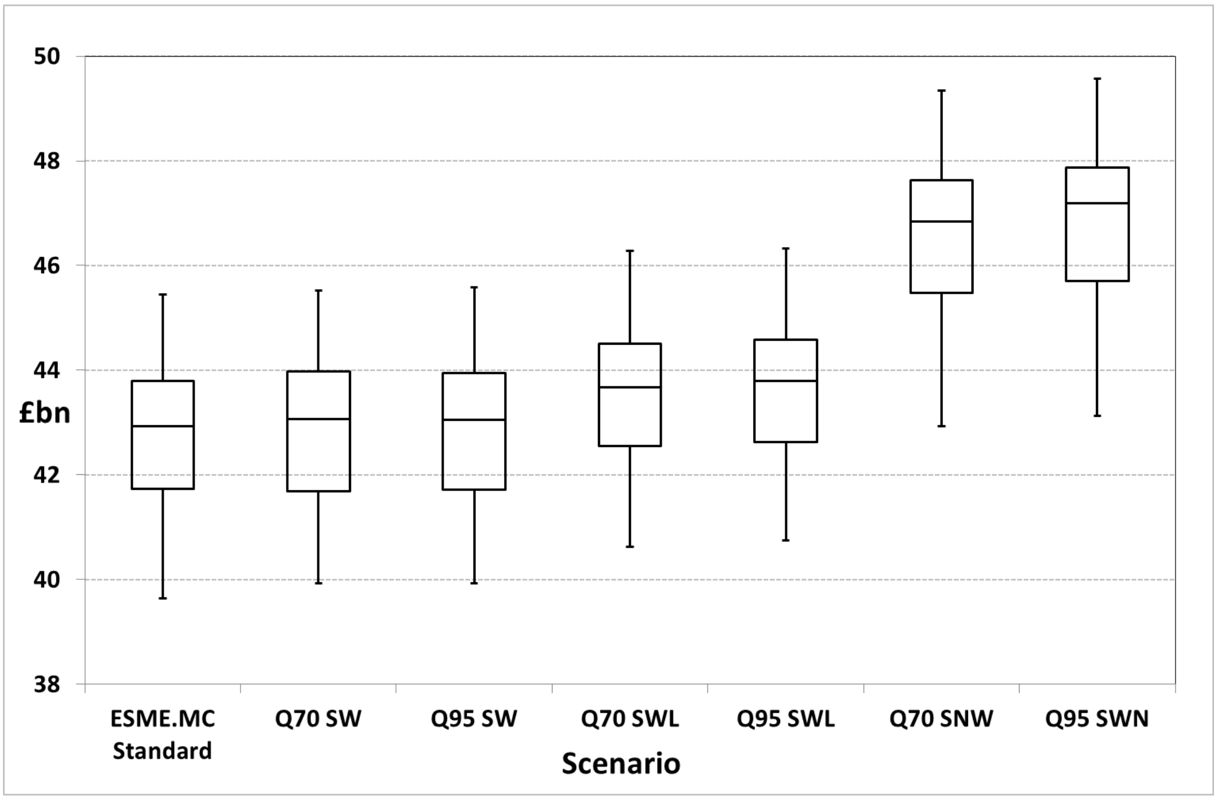

Figure 6.15 Box and Whiskers Plot Annualised Electricity System Cost 2030 (£bn)

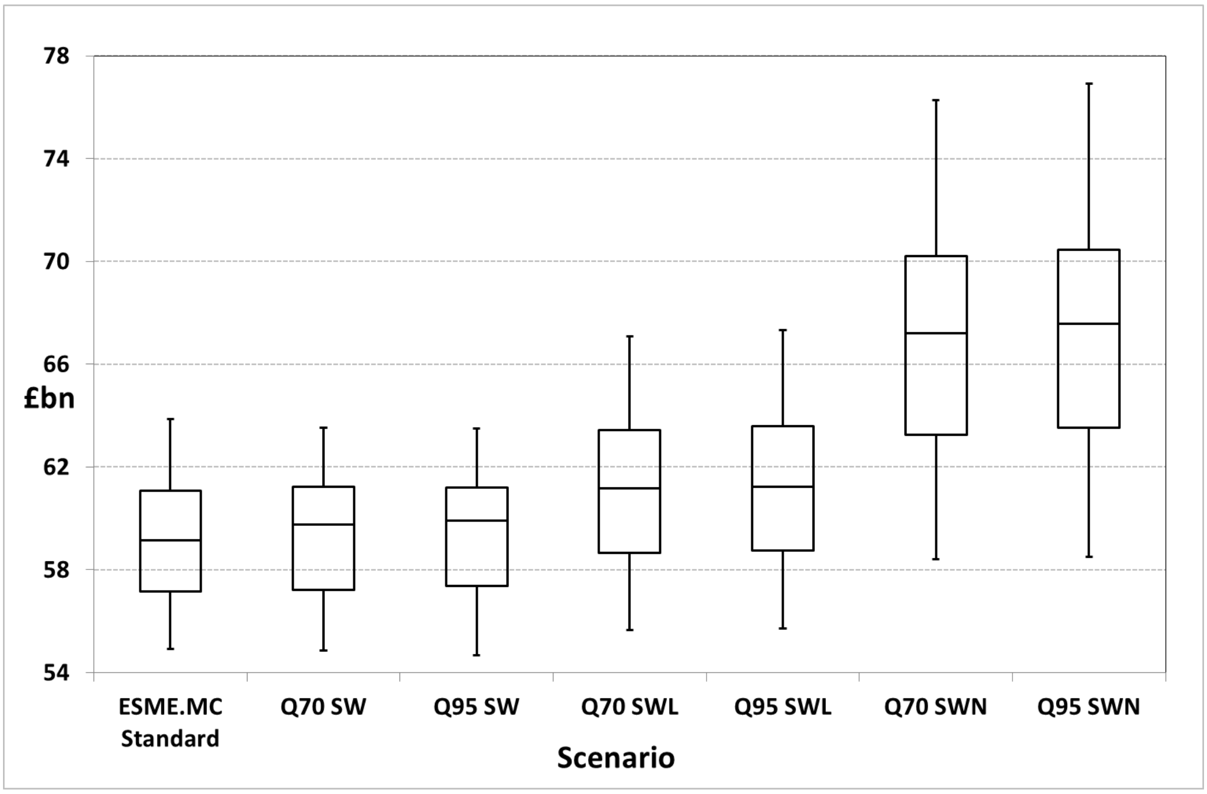

Figure 6.16 Box and Whiskers Plot Annualised Electricity System Cost 2050 (£bn)

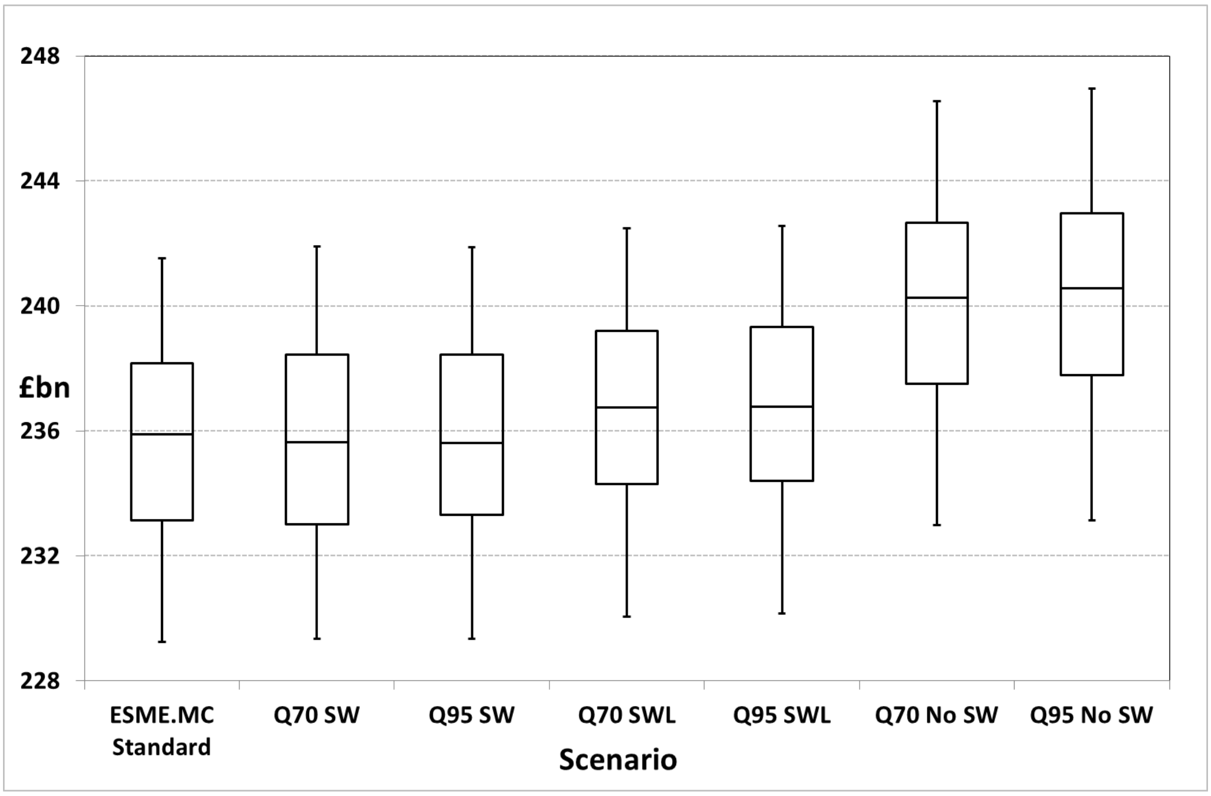

Figure 6.17 Box and Whiskers Plot Annualised Energy System Cost 2030 (£bn)

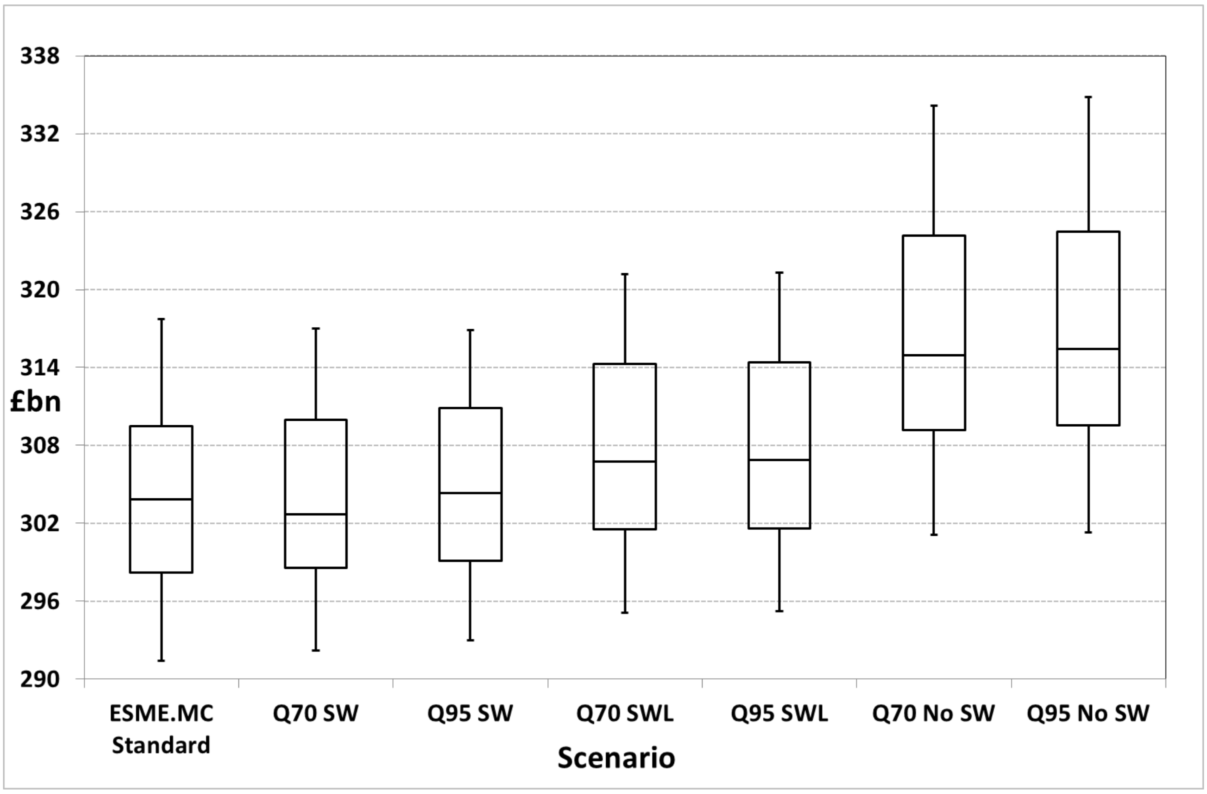

Figure 6.18 Box and Whiskers Plot Annualised Energy System Cost 2050 (£bn)

For both the electricity system and the total energy system, the 2030 and 2050 results show in general the data is relatively evenly spread, despite some variation from scenario to scenario. However, the range of the datasets is greater for the 2050 scenarios, reflecting the greater uncertainty at the longer timeframe. Additionally, at 2050 the datasets of all SWN scenarios are spread more widely about the median, and there is a greater range between the extremes than for the other scenarios. In 2030 the datasets of all SWN scenarios again shows a relatively large range between the extremes. This suggests that any uncertainty around the costs of the future UK electricity system, and indeed the energy system as a whole, increase as seawater is constrained, and at the more distant timeframe.

6.4 Discussion

This chapter has considered how the cost-optimised generation technologies selected by the ESME.MC pathway, to deliver the UK's future demand for secure and affordable electricity could be compromised by a lack of required water. It has shown that when water is not considered, the ESME.MC strategy relies implicitly on increasing the amount of thermal generated electricity to 2050, with nuclear power being the main provider. Based upon this, the ESME.MC pathway is misleading if all the water assumed to be available for the thermal generation is in fact not available.

The relevance of this chapter, and indeed the thesis as a whole, is that the ESME.MC pathway's choice of generation technologies to 2050 is similar to the currently preferred UK energy policy for meeting that demand. This is via a portfolio of thermal generation comprising of new nuclear power and fossil fuel generation fitted with CCS, backed by renewables (DECC, 2015a, HM Government, 2011a). Although the standard ESME.MC pathway does not consider water demand, its generation portfolio and costs are very similar to that of this chapter's SW result. This clearly implies that in effect the ESME.MC pathway assumes the water required for the BAT once-through cooling of its thermal generation is available. Therefore, determining the actual generating cost significance of how the ESME.MC pathway is in practice impacted by the amount of cooling water actually available brings a vital "affordable" reality critique not only to ESME, but also to the UK's energy policy.

Looking at the results obtained by limiting the seawater available, as required by this chapter's methodology, in each case the corresponding Q70 and Q95 figures were found to be similar. The explanation was that even at the higher Q70 volume, the cooling water available was relatively so low compared to that required, the further Q95 constraint made little difference. Comparing the figures of Table 6.1 and Table 6.3 confirms this. They show the freshwater support that can reasonably be expected for any future thermal electricity generation ambition, falls well short of any BAT cooling volumes required. Understanding how the methodology varies the amount of cooling water it makes available provides a yardstick by which to understand the results obtained.

The methodology that produced the results obtained assessed how the water available to the cost-optimised ESME.MC pathway affected the generation and cooling method technology choices that could be made. It did this by considering installed capacity, electricity generation, and associated costs under the ESME.MC pathway, all of which were found to be in line with the water made available (Tables 6.1, 6.2 and 6.3). For 2030, for Q70 flows to meet a generating demand around 330TWh, the study found the annualised cost of the electricity system, under the scenarios compared, to be: SW £42.85bn; SWL £43.52 (+0.67GW, +1.6%); SWN £46.48bn (+3.63GW, +8.5%). For 2050, for Q70 flows to meet a generating demand of the order of 595TWh the annualised costs were: SW £59.44bn; SWL £61.22bn +1.78GW, +3%); SWN £67.05bn +7.61GW, +12.8%).

Ensuring that the UK can meet its future energy generation demand and emissions targets in an affordable manner is rightly a reasonable and fundamental requirement of the UK's energy policy. Indeed, keeping energy bills as low as possible became part of the Government's 2015 election manifesto (Conservative Party, 2015). With 18% of all UK households defined as being fuel poor in 2012 (Sovacool, 2015), it is clear that any policy that increases electricity costs more than necessary needs to be avoided. Thermal infrastructure has lengthy planning procedures, and long operational lifetimes, that from concept to redundancy can span several decades. Energy policy is therefore a long term strategy and the new 2050 generation infrastructure should already be moving from the concept stage, through planning, to becoming confirmed build projects. The UK's recent performance in rolling out new thermal generation is characterised by delay and uncertainty, illustrated by the recent events over the proposed Hinkley Point C nuclear power station (section **7.3.1.1**), to a point where investors (the generators) claim they do not know what the end generation technologies are going to be. The delays have reached a point where the rate old generating plant is being withdrawn or mothballed is so outpacing any new build that OFGEM and the National Grid have commented on the limited spare generation capacity the UK now has available to cover demand emergencies (Newbery, 2016, OFGEM, 2015, Royal Academy of Engineering, 2013).

This chapter finds that it is the current approach to meeting the 'affordable' energy objective that is creating the uncertainty, especially when affordability is a relative term. There is no argument that thermal generation using the BAT once-through cooling, and its associated large quantities of cooling water, will provide cheaper electricity than if the less water intensive cooling methods are used. The existing standoff seems to be around whether electricity generated using the more expensive, but less water intensive cooling methods is still affordable? The generators' argument is the disproportionate priority being given to protecting the environmental and ecological status of water bodies, not only reduces available freshwater for abstraction, but contrary to expectations now seems likely to limit the availability of seawater (Energy UK, 2014). Now only the more expensive generation will be possible. The generators' opinion is the general public and business will not consider it to be affordable, and consequently profit will be difficult to come by (Energy UK, 2014).

Policymakers need to recognise that the future economic wellbeing of the UK will in a price conscious world be determined by its global competiveness; this provides another definition of affordable. In one form, or another, it was found that thermal generation is seen as continuing to be the main provider of global energy. Globally, and in the UK, it was confirmed thermal power stations are already unable to withdraw all the cooling water they would like. Globally, and in the UK, the demand for thermal generation is predicted to increase, and the amount of freshwater available to thermal power stations to get less (section **2.4**). This chapter's findings show that if fully recognised, and acted upon, seawater can provide the UK with a global cost competitive electricity generation advantage. Although this chapter focused on the UK's thermal generation, the generation cost advantages found surely have connotations for other countries with large electricity demands in close proximity to seawater resources.

6.5 Conclusion

This chapter considers how different amounts of sea and freshwater resource made available to each of the UK's regions at 2030, and 2050, would impact the ESME.MC cost optimised choice of generation and cooling method combinations. This is to meet 2030, and 2050, forecasted generation demands. It found that freshwater alone could not support the level of thermal generation required by the ESME.MC pathway in either year without the significant use of the less water intensive cooling methods; this includes the use of air cooling. As the level of seawater made available is constrained to the point where only freshwater is available, the cost optimised level of thermal generation possible falls by 37% in 2050. It is replaced by the now cheaper, and non-water requiring renewable technologies, particularly offshore wind. This incurs an annualised cost increase of 12% (approx. £7.5bn per annum) in the UK electricity system by 2050. This is relative to the non-constrained seawater scenarios. This increase in annualised generation cost is directly attributable to a combination of thermal generation having to resort to the less efficient, less water intensive, cooling methods, and the greater deployment of renewables.

This suggests that the UK, with its high thermal generation ambition, and a large seawater resource, is in the enviable position of having a range of cooling water options, within which it can decide just how globally competitive it wants its future electricity generation to be. The poles between which this decision lies are the costs of providing the coastal environmental protection thought warranted, and the additional electricity generation cost thought acceptable. The uncertainty surrounding this decision has been due to a lack of figures in the environment cost columns; this chapter has gone some way to resolving this uncertainty.

Chapter 7 - Discussion of Results

7.1 Overview

A series of results have been produced by Chapters 4-6, each with accounts of different approaches used to explore how the UK's future energy policy could be disrupted by a lack of available water. This chapter will now discuss the overall implication these results have for a UK energy policy that currently sees building more thermal electricity generation infrastructure as the likely means of meeting an increasing demand for low carbon energy. The basis of this study was the ETI's ESME model, and particularly the ESME.MC pathway, which has been shown to provide a close analogue of the UK's future electricity generation policy. This study's main interest at first was the effect a future shortage of UK freshwater, as seen in section **2.4**, would have for the UK's thermal generation interests. However, with the preliminary results of Chapters 4 and 5 available, and the findings of the literature review undertaken in Chapter 2, there was immediately evidence that the extent the UK's seawater resource was to be made available would be an important factor in defining the consequences of any freshwater shortage. The water demands were therefore thought best studied as - freshwater and total water (defined as being predominantly sea and estuarine water, but with a small freshwater content).

7.2 Summary of Findings

At this stage of the thesis, while other ESME and Carbon Plan pathways water demands were considered at the national level, the ESME.MC pathway is identified as being the thesis' prime interest and will be the focus of further discussion.

7.2.1 Unconstrained National and Regional Water Demands of UK Thermal Generation under the ESME.MC Pathway

In section 4.3 a methodology was developed that could be used to quantify the national water demands, relative to 2010, of the ESME.MC pathways' thermal generation at 2030 and 2050. While the national results were of interest, it was understood the water available will vary from region to region, as will water demand, as will energy demand. Thus while comparative national water demands were of interest, it was further understood they are of limited value from a policy perspective. Chapter 5 therefore developed Chapter 4's methodology to enable the more focused ESME.MC pathway's regional water demands at 2030 and 2050, relative to 2010, to be determined.

The unconstrained regional and national analysis could only provide a subjective comparison of the ESME.MC pathway's future cooling water demands. This was because whether the amount of cooling water needed to make the pathway feasible would be available in the future, was not at this point a modelling consideration. The results obtained at 2030 and 2050 were to be regarded as a wish list of water demands, that in some ways was a pro rata increase from 2010 that matched the increase in generation at 2030 and 2050. The methodologies used to determine the national and regional demands were, however, shown not to employ this simplistic approach. This aside, the national and regional water demand results obtained were informative in pointing out the potential scale of water availability problems that awaited the UK's future thermal generation policy. This has to be judged by comparing the greater amount of water being asked for in the future, against the lower amount asked for in 2010, which it has been shown was not always available, even then.

With the extra layer of detail the regional modelling provided, for the first time, albeit implicitly, there was an unexpected challenge to the concept that all the water required was available. For the West Midlands, because it is landlocked, the methodology makes sea and estuarine water unavailable. The effect of this was that for the West Midlands freshwater is now the only cooling water option available. The ESME.MC pathway can only deploy thermal generation in the West Midlands to the extent that it can use freshwater, and the less water intensive cooling methods. The result is the West Midlands' freshwater abstraction and consumptions demands under the ESME.MC pathway, relative to 2010, were, by 2050, found to increase x7 and x8 respectively. The regional analysis also identified Yorkshire and Humber, the North West and the South East regions, even with seawater available, as having significant freshwater demands by 2050. The regional analysis could now identify regions where a future shortage of freshwater would put the level of thermal electricity generation assumed by the ESME.MC pathway for, 2030 and 2050, at risk.

7.2.2 Constrained Regional Water Demands of UK Thermal Generation under the ESME.MC Pathway

Initially the main focus was on freshwater availability, as published studies had identified there were potential climate change and population growth events that would limit its future availability. However, by Chapter 5 it had been confirmed while a lack of seawater to the West Midlands could not affect the freshwater available, conversely, a lack of seawater would increase greatly that region's freshwater demand by 2050. Consideration of the availability of seawater for cooling (section **2.3**), had established that while seawater resource's physical availability was not questioned, environmental and ecological issues were already constraining its use. Therefore for the UK with an inexhaustible seawater resource it was suggested that seawater's availability is of equal, if not greater importance than an apparently fait accompli shortage of freshwater to any 2050 thermal generation ambition the UK may have.

With the experience gained in working with the ESME.MC pathway Chapter 6 now saw the task to be to develop at the regional level a methodology to examine how the future availability of both freshwater, and seawater, would impact the generation technologies selected by the cost optimised ESME.MC pathway (section **6.2**). This has to be based on the water demand of each generation technology, and cooling method combination, and their associated cost. To do this, a number of additional datasets were developed and built into the

ESME.MC pathway, including cooling water constraint scenarios. The cooling water constraints applied were two that considered each region's available freshwater volumes (their Q70 and Q95 volumes), and three that considered each region's available seawater (SW – unlimited; SWL – limited; SWN – none). The Chapter 6 methodology would, therefore, now provide the cost and make-up of the UK's potential future electricity generation sector for a range of six different combinations of available freshwater and seawater.

The standard (non-water conscious) ESME.MC pathway's cost optimising favours the large adoption of thermal generation, at a cost which automatically assumes the use of the most cost efficient cooling possibility; the water intensive once-through cooling method. In practice it was shown this means the standard ESME.MC pathway assumes (unknowingly) that seawater will be available and unconstrained (i.e. at the SW level), as the freshwater resource available cannot support the cost-optimised level of water demand required. The constraining analysis of Chapter 6 was to confirm this.

As the volume of seawater available reduces, Chapter 6 found the generation technologies chosen by the ESME.MC pathway by 2050 changed dramatically with there being, overall, a distinct trend of less thermal generation (particularly less nuclear), and more renewable generation. The ESME.MC pathway tries to accommodate the shortage of available seawater by bringing the water intensive nuclear and fossil fuel + CCS generation infrastructure inland. Although given a shortage of freshwater made available by the methodology, this can only be achieved by the use of the less water intensive, cost increasing, alternative cooling methods. It is this increase in cost which results in the ESME.MC pathway selecting a greater uptake of renewable technologies.

The extent of the move away from cheaper, more water intensive thermal generation particularly nuclear, to renewables and the more costly, but less water intensive thermal generation, is shown by the results obtained by Chapter 6 (section **6.3**). The major generation technologies chosen by the ESME.MC pathway, under the extremes of the Q70 constraint scenarios modeled for 2050 were:

1. Seawater available (SW): Nuclear (275TWh, 46%), Nuclear SMR (92TWh, 16%), CCGT + CCS (63TWh, 11%), other technologies (163TWh, 27%).
2. Seawater none (SWN): CCGT + CCS (167TWh, 28%), Floating Offshore wind (117TWh, 20%) and Fixed Offshore wind (70TWh, 12%), other technologies (241TWh, 40%).

As a result of the above swings in technologies being used, the cost of generation for the 2050 (and 2030) scenarios inevitably increase as the seawater availability is constrained. Chapter 6 provides the details of the changes in technologies, associated cooling methods, and costs involved.

7.2.3 Cost Implications of Constraining Seawater

As ESME is a cost-optimised model, the changes in generation cost as seawater availability is constrained are reflected by the changing annualised costs of the electricity sector, and more broadly the energy system as a whole. Under Q70 freshwater conditions, the annualised cost of the UK electricity system by 2050 was shown to increase from the SW to SWN scenario by £7.6bn/year (12.8%); for the total UK energy system the cost increase was 12.5bn/year (4.1%). To put these increases in annualised costs into context, the net increase in Government departmental spending, on health and the NHS, in total over the next five years, is estimated at £11bn. £11.7bn was the controversial amount, despite the Government's austerity policy, that continued to be spent on foreign aid in 2014 (Department for

International Development, 2015, HM Treasury, 2016). From a private sector perspective, the estimated project cost of the proposed Hinkley Point C nuclear power station is estimated at £24.5bn (Godsen, 2014). These examples demonstrate that the potential scale of the annualised cost increase to the UK energy system, if thermal generation cannot be built in coastal locations, is nationally significant.

7.3 Limitations of Research Undertaken

The remainder of this chapter will discuss the limitations of the research undertaken, and the impacts this may have on the conclusions drawn from this thesis.

7.3.1 The ESME. MC Pathway's Generation Technology Assumptions

An attempt at this point in time, some three decades before 2050, to forecast the form of the future UK energy system, cannot for all manner of retrospectively found reasons be expected to be all-correct. ESME though, is not a forecasting tool and therefore does not make any attempt to do this. Instead, in the case of the ESME.MC pathway, it works with the data that is built into the model to design the best future energy system. Here 'best' is defined as the cheapest, whilst still meeting projected energy demand, and emissions reduction targets. This allows the implications of choosing individual technologies, and their appropriate cooling methods, within the constraints of the modelling parameters, and their uncertainty range, to be considered and selected.

Despite this design rather than forecasting approach of ESME, within the context of this thesis, it is appropriate to give some consideration to the likely future validity of the energy system, as projected by the ESME.MC pathways' study that has been carried out. The range of input parameters (e.g. energy resources, fuel prices and technology costs) for each technology are subjected to the Monte Carlo process (section **3.2.1**), which while providing an averaged result, also indicates the range of other possible answers that could apply. As the thesis has demonstrated through its sensitivity analysis sections (section **4.5.2** and section **6.3.6**), this does allow ESME's range of possibilities to be known, and thereby inform any decision making process. This is a specific uncertainty mitigation advantage ESME's Monte Carlo ability brought to this study's work. However, many of the generation technologies which the ESME.MC pathway foresees as contributing (many significantly) to the UK electricity sector by 2050, have question marks regarding their selection which will now be discussed.

7.3.1.1 Large Scale Nuclear Generation.

When cooling water is unconstrained, ESME's favoured cost-optimised technology is large-scale nuclear generation, with the ESME.MC pathway's Q70 SW scenario projecting it will provide over 46% (275TWh) of the UK's total generation/ annum by 2050. This thesis has, however, shown that there is a question as to whether nuclear generation achieves the UK's need to meet emission reduction targets in an adequately cost-effective way, if the cooling water required for once-through cooling is not available. This has been a key theme throughout this thesis and the extent to which this is true has been researched. However, given the known importance of nuclear generation to the UK's future energy plans, it would be wrong when considering what could limit nuclear generation, to ignore the compounding delaying factors away from cooling water availability which this research has identified. Especially as these also do have the ability to seriously frustrate the delivery of any new-build UK nuclear generation infrastructure.

The first proposed nuclear new build project in the UK since 1995 (Hinkley Point C), has found that planning and delivering new large scale nuclear generation is a far more protracted and costly affair than initially expected. The accident at the Fukushima Daiichi nuclear plant in Japan in 2011 raised questions about the Hinkley Point C project and delayed the construction plans of all European nuclear power stations whilst lessons were learnt (Joskow and Parsons, 2012). Furthermore for the UK it has been shown that new nuclear generation is already a very emotive issue (section **2.3.3**).

Hinkley Point C was originally due to be operational by 2017, but it has been beset by so many difficulties this date has had to be put back on a numerous occasions, with 2025 becoming a new suggested completion date (BBC, 2016, EDF Energy, 2015), although there is the suggestion the completion date could ultimately be even later (Davies, 2016). The method of financing Hinkley Point C was queried by the European Commission who undertook an investigation to assess whether financing of the project broke state aid rules (Černoch and Zapletalová, 2015). Although the conclusion was it did not (European Commission, 2014b), this created another level of uncertainty and delay.

The main delay arose from EDF's (the developer) decision to use EPR reactors for Hinkley Point C. This was to be a follow-on EPR project to the EPR projects already being constructed in Finland (Olkiluoto) and France (Flamanville). Unfortunately both these projects are proving to be much harder and costlier to build than budgeted. Amongst the EPR design advantages, the claim is it has in-built a high level of anti-terrorist resilience. Nevertheless the complex and expensive safety measures required have caused such cost and time overruns both projects are years behind time, and the viability of the EPR technology is being questioned (Locatelli and Mancini, 2012)..

EDF initially estimated the cost of Hinkley Point C at £16bn; it currently stands at £18bn. The European Commission is suggesting it will be £24.5bn, and warned it may rise as high as £34bn (Godsen, 2014). To incentivise EDF, and show support in light of these cost overruns, in 2013 the Government agreed to pay £92.50/MWh for Hinkley Point C's future generated electricity. Given the time overruns retrospectively, with the cost of fossil fuel and renewable generated electricity recently declining, paying such a high future price for Hinkley Point C's electricity, now raises the question is nuclear energy still the most cost effective means of electricity generation for the UK?. This developing contra position reached the point that when EDF finally confirmed its decision to proceed with Hinkley Point C (July 2016), the Government (under a new prime minister) unexpectedly responded by delaying giving the final approval for the project. It was stated that this was to allow time to carefully consider all the component parts of the project, although an attendant government statement declared "*the UK needs a reliable and secure energy supply and the government believes that nuclear energy will be an important part of the mix*" (Ruddick and Grierson, 2016). The Government has since given the go-ahead to Hinkley Point C (Department for Business Energy & Industrial Strategy, 2016), but this additional delay has raised further questions over the viability of UK nuclear generation as presently envisaged.

Whether these issues are simply an EPR 'first of a kind' issue that will be resolved by the 'learning by doing' process, or whether given the time the UK's nuclear ambitions have taken to materialise there may well be better thermal generation options is yet to be seen. Irrespective of this, the methodology developed in Chapter 6 will, when charged with the appropriate data, enable the ESME.MC pathway to evaluate other cost-optimised, water-constrained thermal generation options.

7.3.1.2 CCGT (and CCS Equivalents)

When seawater is not available the reduction in nuclear generation was found to lead to a greater reliance on CCGT and CCGT + CCS generation. This is to provide required baseload generation cover for the intermittency the replacement renewables introduce, and in respect of CCS to continue to be able to achieve emission targets. With North Sea oil and gas reserves in decline (Focus, 2014), more CCGT generation would lead to an increasing dependence on imported gas; this further increases the UK's exposure to fuel price and security of supply uncertainty (Demski et al., 2014, Wicks, 2009).

While the increased reliance on nuclear generation would increase the UK's need to import more uranium, relatively this is not seen as carrying either the same political, or cost of fuel price uncertainty as importing more natural gas. Uranium resources are spread across many countries, including many that are politically friendly to the UK; with Australia being the obvious example. Uranium has the added advantage that it is relatively easy, and inexpensive to stockpile. Unlike natural gas, the uranium fuel price is a relatively small proportion of a nuclear power station's annualised generation costs, so nuclear generation's cost is less susceptible to raw material price fluctuation (Wicks, 2009). Relative to nuclear generation, in terms of fuel imports, CCGT and CCGT + CCS generation therefore has disadvantages.

With natural gas generation, the great UK unknown is fracking. It is claimed that fracking could provide up to fifty years of the UK's current natural gas demand (British Geological Survey, 2014). If successful this eliminates the price and security of supply risks of gas imports (Hammond and O'Grady, 2016). However fracking is contentious; it is associated with causing well published adverse effects to the local environment; these include noise, odours, and in extreme cases earthquakes (Stamford and Azapagic, 2014, Yan et al., 2015). Then unfortunately many of the fracking locations are in sensitive wildlife habitats, and areas of landscape beauty (Helm, 2015). There are also challenges over fracking's real contribution to reducing greenhouse gas emissions. The claim being while shale gas produces less CO_2 than other fossil fuels, the levels of associated methane also released by fracking creates a net increase in global anthropogenic warming (Schaeffer et al., 2016). A separate study rejects this (Schaefer et al., 2016).

With regard to this thesis' interest in UK future freshwater scarcity, fracking is water-intensive, with the vast majority of the water required being consumed (Jenkns, 2013). Jackson et al. (2014) considered the water use of fracking for six different US shale gas locations. It was found that the average water use across the six locations, including the water required for the initial fracturing process and the extraction of gas was 58ML/TWh. Assuming the efficiency of a CCGT generation plant to be 60%, this equates to a water use of 97ML/TWh electricity generated. When compared to a UK CCGT plant's abstraction and consumption cooling water demands, it is less than even the consumption demand. Nevertheless, this fracking water demand would put added pressure on what is predicted to be a scarce localised resource (Brantley et al., 2014, Jackson et al., 2014). Jackson et al. (2014) did, however, find that the fracking water demand was less than that required to extract and process the equivalent of most other fuels, this includes uranium; but not conventional natural gas. However, when comparing uranium and fracked gas production, the UK imports all of its uranium and so this is largely an irrelevant fact (McAlinden, 2014, Wicks, 2009).

Water contamination, presents another water-energy nexus' related environmental concern of fracking. It is possible for waste water from the fracking process, or leaking gas, to contaminate groundwater supplies (Jackson et al., 2013, Loh et al., 2015). Jackson et al. (2013) analysed 141 drinking wells in north eastern Pennsylvania, and found some residents living close to shale gas wells had water supplies contaminated by leaked gas, mainly methane. Not unexpectedly the threat of contamination of future freshwater groundwater supplies is, for the UK fracking ambitions, a highly controversial issue. Although careful monitoring and managing of fracking operations can minimise the risk of such contamination

(Ochieng et al., 2015), it is questionable as to whether there could be an acceptable level of risk.

When policymakers are considering the environmental and ecological advantages and disadvantages of nuclear and CCGT / CCGT + CCS generation, any judgement that pitches nuclear with once-through cooling at the coast against CCGT / CCGT + CCS inland using hybrid, or air cooling, has to acknowledge that the judgement of the electricity generation costs is not being made on a level playing field. If shale gas, and CCS become a reality, then given some of the concerns that surround nuclear generation, particularly those that are safety related, then CCGT/ CCGT + CCS at the coast could well become the preferred means for the UK of meeting its future thermal generation. In the case of CCGT + CCS, this could be particularly so as with the cost of CO_2 storage being a consideration, coastal generations relative proximity to empty North Sea oil aquifers could possibly have added cost advantages.

7.3.1.3 Coal and Biomass (and CCS Equivalents)

Another option that the ESME.MC pathway uses to replace its lost nuclear generation is coal, or biomass fired generation, and their CCS equivalents. Both of these options are more costly. For this reason, the ESME.MC pathways cost optimising process only selected them in relatively small amounts. Insofar as coal is concerned, given the vast majority of coal is imported, the same energy security and future cost uncertainty arguments associated with natural gas apply. If the global price of coal rises the UK's own coal reserves may be considered economically viable but this may be at a price which makes coal generation as a whole particularly expensive. The same cost and security questions arise with the importing of biomass, with the added complication that it's key driver is its carbon neutral credentials, but this can increasingly be challenged the greater the transporting distance becomes (Röder et al., 2015).

Biomass can be grown in the UK, but although this avoids the issues associated with importing it, there is then the disadvantage that it has to compete with food crops for growing land (Searle and Malins, 2014, Shortall, 2013). There is also then the water-energy nexus concern that to successfully grow biomass freshwater is required. In section **2.5.2** the amount of water needed to grow biomass was considered; it was found that a number of academic studies, and government literature, had identified the lack of available freshwater as a potential problem for growing biomass in the UK (DECC, 2012b, Lovett et al., 2009, Sharmina et al., 2016, Sinclair et al., 2015). However, no specific UK water usage information could be found. A Netherlands based study (which has a similar climate to the UK) concluded $24m^3$ of freshwater were required per GJ of bio-energy produced (Gerbens-Leenes et al., 2009). Assuming the efficiency of a biomass thermal plant to be 35%, this equates to a freshwater demand of $86.4x10^3$ML/TWh. With the work carried out since Chapter 2 it is now possible to recognise this as a level of freshwater demand that, per unit of electricity generated, is comparable to UK once-through cooling water demands. The finding in Chapter 2 was this is a level of freshwater demand that by 2010, was already not available to any inland UK thermal power station with once-through cooling.

7.3.1.4 Nuclear Small Modular Reactors (SMR)

As well as large scale nuclear generation, the ESME.MC pathway also selects a sizeable (92 TWh/Annum (16%)) of nuclear SMR generation in 2050 under Q70SW. Commercial nuclear SMR generation power plants are a developing technology, they are much smaller than traditional nuclear power plants, and the assumption is that they will therefore be easier to site (Middleton, 2015). A potential problem is that because they are smaller they will not be able to achieve the same economies of scale as the larger reactors (Cooper, 2014). Locatelli et al. (2014) disagrees and argues that the diseconomy of scale of nuclear SMR's can be compensated for by the economy of multiples. Middleton (2015) suggests nuclear SMR's could be configured for CHP deployment which would further help their economic case. Two separate studies that assessed how long it would be before SMRs are likely to be operating commercially have produced similar results, with Liu and Fan (2014) suggesting ten years, while Middleton (2015) suggests by 2030. Both of these timescales are compatible with ESME's initial low adoption of Nuclear SMR by 2030. Furthermore, on these timescales the future deployment of SMR technology is by 2050, likely to be decided not by the 'first of a kind cost', but by the 'nth of a kind cost'.

7.3.1.5 Onshore and Offshore Wind

Although offshore wind is a maturing technology, all commercial offshore wind farms currently have fixed foundations. Floating offshore wind, however, is a technology which the ESME.MC pathway foresees providing a significant level of generation at 2050, particularly if seawater is not available. The use of floating foundations would greatly extend the UK's accessible wind resource, but they will have to operate in far more challenging conditions. Floating wind turbines are far more technically complex, largely due to the bigger seas which they have to withstand (Perveen et al., 2014). There has already been a number of floating wind turbine demonstration projects, one being the large scale Statoil 2.3MW 'Hywind' floating wind turbine, in 220m depth of water off the coast of Norway. This has successfully operated for over five years (Kaldellis and Kapsali, 2013, Saini, 2015). Statoil have now been granted a seabed lease to build a 30MW floating wind farm off Peterhead in Scotland, comprising of 5x6MW 'Hywind' turbines, in water depths >100m. This is expected to be operational by 2017 (Carrington, 2016, Statoil, 2014). With the ESME.MC pathway not factoring in any sizeable amount of floating offshore wind until 2050, with the basic concept already being successfully tested for five years, and a sizable floating wind farm already in the planning process, this would not appear to an unreasonable supposition.

The ESME.MC pathway limits all renewable technologies by their available resource which in the case of onshore wind, the most attractive LCOE (Levelised Cost of Electricity) wind generation technology, this has to take into account the current social difficulties of installing onshore wind farms. In addition some of the windiest, and therefore most resource-rich areas of the UK, are currently protected by environmental and landscape protective designations; National Park and Areas of Outstanding Natural Beauty are but two examples, which in affect make it all-but impossible for these areas to host wind developments. Even wind energy developments in areas which do not have any official designated status are often delayed or rejected by the planning system (Cowell, 2007, Wilson and Dyke, 2016). The current planning system perversely overlooks the fact that many of the rural areas that have the highest wind speeds are also the ones that suffer from high levels of national poverty, including fuel poverty (Williams and Doyle, 2016). They are also often areas, where for reasons of austerity, the reduction in central local government grants reduces the community services that can be afforded. A more auspicious approach to community onshore wind projects, could yet recognise the local financial reward, and national electricity generating competitiveness advantages, of cheaper onshore wind generation replacing the more expensive offshore wind. If this is indeed the case then replacing some offshore wind with onshore wind under the SWL and SWN scenarios considered, would reduce the annualised cost increases shown in section **6.3.5**.

7.3.1.6 H_2 Turbines

In addition to fossil fuels with CCS, the ESME.MC pathway also selects a level of generation from H_2 fired turbines. This is for both 2030 and 2050, particularly when seawater is available; 47TWh (8%) for Q70 SW at 2050. The ESME.MC pathway foresees the hydrogen required being produced by gasification, which would need to be in tandem with a CCS technology if the CO_2 produced by this process is to be removed. Although the gasification process itself is well understood having been in use for over two centuries (Breault, 2010), hydrogen turbines are a comparatively new technology. There are concerns that having to now operate turbines with hydrogen, rather than the previous standard natural gas and coal gas, introduces problems due to the difference in their chemical properties; leading to possible cost issues (Taamallah et al., 2015). Despite this, there is already an industrial scale H_2 turbine power plant in operation in Fusina, in Italy. This has been run successfully using hydrogen since 2010 (Standish, 2012, Taamallah et al., 2015), which provides a level of confidence the H_2 turbine technology will be available as the ESME.MC pathway requires.

7.3.1.7 Carbon Capture and Storage

As seawater is reduced, the ESME.MC pathway places a greater emphasis on associated CCS thermal generation, particularly abated CCGT. For 2050, from Q70SW to Q70SWN, it increases from 64TWh/annum to 168TWh/annum. Deployment of CCS is mainly seen by the ESME.MC pathway as a fossil fuel enabling replacement for nuclear generation. This study has, however, already recognised that if the UK had shale gas, coastal generation and viable carbon capture technology and storage facilities, it could have a much higher generation merit for the UK. Although CCS is still very much a developing technology.

In line with this, the UK Government in 2012 launched a commercialisation programme, with the aim of seeing CCS projects developed before 2020. Up to £1 billion pounds was to be made available in capital funding, with additional operational support available through guaranteed price contracts to support the initial stages of commercialisation. However, in November 2015 just before the final bids were to be submitted in this process, the Government unexpectedly announced that the money was no longer available (Cozier, 2016). The de facto opinion is that if the Government is committed to both shale gas, and its climate change targets, it cannot afford to sit back and wait and see if CCS will be available when it is required (CCC, 2015, Clarke, 2016). That is unless the UK Government can successfully rely on ‘bought-in’ technology.

In this respect there are a number of CCS generation orientated projects in the construction phase, including two in the US (Kemper County Energy Facility; Petra Nova Carbon Capture Project). These are due to be operational by the end of 2016 (Global CCS Institute, 2016). There are also a number of countries; the US, China, Canada, Norway, Australia; as well as the IEA and IPCC that have recognised CCS as a vital technology for the reduction of GHG emissions (Kern et al., 2016, Renner, 2014). That is, if fossil fuel electricity generation is in the future going to remain part of the electricity generation mix. Sara et al. (2015) and Davies et al. (2013b) both suggest that the barriers to CCS are largely not technical, but rather financial and regulatory. The fact large scale CCS projects are starting to emerge, and globally the political will for CCS appears to be present, suggests that it can be reasonably assumed a CCS generation technology will be a viable option on the timescale that the ESME.MC pathway envisages.

7.3.2 The UK Abstraction and Consumption Figures

The validity of the results produced by the thesis very much depend on the authority of the abstraction and consumption figures used to find the quantities of cooling water the ESME.MC pathway requires. The integrity of the UK abstraction and consumption figures used is underwritten by the provenance of those who compiled the figures (section **4.3.2.3**), and were authenticated by the EA. Although the results were not comprehensive and missing values had to be calculated, the final abstraction and consumption figures used by this research were successfully subjected to a validation process (section **4.4**).

7.3.3 Climate Change Uncertainty

Finding mitigation and adaption solutions to protecting the UK energy system from a future lack of available freshwater resource is complicated by the vagaries of climate change. Climate change uncertainty is discussed at length in section **2.6**, where it was shown there is an association made between the extent of future climate change, and the degree of reduction that will take place in UK future freshwater availability. UKCP09 provided temperature projections for 2050 under Low, Medium, and High emission scenarios. Even with this probabilistic range of temperatures within each scenario, it is made clear that no one scenario can be regarded as being more likely than another. This lack of temperature and therefore likely climate change and future freshwater availability certainty, becomes even more blurred by the suggestion that UKCP09 modelling underestimates the effect of climate change (Brown and Castellazzi, 2015, Brysse et al., 2013, Cavan, 2011, Cowtan and Way, 2014, Frigg et al., 2013).

In Chapter 6 it was accepted that the levels of freshwater that would be available at 2030 and 2050 were unknown, and so a range of freshwater availabilities, supported by assumed quantities of seawater was used (section **6.2**). The ESME.MC pathway's Monte Carlo approach allowed the difference in annualised generation costs across this range of freshwater cooling water possibilities to be investigated (section **6.3.6**). This approach mitigates the uncertainty around future freshwater availability as much as possible, but when interpreting these results the inherent uncertainty of the role of climate change on the hydrosphere must be borne in mind.

7.3.4 Disruptive Technologies and Events

The ESME.MC pathway confines itself to only considering a large, but finite, selection of chosen technology options. A disruptive technology can be defined as one that proves to be so different to current technologies that it disrupts the existing system (Hardman et al., 2013, Richter, 2013). An example would be the introduction of MP3 players displacing the market for CD players (Hardman et al., 2013). A disruptive event produces a similar end result. Panteli and Mancarella (2015), in the context of energy systems, refer to such 'disruption' as '*extraordinary and high-impact low probability events*'. Often, one of the reasons these technologies and events are so disruptive is they are deemed to be improbable, and therefore difficult to predict. This makes them hard to forecast, or model (Haegeman et al., 2013, Soojung-Kim Pang, 2010). However, when considering the ultimate validity of this research, it will have been a dull energy development path to 2050 if the boundaries of thermal generation that limits the ESME.MC pathways choice of technology options do not, in the context discussed, suffer from the same disruption. The very definition of disruption, however, makes this a difficult aspect to consider.

The ESME model has the option to, and in some cases does, select technologies which could be considered to be disruptive. Hydrogen vehicles, electric vehicles, certain energy storage technologies and renewable technologies (particularly micro solar PV and micro wind) are possible examples. With this thesis' focus on electricity generation, energy storage and renewable generation technologies are of particular interest. Their potential to be disruptive could be via a large adoption of community-scale, and potentially community-led renewable energy projects, supported by a viable energy storage technology, which could result in a more autonomous, decentralised and financially more attractive, distributed energy system, rather than the current mainly centralised system (Alstone et al., 2015).

When operating in a decentralised system, generation technologies work under substantially different business models. This would lead to a significant change in market conditions (Richter, 2013, Tabors et al., 2016). Although the ESME.MC pathway does select renewable energy technologies and some energy storage, under its cost optimised approach, it largely restricts its interest to large scale renewable and energy storage technologies, as part of a centralised system. This is in line with the UK's current, largely thermal generation based, and therefore centralised approach to future energy policy (DECC, 2015a, HM Government, 2011a, House of Commons Energy and Climate Change Committee, 2016). Richter (2013) interviewed senior representatives from 18 German energy companies, and found the majority felt renewable technologies (and energy storage) would continue to be used in a predominantly centralised way. Nevertheless, there are supporters of more decentralised renewable energy based systems who disagree (Chmutina and Goodier, 2014, Funcke and Bauknecht, 2016). Although a decentralised system may be considered unlikely, the ESME Patchwork pathway (section **3.2.2**) does allow a more decentralised system to be considered.

With respect to disruptive events, the UK's recent (23rd July 2016) vote to leave the European Union is an obvious example, and one that even on the day was not expected. Its direct impact on this thesis is likely to be minimal due to the range of scenarios and pathways considered. However the UK could well, to its advantage, have a game changing interest in rethinking the existing European environmental and ecological regulations (section **2.3.4**), insofar as coastal thermal generation is concerned.

7.4 Implications of Results for UK Energy Policy

Despite the limitations of this research it does have a number of key implications for UK energy policy. Although it is clear that a lack of freshwater has the potential to constrain thermal generation in the future, a reliance on sea and estuarine water can entirely mitigate this problem. However for this to happen it is likely that policymakers will have to reduce the level of environmental regulations which are currently restricting thermal power stations from being sited in coastal locations. Lowering environmental regulations must not be undertaken lightly, but when considering if this is necessary policymakers must take into account that without access to sea and estuarine water the UK's energy system may effectively have to pay a £12.5bn annual penalty by 2050. This will clearly reduce the UK's ability to be globally competitive.

As part of the initial national water demand modelling undertaken in Chapter 4 two future energy pathways which relied heavily on renewable energy were considered (High Renewables and Patchwork Pathway). Both of these were found to have relatively low future water demands but further analysis of these pathways was not carried out. In the case of the High Renewables pathway this was because it lacked a regional functionality, however this was not the case for the Patchwork pathway. The Patchwork pathway was not given further consideration as it was deemed to be an expensive option for the UK's energy system, largely due to the need to balance a significant amount of intermittent generation (Section **3.3.2**). This view on the cost of the Patchwork pathway is based on ESME's current understanding of the likely future costs of balancing, but as discussed in section **7.3.4** this is an area where disruptive technologies may yet come into play. In particular if energy storage technologies can become financially viable then the cost of balancing intermittent generation may reduce significantly, making the energy system according to the Patchwork pathway a much more attractive proposition. If this was the case then a future UK energy system based predominantly around renewable energy would provide another mitigation option to the lack of freshwater for thermal generation.

The uncertainty around disruptive technologies, especially energy storage technology, presents a problem for policymakers. Investing in energy infrastructure is a long term strategy and policy decisions which will affect the UK energy system in 2050 have to be taken soon. Whilst a concerted effort to develop energy storage technology would appear a sensible policy, at this point in time it is suggested that it should be alongside an approach that looks to site thermal generation at the coast.

Chapter 8 - Conclusions and Recommendations for Further Work

8.1 Conclusions with Respect to the Research Question, Aim and Objectives

This thesis asked the question "*what impact will a lack of available water have on UK thermal generation by 2050, in terms of physical make-up and associated costs*?" To answer this question the following aim was set "*to quantify the impact of future water availability on the UK thermal generation power station fleet by 2050, in terms of cost, type of generation technology, and cooling method chosen*". To meet this aim five objectives were developed in Chapter 1. This chapter considers the work undertaken to achieve each objective and then the thesis aim, it then considers how this answered the research question. This is before finally recommending areas where further work is required.

8.1.1 Objective 1

Identify the key water constraints to UK thermal generation and determine the role water availability plays as a constraining factor. Also consider current mitigation and adaptation options.

An in depth review of the current literature regarding the water-energy nexus, and in particular the impact of water availability on thermal power generation was undertaken in Chapter 2. It was found that already the UK's freshwater resources cannot support the more efficient, high water intensity, once-through cooling method for its existing thermal power stations (section **2.4**). Future freshwater resources are predicted to decrease, when the UK's thermal generation to 2050 will almost certainly be required to increase. Limiting the future demand for freshwater by extending the current use of the less water intensive, more inefficient cooling methods, particularly air cooling, will merely significantly increase the UK's generation costs and CO_2 emissions.

When it comes to limiting the use of freshwater as the means of thermal power station cooling, section **2.4.1** identified the UK's abundant seawater resource as potentially providing a much more efficient and commercially cost attractive method. There is, however, a question as to the extent the use of seawater is feasible due to existing environmental and ecological constraints. This and other mitigation options were identified and discussed in Chapter 2.

While it is not in itself a constraint, section **2.6** shows that the uncertainty surrounding climate change makes it very difficult to judge just how much freshwater will be available in the future. This creates obvious challenges for this research that are further discussed in section **7.3.3**.

8.1.2 Objective 2

Determine water demands of different thermal electricity generation and cooling method combinations which are applicable to the UK.

Previous studies which have assessed the future water demand of the UK electricity sector have used abstraction and consumption figures which predominantly relate to power stations in the US. This research obtained abstraction and consumption figures for a series of generation technology and cooling method combinations which were specific to UK power stations. A number of figures were missing from the data obtained. A method for calculating the missing figures from the known figures was developed (section **4.3.2.3**). This was based upon the principle that water use of thermal power stations could be categorised by cooling method rather than generation technology.

The abstraction and consumption figures used were subjected to a validation process and deemed to be satisfactory (section **4.4**). These were the figures used for the modelling analysis carried out in respect of Objective 3. The UK abstraction and consumption figures were compared to the equivalent figures from the US used in previous work on this subject. It was found that the US abstraction figures underestimate the UK demand, whereas for water consumption in most instances the opposite was found to be the case.

8.1.3 Objective 3

Model the future national water demand of the UK electricity sector. Downscale these results to the regional level to identify regions most likely to be constrained by water availability.

The Byers et al. (2014) framework quantifies the future operational water requirements of electricity generation networks, in terms of their water abstraction and consumption; per generation technology, per cooling method, per time-frame. In Chapter 4 this framework was applied to the three ESME pathways (Patchwork, Clockwork and ESME.MC), as well as six pathways taken either directly from, or based upon, the UK Carbon Plan pathways.

The detail of the work that was carried out to achieve objective 3 is set out in Chapter 4 and Chapter 5. The aim of Chapter 4 was to attribute at the national level cooling water demands to the pathways selected at 2030 and 2050, relative to 2010 (section **4.5**). The future water demands obtained were found to be heavily pathway dependent, but with the significant increase in electricity demand by 2050, not surprisingly the majority of pathways showed a corresponding increase in their total and/ or freshwater demands. The greatest increases were for the pathways that favoured increasing thermal generation. The smallest increases, and in some cases reductions, were for pathways like the Patchwork pathway, that favoured increasing the renewable technology options. As future water availability and future energy demands will vary regionally, the national results of Chapter 4 were regarded as only indicative.

Chapter 5 used the ESME.MC pathway's ability to disaggregate its national generation projections to the regional level to carry out a similar exercise to Chapter 4, to now model the regional generations' corresponding regional water demands (total and freshwater), at 2030 and 2050 (section **5.3.1**). At this regional level it was identified that under the methodology described in Chapter 5 (section **5.2**), several regions had high thermal generation freshwater demands that would by 2050, be likely to compromise their ability to meet their demand for electricity.

8.1.4 Objective 4

Develop a range of regional water availability scenarios to allow the modelling of future water availability alongside water demand. Determine the costs of different thermal electricity generation and cooling method combinations.

The methodology used to achieve this objective is explained and discussed at length in Chapter 6. To this point in the thesis, the modelling of the future water demands at 2030 and 2050, are based on assumed thermal generation pathways that are not directly constrained by likely future water availability. To allow actual water availability to be considered, a range of sea and freshwater scenarios (section **6.2.2**), were used to prepare datasets of available regional cooling water for 2030 and 2050. In respect of determining the costs of the different thermal electricity generation and cooling method combinations, these were calculated using a number of sources, and are shown in Tables 6.5 and 6.5.

8.1.5 Objective 5

Model future water availability alongside the water demand, and cost of, thermal electricity generation and cooling method combinations, allowing the impact of future water availability on the UK thermal generation power station fleet to be quantified and discussed.

To achieve this objective the datasets developed and identified in Objective 4, were built into the ESME.MC pathway. An additional dataset, based on that produced to meet objective 2, containing the water demands of the required generation and cooling method combinations was also built into the ESME.MC pathway **(**Table 6.4**).**

The ESME.MC pathway was then perturbed under the range of water availability scenarios adopted by this thesis in section **6.2.2.** This allowed the impact of future water availability on the UK thermal generation power station fleet to be quantified and discussed. It was found that the annualised cost penalty of not having the required water available by 2050, could be as much as £7.5bn for the UK electricity system, and £12.5bn for the energy system as a whole.

8.1.6 Research Question and Thesis Aim

What impact will a lack of available water have on UK thermal generation by 2050, in terms of physical make-up and associated costs?

To quantify the impact of future water availability on the UK thermal generation power station fleet by 2050, in terms of cost, type of generation technology, and cooling method chosen

In Chapter 1 the research question was formed. A corresponding thesis aim was then set to allow this question to be answered, and five objectives were developed to achieve the thesis aim. It has been shown all the objectives were successfully met, thereby allowing the overall aim to be accomplished, and the research question to be answered. It was found that freshwater alone will not be able to support the level of thermal generation foreseen by 2050, without a heavy reliance on the most expensive and greatest CO_2 emitting air cooling. This is particularly the case if there is a large adoption of fossil fuel + CCS generation. A reliance on sea and estuarine water allowing the use of the cheapest once-through cooling method is a potentially viable mitigation measure. If there is sufficient access to sea and estuarine water then large levels of thermal generation using the cheapest, but most water intensive, once-through cooling are achievable. This case results in the cheapest electricity system, and relies predominantly on large scale nuclear generation supported by nuclear SMR generation.

However this will only be the case if UK policymakers recognise it as so when they set the height of the environmental regulatory bar thermal power stations must clear if they want to be sited in coastal locations. If this is not the case, then a substantial reliance on freshwater, and the more expensive, but less water intensive cooling methods, particularly air cooling, will significantly increase the annualised cost of the UK energy system. It will also see a greater reliance on CCGT + CCS generation as well as offshore wind generation.

8.2 Recommendations in Respect of Further Work

In undertaking this research a number of areas were identified where further work would be beneficial. It was found that the recommendations for work to be undertaken generally applied to one or more of three different stakeholders; Government, the energy industry and research/academic institutions. The following sections provide details on these recommendations and the stakeholder(s) they relate to. A final section then looks to form a single recommendation focusing more broadly on the combined action to be taken by these stakeholders.

8.2.1 Scotland and Northern Ireland Data

Although this thesis considered the UK as a whole there were two areas where the datasets obtained did not provide figures for Scotland and Northern Ireland. The dataset omissions were:

i) The water abstraction data from freshwater and estuarine sources provided by the EA, needed to validate the water demand modelling framework (section **4.4**), were only for England and Wales.

ii) The future Q70 and Q95 Case for Change freshwater availability projections that were obtained from the EA were also only for England and Wales (section **6.2.1**).

It has been shown that neither of these omissions materially altered the thesis' conclusions derived from the results that were obtained. Although the UK is comprised of devolved governments in many ways it has to function as one entity; power generation and transport are cases in point. This study clearly identifies that any future research undertaken within a UK energy context, would benefit if the UK Government facilitated better coordination of the data each devolved authority keeps, so there is better access to UK wide datasets. This is a recommendation made as a result of the experience gained in carrying out the research needed for this thesis.

8.2.2 Abstraction and Consumption Figures

Abstraction and consumption figures specific to UK power stations were acquired, but there was considerable difficulty in obtaining this dataset, and there were omissions which then had to be calculated (section **4.3.2.3**). As this thesis identifies, previous studies in what for the UK is an important research area, were unable to obtain any substantial, UK specific, power station water abstraction and consumption data. These studies had to base their work on American, or assumed figures. This clearly limited the value of their results for UK policymakers involved in formulating future UK energy policy. This study found that much of the difficulty in obtaining applicable research data is a consequence of much of the energy industry's working data being regarded as commercially sensitive. The strange anomaly in this case was that when the UK data required was finally released it did not identify individual power stations, and so was completely anonymous. Here there seems to be a general lesson to be learnt in respect of UK research work. That is for UK research funded authorities, and, if necessary, the government, to work more closely with the energy industry, to decide what UK specific research information can, or cannot, be made available.

8.2.3 Constraining the ESME.MC Pathway by Thermal Generation Water Consumption

Chapters 4 and 5 considered water abstraction and consumption demands of future UK thermal generation. It was found that under the ESME.MC pathway the demand for water abstraction was far more likely to impact future thermal generation, than the water lost due to consumption. Therefore, when constraining the ESME.MC pathway by water availability in Chapter 6, only the abstraction demands of thermal power generation was considered.

While consumption cannot be a thermal generation limiting factor when there is an abundant cooling water resource (sea and estuarine water), it is conceivable that under certain low freshwater flows water consumption could create problems for other downstream users, or impact low volume cooling pond facilities. Therefore it is suggested that as a research project the ESME.MC pathway, just as it was adapted to study abstraction impact, should be adapted to quantify cooling water consumption losses of specific generation technologies. This would identify any associated downstream operational consequences.

If for such a purpose freshwater consumption were to be built into the ESME.MC pathway, then a number of additional challenges will have to be overcome. These include recognising the water demand of the other downstream users, and consideration of any freshwater replenishment that takes place in-between.

8.2.4 Water Use of UK Biomass Growth

If seawater is not available on a significant scale, or for other reasons the level of nuclear generation is reduced, potentially there would be the opportunity for biomass to make a significant, and sustainable contribution to meeting the supply of electricity generation required. Furthermore, if the biomass is natively grown then the issues over importing fuels and energy security discussed previously would be avoided. However it is noted in section **7.3.1.3**, that per unit of electricity generated, the growth of biomass requires quantities of freshwater on a par with once-through cooled thermal generation. This it has been shown is already not sustainable with the UK's current available freshwater resources. There are then serious questions as to whether growing any meaningful quantities of biomass in the UK can be a viable proposition. Although the focus on biomass in this study has only been considered in respect of electricity generation, biomass has a much wider application, for example, as a fuel for heat and transport. Yet to the best of the author's knowledge there has been no UK wide study that looks across the whole spectrum of biomasses' potential use, and the water demand associated with this level of growth. Such a study, led by research institutions but supported by the Government and energy industry as necessary, could provide support for the projects being carried out by the ETI, and the Dartmoor National Park, to use the UK's currently unproductive moorlands and hillsides as sources of sustainable biomass (Johnstone, 2016; Webb, 2010).

8.2.5 Water Use of Whole Energy System

This study by design focussed on the water demands of future UK thermal electricity generation, and the future water resource that was likely to be available. Here, the approach to investigate the cost implications of water availability on future thermal generation provides fundamentally important cost versus generation details for policy makers. As briefly discussed in section **7.3.1**, there are a number of other areas within the energy system that require substantial operational volumes of water. Therefore a study which built on the cost approach undertaken in this thesis, (and any work based on recommendation **8.2.4**), that modelled the water requirement of these other areas of the UK energy system, would provide a broader understanding of the UK water-water nexus issues for policy makers. With the obvious benefit to policymakers it is suggested that whilst research institutions may lead this study there should be Government involvement.

8.2.6 Water Constraining of Other Energy System Models

ESME is a strategically important energy system model for UK policymakers; DECC and the CCC's use of it supports this view. There are, however, other models some of which use entirely different approaches (section **3.1**) which could be used, including the UKTM model, the successor to UK MARKAL. Although in respect of this thesis' interests UKTM's usefulness for reasons that have been explained is limited. However, if used, UKTM would have looked for somewhat different solutions when applied to Chapter 6's water constraining methodology. UKTM models energy demand in much more detail than ESME does (Heaton, 2014, HM Government, 2011), and therefore it is likely it would have adopted more energy efficiency measures, or other options, to reduce demand than the ESME model. This is not an unreasonable approach. In light of other such possible different approaches, further academic research similar to that undertaken in Chapter 6, but using other energy system models is suggested. This would enable the issues surrounding the future water demand of the UK's thermal generation to be viewed from different vantage points.

8.2.7 Future Energy Storage Technologies

This study has looked at the consequences that a predicted shortage of future available water resource could have for UK thermal electricity generation. It found that there are major shortcomings in the amount of freshwater likely to be available for electricity generation with the most cost efficient once-through cooling to be possible in the future. One approach to resolve this problem, and still meet CO_2 emission targets, is to increase the uptake of renewable generation technologies, but significant adoption of these technologies leads to an increase in the total cost of the UK's energy system (section **6.3.5**). Technically possible, and economically viable energy storage technologies, would lower the cost of renewable generation and make the renewable approach a much more attractive proposition. There is already a substantial research drive in the energy storage area, but the results of this thesis emphasise the need for this work. Due to the potential importance of energy storage it is felt that this recommendation applies to the Government, energy industry and research institutions.

8.2.8 Future Carbon Capture and Storage Technologies

The water constraining analysis carried out in Chapter 6, showed that carbon capture and storage will allow the UK to continue to meet its future energy demands while adhering to future CO_2 emissions targets, in conjunction with, or as possible alternative to, nuclear generation. This it does by permitting the continued use of fossils fuels for thermal electricity generation. This study has identified that CCS is still a developing technology, and although internationally there is research being carried out, the potential importance of CCS is such that further CCS research work specific to the UK should be a priority. However, with the water – energy nexus theme in mind, it has been shown that for any thermal generation and cooling method combination, the use of CCS significantly increases water demand. For the UK this suggests that any further research that is looking for a viable industrial CCS solution should focus on overcoming the barriers to siting CCS in coastal locations, as this is ultimately likely to be more rewarding than relying on freshwater resources (section **7.3.1.2**). It is again felt due to the potential importance of CCS this recommendation applies to the Government, energy industry and research institutions.

8.2.9 Final Recommendation to all Stakeholders

This thesis has found that whilst a lack of freshwater has the potential to constrain thermal generation and increase the cost of the energy system in the future, there are mitigation options available. A reliance on sea and estuarine water is currently the most realisable option although a lowering of environmental regulations is likely to be needed to facilitate this. A future electricity generation system which relies heavily on renewable energy is another feasible option but the impact this will have on the cost of the energy system and therefore the UK's global competitiveness is, in the absence of financially viable energy storage technologies, likely to be significant.

Therefore it is suggested that Government, the energy industry and research institutions work together to help enable the development of thermal generation at coastal locations, whilst at the same time continuing to develop energy storage technology.

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Appendix A: Published Papers

Appendix A1

Water and Environment Journal Promoting Sustainable Solutions CIWEM

Water and Environment Journal. Print ISSN 1747-6585

The water-energy nexus: future water resource availability and its implications on UK thermal power generation

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Keywords
abstraction; energy; climate change; water framework directive; water resources.

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Abstract

An increasing population coupled with the uncertain, but increasingly likely, impacts of climate change have led to a heightened level of global academic attention to the interdependencies that exist between the water and energy infrastructure networks. However, to date there has been limited research considering the water-energy nexus within a UK context. This article reviews the global and national literature to identify how a future lack of available water resource will impact upon the UK thermal power generation fleet, both in terms of freshwater resource and environmental constraints. It concludes that a combination of freshwater resource management and adaptation to use alternative water sources will be key in mitigating and adapting to climate impacts.

[The full-text of this article is removed from the online version of the thesis due to copyright restraint. The article can be found on the journal: Murrant, D., Quinn, A. and Chapman, L. (2015), The water-energy nexus: future water resource availability and its implications on UK thermal power generation. Water and Environment Journal, 29: 307–319. DOI: https://doi.org/10.1111/wej.12126]

Appendix A2

Water Use of the UK Thermal Electricity Generation Fleet by 2050: Part 1 Identifying the Problem

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Abstract: The combined effects of increasing water and energy demand due to a growing population and climate change pose a growing threat to many national infrastructure strategies. Within the UK there is concern that a future lack of available water will compromise the UK's current energy policy to meet an increasing demand for a secure and affordable supply of electricity by more thermal generation. This paper investigates this by modelling the water demand of the UK's thermal electricity generation in 2030 and 2050, relative to 2010, for the strategically important Carbon Plan, and the Energy Technologies Institutes' ESME generation pathways. Unlike previous studies this paper has obtained water abstraction and consumption figures specific to UK power stations.

Whilst the water demand of thermal electrcity generation was found to be heavily pathway dependent the direction of travel to 2050 is that a much greater availbility of cooling water will be required. This paper suggests that if increasingly stringent environmental regulations restrict coastal generation then any scarcity of freshwater would limit inland thermal generation to using the less water intensive, more costly, greater CO_2 emitting, cooling methods. The logical consequence of this will increasingly be a decrease in the UK's commercial global competitiveness.

Key Words: Water-energy Nexus; UK Energy Policy; Water Resources; Climate Change; Power Station Cooling.

Acknowledgments: This work is funded by the Engineering and Physical Sciences Research Council and the Energy Technologies Institute. The authors would like to thank Maria Brierley from the Environment Agency for her help in obtaining validation data. The authors would also like to thank Den Gammer from the Energy Technologies Institute for his help.

Compliance with Ethical Standards: This work is funded by the Engineering and Physical Sciences Research Council and the Energy Technologies Institute. There are no conflicts of interest and the research did not involve human or animal participants.

Conflict of Interest: The authors declare that they have no conflict of interest.

Appendix A3

Water Use of the UK Thermal Electricity Generation Fleet by 2050: Part 2 Quantifying the Problem

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Abstract: Affordable energy is the driver of global wealth and therefore of the world population's economic wellbeing. The increasing demand for energy is expected to predominantly be met from a global expansion of water intensive thermal electricity generation. Most countries will in future have less freshwater available when inevitability the cost of thermal generation depends on water availability. A country's future energy costs will directly affect its future global competiveness. Many studies have identified that the solution to the UK's future energy policy mismatch between thermal generation and freshwater availability is to make greater use of its seawater resource. The fact the UK with a long learning curve of successful coastal generation is not progressing coastal generation more enthusiastically raises fundamental policy questions. This paper considers the issues involved. A methodology was developed to assess how the UK's electricity generation portfolio will change in terms of the technologies adopted, and their cost, as access to seawater is varied under Q70 and Q95 freshwater conditions. It was found the emphasis UK energy policy gives to the competing poles of low cost electricity generation and environmental protection will have significant impacts on the cost and make-up of the UK's future electricity generation portfolio.

Key Words: Water-energy Nexus; UK Energy Policy; Water Resource Management; Water Abstraction Reform; Climate Change; Power Station Cooling.

Acknowledgments: This work is funded by the Engineering and Physical Sciences Research Council and the Energy Technologies Institute. The authors would like to thank Adam Thirkill from the Energy Technologies Institute for his help.

Compliance with Ethical Standards: This work is funded by the Engineering and Physical Sciences Research Council and the Energy Technologies Institute. There are no conflicts of interest and the research did not involve human or animal participants.

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Appendix A4

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Quantifying the UK's Future Thermal Electricity Generation Water Use: Regional Analysis

Daniel Murrant, Andrew Quinn, Lee Chapman

International Science Index, Economics and Management Engineering Vol:10, No:3, 2016 waset.org/Publication/10003910

Abstract**—**A growing population has led to increasing global water and energy demand. This demand, combined with the effects of climate change and an increasing need to maintain and protect the natural environment, represents a potentially severe threat to many national infrastructure systems. This has resulted in a considerable quantity of published material on the interdependencies that exist between the supply of water and the thermal generation of electricity, often known as the water-energy nexus. Focusing specifically on the UK, there is a growing concern that the future availability of water may at times constrain thermal electricity generation, and therefore hinder the UK in meeting its increasing demand for a secure, and affordable supply of low carbon electricity. To provide further information on the threat the water-energy nexus may pose to the UK's energy system, this paper models the regional water demand of UK thermal electricity generation in 2030 and 2050. It uses the strategically important Energy Systems Modelling Environment model developed by the Energy Technologies Institute. Unlike previous research, this paper was able to use abstraction and consumption factors specific to UK power stations. It finds that by 2050 the South East, Yorkshire and Humber, the West Midlands and North West regions are those with the greatest freshwater demand and therefore most likely to suffer from a lack of resource. However, it finds that by 2050 it is the East, South West and East Midlands regions with the greatest total water (fresh, estuarine and seawater) demand and the most likely to be constrained by environmental standards.

Keywords**—**Water-energy nexus, water resources, abstraction, climate change, power station cooling.

I. Introduction

THERE are a number of interdependencies that exist between the supply of water and the generation of energy, the relationship between these interdependencies is referred to as the water-energy nexus.

Globally both water and energy demand are increasing, largely due to a growing population [1]. This increasing demand, in combination with climate change and an increasing need to maintain and protect the natural environment, poses a potentially severe threat to many national infrastructure systems. Greater insight into the water-energy nexus issues will play a vital role in understanding and mitigating such threats.

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A number of studies have considered the impact of the water-energy nexus on energy generating systems [2]-[6]. They conclude that a future lack of available water will create a threat to many energy systems across the world, although the extent of the threat depends heavily on location and climate.

Concentrating on the UK, until recently research into the water-energy nexus was limited, although there is now a growing body of academic literature [2], [7]-[10]. This literature concludes that a reduction in the future availability of water may at times constrain thermal electricity generation, and therefore hinder the UK in meeting an increased demand for a secure and affordable supply of low carbon electricity. This is significant as UK electricity demand is expected to rise from 359TWh in 2013 [11], to a potential 610 TWh by 2050 with a large proportion of this growth expected to come from thermal generation [12].

To understand how the UK water-energy nexus may constrain thermal electricity generation it is necessary to quantify the future water demand of the UK thermal electricity generation fleet. Before this can be done, a future generation pathway is required both in terms of electricity demand and how this demand will be met. There are a multitude of pathway scenarios projecting the make-up of a future UK electricity sector, of which the Energy Technologies Institute's (ETI) Monte Carlo (MC) pathway, produced by their Energy Systems Modeling Environment (ESME) model is one.

ESME uses a least-cost optimised approach to projecting the future UK energy system, and is widely used by the ETI's private and public members, including the UK Government's Department for Energy and Climate Change (DECC) and the Committee on Climate Change [13], [14]. It is therefore felt using ESME's MC pathway to determine its future water demands, both in terms of abstraction and consumption, will make a meaningful contribution to the UK's understanding of its future water-energy nexus impacts.

The ESME model is unique compared to other UK least-cost optimised models in that it is much more spatially disaggregated [15], this not only allows for the large variation in regional energy supply and demand to be better accounted for but also means it readily lends itself to the calculation of water consumption and abstraction at the regional scale.

Reference [7] developed a model framework to quantify the operational water demand of a number of future UK electricity pathway scenarios. However, this did not include the MC pathway and was only undertaken at the national level.

At a regional level future water demand has only been previously calculated for the UK electricity sector by the Infrastructure Transitions Research Consortium, [16] and then not for the MC generation pathway. Furthermore, [7] and [16], with no specific UK data available used water abstraction and consumption factors based on a study carried out by the USA's National Renewable Energy Laboratory (NREL) [17]. The authors of this paper have been given access to UK water abstraction and consumption figures compiled by the Joint Environmental Program (JEP) and provided through the Environment Agency (EA).

For this paper, the figures will now be referred to as the UK abstraction and consumption figures.

By adapting the model framework developed in [7], and using the UK abstraction and consumption figures this paper will attribute 2030 and 2050 regional water abstraction and consumption demands to the MC pathway, shown in Table I.

TABLE I
REGIONAL ABSTRACTION AND CONSUMPTION, (x10³ ML/ANNUM)

	2010 Abstraction				2010 Consumption				2030 Abstraction				2030 Consumption				2050 Abstraction				2050 Consumption			
Regions	FW	EW	SW	Tot.	FW	EW	SW	Tot.	FW	EW	SW	Tot.	FW	EW	SW	Tot.	FW	EW	SW	Tot.	FW	EW	SW	Total
East	10	862	1,258	2,129	4	1	1	6	8	1,134	1,274	2,416	3	1	1	5	14	864	10,234	11,112	4	3	9	16
E.Mids	49	78	0	127	17	26	0	43	6	5	2,336	2,347	2	2	2	6	10	36	8,098	8,144	2	8	7	17
London	0	438	0	438	0	1	0	1	0	3,210	0	3,210	0	14	0	14	0	2,633	0	2,633	0	27	0	27
N.E.	4	1,262	109	1,376	1	3	0	4	1	1,098	30	1,129	0	5	0	6	7	2,197	428	2,632	2	6	0	8
N.W	12	31	1,315	1,358	5	10	1	16	23	163	3,651	3,837	8	3	3	14	37	174	6,791	7,001	9	11	6	26
N.I.	0	291	879	1,170	0	0	1	1	0	89	151	240	0	0	0	0	0	164	273	436	0	0	0	0
Scotland	0	1,532	3,546	5,078	0	1	3	5	0	60	2,762	2,822	0	0	3	3	0	77	2,542	2,619	0	0	2	2
S.E.	43	1,485	1,099	2,627	15	12	1	27	22	510	2,434	2,966	3	3	2	9	57	1,034	5,409	6,500	7	12	5	24
S.W.	0	831	926	1,757	0	5	1	6	0	1,193	2,279	3,472	0	2	2	4	4	2,770	5,821	8,595	1	5	5	11
Wales	0	24	2,088	2,112	0	10	2	11	0	8	104	112	0	3	0	4	3	8	3,802	3,814	1	2	3	6
W.Mids	31	0	0	31	10	0	0	10	121	0	0	121	51	0	0	51	212	0	0	212	67	0	0	67
York & Hum	144	971	0	1,115	34	34	0	67	34	721	195	950	4	15	0	19	34	316	5,155	5,504	4	11	5	20
Totals	293	7,804	11,221	19,319	85	101	10	197	214	8,191	15,217	23,622	71	50	14	135	378	10,273	48,551	59,202	97	86	42	225

A. Energy Systems Modelling Environment (ESME)

The ETI was formed in 2007 to accelerate the development of new energy technologies for the UK's transition to a low carbon economy [14].

The ETI initially developed ESME in 2007 as a tool to help identify and design investments in technology development and innovation programmes which would most contribute to the ETI's aim of assisting the UK's transition to a low carbon economy [14], [18].

Due to its use in supporting the ETI's investment decisions, ESME is a design tool rather than a forecasting tool and adopts a least-cost optimisation approach to modelling the UK energy system, whilst still adhering to a number of specified targets and constraints. These targets and constraints include emission targets, resource availability, technology build rate and meeting the projected energy demand [14].

When modelling the future UK energy system, ESME adopts a whole system scope which includes all the major flows of energy: electricity generation, fuel production, energy use for heating, industrial energy use, and transportation of people and freight. A range of technology options are available encompassing all the energy flows above, including power stations, vehicle and heater type, each with a number of input parameters such as available resources, fuel prices and technology costs [19].

ESME then uses the least cost optimisation method to analyse the various permutations of technology choices and selects those which produce the least-cost energy system out to 2050, whilst still meeting and adhering to the specified targets and constraints. As already noted ESME's insight is it can also describe the modelled energy system at a regional level providing an extra level of detail and allowing variations in resource supply and demand across the UK to be better accounted for [15]. The regions modelled by ESME are shown in Fig. 1.

Fig. 1 ESME Regions

Any model has inherent uncertainties, particularly one as complex and broad as ESME, and whilst it is impossible to entirely remove these uncertainties, ESME uses the Monte Carlo technique to manage and quantify them. Rather than producing a single model run, ESME produces hundreds, or even thousands of runs, where the input parameters vary for each run according to the probabilistic distribution of the corresponding parameter. As well as showing the individual model results, a final result is produced by averaging the results of each model run. This approach allows a range of possible future energy systems to be considered, from which technologies can be identified that appear to have little chance of contributing to the future energy system and those which appear highly likely to contribute, as well as those which may, or may not, contribute depending on how the input parameters materialise in the future.

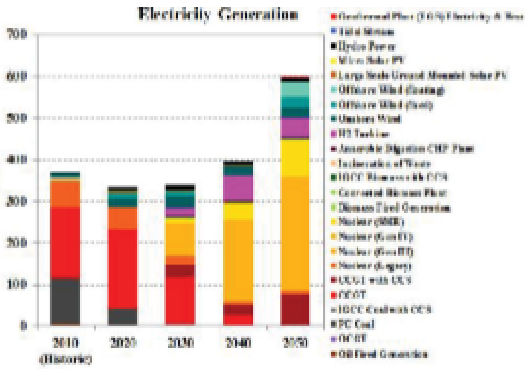

Fig. 2 ESME Monte Carlo (MC) National Electricity Generation Pathway

The result produced by ESME, like any model, is dependent on the inputs. When ESME is run with the standard probabilistic distribution for each input parameter, when using the Monte Carlo approach, the final result is the MC pathway and represents ESME's "best design" of the future UK energy system. Whilst ESME models the whole UK energy system, this research focuses on its modelling of future UK electricity generation, this is the MC pathway shown as Fig. 2.

II. Methodology

The model framework used to assess regional water demand is derived from the model framework in [7], and the assumptions it makes are described in detail in that paper, and so will not be duplicated here. Nevertheless, a summary of the framework is required, the further modifications required to allow the framework to model the water use of the MC pathway at a regional level are then described in II.*A.* Modification of Model Framework.

A future electricity pathway is defined by its year (t) being, for this analysis 2030 and 2050, and an annual generation output (g) of each individual pathway technology, represented by a matrix **G** with dimensions ($n_t \times n_g$). The framework then requires the distribution of cooling water source (w) between freshwater, estuarine, and seawater and the distribution of cooling method used (m) between once-through, evaporative, hybrid, and air cooling to be identified. This defines a **4-D** array S with dimensions ($n_w \times n_m \times n_t \times n_g$). The known UK water abstraction and consumption figures per generation technology, per cooling method, per water source, can then be introduced and are represented by matrices **A** and **C** respectively as (ML/TWh) see II.*A.2* Abstraction and Consumption Factors.

Element-wise multiplication of the arrays **GSA** and **GSC** gives water abstraction and consumption results for each water source and cooling method combination, per generation technology for the year in question:

$$(a_{t,g,m,w} = g_{t,g} a_{g,m,w} S_{t,m,w,g},\ c_{t,g,m,w} = g_{t,g} c_{g,m,w} S_{t,m,w,g});$$

Summation of the relevant combinations will allow total water abstraction and consumption of any given pathway generation technology to be calculated ($a_{t,g,w} = \sum_{m=1}^{n_m} a_{t,g,m,w}$, $a_{t,g} = \sum_{w=1}^{n_w} a_{t,g,w}$, $c_{t,g,w} = \sum_{m=1}^{n_m} c_{t,g,m,w}$, $c_{t,g} = \sum_{w=1}^{n_w} c_{t,g,w}$). Similarly, summation of all combinations would produce the total pathway water abstraction and consumption for any given year ($a_t = \sum_{g=1}^{n_g} a_{t,g}$, $c_t = \sum_{g=1}^{n_g} c_{t,g}$).

A. Modification of Model Framework

1) Regional Generation

Despite the same broad framework being used as in [7] a number of significant adjustments were required to allow the MC pathway to more accurately portray water usage at the regional level. The MC pathway provides regional electricity generation pathways for 12 UK regions; each of the 9 English Government Office Regions [20], as well as Scotland, Wales and Northern Ireland (Fig. 1). The electricity generated in each region is determined by a number of variables including future electricity demand, availability of renewable resources, and in the case of CCS plants connection to any future CO_2 network. Crucially however, available water resource is not taken into account. To account for this regional generation, the generation array **G** became $\mathbf{G}_{region}$ creating 12 generation arrays, representing an independent MC generation pathway for 2030 and 2050 for each of the 12 UK regions. The thermal generation by technology, for each region, according to the MC pathway for 2030 and 2050 are shown as Figs. 3 (a), (b).

2) Abstraction and Consumption Factors

It is considered unlikely that the UK abstraction and consumption figures being used will have significant regional variation and as such the arrays **A** and **C** were identical for each region. The JEP (who compiled the UK abstraction and consumption figures) has a research and development objective to understand and expand knowledge of the environmental science and impacts related to the generation of fossil fuel electricity, and is made up of nine of the leading generators in the UK [21].

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The UK abstraction and consumption data provided was wide-ranging and it was the mid-point values that were used [22].

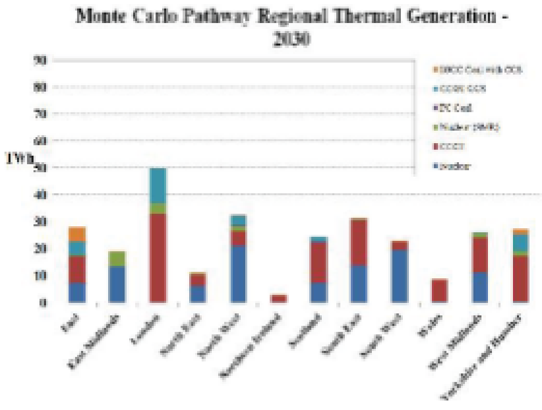

Fig. 3 (a) ESME Monte Carlo Pathway Regional Thermal Generation Technologies – 2030

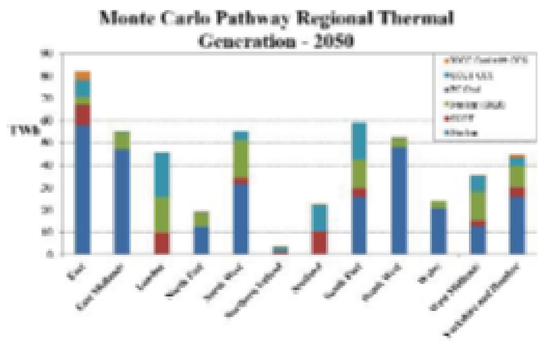

Fig. 3 (b) ESME Monte Carlo Pathway Regional Thermal Generation Technologies – 2050

A small number of abstraction and consumption factors were missing from the data provided, but these were calculated using the known ratios between cooling methods to determine and obtain the missing values in accordance with the opinion expressed in [17] that water demand is predominantly driven by cooling method rather than fuel type.

3) Cooling Method and Water Source Distribution

For the array S a similar approach was taken as for generation, where instead of a single array S, there now became 12 x S_{region} arrays each representing the cooling distribution of their region. It is, however, recognized the distribution of water source and cooling method may change between regions and reflecting this in a manner which produced realistic predictions of regional water demand by 2050 presented a challenge for this modelling analysis. Acknowledging this challenge, it was realised that the objective was not to just predict what the future regional water demand of the power sector would be but rather to identify what additional risks the future water demand of power generators, under the MC pathway, may pose on a regional scale, and to identify those regions where mitigation options are likely to be needed. It was decided that the current regional cooling regimes and water sources could be used to determine the extent the current 'business-as-usual' operation, applied to the MC pathways generation, increased the demand for cooling water, and provide a methodology that would identify any likely future water resource issues. To apply this business-as-usual approach the S_{region} arrays were populated with the respective regional water sources and cooling technologies that applied in 2010: for the CCS technologies not in operation in 2010, it was assumed the array distribution would be per their respective non-CCS technologies. The regional distributions produced are shown in Table II.

Nuclear Small/Medium Reactors (SMR) are a new technology, being smaller than traditional nuclear power stations they would attract less rigorous siting constraints and for this reason they are classed as a separate technology. As a new technology no current siting history exists; the deployment assumed by this study is based on discussions held with the ETI's nuclear team and allowed on the basis of likely siting constraints.

By 2050 CCGT is predicted for the West Midlands as is coal or its CCS equivalent in the South West when neither were present in 2010. Subsequently, to ensure water sources which are available in that region are being used, the distribution of an alternative generation technology which was present in these regions in 2010 was chosen; coal for the West Midlands and CCGT for the South West. All regional distributions are shown in Table II.

B. Validation

Comprehensive UK regional power station water use data is not publicly available and therefore a validation of the regional analysis carried out is not possible.

A validation on a national analysis undertaken in [7] and an as yet unpublished validation of a national analysis undertaken by the author do provide a level of endorsement for the methodology used for this regional analysis. Further, in [16] a similar study was undertaken to calculate the UK regional power sector's freshwater use for a number of generation trajectories to 2050. The regions and trajectories used are not directly comparable with the MC pathway; nevertheless, a number of key findings, such as high regional CCS freshwater consumption, and high freshwater abstraction in Yorkshire and Humber, are in line with the conclusion of this paper, lending additional confidence to the results.

III. Results

Table I shows future regional abstraction and consumption by water source for the ESME MC pathway in 2030 and 2050 alongside a calculated 2010 baseline. Figs. 4-11 then show this regional abstraction and consumption as a percentage of the national total for 2030 and 2050.

The major change Table I finds for the MC pathway is the large increase there is in total water (fresh, estuarine and seawater) abstraction from 2010 through to 2050 which increases from 19,319 to 59,202 $x10^3$ ML/annum, however, of this $58,824x10^3$ ML/ Annum is sea or estuarine water. For freshwater abstraction the change is from 293 to $378x10^3$ ML/annum. With the consumption of coastal water not being a factor, the change in freshwater consumption is for 2010 – 2050 from 85 to $97x10^3$ ML/annum. The ESME MC pathway is defined by its high saline water, low freshwater demand.

For total water abstraction, the high demand regions identified at 2030 are the North West, South West and London; at 2050 the regions are East, South West, East Midlands. For freshwater abstraction, the high demand regions at 2030 and 2050 are the same being West Midlands, Yorkshire and Humber, South East and North West with the West Midlands being greater than 50% of the national demand. High freshwater consumption for 2030 and 2050 identifies the same regions.

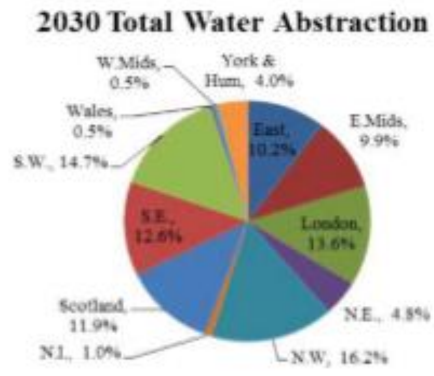

Fig. 2 2030 Regional Total Water Abstraction (% of Total)

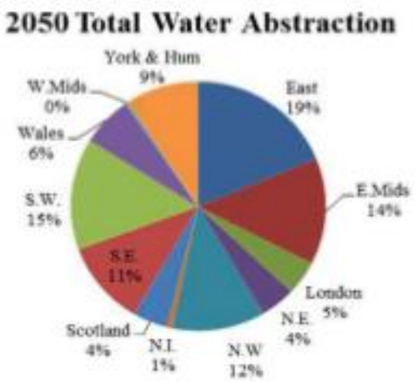

Fig. 3 2050 Regional Total Water Abstraction (% of Total)

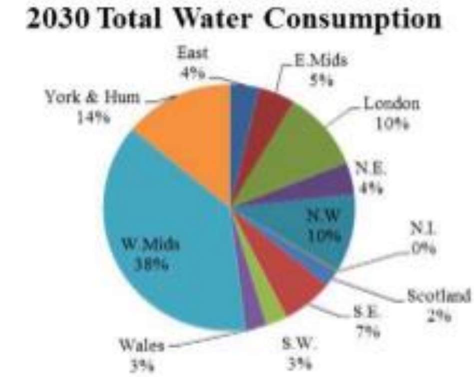

Fig. 4 2030 Regional Total Water Consumption (% of Total)

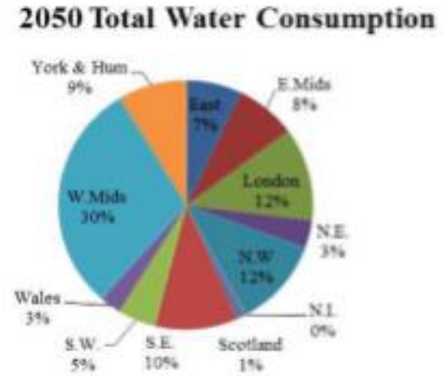

Fig. 5 2050 Regional Total Water Consumption (% of Total)

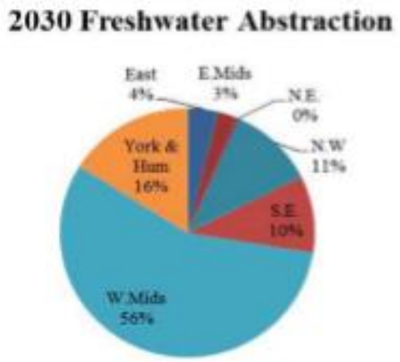

Fig. 6 2030 Regional Freshwater Abstraction (% of Total)

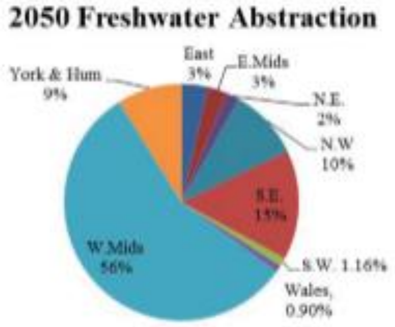

Fig. 7 2050 Regional Freshwater Abstraction (% of Total)

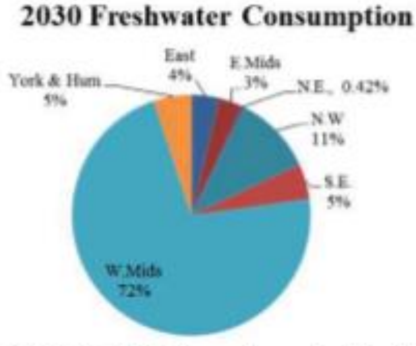

Fig. 8 2030 Regional Freshwater Consumption (% of Total)

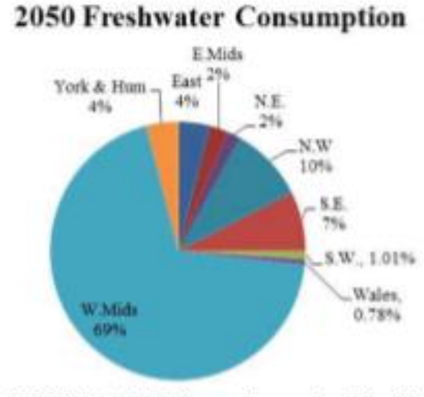

Fig. 9 2050 Regional Freshwater Consumption (% of Total)

A. Results by Generation Technology

Figs. 12-14 expand on Table I and show total water abstraction and fresh water abstraction and consumption broken down by technology for each region. Consumption values are small and therefore only an issue for scarce resources (i.e. freshwater) and so it was not felt necessary to show total water consumption.

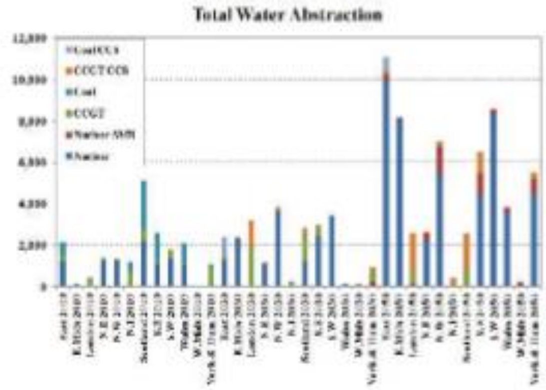

Fig. 12 Total Water Abstraction by Generation Technology (x10³ ML/Annum)

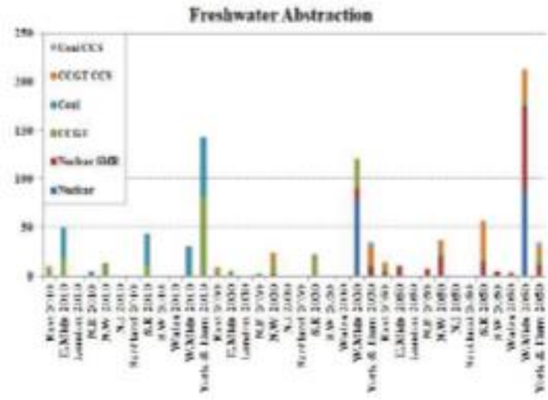

Fig. 13 Freshwater Abstraction by Generation Technology (x10³ ML/Annum)

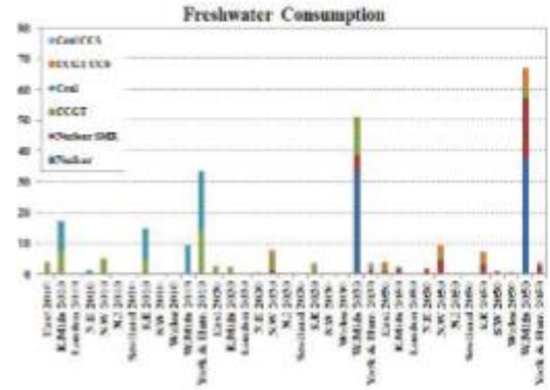

Fig. 14 Freshwater Consumption by Generation Technology (x10³ ML/Annum)

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TABLE II
REGIONAL DISTRIBUTION OF COOLING METHOD AND WATER SOURCE

		Nuclear				CCGT and CCGT CCS				Nuclear SMR				Coal, Biomass and Coal CCS			
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
East:	FW	0%	0%	0%	0%	0%	18%	0%	0%	0%	17%	0%	0%	0%	0%	0%	0%
	EW	0%	0%	0%	0%	11%	0%	0%	0%	0%	41%	0%	0%	93%	0%	0%	0%
	SW	100%	0%	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	71%	0%	0%	0%	0%	0%	0%	0%	7%
				Total:	100%			Total:	100%			Total:	100%			Total:	100%
E.Mids:		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	0%	0%	0%	0%	40%	0%	0%	0%	17%	0%	0%	0%	33%	0%	0%
	EW	0%	0%	0%	0%	0%	26%	8%	0%	0%	41%	0%	0%	0%	67%	0%	0%
	SW	0%	0%	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	26%	0%	0%	0%	0%	0%	0%	0%	0%
				Total:	0%			Total:	100%			Total:	100%			Total:	100%
London:		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	EW	0%	0%	0%	0%	71%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%
	SW	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	29%	0%	0%	0%	0%	0%	0%	0%	100%
				Total:	0%			Total:	100%			Total:	100%			Total:	100%
N. East		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	0%	0%	0%	0%	2%	0%	0%	0%	17%	0%	0%	0%	80%	0%	0%
	EW	100%	0%	0%	0%	0%	98%	0%	0%	0%	41%	0%	0%	0%	0%	20%	0%
	SW	0%	0%	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
				Total:	100%			Total:	100%			Total:	100%			Total:	100%
N. West		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	0%	0%	0%	0%	65%	18%	0%	0%	17%	0%	0%	0%	0%	0%	0%
	EW	0%	0%	0%	0%	17%	0%	0%	0%	0%	41%	0%	0%	0%	100%	0%	0%
	SW	100%	0%	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
				Total:	100%			Total:	100%							Total:	100%
N. Ireland		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	0%	0%	0%	0%	0%	0%	0%	0%	17%	0%	0%	0%	0%	0%	0%
	EW	0%	0%	0%	0%	40%	0%	0%	0%	0%	41%	0%	0%	0%	0%	0%	0%
	SW	0%	0%	0%	0%	60%	0%	0%	0%	42%	0%	0%	0%	100%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
				Total:	0%			Total:	100%			Total:	100%			Total:	100%
Scotland		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	0%	0%	0%	0%	0%	0%	0%	0%	17%	0%	0%	0%	0%	0%	0%
	EW	0%	0%	0%	0%	0%	0%	0%	0%	0%	41%	0%	0%	66%	0%	0%	0%
	SW	100%	0%	0%	0%	100%	0%	0%	0%	42%	0%	0%	0%	33%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%
				Total:	100%			Total:	100%			Total:	100%			Total:	100%
South East		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	0%	0%	0%	1%	0%	31%	0%	0%	17%	0%	0%	0%	51%	0%	0%
	EW	0%	0%	0%	0%	37%	15%	0%	0%	0%	41%	0%	0%	49%	0%	0%	0%
	SW	100%	0%	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	17%	0%	0%	0%	0%	0%	0%	0%	0%
				Total:	100%			Total:	100%			Total:	100%			Total:	100%
South West		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	0%	0%	0%	0%	0%	0%	0%	0%	17%	0%	0%	0%	0%	0%	0%
	EW	33%	0%	0%	0%	28%	0%	41%	0%	0%	41%	0%	0%	28%	0%	41%	0%
	SW	67%	0%	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	30%	0%	0%	0%	0%	0%	0%	0%	30%
				Total:	100%			Total:	100%			Total:	100%			Total:	100%
W.Mids		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	FW	0%	100%	0%	0%	0%	100%	0%	0%	0%	100%	0%	0%	0%	100%	0%	0%
	EW	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

		Nuclear				CCGT and CCGT CCS				Nuclear SMR				Coal, Biomass and Coal CCS			
	SW	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
				Total:	100%			Total:	100%			Total:	100%			Total:	100%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
Wales	FW	0%	0%	0%	0%	0%	0%	0%	0%	0%	17%	0%	0%	0%	0%	0%	0%
	EW	0%	0%	0%	0%	0%	14%	51%	0%	0%	41%	0%	0%	0%	0%	19%	0%
	SW	0%	0%	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	81%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	35%	0%	0%	0%	0%	0%	0%	0%	0%
				Total:	0%			Total:	100%			Total:	100%			Total:	100%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
York + Hum	FW	0%	0%	0%	0%	2%	4%	0%	0%	0%	17%	0%	0%	0%	50%	0%	0%
	EW	0%	0%	0%	0%	31%	19%	44%	0%	0%	41%	0%	0%	0%	50%	0%	0%
	SW	0%	0%	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	0%	0%	0%	0%
	Air	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
				Total:	0%			Total:	100%			Total:	100%			Total:	100%

Fig. 12 finds that the large increase in total water abstraction from 2010 to 2050 is a consequence of the MC pathway's preference for nuclear generation at sea and estuarine locations with an interest in least cost-optimisation using Best Available Technology (BAT) [23], high water abstraction intensity once-through cooling. Of the regions with high total water abstraction the only one that does not have significant nuclear generation is London where the high abstraction explanation is the generation means is not only CCGT, but in addition high water abstraction intensity CCGT + CCS.

Fig. 13 shows the technologies that make-up the regional freshwater abstraction and identifies CCGT + CCS and Nuclear SMR as the main abstractors. These are after nuclear favoured by the MC pathway with its low CO_2 least cost optimised interest.

The exception to nuclear at the coast is the West Midlands, which despite being landlocked has a small amount of nuclear with evaporative cooling. This in addition to the inclusion of nuclear SMR and CCGT + CCS generation is the reason for the extremely high growth in freshwater abstraction demand found in the West Midlands.

Freshwater consumption (Fig. 14) across the regions is in tandem with freshwater abstraction, and for comparable reasons, is seen to exhibit from 2010 – 2050 a similar high level of growth in demand for the West Midlands.

IV. Discussion

It is clear from the results that in general the high regional total water abstraction of the MC pathway is a result of its high uptake of nuclear generation which relies on sea and estuarine water with resource availability therefore not an issue; this in turn permits using BAT, high water abstraction intensity, once-through cooling. Whilst water resource is not a concern there are serious environmental issues for coastal (sea and estuarine) generation, such as entrainment of fish on screens at the cooling water inlet, and temperature discharge issues at the cooling water outlet, both of which impact marine species. These issues are monitored by a number of regulations including the EU Water Framework Directive (Directive 2000/60/EC) and the EU Habitats Directive (Council Directive 92/43/ECC) [24], [25].

The EU Water Framework Directive Commits European Union member states to achieve good qualitative and quantitative status of all water bodies by 2015; The EU Habitats Directive sets the criteria for the protection of habitat sites and species [24]. This environmental legislation has the potential to severely limit new coastal power station builds, particularly nuclear [25], indeed historically, nuclear power stations in the UK have been required to reduce their load to comply with thermal discharge temperature standards [26]. This contradicts government policy to reduce regulatory and planning barriers for low carbon generation [27]. This will also limit MC type pathways (high coastal generation) from providing the UK with a means of mitigating a future lack of inland regional freshwater for cooling, which this study's finding substantiates, will only support generation allied to less water requiring, less efficient cooling methods.

Under the MC pathway nuclear generation is considered particularly desirable due it its low carbon, low cost credentials, particularly so when placed at the coast and able to use BAT once-through cooling. Given this environmental BAT dichotomy it is important to have a better understanding as to what the relative financial and environmental cost difference of replacing nuclear generation at the coast with alternative regional inland generation requiring freshwater cooling alternatives is likely to be. This is particularly so as UK government policy seemingly favours nuclear and CCS generation (alongside renewables) [28], [29], both of which are likely to be located at coastal locations.

Total water consumption per region is orders of magnitude less than abstraction, and it is therefore felt that consumption is likely to only be an issue where there is a lack of available resource, i.e. freshwater consumption.

For future freshwater abstraction and consumption as Figs. 8–11 illustrate, for some regions high levels of demand are predicted by the MC pathway, particularly the West Midlands, but also Yorkshire and Humber, North West and South East, which makes a potential lack of freshwater likely in these regions. This is further underlined by areas in the West

Midlands and the South East being already classified by DEFRA as being water-stressed [30]. The Environment Agency have produced a number of 2050 UK regional scenarios for freshwater that express demand as a percentage of supply. The South East, Yorkshire and Humber and the West Midlands are identified as being regions with areas where during summer flows demand is expected to exceed supply [31].

While regional abstraction and consumption demands of future electricity generation scenarios can, with UK abstraction and consumption factors available, be determined with some confidence, without greater clarity as to water availability and the impacts of climate change then the real issues remain an intriguing puzzle. Nevertheless, despite the limitations, by using the ESME MC pathway it has been possible to add weight to one important claim. The Environment Agency state in [31] "Future electricity generation [will] have minimal impact on the overall picture of future water availability because of the significant reliance of the industry on saline / tidal waters." By using the MC pathway, the potential for coastal generation to resolve the UK's future water problem is confirmed. It was also established that attempts to bring the high water abstraction intensity, but low-carbon nuclear and CCGT +CCS generation inland would due to a lack of regional freshwater incur a range of as yet unidentified additional cost and additional CO_2 emission penalties.

V. Conclusion

This paper investigated the risk the future water demand of thermal electricity generation relative to the belief there will in future be less regional water available may pose for the UK power sector. It did this by modelling the regional water demand of the UK power sector under the ESME Monte Carlo pathway for both 2030 and 2050. This is a relevant study as it is predicted that the growth in UK electricity demand will rise from 359TWh in 2013 to a possible 610 TWh by 2050 and it is proposed a large proportion of this growth will come from an expansion of thermal generation.

A possible divergence in UK government policy as to how this extra demand will be met and the reality of events was found. The policy sees meeting the demand at 2050 with a mixture of renewable technology, but with the bulk coming from new nuclear power and fossil fuel power stations fitted with new Carbon Capture and Storage (CCS) technology; with a commitment to reduce regulatory and planning barriers for low carbon generation. The reality of events is it has been found the regulatory environment for building more nuclear generation at the coast has become more hostile. This regional study has shown that any attempt to bring the high water intensity nuclear and fossil fuel + CCS generation inland where it will be necessary to deploy less efficient cooling systems will not only introduce future summer security of generation issues but more importantly incur as yet unknown additional ongoing costs and CO_2 emissions. This paper identifies the need for further work to be carried out to quantify these issues.

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Appendix B: UK Thermal Power Stations 2010

Station Name	Capacity (MW)	Type	Cooling Source	Cooling Type	Location
Aberthaw B	1586	Coal	SW	Once-through	Wales
Aberthaw GT	51	GT/OCGT	AC	Air cooled	Wales
Baglan Bay	510	CCGT	TW	Evaporative	Wales
Ballylumford B	540	GT/OCGT	AC	Air cooled	Northern Ireland
Ballylumford B OCGT	116	GT/OCGT	AC	Air cooled	Northern Ireland
Ballylumford C	616	CCGT	SW	Once-through	Northern Ireland
Barking	1,000	CCGT	TW	Once-through	London
Barry	230	CCGT	AC	Air cooled	Wales
Blackburn Mill	60	CCGT	FW	Hybrid	North West
Burghfield	47	CCGT	FW	Once-through	South East
Castleford	56	CCGT	FW	Once-through	Yorkshire & Humber
Charterhouse St Citigen London	31	GT/OCGT	AC	Air cooled	London
Chickerell	45	GT/OCGT	AC	Air cooled	South West
Cockenzie	1152	Coal	SW	Once-through	Scotland
Connahs Quay	1380	CCGT	TW	Hybrid	Wales
Coolkeeragh	408	CCGT	TW	Once-through	Northern Ireland
Coolkeeragh	53	GT/OCGT	AC	Air cooled	Northern Ireland
Corby	401	CCGT	AC	Air cooled	East Midlands
Coryton	800	CCGT	AC	Air cooled	East
Cottam	2,008	Coal	TW	Evaporative	East Midlands
Cottam Development Centre	390	CCGT	TW	Hybrid	East Midlands
Cowes	140	GT/OCGT	AC	Air cooled	South East
Damhead Creek	800	CCGT	AC	Air cooled	South East
Deeside	515	CCGT	TW	Hybrid	Wales
Derwent	228	CCGT CHP	FW	Evaporative	East Midlands
Didcot A	1958	Coal	FW	Evaporative	South East
Didcot B	1430	CCGT	FW	Hybrid	South East
Didcot GT	100	GT/OCGT	AC	Air cooled	South East
Drax	3,870	Coal	TW	Evaporative[1]	Yorkshire & the Humber
Drax GT	75	GT/OCGT	AC	Air cooled	Yorkshire & the Humber
Dungeness B	1,040	Nuclear	SW	Once-through	South East
Eggborough	1,960	Coal	FW	Evaporative	Yorkshire & the Humber

Elean	38	Biomass	AC	Air cooled	East
Enfield	408	CCGT	AC	Air cooled	London
Fawley GT	68	GT/OCGT	AC	Air cooled	South East
Fellside CHP	180	CCGT CHP	FW	Hybrid	North West
Ferrybridge C	1960	Coal/Biomass	FW	Evaporative	Yorkshire & the Humber
Ferrybridge GT	34	GT/OCGT	AC	Air cooled	Yorkshire & the Humber
Fiddler’s Ferry	1961	Coal/Biomass	TW	Evaporative	North West
Fiddler's Ferry GT	34	GT/OCGT	AC	Air cooled	North West
Glanford Brigg	260	CCGT	FW	Evaporative	Yorkshire & the Humber
Grain	1320	CCGT CHP	TW	Once-through	South East
Grain	1300	GT/OCGT	AC	Air cooled	South East
Grain GT	55	GT/OCGT	AC	Air cooled	South East
Great Yarmouth	420	CCGT	TW	Once-through	East
Hartlepool	1,180	Nuclear	TW	Once-through	North East
Heysham 1	1,160	Nuclear	SW	Once-through	North West
Heysham 2	1,220	Nuclear	SW	Once-through	North West
Hinkley Point B	870	Nuclear	SW	Once-through	South West
Hunterston B	890	Nuclear	SW	Once-through	Scotland
Immingham CHP	1,240	CCGT CHP	TW	Hybrid	Yorkshire & the Humber
Indian Queens	140	GT/OCGT	AC	Air cooled	South West
Ironbridge	940	Coal	FW	Evaporative	West Midlands
Keadby	710	CCGT	TW	Once-through	Yorkshire & the Humber
Keadby GT	25	GT/OCGT	AC	Once-through	Yorkshire & the Humber
Killingholme A	665	CCGT	TW	Hybrid	Yorkshire & the Humber
Killingholme B	900	CCGT	TW	Hybrid	Yorkshire & the Humber
Kilroot	520	Coal	SW	Once-through	Northern Ireland
Kilroot OCGT	142	GT/OCGT	AC	Air cooled	Northern Ireland
King's Lynn	99	CCGT	AC	Air cooled	East
Kingsnorth	1940	Coal	TW	Once-through	South East
Kingsnorth GT	34	GT/OCGT	AC	Air cooled	South East
Knapton	42	GT/OCGT	AC	Air cooled	Yorkshire & the Humber
Langage	905	CCGT	AC	Air cooled	South West
Little Barford	714	CCGT	FW	Evaporative	East

Little Barford GT	17	GT/OCGT	AC	Once-through	East
Littlebrook GT	105	GT/OCGT	AC	Air cooled	South East
Longannet	2304	Coal	TW	Once-through	Scotland
Marchwood	842	CCGT	TW	Once-through	South West
Medway	688	CCGT	TW	Evaporative	South East
Oldbury	424	Nuclear	TW	Once-through	South West
Peterborough	405	CCGT	AC	Air cooled	East
Peterhead	1180	CCGT	SW	Once-through	Scotland
Ratcliffe	1960	Coal	FW	Evaporative	East Midlands
Ratcliffe GT	34	GT/OCGT	AC	Air cooled	East Midlands
Rocksavage	810	CCGT	FW	Evaporative	North West
Roosecote	229	CCGT	TW	Once-through	North West
Rugeley	1006	Coal	FW	Evaporative	West Midlands
Rugeley GT	50	GT/OCGT	AC	Air cooled	West Midlands
Rye House	715	CCGT	AC	Air cooled	East
Saltend	1200	CCGT	TW	Evaporative	Yorkshire & the Humber
Sandbach	50	CCGT	FW	Evaporative	North West
Seabank 1	812	CCGT	TW	Hybrid	South West
Seabank 2	410	CCGT	TW	Hybrid	South West
SELCHP (South East London CHP)	32	Waste	AC	Air cooled	London
Severn	848	CCGT	AC	Air cooled	Wales
Shoreham	400	CCGT	TW	Once-through	South East
Shotton	210	CCGT CHP	AC	Air cooled	Wales
Sizewell B	1,191	Nuclear	SW	Once-through	East
Slough	61	Biomass	FW	Evaporative	South East
South Humber Bank	1,285	CCGT	TW	Once-through	Yorkshire & the Humber
Spalding	880	CCGT	AC	Air cooled	East Midlands
Staythorpe C	1724	CCGT	FW	Evaporative	East Midlands
Steven's Croft	50	Biomass	AC	Air cooled	Scotland
Sutton Bridge	819	CCGT	AC	Air cooled	East
Taylor's Lane GT	132	GT/OCGT	AC	Air cooled	London
Teeside CCGT	1875	CCGT	TW	Evaporative	North East
Teeside Power station	45	CCGT	FW	Evaporative	North East
Thetford	39	Biomass	AC	Air cooled	East
Thornhill	50	CCGT	FW	Once-through	Yorkshire & the Humber

Tilbury B	1063	Biomass	TW	Once-through	East
Tilbury GT	68	GT/OCGT	AC	Air cooled	East
Torness	1,190	Nuclear	SW	Once-through	Scotland
Uskmouth	363	Coal/Biomass	TW	Hybrid	Wales
West Burton	2,012	Coal	TW	Evaporative	East Midlands
West Burton CCGT	1270	CCGT	TW	Evaporative	East Midlands
West Burton GT	40	GT/OCGT	AC	Air cooled	East Midlands
Wilton 10	38	Biomass	TW	Hybrid	North East
Wilton GT 2	42	GT/OCGT	AC	Air cooled	North East
Wilton Power Station Coal/biomass	150	Coal/Biomass	FW	Evaporative	North East
Wilton Power Station Gas	130	GT/OCGT	FW	Air cooled	North East
Wylfa	960	Nuclear	SW	Once-through	Wales