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

Daniel Murrant, Andrew Quinn, Lee Chapman

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, (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**	**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.

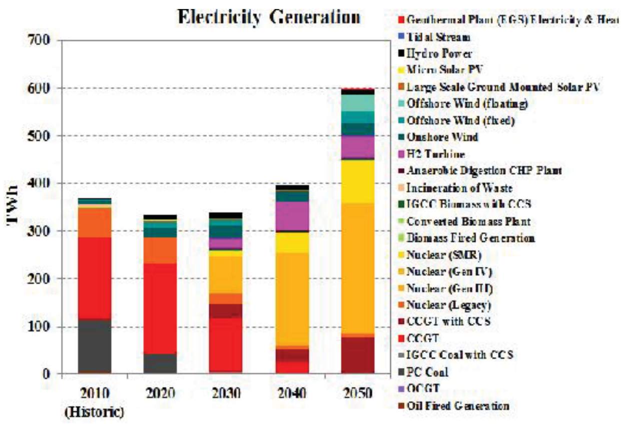

Fig. 2 ESME Monte Carlo (MC) National Electricity Generation Pathway

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 x 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 x n_m x n_t x 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].

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

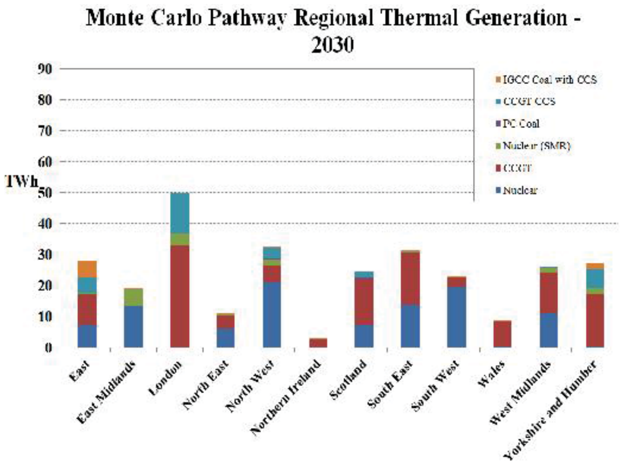

Fig. 3 (a) ESME Monte Carlo Pathway Regional Thermal Generation Technologies – 2030

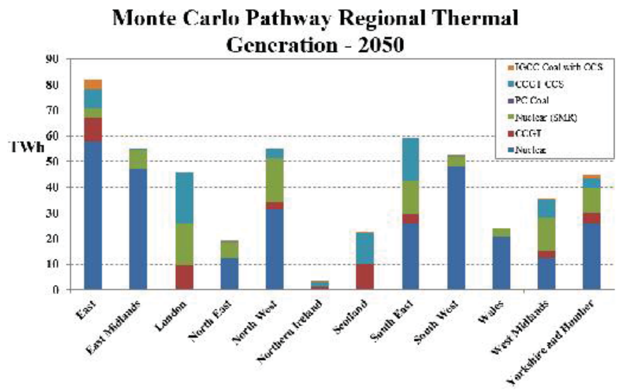

Fig. 3 (b) ESME Monte Carlo Pathway Regional Thermal Generation Technologies – 2050

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 $\mathbf{S_{region}}$ 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 $\mathbf{S_{region}}$ 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.

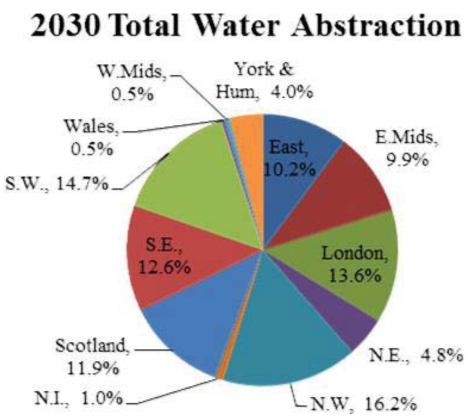

Fig. 2 2030 Regional Total Water Abstraction (% of Total)

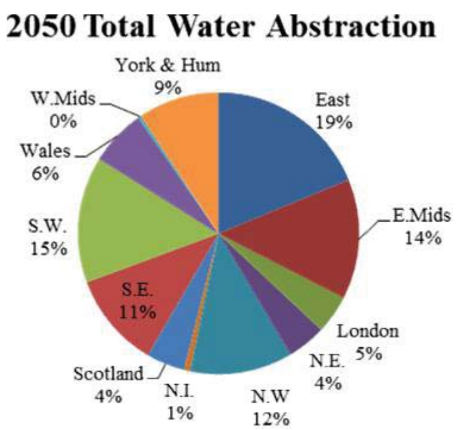

Fig. 3 2050 Regional Total Water Abstraction (% of Total)

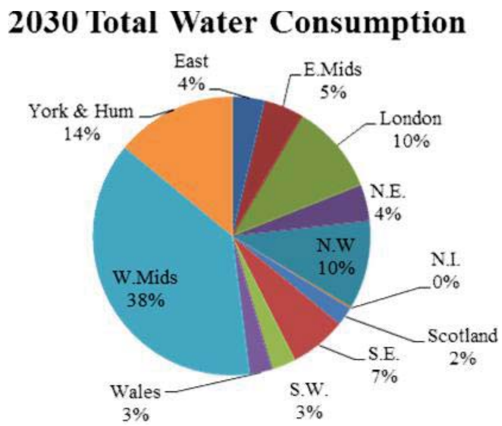

Fig. 4 2030 Regional Total Water Consumption (% of Total)

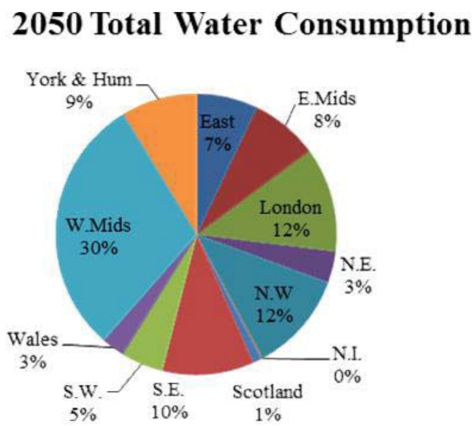

Fig. 5 2050 Regional Total Water Consumption (% of Total)

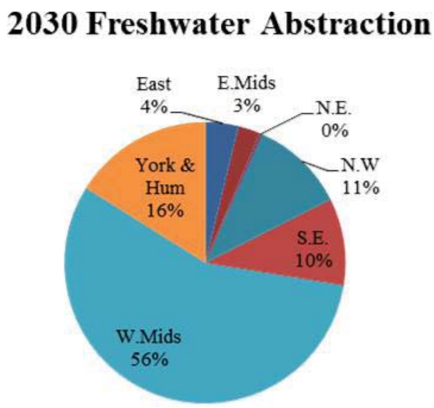

Fig. 6 2030 Regional Freshwater Abstraction (% of Total)

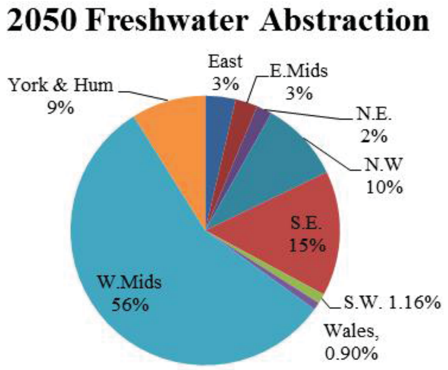

Fig. 7 2050 Regional Freshwater Abstraction (% of Total)

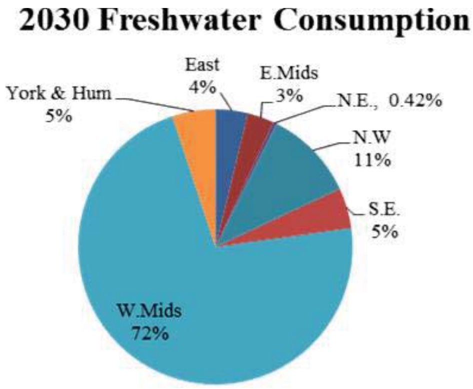

Fig. 8 2030 Regional Freshwater Consumption (% of Total)

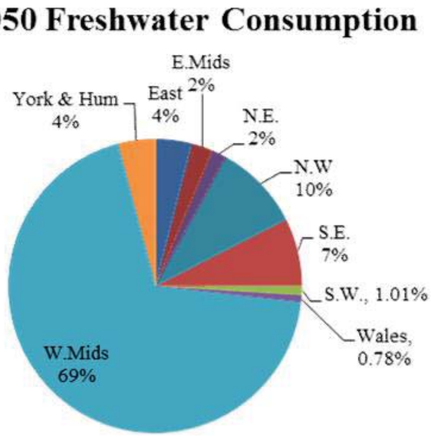

Fig. 9 2050 Regional Freshwater Consumption (% of Total)

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.

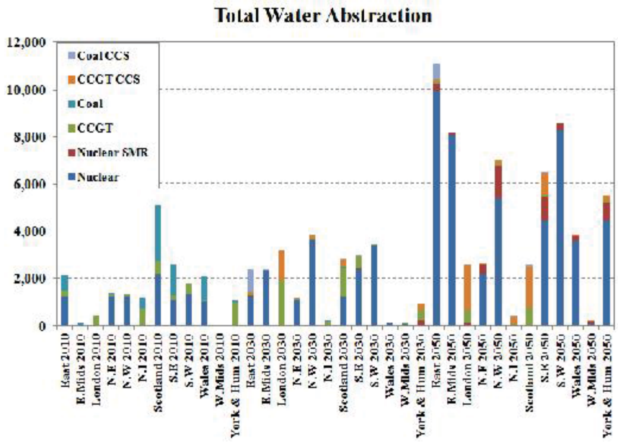

Fig. 12 Total Water Abstraction by Generation Technology (x10^3 ML/Annum)

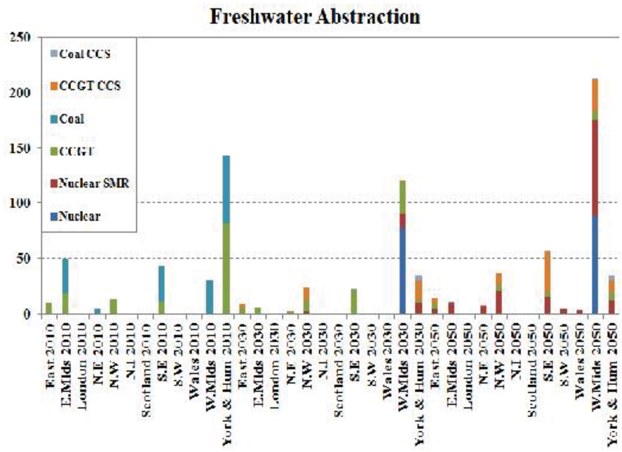

Fig. 13 Freshwater Abstraction by Generation Technology (x10^3 ML/Annum)

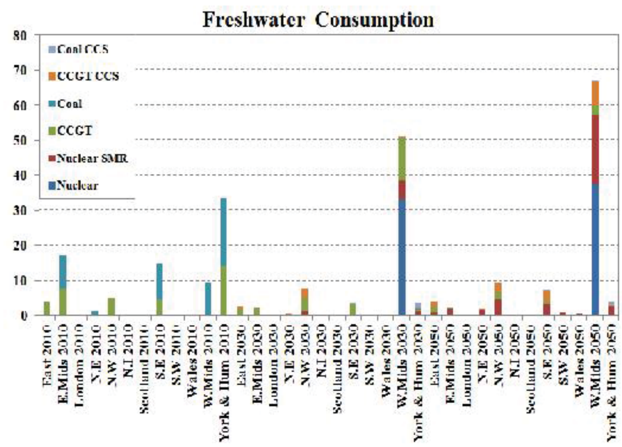

Fig. 14 Freshwater Consumption by Generation Technology (x10^3 ML/Annum)

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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
Scotland	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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
South 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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
South 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%
		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
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%

		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%
Wales		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%	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%
York + Hum		Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air	Open	Closed	Hybrid	Air
	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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