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Water use of the UK thermal electricity generation fleet by 2050: Part 2 quantifying the problem

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ABSTRACT

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's mismatch between thermal generation and freshwater availability is for the UK to make greater use of its seawater resource. The fact the UK with a long learning curve of successful nuclear coastal generation is not progressing coastal generation more enthusiastically raises fundamental policy questions. This paper considers the issues involved. A methodology is 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 demands 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.

1. Introduction

The water–energy nexus' importance in global affairs is that available energy is the driver of global wealth, this in turn makes it a precursor of the world population's economic wellbeing. However, energy production depends on the availability of large amounts of freshwater (UN WWAP, 2015). 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).

The International Energy Agency (2012) reports that the global water use for energy production in 2010 is 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 freshwater they require in the summer. This is a situation made worse by the increasing effects of climate change and population growth (Miletto, 2015; Wong and Johnston, 2014). EIA (2013) predicts world energy demand will grow by 56% from 2010 to 2035 with fossil fuels and nuclear generation still being 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).

While a reduction in water withdrawal for thermal generation is possible by using alternative cooling systems this inevitably incurs higher capital costs and losses in plant efficiency. Another trade-off required when deploying less water intensive cooling methods is while they reduce withdrawal demand they incur greater water consumption, with net increases in global energy water consumption of over 80% suggested due to this (International Energy Agency, 2012). In freshwater stressed areas this reduces the water available to other downstream users. Another means of power station cooling is the use of seawater, which for countries like Japan, Korea, Australia, and the UK has been accepted as providing an abundant and secure cooling water resource.

The UK energy system is in a state of transition with ageing energy infrastructure needing to be replaced in a way that in the future provides an energy system that is secure, affordable and decarbonised. There are many organisations involved in this and there is a wealth of literature on the subject, some unfortunately often record the difficult process that 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 on the basis of the immediate environmental concern, rather than the more

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distant consequences inflicted upon the future secure and affordable generation objective. The UK energy transition is not just about replacing outdated plant, there is also a need to increase generation from 384 TW h (MacLeay et al., 2011) to a possible 610 TW h/annum by 2050 (HM Government, 2011a). The UK Government's Carbon Plan sees this growth coming largely from an expansion of thermal generation (HM Government, 2011a), which requires more cooling water when, particularly in future summers, the intelligence suggests there will be less (Environment Agency, 2011; Wade et al., 2013).

The UK, with no load centre being more than 70 miles from the coast, has since 1956 established a successful nuclear coastal generation provenance which at its peak was generating over 25% of the UK's electricity (World Nuclear Association, 2016; Bolton, 2013). With less freshwater being predicted, and taking into account a fifty year learning curve of coastal thermal generation, a policy to build the new thermal generation required near the coast would seem to be the obvious option. In the global context, the fact the UK with its long experience of successful coastal generation is not progressing coastal generation more enthusiastically makes this an interesting case study. A number of studies have modelled the future water demand of the UK power sector (Byers et al., 2014; Gasparino, 2012; Murrant et al., 2015; Schoonbaert, 2012). There is agreement that if thermal generation were to be the means of the UK meeting its 2050 predicted generation then there would likely be a considerable mismatch between the onshore cooling water needed and that available. The common identified solution is for the UK to make greater use of its seawater resource. However, the matter remains complex as although the freshwater and seawater environmental issues are well known, unfortunately neither can be argued with the requisite financial facts to hand.

A body tasked with informing the UK's energy transition to 2050 by accelerating the development of low carbon technologies is the Energy Technologies Institute (ETI) formed in 2007 (Heaton, 2014). To this end, the ETI developed the Energy System Modelling Environment (ESME) model which identified cost and emission optimised investment opportunities by modelling the future UK energy system. Unlike other models, ESME can deliver not only national outcomes but can relate UK national results to UK regional results (see Section 3.1). ESME has since been used by the Committee on Climate Change (CCC) for their review of carbon budgets, and by the Department for Energy & Climate Change (DECC) when developing the Carbon Plan (CCC, 2013; HM Government, 2011a). This paper aims to adapt ESME to explore how, at the regional level, the availability of seawater for cooling under future (2030 and 2050) freshwater conditions impacts the generation costs and technology mix of the UK energy system. This will then better inform UK policymakers when making future UK energy policy decisions.

2. UK water and energy policy background

2.1. Water over-abstraction in the UK

The UK 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 (the UK's Water Services Regulation Authority) 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 (2011) with the task of initiating the reform required identified that seawater abstraction and discharge was an issue stating “*changes in seawater temperature could adversely affect maritime biodiversity*.”

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 policed by the EU Water Framework Directive (Directive 2000/60/EC), Habitats Directive (Council Directive 92/43/ECC) and Environmental Flow Indicators, (Collins et al., 2012; Morris et al., 2014; Environment Agency, 2013c).

Both OFWAT and Environment Agency (2011) accepted the problem of over-abstraction and 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 licences. 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, power stations 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 water for power station cooling (Murrant et al., 2015; Turnpenny et al., 2010).

This advice is also contrary to the opinion that the use of saline water for power station cooling water would resolve any lack of freshwater issues (see Section 2.2). DEFRA's instructions to OFWAT on tackling over-abstraction was 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 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 Environment Agency's Environmental Flow Indicator 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).

2.2. Water abstraction of the 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 the new legally-binding emission targets all suggested the demand for water may increase. The position of electricity generators would therefore be assessed as a study undertaken by the Government, the Environment Agency and the power sector.

This study's publication (Environment Agency, 2013b), coincided with the reformed abstraction consultation (DEFRA, 2013b). After considering four UKCP09 Regional Climate Model simulations applied to future electricity demand the view was power stations would in future rely on 'saline/tidal water' so there would be no freshwater cooling impacts. A concurrent paper (Environment Agency, 2013d), appeared equally positive on coastal generation by deciding any linking of Environmental Flow Indicator 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:

(i) Large quantities of cooling water available.
(ii) Large water bodies with their high thermal capacities are capable of receiving the necessary high levels of cooling water discharge.
(iii) In the case of seawater, relative to freshwater and estuary abstraction, complying with regulatory requirements of coastal discharge is more easily managed.

2.3. Coastal v freshwater water sources for power stations

The reality of UK coastal generation is in practice not this straightforward. An examination of recent nuclear energy policy provides a good, but not isolated example. Similarly, the case of the CCGT plant at Pembroke provides another instance (Lewis, 2015). The Strategic Siting Assessment consultation for finding sites for England and Wales for new nuclear infrastructure was launched by the department for Business Enterprise and Regulatory Reform (BERR, 2008a, 2008b). All sites explored were coastal yet with some 7000 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'.

In addition to the European regulation, the UK's own planning constraints also restrict infrastructure development, and they frequently provoke 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 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 also became a casualty.

Leading UK electricity generators, in view of the new legislative and regulatory thinking, initiated The Joint Environmental Programme 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 cooling water that will be available, that no conclusion could be reached. Their view was if the Government's preference remained thermal generation, providing the right investment opportunities are created the Government could either opt to use saltwater instead of freshwater for cooling, or adopt less freshwater intensive cooling methods.

The Energy UK (2014) response to the abstraction reform consultation (DEFRA, 2013b), was more forthcoming but there was scepticism over Government policy. 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 European Parliament's Directive 2010/75/EU on Industrial Emissions that acknowledged once-through cooling to be the Best Available [cooling] Technique (BAT) (European Commission, 2001). The increased efficiency compared to other cooling methods provided more electricity per unit of fuel employed thereby reducing greenhouse gas emissions and generation costs (European Commission, 2001).

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 (DEFRA, 2011). 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 power stations. There is presently no cost information available as to what extent coastal generation using seawater cooling would reduce household and business energy costs, making it difficult for policymakers to make informed decisions. This paper now attempts to provide this information.

3. Methodology

ESME is an internationally peer-reviewed, cost-optimised model of the UK's energy system out to 2050 (Heaton, 2014; ETI, 2016). An in depth description of the ESME model is given by Heaton (2014) and a summary is provided in this study's companion paper which forms the first part of this series of work (Murrant et al., 2016); a generalised ESME flow chart is provided, Fig. 1. In broad terms the methodological approach of this study is to modify the ESME model to allow it to account for the water demand of thermal generation technologies and the future water resource available to these technologies.

To do this the ESME model has to recognise the water demand of different thermal generation technology and cooling method combinations, the regional levels of available freshwater and seawater, and the cost consequences of selecting different cooling methods. This involves adding additional data to the technology profiles of the ESME model, as well as allowing it to consider water as an energy resource, see Fig. 1. With these modifications, it will be possible for the ESME model to produce a future energy system design which shows how the availability of seawater for cooling, under future 2030 and 2050 freshwater conditions, impacts the generation costs and technology mix of the UK energy system. The remainder of this methodology section will now focus on the details of ESME relevant to this study and the additional data which has to be incorporated in to the ESME model.

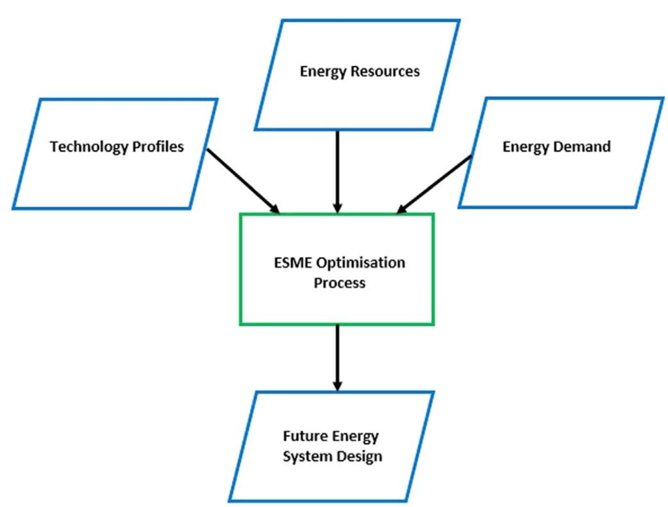

Fig. 1. ESME Flow Chart.

3.1. ESME

Unlike other models, ESME can deliver not only national outcomes but can uniquely also provide UK regional results, Fig. 2. Comparative present and future national UK electricity thermal generation water demand results like those produced in the companion paper are of interest, and begin to highlight the issues a lack of water may pose to thermal generation. However, the demand for power varies significantly from region to region, as does water demand, as does water availability. So for policymakers national results, such as those produced in the companion paper, are of limited practical use. To provide the level of detail required it becomes necessary to now work at the regional level. Being able to work at the regional level brings a greater level of detail to this papers research as to how the lack of assumed available freshwater, which varies regionally, will affect the generation costs of a future UK energy system.

Whilst it is impossible to entirely remove all uncertainties, ESME uses the Monte Carlo method to manage and quantify them. ESME carries out many runs where an input parameter (e.g. energy resources, fuel price, technology cost) is varied according to its probabilistic distribution. The sensitivity analysis this allows to be carried out is extremely useful in identifying the range of uncertainty that policy-makers have to consider when making decisions. When ESME uses the Monte Carlo approach it is known as the ESME.MC pathway. This represents ESME's best design of the future UK energy system and is the pathway worked with for the remainder of this paper.

This paper derives six additional scenarios from this pathway, each of which has different levels of fresh and seawater availability built into them (see Table 1). As well as the scenarios derived, the equivalent ESME.MC Standard result (i.e. the ESME.MC pathway without any water consideration) is also considered, and for the remainder of this study is referred to as the Standard Scenario.

This paper will build the datasets for the relevant water-energy nexus parameters that affect the electricity generation costs into ESME so they become part of the ESME cost optimising process. The objective is not simply to find a cost optimised result but to determine how varying the water available alters the costs, the generating technology and cooling methods selected. To do this the following datasets were prepared where necessary and modelled as appropriate.

(i) Future 2030 and 2050 regional freshwater available at Q70 and Q95 flows, shown in Table 1s of the supplementary information,[1] (Environment Agency, 2013a). Q70 and Q95 flows are defined as being the long-term average flows which are exceed 70% and 95% of the time respectively.
(ii) Cooling water scenarios to be tested, Table 1
(iii) 2030 and 2050 regional seawater available Table 2s.
(iv) Water abstraction demands for generating technologies and cooling methods shown in Table 3s and developed in the companion paper (Murrant et al., 2016).
(v) Freshwater/seawater capital expenditure (CAPEX) and operational expenditure (OPEX) costs of generating technologies and cooling methods, Tables 4as and 4bs, (Maulbetsch, 2012).
(vi) ESME's operational fuel costs, Table 5s.

3.2. Regional freshwater and seawater 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 for the 2010 baseline as well as projections for 2050 for the 117 catchments in England and Wales. Using GIS it was possible to allocate

Fig. 2. ESME Regions.

each catchment's water to a region(s) with the percent overlay known. For each catchment, the assumption was the water transferred to a region(s) is proportional to the relative overlap. This found each region's total freshwater available for abstraction. The percentage of the total regional freshwater allocated to the energy sector (excluding hydropower) was found using DEFRA's regional freshwater abstractions by sector estimations for 2000–2013 (DEFRA, 2016). The amount of freshwater available at Q70 and Q95 for electricity generation in each region was then obtained by multiplying each region's total available freshwater by each region's calculated electricity generation percentage.

In practice the EA CAMs' data gave 60 different freshwater availability scenarios for 2050, for both Q70 and Q95, for the 117 catchments. Therefore there were in fact 60 different individual regional Q70 and Q95 freshwater availability results. Each of the equivalent results from each scenario were totalled to give 60 national results for Q70 and Q95 respectively. Separately the sixty Q70 and Q95 totals were sorted to provide a high, medium and low national result, from which corresponding high, medium and low regional results were found. This provided the 2050 triangular distribution of regional freshwater availability used by ESME for its Monte Carlo approach for creating the 2050 Q70 and Q95 distribution of freshwater figures. ESME determined the 2030 values by extrapolation from the 2010 and 2050 figures. The freshwater values used in 2030 and 2050 along with the 2010 baseline values are shown in Table 1s.

Freshwater data for Scotland and Northern Ireland was not available but modelling work undertaken in the companion paper indicated that both countries would continue to use only sea and estuarine water for power station cooling (Murrant et al., 2016). Therefore in the absence of any data, this paper adopts this assumption.

3.3. Scenarios tested

In contrast to freshwater, estuarine and seawater resources are both abundant and therefore this paper now uses seawater to refer to both

[1] Hereafter all Tables and Figures in the supplementary information will be denoted by an s.

Table 1
Scenarios tested.

Scenario	Assumption
Q70 SW	Seawater is available at each region's required once-through cooling demand. Freshwater also available at each region's 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 (see Table 2s). Freshwater also available at each region's Q70 flow.
Q95 SWL	Seawater is available but constrained at half the level of each region's SW scenario (see Table 2s). Freshwater also available at each region's Q95 flow.
Q70 SWN	Freshwater is available only at each region's Q70 flow. Seawater is unavailable.
Q95 SWN	Freshwater is available only at each region's Q95 flow. Seawater is unavailable.

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 affects the cost of UK thermal generation is explored by adopting an arbitrary range of 3 seawater scenarios under both Q70 and Q95 freshwater conditions, resulting in the six scenarios (Table 1) for ESME to model. The basis of the seawater scenarios is at SW all the seawater needed by ESME's 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, only the Q70 and Q95 volumes of freshwater. The volumes of seawater available for each scenario are shown by Table 2s. As seawater is abundant it was assumed all seawater cooling would use the once-through cooling method. The additional assumption 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 are three exceptions. Firstly, the West Midlands has no coastline so the only cooling water available is its 2030 and 2050, Q70 and Q95 freshwater volumes. Secondly, although 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. 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.

3.4. Cooling methods

The costs and water demands of the four cooling method's being considered [once-through, evaporative, hybrid, air] were built into ESME, and available to each generating technology on the basis of the

Table 2
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	33.3 10%	33.57 11%	36.67 21%	37.01 22.4%
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 (TW h)	283.82 0%	283.16	283.77	268.74 −5%	265.99 −6.3%	257.73 −9%	256.92 −9.5%
Non-thermal Generation (TW h)	53.05 0%	53.56	53.27	60.19 12%	60.80 14%	67.91 27%	68.72 29%
Total Generation (TW h)	**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 (TW h)	497.15	490.35	491.14	395.67 −19%	393.05 −20%	308.45 −37%	306.13 −38%
Non-thermal Generation (TW h)	99.91 −2%	102.32	103.39	186.18 81%	188.84 83%	288.03 181%	291.82 182%
Total Generation (TW h)	**597.07** 0%	**592.67**	**594.54**	**581.85** −2%	**581.90** −2%	**596.48** 0%	**597.95** 0%

cooling water available, and ESME's cost optimised choice. The water required by each combination of generating technology and cooling method is shown by Table 3s. It is based on data used and developed in the companion paper (Murrant et al., 2016), with additional input provided by the ETI. The costs of the cooling methods and generation technologies are broken down into two separate sub-tables, shown as Tables 4as and 4bs respectively. The thermal generation technology capital costs used by the ESME.MC pathway assume once-through cooling is employed. The additional capital costs of the alternative cooling methods were derived using data taken from EPRI (2012) with all other technology costs already built into the ESME model by the ETI. The means of adjusting the operational cost of the alternative cooling methods was according to their relative efficiencies. This was interpreted as requiring the installed capacity, and hence total capital cost, to be proportionately increased to still meet the design load. Relative to once-through cooling the difference allowed in efficiency, and, therefore increase in operational costs are, as shown in Table 4bs, Evaporative +4%, Hybrid +6.5%, Air +10%. Cooling with seawater incurs an additional capital charge due to a corrosion factor of around 35–50% (Maulbetsch and DiFilippo, 2010). This was recognised by increasing the once-through and evaporative seawater cooling capex costs by 45%. For completeness the relative fuel costs used by ESME are shown in Table 5s. 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).

4. Results and discussion

4.1. General

As well as the water availability scenarios being tested, the equivalent ESME Standard result (i.e. the ESME.MC pathway without water consideration) is included. Table 2 summarises the changes in installed capacity and electricity generation between the scenarios and shows that the results for the ESME Standard and SW scenarios are invariably alike for both 2030 and 2050. It also shows the equivalent Q70 and Q95 figures are similar and move in tandem. Tables 1s and 2s do provide an explanation as to why the Q70 and Q95 results move in tandem when the relative quantities of freshwater (Q70, Q95), and seawater water made available are compared. This is because even at the higher Q70 volume the cooling water available was so low that the further Q95 constraint made little difference. Instead it is the much larger change in available seawater volumes which drives any change in technology choice or costs for the results shown in this paper. Therefore although the Q95 results are shown for brevity only the Q70 results will be discussed in this paper.

4.2. Electricity generation technology installed capacity

Table 2 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 2 also shows there is an increase in total installed capacity due to the extra reserve provision needed to cover the 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 3 and 4 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. The increase in non-thermal capacity is mainly due to an increase in onshore wind, offshore wind fixed and offshore wind floating. With this reduction in nuclear

Table 3
Electricity Generation Installed Capacity 2030.

Generation Technology	Installed Capacity 2030 (GW)						
	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
Interconnector Benelux-Germany (Electricity)	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Interconnector France (Electricity)	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Interconnector Ireland (Electricity)	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Interconnector Nordel (Electricity)	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Table 4
Electricity generation installed capacity 2050.

Generation Technology	Installed capacity 2050 (GW)						
	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
Interconnector Benelux-Germany (Electricity)	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Interconnector France (Electricity)	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Interconnector Ireland (Electricity)	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Interconnector Nordel (Electricity)	2.0	2.0	2.0	2.0	2.0	2.0	2.0

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 and IGCC Biomass+CCS.

4.3. Electricity generation

The results for the electricity generated at 2030 and 2050 are provided by Tables 5 and 6. As 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 2, do better underline the increased magnitude of the challenge UK energy policy has to accommodate in the period from 2030 to 2050 than for the current 2010–2030 period.

4.4. Regional generation by technology and cooling method

In this revised water-conscious version of ESME 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 flows determines the total regional generation, and the cooling methods selected for each generation technology, in each region for 2030, are shown by Figs. 3–6; for 2050 by Figs. 7–10. Again the Q95 results are similar and are therefore not included in the main text, but are shown by Figs. 1s–6s.

As per the methodology for 2030 and 2050 both SW scenarios (Figs. 4 and 8) confirm that with the exception of the West Midlands and London, all thermal generation does use once-through cooling. As the West Midlands and London are limited to Q70 freshwater, or evaporative cooling with estuarine water respectively, neither region can be a major generator. This is because ESME calculates for the SW scenario it will be cheaper to 'import' electricity from neighbouring regions rather than the West Midlands and London resorting to deploying their own more costly but less water intensive cooling methods. This affect is in general reduced as the move to SWL, and particularly SWN, increases the generation costs of the other regions.

For SWL at 2030 (Fig. 5) 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 SWL at 2050 (Fig. 9) for while seawater is still available there is relatively less freshwater and, far more thermal generation to support. The result is a significant reduction in thermal generation. At SWN even at 2030 (Fig. 6) 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 evaporative cooling it is now significant. For SWN at 2050 (Fig. 10) the amount of Q70 freshwater available is so little that 37% of the original thermal generation is now lost.

The results also show that as the nuclear generation is lost for both 2030 and 2050 the fossil fuel +CCS generation required to provide baseload, 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 select the less water intensive, more costly evaporative, hybrid and air cooling methods as seawater is reduced from the SW to SWN scenarios.

4.5. Annualised cost differences of limiting the seawater available for cooling

For 2030 and 2050 the cost consequences of limiting seawater are shown by Tables 7 and 8. They show for each year the itemised annualised costs of ESME's total energy system attributable to electricity generation for each ESME scenario. Table 9 for discussion purposes summarises the results obtained. Again only the Q70 results are discussed.

At 2030 the increase in cost relative to SW attributed to constraining seawater is at SWL £0.67bn (+1.56%); and at SWN £3.63bn (+8.48%): for 2050 at SWL £1.75bn (+2.95%); at SWN, £7.61bn

Table 5
Electricity generation 2030.

Generation Technology	Generation 2030 (TW h)						
	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

(+12.8%). Looking for the reason(s) for the increase in cost at 2030 it can be seen, from Table 7, to be due to an increase in Resource cost. This is consistent with the reduction in generation efficiency 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 need to move electricity around more incurs a greater Transmission Investment cost. An increase in Fixed Technology Operational costs is offset by a reduction in Technology VOM costs (Variable Operations and Maintenance).

Constraining seawater for thermal 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 results for information as Tables 10 and 11; summary Table 12. Comparing the Electricity Generation and Total Energy cost it is seen both are of a similar form but it is the electricity generation that is seen to carry the bulk of any cost increase across the scenarios.

Table 6
Electricity generation 2050.

Generation Technology	Generation 2050						
	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	0.0	0.0
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

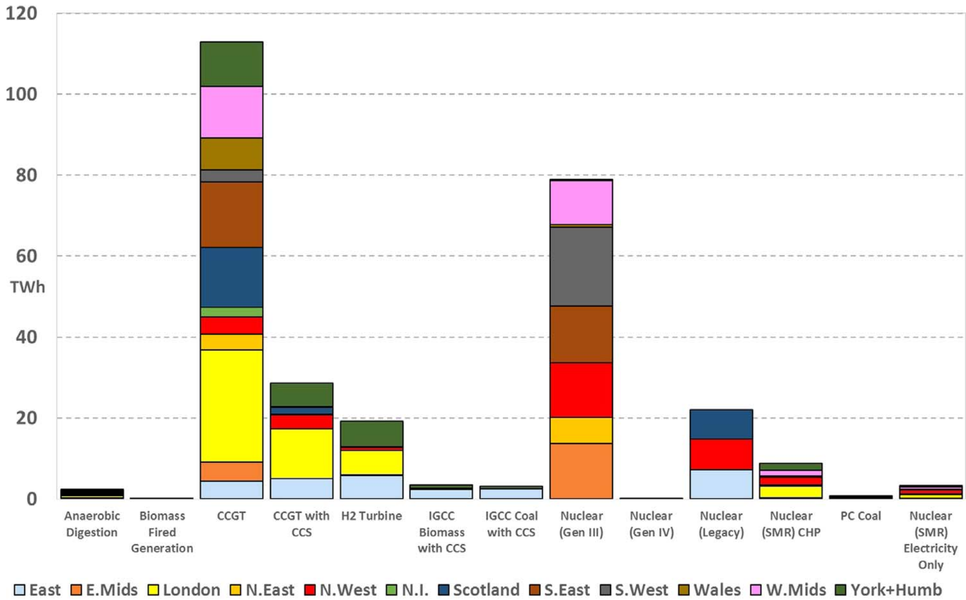

Fig. 3. Regional Generation ESME Standard 2030.

4.6. Sensitivity analysis

The Monte Carlo approach employed by ESME means that for each input parameter a result is produced for each of the 100 simulations. The methodology uses the averaged value of these results but in the case of cost it was felt necessary to show the range of the results obtained. Figs. 11 and 12 show the range of ESME electricity system costs obtained for 2030 and 2050. The extremes shown are the 5th and 95th percentile. Equivalent figures for the Total Energy System were found to show a similar trend and are included as Figs. 7s and 8s.

Both 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 both SWN scenarios are spread much more widely about the median and there is a greater range between the extremes than for the other scenarios. This suggests that any uncertainty around the costs of the future UK electricity system increase at the more distant timeframe, particularly when there is no access to seawater.

5. Policy implications

This study has considered how the optimised costs and generation technologies of EMSE's chosen path to deliver the UK's future demand for secure and affordable electricity could be compromised by a lack of required cooling water.

The relevance of this study is that ESME'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 (Committee on Climate Change, 2015; DECC, 2015; HM Government, 2011a). Although the ESME Standard pathway does not consider water demand its generation

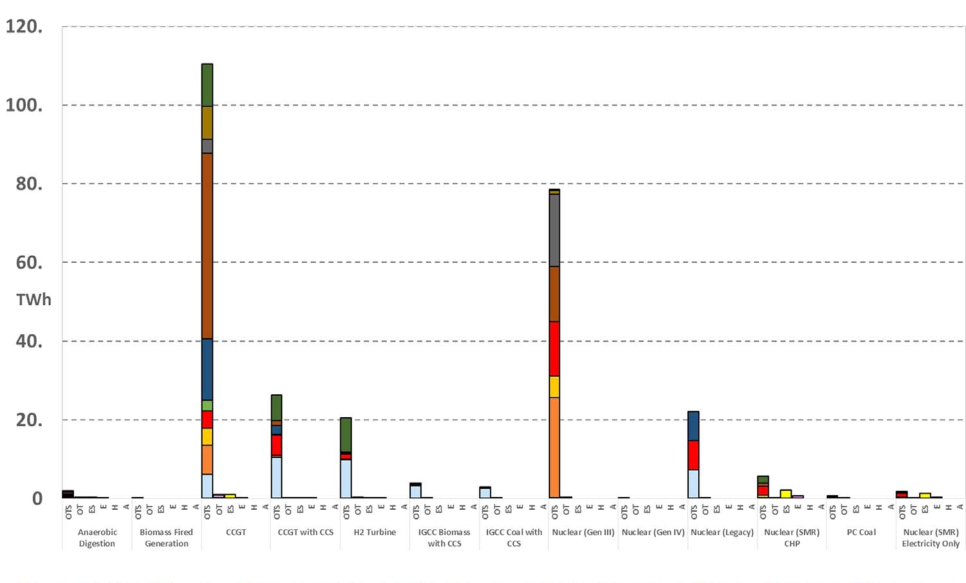

Fig. 4. Regional generation by technology and cooling method 2030 Q70 SW. Cooling method abbreviations: OTS – Once-through cooling seawater, OT – Once-through cooling, ES – Evaporative Cooling Sea E – Evaporative cooling, H – Hybrid cooling, A – Air cooling (applies for Figs. 4–6 and 8–10).

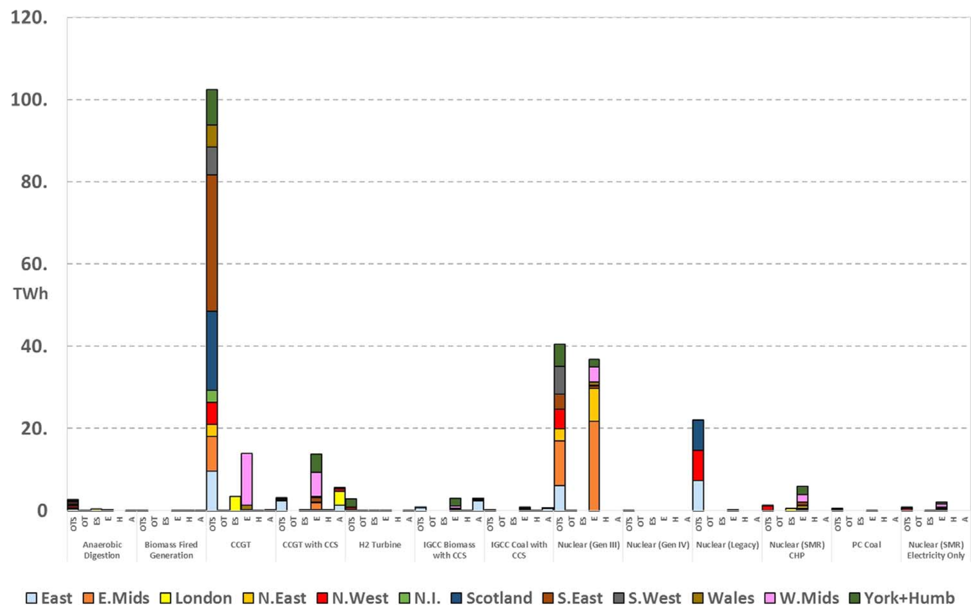

Fig. 5. Regional generation by technology and cooling method 2030 Q70 SWL.

portfolio and costs have been shown to be very similar to that of the methodology's SW result. This shows that in affect the ESME Standard pathway implicitly 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 model is in practice impacted by the amount of cooling water actually available brings a vital "affordable" reality critique not only to ESME, but also of the UK's energy policy.

The methodology assessed how the cooling water available to the cost-optimised ESME model affected the generation and cooling method technology choices it made. It did this by considering installed capacity, electricity generation, and associated costs under the ESME model, all of which were found to be to be in line with the cooling water made available.

Looking at the results obtained by the methodology set out in this paper, at 2050, for Q70 to meet a generating demand of the order of 595 TW h the annualised cost of the electricity system was found to be – SW £59.44bn; SWL £61.22bn [+1.78bn, (3%)]; SWN £67.05bn [+7.61bn, (12.8%]). The corresponding annualised costs for the total energy system were SW £304.07bn; SWL £307.51bn [+£3.44bn (1.13%)]; SWN £316.57bn [+£12.5bn, (4.11%]). An indication of the implications of this in the context of the UK's GDP is provided by Ernst and Young (2011) that finds the energy sector contributes around 8% of the UK GDP. For the UK with a GDP of £1869.5bn in 2015 (Statista, 2015), this equates to a £139.87bn energy sector contribution. The percentage cost increases incurred under SWL and SWN scenarios are therefore significant. Furthermore any increased generation costs that are incurred at SWL and SWN would not of course be distributed pro rata across this GDP but would affect the more electricity dependant GDP to a greater extent. This was confirmed in Section 4.1 which showed that the electricity system carried the bulk of any cost increase across the scenarios. For policymakers it is important to recognise the proportion of the UK's GDP that is attributable to the electricity system can only grow with UK's policy for the future electrification of the UK's

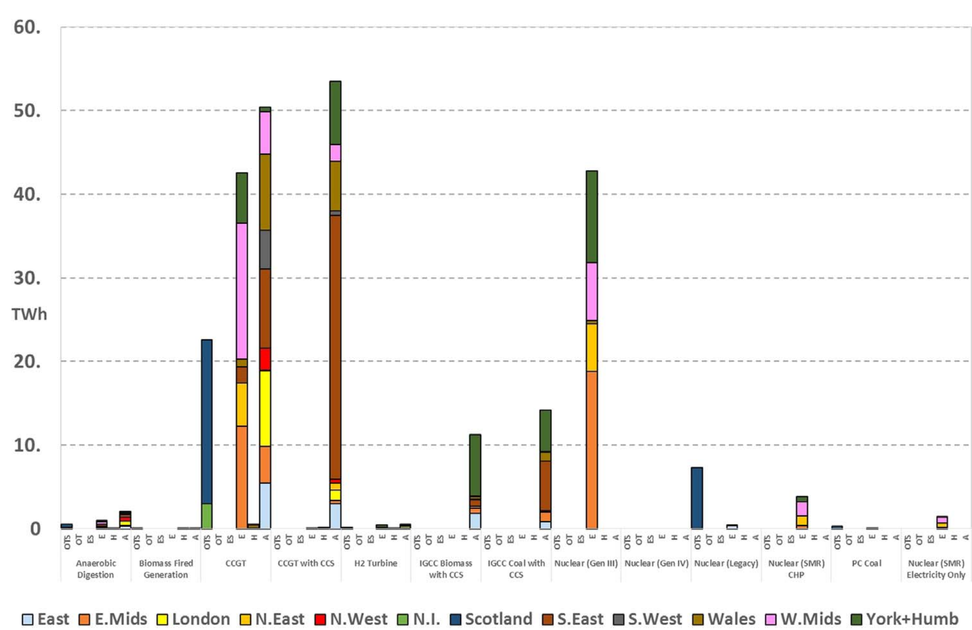

Fig. 6. Regional generation by technology and cooling method 2030 Q70 SWN.

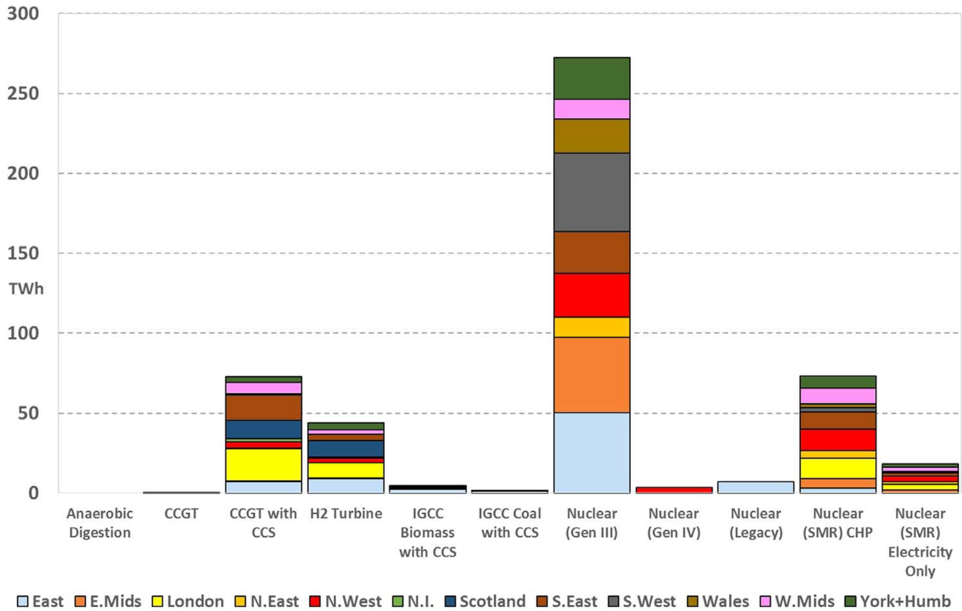

Fig. 7. Regional generation ESME Standard 2050.

road transport system. This will make any cost increase due to lack of water for thermal generation even more significant in GDP terms.

Ensuring that the UK can meet its future energy generation demand and emission targets in an affordable manner is rightly a fundamental requirement of any country's energy policy. Indeed keeping energy bills as low as possible became part of the current 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. But thermal infrastructure has lengthy planning procedures, and long operational lifetimes that from concept to redundancy can span fifty years. 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 a confirmed infrastructure build. The UK's recent performance in rolling out new thermal generation is characterised by delay, and uncertainty, 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 Ofgem and the National Grid, have commented on the limited spare generation capacity the UK now has available to cover demand emergencies (OFGEM, 2015; Royal Academy of Engineering, 2013).

This study 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 the 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 is electricity generated using the more expensive, but less water intensive cooling methods still affordable? The generators' argument is the disproportionate priority being given to protecting the ecological status of water bodies not only reduces freshwater abstraction, but contrary to expectations seems likely to limit the availability of seawater. Now, only the more expensive generation will be possible. The generators' opinion is the

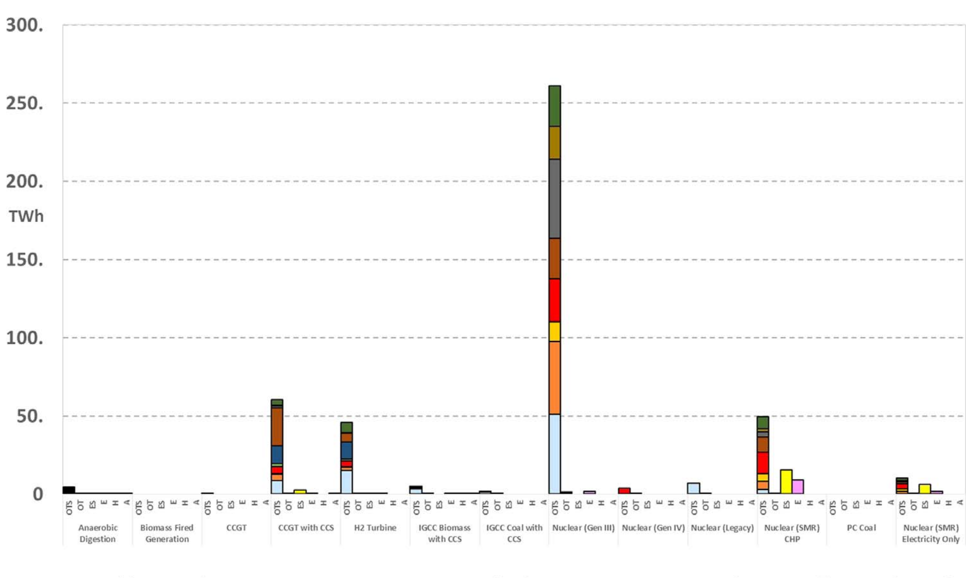

Fig. 8. Regional generation by technology and cooling method 2050 Q70 SW.

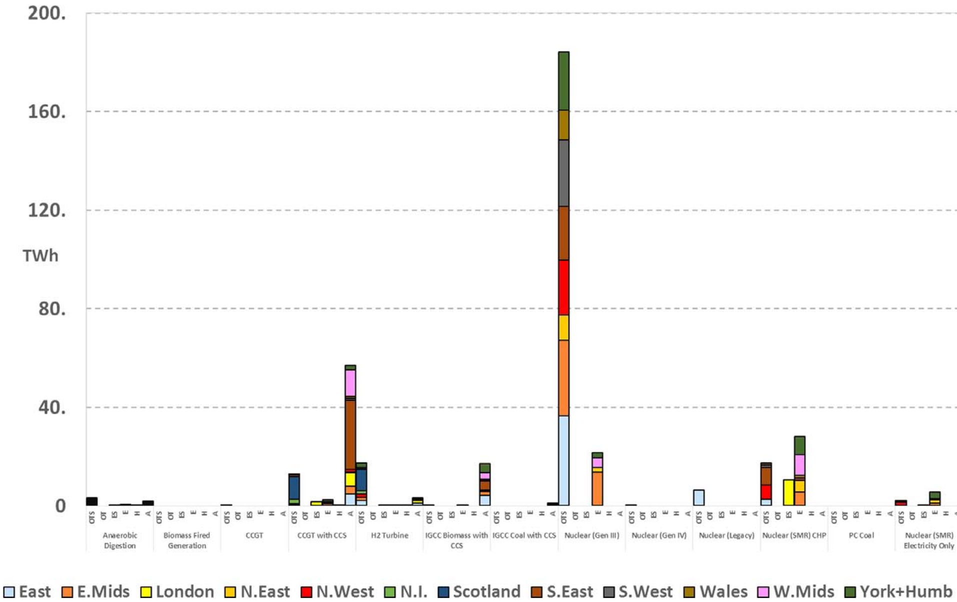

Fig. 9. Regional generation by technology and cooling method 2050 Q70 SWL.

general public and business will not consider it to be affordable and consequently profit will be difficult to come by.

Policymakers have to recognise that the future economic wellbeing of the UK will in a price conscious world be progressed by its global energy competiveness (European Commission, 2014; World Energy Council, 2016). 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 already in the UK, it was confirmed thermal power stations are already unable to withdraw all the BAT water they would prefer. Globally, and in the UK, the demand for thermal generation is predicted to increase, and the amount of freshwater available to get less. This study'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 study focused on the UK's thermal generation the generation cost advantages found of having seawater available surely have connotations for other countries with large energy demands in close proximity to coastal seawater resources.

6. Conclusion

In summary, this paper has established that in the future, as in the past, energy will be the foundation on which the world population's wellbeing will be built. To meet a demand for energy, increased by a growing population, and equity of wealth, the intention is to build more thermal power stations. The scarcity of freshwater for cooling these power stations, and stricter environmental oversight, will mean a large proportion of this demand will be where water is so restricted only low water intensity, higher cost, methods of power station cooling can be used. This will be compounded where CCS is required so the emissions of fossil fuel generation meets required targets. The additional generation cost will inevitably decrease these countries' commercial competitiveness.

The UK with its high thermal generation ambition, but with a large seawater resource, is in the enviable position of having a range of cooling water options within which it can decide how globally competitive it wants its future electricity generation to be. However,

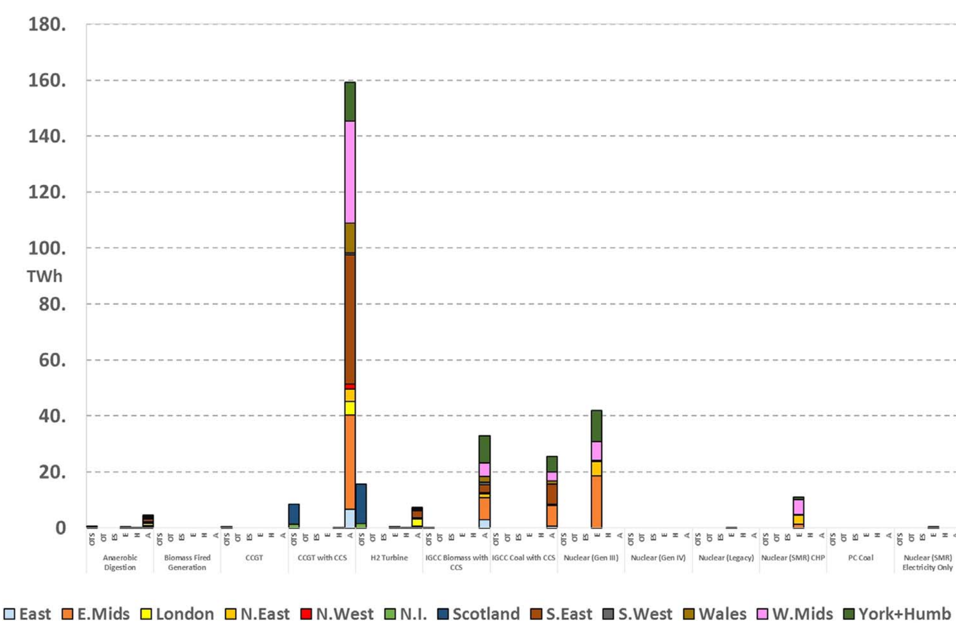

Fig. 10. Regional generation by technology and cooling method 2050 Q70 SWN.

Table 7
Annualised electricity systems costs 2030 (£billion).

2030 Annualised Costs (£bn)	Scenarios						
	ESME 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**

VOM: Variable Operations and Maintenance.

Table 8
Annualised electricity systems costs 2050 (£billion).

2050 Annualised Costs (£bn)	Scenarios						
	ESME 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**

VOM: Variable Operations and Maintenance.

Table 9
Difference in electricity system cost between scenarios.

	2030	2050		2030	2050
Difference Q70 SW total cost and Q70 SWL total cost (£bn)	0.67	1.75	**Difference Q95 SW total cost and Q95 SWL total cost (£bn)**	0.75	1.86
% Difference	1.56	2.95	**% Difference**	1.75	3.13
Difference Q70 SW total cost and Q70 SWN total cost (£bn)	3.63	7.61	**Difference Q95 SW total cost and Q95 SWN total cost (£bn)**	3.89	7.87
% Difference	**8.48**	**12.8**	**% Difference**	**9.09**	**13.2**

Table 10
Annualised total energy systems costs 2030 (£billion).

2030 Annualised Costs (£bn)	Scenarios						
	ESME 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**

VOM: Variable Operations and Maintenance.

Table 11
Annualised total energy systems costs 2050 (£billion).

2050 Annualised Costs (£bn)	Scenarios						
	ESME 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**

VOM: Variable Operations and Maintenance.

Table 12
Difference in total energy system cost between scenarios.

	2030	2050		2030	2050
Difference Q70 SW total cost and Q70 SWL total cost (£bn)	0.89	3.44	**Difference Q95 SW total cost and Q95 SWL total cost (£bn)**	0.88	2.79
% Difference	0.38	1.13	**% Difference**	0.37	0.92
Difference Q70 SW total cost and Q70 SWN total cost (£bn)	4.37	12.49	**Difference Q95 SW total cost and Q95 SWN total cost (£bn)**	4.55	12.10
% Difference	1.85	4.11	**% Difference**	1.93	3.97

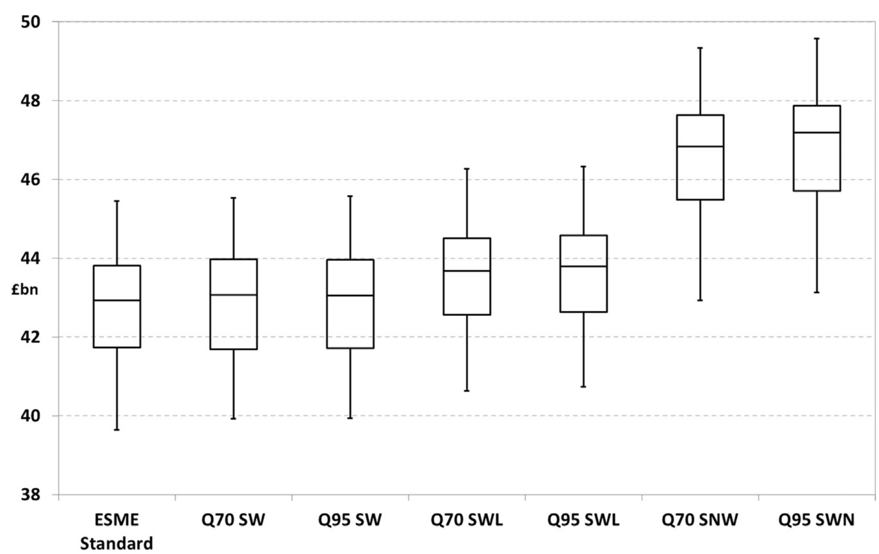

Fig. 11. Box and Whiskers Plot Annualised Electricity System Cost 2030 (£billion).

indecision is seriously delaying building the answer. The poles between which the decision lies are 'environment protection' and the 'cost of electricity generation'. The uncertainty has been due to a lack of figures in the environment cost columns, and in this respect, this paper has hopefully moved the debate on.

Compliance with Ethical Standards

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Conflict of interest

The authors declare that they have no conflict of interest.

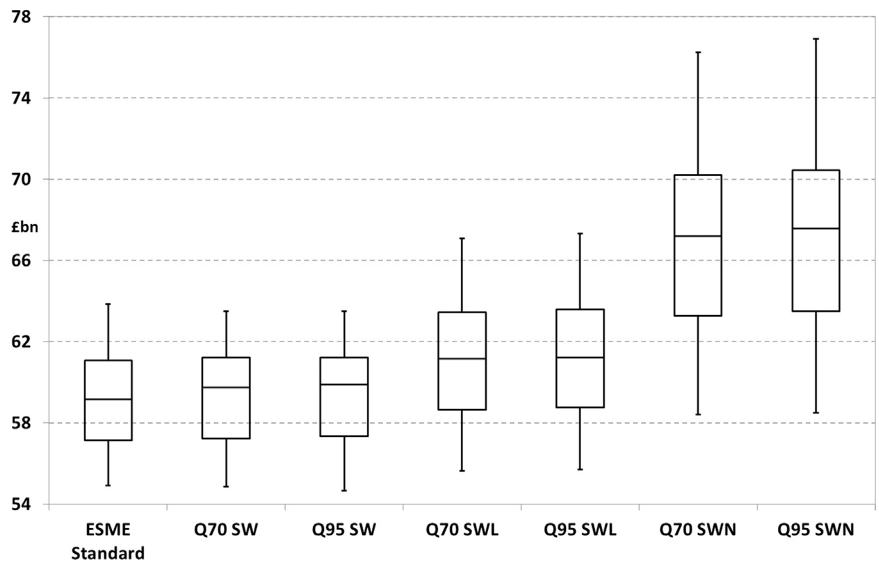

Fig. 12. Box and Whiskers Plot Annualised Electricity System Cost 2050 (£billion).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2017.03.047.

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