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Electricity generation and cooling water use: UK pathways to 2050

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ABSTRACT

Cooling of thermoelectric … England and Wales, the … and 40% of non-tidal surface water abstractions. We present a model that quantifies current water use of the UK electricity sector and use it to test six decarbonisation pathways to 2050. The pathways consist of a variety of generation technologies, with associated cooling methods, water use factors and cooling water sources. We find that up to 2030, water use across the six pathways is fairly consistent and all achieve significant reductions in both carbon and water intensity, based upon a transition to closed loop and hybrid cooling systems. From 2030 to 2050 our results diverge. Pathways with high levels of carbon capture and storage result in freshwater consumption that exceeds current levels (37–107%), and a consumptive intensity that is 30–69% higher. Risks to the aquatic environment will be intensified if generation with carbon capture and storage is clustered. Pathways of high nuclear capacity result in tidal and coastal abstraction that exceed current levels by 148–399%. Whilst reducing freshwater abstractions, the marine environment will be impacted if a shortage of coastal sites leads to clustering of nuclear reactors and concentration of heated water discharges. The pathway with the highest level of renewables has both lowest abstraction and consumption of water. Freshwater consumption can also be minimised through use of hybrid cooling, which despite marginally higher costs and emissions, would reduce dependence on scarce water resources thus increase security of supply.

1. Introduction

Globally, 80% of electricity generation comes from thermoelectric power stations (such as fossil fuels and nuclear), all of which require cooling for efficient and safe operation (International Energy Agency, 2009). Most of this cooling is provided by water abstractions from, and thermal discharges to, the natural environment, including rivers, tidal estuaries and coasts. Some of the water abstracted (also referred to *withdrawals* in much of the US literature) is consumed in the process (*consumption*), whilst the rest of the water may be returned to the water body, depending on the cooling technology used. In industrialised countries, electricity sector abstractions can be in the order of 40% of abstractions from freshwater sources (EA, 2008a; EEA, 2010; Pan et al., 2012; U.S. DOE, 2006). Freshwater resources and the marine environment are under increasing pressure, primarily from growing populations and changing socioeconomic conditions (Vorosmarty, 2000), but also climate change (Arnell et al., 2001; Kundzewicz et al., 2007).

Policies to mitigate climate change are driving the decarbonisation of electricity generation worldwide and may be tackled by a combination of technologies, from renewables like hydro, wind and solar, to fossil fuels with carbon capture and storage (CCS) and nuclear power. Thermoelectric generation capacity has different water-use intensities (Macknick et al., 2012a, 2011; McMahon, 2010; NETL, 2007), which depends on a number of factors but primarily the type of cooling method chosen and the thermal efficiency of the plant. The long term availability of a cooling resource is a vital consideration for power station developers as cooling equipment is costly and retrofit or poor performance could hamper the financial viability of a project (EC JRC, 2001; Förster and Lilliestam, 2009). Conversely, the lifespan of energy infrastructure spans decades so the long-term availability of water to other users may be threatened if the impacts of the sector are not fully taken into consideration in wider water resources planning. Already across the world heatwaves and droughts have limited output and even shut down thermoelectric power stations because

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of insufficient cooling water availability, discussed further in Section 1.3.

In the UK, 90% of electricity generation comes from thermo-electric power stations, whilst electricity sector abstractions make up approximately half of all water abstractions in England and Wales (EA, 2008a,b). Besides regional distribution, little is known, published or publicly available about what makes up this considerable volume. Schoonbaert's thesis (2012) provides very useful coverage of electricity sector abstractions in England and Wales, for its current state, planned capacity and with projections to 2030 and 2050. Our work, which uses similar datasets provides a more detailed and continuous picture of water use through to 2050 for the whole of the UK. Most importantly, we have validated our work based on Environment Agency data, and subsequently report considerably different results to Schoonbaert, discussed in the validation section. The general trends of our results, are however, similar to those of a similar study for the U.S. done by Macknick et al. (2012b). Our study begins by quantifying the current volumes and sources of both abstraction and consumption in the UK, by different types of electricity generation, water source and cooling method. This model is then used to estimate future water use for different electricity sector pathways to 2050.

This paper provides an overarching assessment of the demand for water resources from national-scale electricity decarbonisation pathways for the UK. We introduce general characteristics of power station cooling and bring this into context with a summary of the UK's electricity sector and wider pressures faced by the UK. Section 2 presents the generalised model framework for calculation of water use of future electricity sector pathways. Following similar approaches by Macknick et al. (2012b) and Schoonbaert (2012) whilst using different tools, the modelling work in Section 3 uses familiar energy pathways to inform decision makers of the scale of demands on water resources as different decarbonisation strategies take shape. In Section 4 we explore the benefits and risks of futures dominated by nuclear and carbon capture and storage, the possible implications of the forthcoming UK Energy Bill and the consequences that may result from full decarbonisation beyond 2030. We conclude the methods, assumptions and results presented provide useful indicators to the challenges faced by future electricity systems and to the potential risks to water resources and environments.

1.1. Water use for cooling of power stations

There are 4 main types of cooling employed by the electricity sector which use varying amounts of water and energy, summarised in Table 1. The table summarises, for abstraction and consumption, the range of medians presented in (Macknick et al., 2011); performance may well be observed outside these ranges, whilst further information can be found in (EA, 2010; EC JRC, 2001; Macknick et al., 2012a, 2011; McMahon, 2010; NETL, 2009a, 2007).

Cooling systems which use less water tend to have both higher capital and operational costs; the former from cooling tower construction whilst an energy penalty from pumping, fans and a higher condenser back pressure all affect the economics of operation, although to an extent that is contested between theoretical and empirical studies (Martín, 2012; NETL, 2009a, 2007; Rutberg, 2012). On this basis, open cooling is usually the preferred choice of developers, if there is water available and environmental regulations permit.

When inland water resources are unavailable or unreliable, power generators are faced with locating near the coast to use sea water or using more costly air-cooled and hybrid systems. The resultant energy penalty from these latter alternatives places a significant value on the water made available to power stations that enable them to operate at inland locations. Over the years all inland coal plants in the UK have switched from open to closed loop cooling, whilst gas plants are a mixture of both. Closed loop reduces environmental impacts as thermal discharge is to the air (instead of to water) and abstraction volumes are small, although consumptive losses are higher. Coastal power stations almost always use open loop cooling, but the effects of thermal pollution and fish entrainment and impingement on local ecology can be substantial (EA, 2010).

Hybrid cooling offers the possibility of using water when available and mechanical air draft when not. Uptake in the UK is at 14% for current gas installations and 3% for coal, proportions that we expect to increase (to 36% and 39% respectively) based on more recent capacity developments and the high water intensity of carbon capture equipped generation. As detailed by Zhai et al. (2011), the addition of post-combustion carbon capture and storage technology to a pulverised coal plant not only reduces the net plant efficiency (from 38.3% to 26.4%), but that the cooling of the carbon capture system in fact marginally exceeds the cooling required for the steam cycle.

Air cooling results in parasitic energy use estimated to be 40% higher than closed loop cooling (EC JRC, 2001), due to the high throughput of air required by mechanical draft fans as there is no evaporative heat transfer from cooling water. When considered in the context of the whole plant, electrical output reduction may be between 3% and 11%, depending on the ambient temperature: the

Table 1
Characteristics of different power generation cooling systems.

Cooling system	Description	Abstraction volumes l/kWh[a]	Consumptive losses (% of abstraction)[b]	Energy penalty as % of electrical output[c]
Once through (open loop)	Heat is removed through transfer to a running water source (can be direct or indirect).	43–168	0–1%	0.7–2.3
Closed (re-circulatory)	Heat is removed to the air by recirculating water cooled in ponds or under cooling towers that may be fan-assisted or natural draught.		Wet tower	
		1–5	61–95%	1.8–6.3
			Pond	
		22–67	4–9%	1.8–6.3
Air-cooled	Heat is removed by air circulation via fans and radiators. A setup that can operate without water.	0	–	3.2–11.2
Hybrid [d]	Cooling towers that can operate both with and without cooling water – either combining a wet/dry cooling tower, or a dry then wet system in series.	Between Closed and Air-cooled	61–95%	1.8–11.2

[a] Range of the medians for different cooled technologies taken from Table 3.
[b] Range of the medians for different cooled technologies taken from Table 2.
[c] Energy penalty range calculated from the ranges in the European Commission Joint Research Centre (2001, p. 69) report, by assuming plant thermal efficiencies from 60% to 30%.
[d] We present the range between closed and air-cooled, and not the figure quoted for hybrid, since the operational split between closed and air-cooled cooling is not specified in the report.

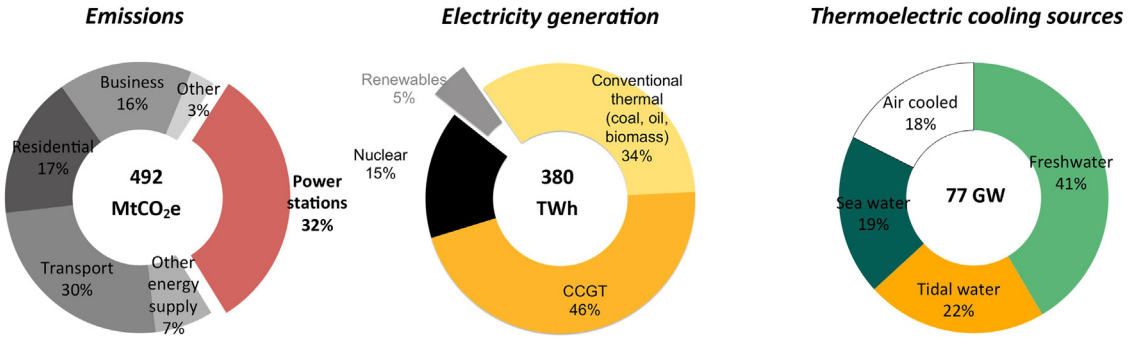


Fig. 1. The UK electricity sector in 2010.

hotter the air temperature, the less efficient the cooling and higher the use of fuel and resultant greenhouse gas emissions.

1.2. UK electricity sector

The UK electricity mix is dominated by thermoelectric generation capacity which contributes to 90% of the roughly 380 TWh generated each year (Fig. 1). Of electricity supplied to the grid (after losses and own-use requirements and excluding imports), in 2010 conventional thermal contributed 124 TWh (34%), combined cycle gas turbines (CCGT) 168 TWh (46%), nuclear 56 TWh (15%) and the remaining 17 TWh (5%) was renewables (DECC, 2012a). Currently, the sector is responsible for 32% of the UK's carbon dioxide emissions (DECC, 2011a) and has been identified as a key component of the UK's efforts to reduce emissions by 80% by 2050, a legally binding target of the Climate Change Act 2008. To meet the challenges, considerable change in the generation capacity is planned and expected, with a range of low-carbon technologies at the forefront, primarily nuclear, coal and gas with carbon capture and storage (CCS) and renewables such as wind power and solar photo-voltaics (PV). Because of the phasing out of old plants, a significant capacity deficit is expected over the next decade, with the capacity margin expected to reach a low of only 4% in 2015/6 (Ofgem, 2012), from a margin of 14% in 2012/13. This narrowing of capacity margins resulted in the Government responding with the UK Gas Generation Strategy as a stopgap measure (DECC, 2012b) "to keep the lights on". The Energy Bill currently being legislated will facilitate future thermoelectric generation capacity hence the potential for long-term lock-in of water intensive electricity generation is a distinct possibility.

The current focus of UK energy policy is on decarbonising whilst maintaining affordability and security of supply (DECC, 2011b; HM Government, 2009; Infrastructure UK, 2011, 2010; Mackay, 2009) with many suggestions as to how this could be achieved (CCC, 2009; DECC, 2012c; HM Government, 2011; UKERC, 2009; Winskel et al., 2009). Water availability and use is not normally considered within UK energy strategy despite potential impacts on the price of production, security of supply and carbon emissions, which we address in the discussion.

We have calculated that water is abstracted for cooling at 82% of the 77 GW of thermoelectric power stations in the UK, the rest of which are air-cooled or require no cooling. About 20 GW of this capacity lies on non-tidal surface water, by the EA classification, referred to as freshwater hereon (which may normally include groundwater). The remainder is abstracted from tidal surface waters and the sea. The capacity on freshwaters generates an estimated 88 TWh per year, 23% of the UK's electricity generation in 2010 with a market value we estimate to be £7 billion per annum (DECC, 2012d, 2011a). This generation capacity however is fossil-fuelled, contributing an estimated 76 $MtCO_2$ per year, approximately half of the sector's emissions and 15% of the UK's CO_2 emissions (DECC, 2012d).

Pertinent to all water-energy nexus studies, we define this work's boundary at the use of cooling water, which is not the only water use associated with electricity production. There is a water footprint for the manufacture of equipment and materials, from steel and concrete to PV solar panels, which is usually freshwater. Operational use of freshwater for emissions treatments and boiler and turbine feedwater increase use by 5–10% for coal, 1–2% for combined cycle gas turbines (NETL, 2009a) and 18% for coal with carbon capture and storage (Zhai et al., 2011). Most crucially, water is used for the extraction and production of fossil fuels ((McMahon, 2010; Olsson, 2012). Albeit predominantly U.S. data, approximate figures for extraction in litres/GJ are: coal, 5–70; shale gas, 36–54; Uranium, 4–22; biofuels (various), 9000–574,000. Transformation and refinement of these fuels (excluding coal) ranges from 7 to 50 l/GJ. The UK imports two thirds of its coal and just under half of its gas whilst power stations consume 81% and 30% of all coal and gas (DECC, 2011a). Transitions dependent on coal, gas (including domestic shale gas) and biomass for electricity production will continue to have a water footprint, both in the UK and abroad, and although excluded from this analysis is an area that requires investigation.

1.3. Pressure will mount on already high levels of abstraction and consumption

Pressures on water availability in the UK and worldwide include population growth, increasing demand for food production, and increasing hydrological variability in a changing climate, all of which will complicate the operation of water cooled thermoelectric power generation. The population of the UK is expected to grow by 24% to 76 million by 2050. An ageing population, decreasing household occupancy and more single-occupancy households may stifle improvements in per-capita energy and water consumption as resources are used less efficiently. Currently in England and Wales, of 119 water resource catchment 'units', 18% and 15% already find themselves in the categories of 'over-licensed' and 'over-abstracted', respectively, with the consequence of 'unacceptable environmental damage' at low flows (EA, 2008c). A further 35% of catchment units have 'no water available' for further licensing at low flows. These are all challenges also faced by the water sector, which is slowly coming to terms with the energy and greenhouse gas intensity of its operations (Rothausen and Conway, 2011).

The UK Climate Projections 2009 (UKCP09) (Murphy et al., 2009) have projected a range of climatic changes for the UK, in particular increased hydrological variability, decreased summer rainfall and higher summertime air temperatures, potentially impacting the cooling of thermoelectric generation. Higher

temperatures reduce the thermal efficiency and cooling of power stations when cooled by closed, hybrid and air-cooled systems. Mean summer air temperatures in the 2050s medium emissions central case (50%) are expected to rise by 2–2.8 °C whilst mean daily maximum air temperatures by 2.5–3.8 °C (Murphy et al., 2009). If streamflow temperatures also increase as expected (Morrill et al., 2005; van Vliet et al., 2013), cooling efficiency may be further reduced and the subsequent emissions intensity of generation will increase.

A recent study in the UK, Future Flows and Groundwater Levels, has produced a nationally-consistent ensemble of river flow and groundwater level time series simulated using 11 downscaled climate outputs from HadRM3-PPE (Prudhomme et al., 2012). Projections of future runoff in these climate change scenarios are uncertain, though the central estimate is expected to decrease in summer with a range from +20% to −80%, with the greatest changes occurring in the north and west. Decreases in autumn flows are also predominantly expected, although most severely in the south and east by up to 80%. With new abstraction licenses in many catchments only available with increasingly stringent 'hands-off' flow restrictions, developers must accept that operation may not be permitted when low flows below specified levels occur.

When sufficient cooling functions are not possible, power station operators are required to 'ramp down' the generation output in order to reduce cooling demand, whether this is to maintain safe and efficient operation or to protect the aquatic environment according to legislative constraints on abstraction volumes and discharge temperatures. As has been the case before in France, Germany, Spain, the US amongst others (Godoy, 2006; Kossida et al., 2012; Macknick et al., 2011; Müller et al., 2007; NETL, 2009b; World Nuclear Association, 2011), in some cases with nuclear power plants (ASN, 2004; Godoy, 2006; Poumadère et al., 2005; World Nuclear Association, 2011), a decision will compromise either the environment or security of electricity supply. Often this occurs in places where electricity demand peaks in summer, when water demands are greatest or when water availability is lowest. This problem is expected to worsen with climate change as shown by van Vliet et al. (2012) for European and U.S. coal and nuclear power plants.

2. Methods

Whilst the calculation of water use from a power plant is usually straightforward, the problem becomes more complex when considering multiple generation technologies, cooling methods and available water sources. For consideration of future electricity pathways, cooling methods and water sources are usually not known, hence we assume distributions. Our framework, whilst presented for the UK, can be applied easily to regional or continental projections of electricity generation, whilst helping frame the problem in a logical structure. This section works through our approach in detail, including the model validation, which can be challenging depending on data availability.

2.1. Model framework for deriving future electricity pathways and water usage

We present a model that quantifies current water use of the UK electricity sector, disaggregated by generation type, cooling method and cooling source. We test six decarbonisation pathways for the UK by combining projections of cooling methods and cooling sources for future thermoelectric generation to estimate water use for the desired timeframe (Fig. 2). In its simplest form, water use is calculated by multiplying the electricity generated from a technology by the abstraction and consumption factors for that technology.

We can define an electricity generation pathway with an $n_t \times n_g$ matrix $\mathbf{G}$ whose elements $g_{t,j} = 1,\ldots,n_t, j = 1,\ldots,n_g$ define the amount of electricity generated (in TWh) by generation technology j in year t. Subsequently, the $n_t \times n_g \times n_m \times n_w$ array $\mathbf{S}$ defines for each generation technology the percentage split across $m = 1,\ldots,n_m$ cooling methods and $w = 1,\ldots,n_w$ cooling sources for specified timestep $t = 1,\ldots,n_t$. The first timestep is an observation of the current distribution amongst cooling sources and cooling methods

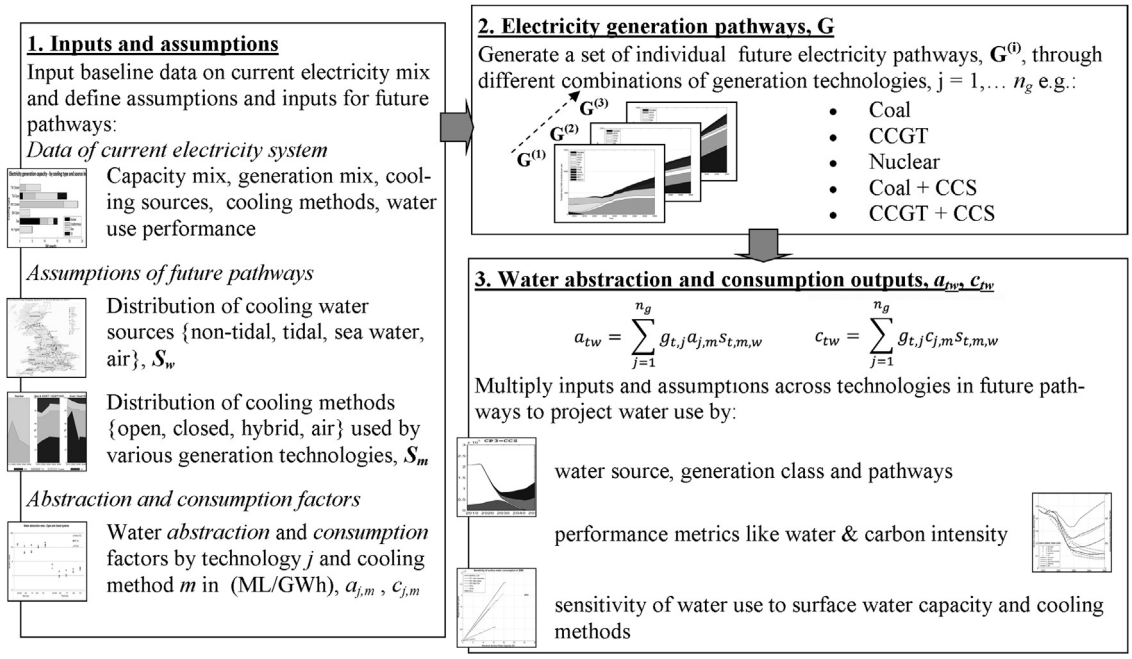


Fig. 2. Model framework diagram for estimating water use from electricity generation pathways. With an abundance of generation pathways being developed, the greatest challenge lies in acquiring data for the use and distribution of water sources, especially needed for validation.

Table 2
Description of the electricity pathways.

Label	Name	Narrative
UKM-326	UK MARKAL 3.26	*Core run of cost-optimised UK MARKAL 3.26.* A steady mix of renewables, nuclear and CCS is combined with ambitious energy demand reductions across all sectors, this is a least-cost pathway.
CP1-REN	Carbon Plan 1 – Renewables	*Higher levels of renewables and more energy efficiency*. Investment and innovation in renewables and storage driven by high fossil fuel prices and global commitment to tackling climate change. Mix of wind, solar and marine renewables, backed up by gas.
CP2-NUC	Carbon Plan 2 – Nuclear	*Higher nuclear and less energy efficiency*. Nuclear dominates and CCS not commercially viable. Gas meets peak demands and energy efficiency is low. Heat and transport are largely electrified.
CP3-CCS	Carbon Plan 3 – CCS	*Higher carbon capture and storage (CCS) and more bioenergy*. Commercial deployment of CCS for generation and industry fuelled by high levels of natural gas imports due to low fossil fuel prices and extensive shale gas. Involves negative emissions through Biomass-CCS.
CCS+	CCS+	*Higher carbon capture and storage (CCS) and no nuclear.* Similar to CP3-CCS although nuclear is replaced with further coal CCS, biomass, waste and renewables.
UKM+	UK MARKAL 3.26+	Similarly proportioned mix to the cost-optimised MARKAL run, although specified to meet 26% higher demand.

whilst assumptions are made about future distributions. The matrices **A** and **C**, of size $n_m \times n_g$, specify respectively abstraction and consumption factors for water use per unit of electricity generated (in ML/TWh) corresponding to the n_m cooling methods that are available to the n_g generation technologies.

Abstraction and consumption for any combination of generation technology and cooling method is obtained by element-wise multiplication of **A** and **C**, respectively, with **G** and **S** to give **GAS** and **GCS**. Thus the abstraction a or consumption c for pathway **G** on cooling source w in year t is equal to the sum of water use for all generation classes in **G** multiplied by the cooling methods and source distributions in **S**:

$$a_{t,w} = \sum_{j=1}^{n_g} g_{t,j} a_{j,m} s_{t,m,w} \quad (1)$$

$$c_{t,w} = \sum_{j=1}^{n_g} g_{t,j} c_{j,m} s_{t,m,w} \quad (2)$$

The modelling work presented is also described by Fig. 2 and has:

- $n_g = 7$ generation technologies: nuclear, gas open cycle gas turbine (OCGT), gas combined cycle gas turbine (CCGT), oil, coal/biomass sub-critical, gas CCGT with carbon capture and storage, super-critical coal with carbon capture and storage.
- $n_w = 4$ cooling sources: non-tidal surface water (FW), tidal surface water (TW), sea water (SW) and air-cooled (AC). The water nomenclature refers to the categories used by the Environment Agency, although for brevity we refer to "non-tidal surface water" as freshwater (FW).
- $n_t = 13$ timesteps: 2007:2011, 2015:5:2050. Results are interpolated linearly on an annual basis for graphical reproduction
- $n_m = 4$ cooling methods: open loop (O), closed loop (C), hybrid (H), air-cooled (A).

2.2. Future electricity pathways

The six electricity pathways chosen for analysis explore the boundaries of how the UK electricity mix could evolve. They do not cover all eventualities given the multitude of realistic policy options available, but they give an indication of how some quite different pathways perform. We test the four pathways presented in the UK Government's 'Carbon Plan', a document that outlines the strategy space for achieving the goals in the Climate Change Act 2008 and keeping the country in line with the carbon budget framework. We also add two new pathways, CCS+ and UKM+, for reasons explained below. The pathways are labelled according to their source in Table 2 with their electricity mix in 2050 presented in Fig. 3. For more details see also The Carbon Plan (HM Government, 2011).

UKM-326 is a cost-optimised pathway that results in a balanced electricity mix and relies heavily on demand reductions. The Carbon Plan pathways, CP1-3, push the boundaries of the three main generation categories of renewables, coal and gas with carbon capture and storage, and nuclear. Whilst CP2-NUC assumes a future of commercially unviable carbon capture, there is no pathway corresponding to a future where no further nuclear power is deployed. Hence, CCS+ is similar to CP3-CCS yet replaces nuclear with more CCS generation and renewables. Our analysis of the cost-optimised UKM-326 pathway identifies highly ambitious challenges in demand reduction (DECC, 2011c) and it is possible not all would be achieved (DECC, 2010). As such UKM+ comprises a similarly balanced and proportional mix to UKM-326 yet meets a 26% higher electricity demand and the

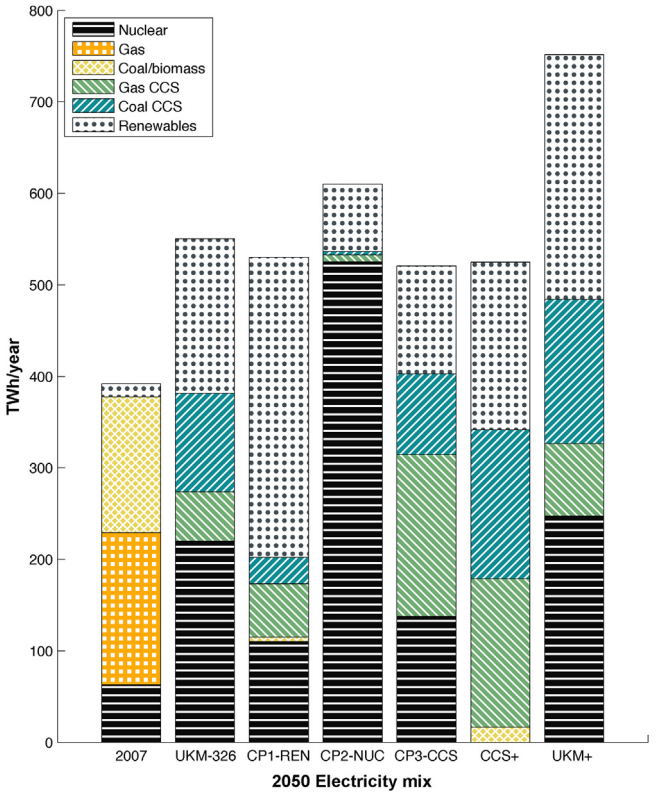


Fig. 3. Stacked bar chart of the 2007 and future pathways showing electricity generation per year in 2050.

carbon reduction targets. Overall the six pathways cover both a range in meeting demand from 520 to 752 TWh/year whilst also testing various proportions of nuclear, CCS and renewable generation mixes.

2.3. Cooling water use for UK electricity generation

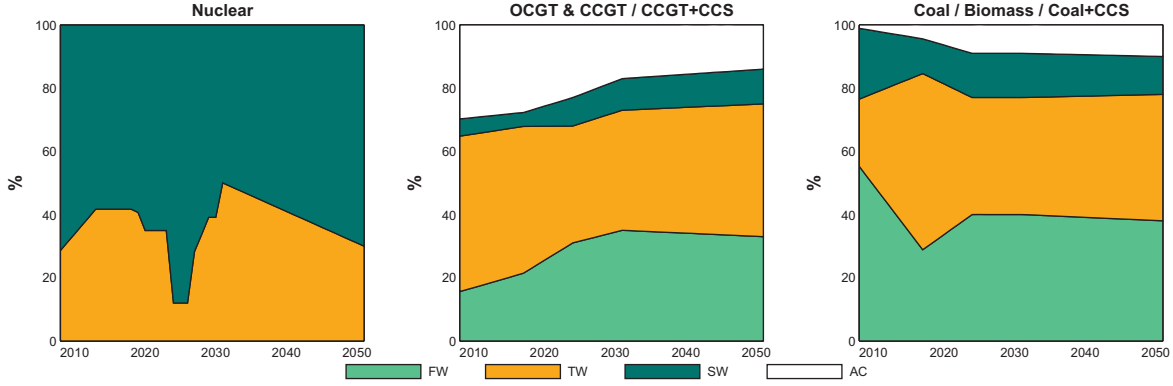
As new plants are commissioned in the future, the model must attribute this capacity to cooling sources and methods. The attribution must be consistent with past and present decisions and is performed using a set of rules and distributions that represent decisions on future location choices. This is translated into percentages and intermediate years are interpolated.

The UK lacks at this time a definitive dataset detailing the exact cooling method and water source of all thermoelectric power stations. All power stations over 17 MW were categorised by both cooling method, (open loop, closed (tower), hybrid or air) and by cooling water source, (freshwater (FW), tidal water (TW), coastal/sea water (SW)), which was verified using satellite imagery and company documents. Air-cooled (AC) power stations were also included, but not attributed to a cooling water source. This data was incorporated into a pivot table split by power station type for 2010 (see Fig. 3 and Supplementary Information). Further trajectory splits have been defined at the intervals of 2016, 2023, 2030 and 2050. To 2016, and as applied by Schoonbaert (2012), the split is defined to represent closure of capacity from the Large Combustion Plant Directive (LCPD) as well as planned and approved capacity from the DECC Energy Infrastructure Portal, an online planning application repository for England and Wales. We also assume that all future capacity on freshwater will use wet closed loop or hybrid cooling towers, to test a policy of minimising the volume of abstractions, similar to the U.S. EPA policy under the Clean Water Act (Environmental Protection Agency, 2001). Further assumptions are detailed in Fig. 4.

Given that water use factors for the UK are not available, a composite set of factors was created from a range of sources required to complete the dataset for all generation technologies. This was based principally on data from Macknick et al. (2011) and if available averaged with figures from either National Energy Technology Laboratory (2009b) or EPRI (2002). Figures for generation with carbon capture and storage were taken from Tzimas (2011) and checked against figures in Zhai et al. (2011) and Zhai and Rubin (2010). We note that although the figures for the UK will differ slightly, the US data in the various aforementioned reports has shown consistency over time and is thus considered suitable for this study, similarly concluded by Schoonbaert (2012) and detailed further in the Supplementary Information. Similar to Macknick et al. (2012b) water use factors are not time-variable in this study, although it is likely that slight thermal efficiency improvements will reduce water use in future. Considering the realistic improvements that may be achieved, the scale of these changes on water use will be extremely minor when compared to other decisions such generation technology and cooling methods. Figures for unabated coal are for sub-critical technology, whilst for CCS super-critical is assumed.

2.4. Validation

Aggregate water abstraction figures were compared with estimated abstraction data from the Environment Agency (EA, 2012) to validate the model over a control period from 2007 to 2011 using reported generation data from DECC (2012b, 2009). The publicly available Environment Agency data, includes hydropower



Nuclear
The new generation of nuclear plants will be split 50:50 between sea water (SW) and tidal water (TW) following the classifications of past sites stated by the Environment Agency (2010) and the identified future sites. Decommission and commission will be staggered and hence reduces overall TW proportion in the 2020s but increases again by 2030. Beyond the first generation (up to 26GW), from 2030 to 2050 we assume a split of 70:30 between SW and TW due to less availability of sites on estuaries and environmental legislation.

OCGT & CCGT / CCGT+CCS
The trend observed from planning applications since 2005 has indicated an increase in combined cycle gas turbines cooled by freshwater (FW) (in closed loop, AC and hybrid configurations) which have and will replace, in some cases, smaller air-cooled open cycle gas turbines (OCGT). Due to their peaking capacity and black-start capability however, some OCGT capacity remains. Past 2030, plants will require additional abstraction rights for carbon capture retrofit which may limit further FW development, hence slightly higher levels of TW and sea-cooled capacity can be expected.

Coal / Coal+CCS (or biomass)
Tidal water (TW) reduces towards 2016 as older plants are decommissioned with the Large Combustion Plant Directive. Beyond this, the use of legacy sites and higher water requirements (roughly double for carbon capture) compared to combine cycle gas turbines increases a shift towards tidal water and sea water sites. Past 2030, plants will require additional abstraction rights for carbon capture retrofit which may limit further freshwater development. Increase in air-cooled capacity is due to smaller biomass plants.

Fig. 4. Cooling water source trajectories as a percentage of installed capacity type. In the 2030s Gas and Coal generation transition to their equivalents with CCS respectively. Further details in Tables S2–3 and 5.

and pumped storage, thus separate datasets to remove the hydropower component were obtained. The data only covers England and Wales thus validation of the model was for these nations only. All of the UK's freshwater cooled thermoelectric generation is in England and Wales whilst for tidal water the proportion is 91%, thus modelled figures were scaled down accordingly. Wales has very little freshwater-cooled thermoelectric capacity, totalling 515 MW from Deeside CCGT power station, which has incidentally reported hybrid cooling water usage at the plant since 2001. Hence, abstractions reported for Wales by the Environment Agency are almost exclusively hydro and pumped storage (99.9%) and thus not reported below.

For both freshwater and tidal water our model has approximated abstractions in the majority of cases to within 10%, with a general trend of slight overestimation. For the period 2009–2011 the model overestimates in the range of 2.2–8.5%, whilst reported values for 2007 freshwater and 2008 tidal water are unusually high. The accuracy increases from 2007 towards 2011, as would be expected given that the data and satellite images are from the more recent years. For the purposes of this analysis this was judged to be satisfactory when considering that the Environment Agency data are only estimates and the uncertainties that arise from the model, discussed below.

For the period of 2000–2011, year-to-year electricity sector abstractions in England have peaked at 3.480×10^6 ML in 2001 and dropped to 1.070×10^6 ML in 2006–2007 due to variability in both hydropower and thermoelectric power abstractions. The modelled abstractions are dominated by the small number of plants that use open cooling whose abstraction rates are two orders of magnitude higher than the majority of plants which use closed loop evaporative cooling. Along with the hydropower abstractions, this has made validation very sensitive to the few plants that use open loop cooling on freshwater. The estimated abstraction records in all sectors have considerable variability that make it difficult to validate on a year to year basis, in some cases this has been due to licences switching categories between electricity supply and 'other industry'. Similarly, whilst the constituent generation capacity may only change a little from year to year with the addition or decommission of a few power plants, generation is more variable and may depend on summer maintenance cycles, weather, fuel prices and the electricity market balancing.

Parametric uncertainty comes primarily from the uncertainty in the EA classifications of power station abstraction sources and cooling methods, but also from the water use factors. Water use factors were derived mostly from US data reported in sector-wide meta-analyses. Whilst the machinery and power stations are largely the same, load factors, ambient conditions and age distribution are likely to be different to the UK. Further operational decisions, such as number of cooling cycles, may influence the factors and may vary between freshwater and tidal water plants. The cooling methods, classified from satellite images and online search for records, were verified subsequently against the data of Schoonbaert (2012) and is available in SI Table S4. The split of power stations between freshwater, tidal surface water and sea water was defined in the same way, and checked against the Maps of Freshwater Limits and Ordnance Survey online mapping, the latter of which in many cases details the locations of the pump houses and sluices. Thus we have a high level of certainty that our cooling sources and methods are accurate. We believe the significant differences from Schoonbaert's freshwater abstraction estimates are explained by disagreements in cooling source and method. We were unable to check the sources (as they are not provided in the article), whilst a few differences were found in the methods. Furthermore, Schoonbaert uses the term estuarine although it is unclear what definition of estuarine limits have been used, which may explain the fact that his freshwater abstractions are much greater than we report. Taking the River Trent as an example, the tidal waters extend over 50 km inland from the mouth of the river where it meets the Ouse at the Humber, meaning several power stations that we have attributed to tidal waters have been classified as freshwater by Schoonbaert. Unfortunately, until regulators and industry bodies release the data they hold required to complete this analysis, greater certainty on the true scale of water abstractions will be difficult to confirm (Table 4).

3. Results

First we present a comprehensive set of results that breakdown the water abstraction and consumption of current UK thermoelectric capacity and generation (Table 5). We then present our projections to 2050, firstly for all water sources, and then exclusively

Table 3
Summary table of the water use factors used for the projections, split by generation and cooling technology. O, Open loop, C, Closed loop recirculating, H, Hybrid cooling (35% dry, 65% wet). Full information, sources and assumptions in the Supplementary Information Table S7.

Litres/kWh ML/GWh	Nuclear			Oil-fired (steam)			CCGT			Coal (sub-critical)			CCGT + CCS			Coal + CCS (super-critical)		
	O	C	H	O	C	H	O	C	H	O	C	H	O	C	H	O	C	H
Abstraction	164	3.88	2.52	134	2.08	0.68	47.6	0.93	0.59	118	2.11	1.33	90.0	1.82	1.19	220	4.29	2.79
Consumption	1.27	2.66	1.71	1.14	1.82	0.59	0.38	0.72	0.47	0.78	1.77	1.17	0.90	1.36	0.88	2.10	3.22	2.09

Table 4
Model validation for 2007–2011. The validations compare modelled cooling water abstractions (in ML year^{-1}) from freshwater (FW) and tidal surface water (TW) against figures reported by the Environment Agency (EA) in 2012. Cooling water demands are presented in Table 5. G_g is the total electricity generation in that year (including renewables) from (DECC, 2012d).

Abstractions in mega litres per year										
	FW ($\times 10^6$) (England only)				TW ($\times 10^6$) (England and Wales)			FW + TW ($\times 10^6$) (England and Wales)			G_g (UK)
	EA hydro	EA non-hydro	Model	Δ%	EA	Model	Δ%	EA	Model	Δ%	TWh
2007	0.870	0.202	0.248	+18.5	8.10	7.16	−13.1	8.30	7.41	−12.0	397
2008	0.892	0.766	0.232	−230	6.69	6.71	+0.3	7.46	6.95	−7.4	389
2009	1.329	0.179	0.196	+8.5	6.83	7.02	+2.8	7.00	7.22	+3.0	377
2010	1.587	0.194	0.198	+2.2	6.53	7.00	+6.7	6.72	7.20	+6.6	382
2011	1.251	0.173	0.179	+3.6	6.82	7.29	+6.5	6.99	7.47	+6.4	368
μ	1.259	0.187	0.205	+8.2[a]	6.99	7.03	−0.8	7.29	7.25	−0.7	376

[a] The means reported for Freshwater exclude 2008 values.

Table 5
UK thermoelectric electricity Capacity and Generation in 2010 with resultant Abstraction and Consumption. Each generation class is split by cooling method (open, closed, hybrid) and the cooling sources in *W* of freshwater (FW), tidal surface water (TW) and sea water (SW). Air-cooled (AC) capacity has also been included.

2010	Capacity (GW)				Generation (GWh)				Abstraction 10^3 ML/year				Consumption 10^3 ML/year			
	FW	TW	SW	Sum	FW	TW	SW	Sum	FW	TW	SW	Sum	FW	TW	SW	Sum
Coal and biomass																
Open	–	5	5	10	–	19,965	22,725	42,690	–	2365	2692	5057	–	16	18	33
Closed	14	4	–	18	56,745	17,715	–	74,460	120	37	–	157	100	31	–	132
Hybrid	–	1	–	1	–	2326	–	2326	–	3	–	3	–	3	–	3
Gas and CCGT																
Open	0	5	2	7	1254	26,421	8973	36,648	55	1169	397	1621	–	9	3	13
Closed	4	9	–	13	22,159	45,015	–	67,174	19	39	–	58	15	30	–	45
Hybrid	1	3	–	4	7400	13,363	–	20,763	4	7	–	11	3	6	–	9
Nuclear																
Open	–	4	6	10	0	22,658	39,482	62,140	–	3725	6490	10,215	–	29	50	79
Oil																
Open	–	3	–	3	–	3203	–	3203	–	430	–	430	–	4	–	4
Air-cooled (AC), mostly OCGT																
AC				11.5				56,857	–	–						
Totals (excluding AC)																
Sum	20	33	14	66[a]	87,558	150,667	71,179	309,404[a]	198	7776	9579	17,553	119	127	71	317
%	30	50	21	100	28	49	23	100	1	44	55	100	37	40	22	100

[a] Total figure excludes capacity/generation from thermoelectric air-cooled capacity.

for freshwater, disaggregated by generation technology. Lastly, we present the results of our cooling method and source sensitivity analysis, as well as performance metrics to assess the carbon and water intensity of future UK electricity generation.

3.1. Water use: abstraction and consumption

Freshwater abstractions in England and Wales are as high for the electricity sector (including hydro and pumped storage) as they are for public water supply, averaging 4.309×10^6 and 4.157×10^6 ML per year, respectively between 2007 and 2011 (EA, 2012). Table 5 reveals that 5% of this relates to thermo-electric generation, 62% of which is consumptive at approximately 0.119×10^6 ML per year, equivalent to domestic water demand of 900,000 households. When hydro is excluded, thermoelectric in the UK is responsible for only 3% of freshwater abstractions; compared to the US for which thermoelectric makes up 39% of abstractions (U.S. DOE, 2006). The current levels of tidal and sea water abstraction are 40–50 times higher than freshwater abstraction, although consumptive proportions are only 2% and 1% respectively, due to the use of once through cooling.

61% of freshwater abstractions come from a few closed loop coal power stations, whilst the same plants result in 84% of freshwater consumption. For tidal water and sea water abstractions, nuclear power makes up 58% of abstractions whilst only contributing 20% of thermoelectric generation (Table 5).

Considering all sources in the future (Fig. 5), water use by the electricity pathways increases on 2007 levels in all cases besides

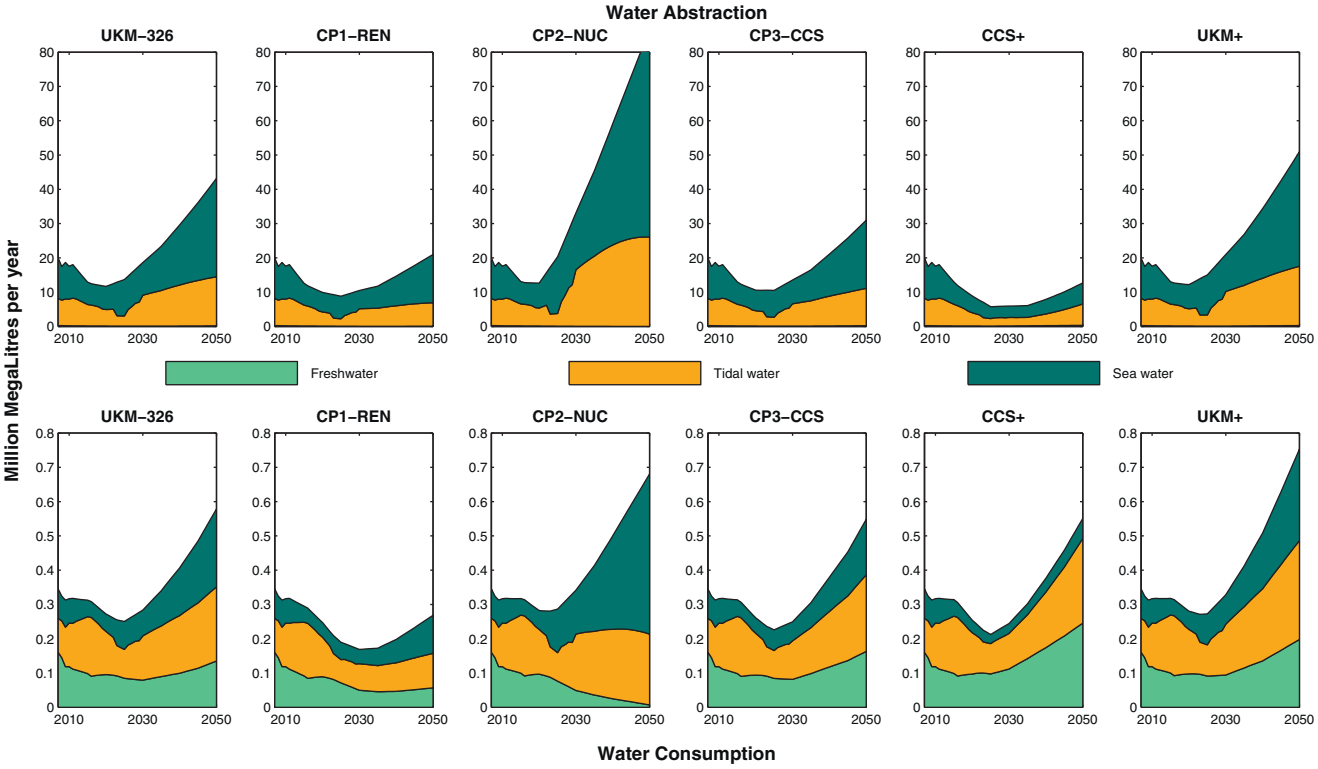


Fig. 5. Water abstraction and consumption over all sources for the 6 pathways from 2007 to 2050.

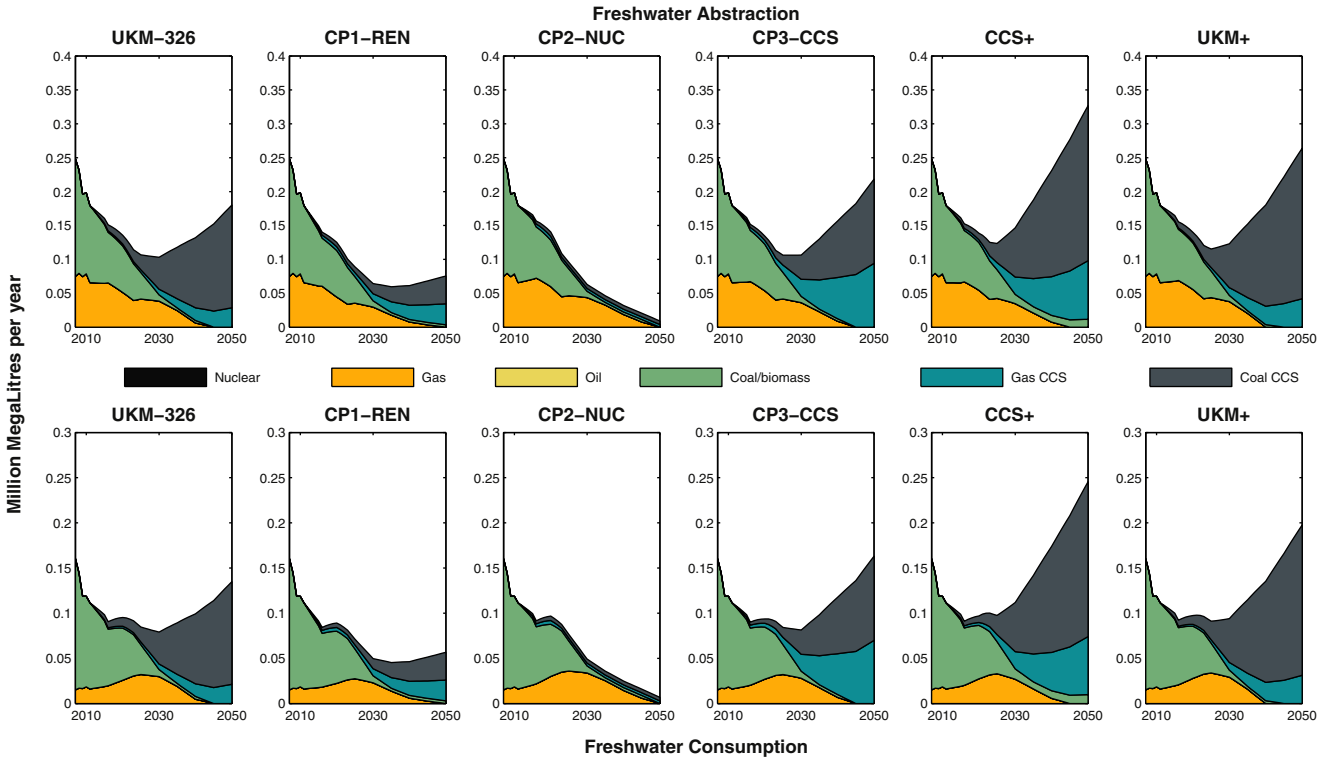


Fig. 6. Water abstraction and consumption by generation class for freshwater from 2007 to 2050.

CCS+ abstraction and CP1-REN consumption. Nuclear power significantly affects the level of tidal and sea water abstraction and consumption, demonstrated by difference between the two polarised pathways of CP2-NUC and CCS+. For abstraction, the range of 2050 values is between −28% and +394% over the 2010 value, with a median increase of 111%. The largest increases come from the two pathways CP2-NUC and UKM+, heavily influenced by the presence of nuclear plants on coastal and tidal sites, with sea water abstraction in CP2-NUC increasing more than a six-fold. Again, for tidal water there is a 235% abstraction increase in CP2-NUC pathway compared to a 20% decrease in the nuclear-free CCS+ pathway.

For consumption, the range of 2050 values is between −15% and +138% over the 2010 value, with a median increase of 78%. What differs in these pathways are the levels of freshwater use from carbon capture and storage generation, indicated by the particularly high levels of freshwater consumption in UKM+ (see Figs. 5 and 6), and the very low levels of freshwater use in CP1-REN and CP2-NUC.

The results for freshwater use presented in Fig. 6, especially in the context of growing socio-economic demands and the impacts of climate change, are arguably of more importance. In all cases there are large decreases in abstraction, driven principally by the transition to closed loop, hybrid or air cooling for all plants that abstract from freshwater sources. A few small combined cycle gas turbine plants, which are already inherently water efficient in open cooling configuration, have their abstractions reduced through this switch of cooling methods. This coincides with some decommissioning and a gradual transition to carbon capture equipped capacity. Abstractions are also affected by the reduction of coal capacity, which despite already being predominantly closed loop cooling continue to be abstraction intensive.

For consumptive water use, the decommission of coal plants results in rapid reduction of consumption despite a slight increase in gas consumption towards 2030 as more plants come online through the UK's Gas Generation strategy. They are considerably more water efficient (0.72 ML/GWh) than the coal plants (1.77 ML/GWh) they replace, hence the overall decline. From 2030 onwards to 2050 it is projected that almost all fossil fuel generation is abated by carbon capture and storage (CCS) making it possible to analyse overall effects of CCS on water use. CP2-NUC is the only pathway without significant CCS capacity and thus surface water use approaches zero as electricity demand is met mainly through nuclear and renewables. The CCS+ pathway, with no further nuclear, results in not only the highest freshwater abstraction but also consumption, exceeding 2010 by the 2040s and is 107% higher by 2050. CP3-CCS and UKM+ in 2050 were respectively 37% lower and 67% higher than 2010. Worth noting also are the CCS distributions between coal and gas and the effect on overall water use. UKM-326 and UKM+, both low cost pathways, have 67% coal and 33% gas generation with CCS; thus coal CCS's higher consumptive water intensity (3.22 vs. 1.36 ML/GWh) dominates water use results. CP1, CP2 and CP3 are the opposite; 33% coal and 67% gas result in a more even water use split. CCS+ is split 50:50 and therefore water use from coal is again higher. In summary, replacing and upgrading current coal and gas capacity to CCS equivalents results in freshwater consumption that approaches, if not exceeds, current levels.

3.2. Sensitivity analysis of the cooling scenarios

For the six pathways we tested the sensitivity of freshwater consumption in 2050 to different levels of generation capacity on surface water, the distribution between freshwater and tidal water capacity and balance between closed loop and hybrid cooling. By limiting the level of capacity on freshwater we established the sensitivity of freshwater consumption for each pathway, which in 2010 was 6009 ML/GW of thermoelectric capacity. For UKM-326, UKM+, CP3-CCS pathways freshwater consumption increases to the range of 11,104–11,731 ML/GW, 13,574 for CCS+ whilst the CP1-REN and CP2-NUC pathways were considerably lower, at 4089 and 1357 ML/GW. For assessment on a national scale, these figures

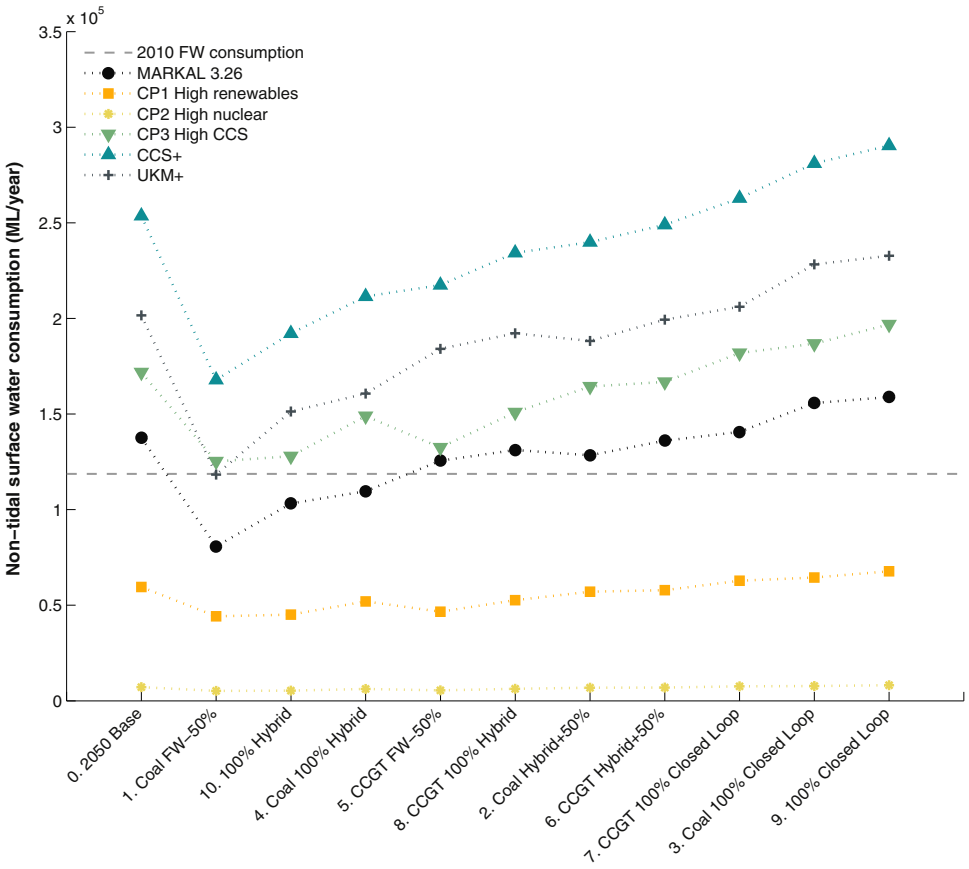


Fig. 7. 2050 freshwater (FW) consumption using the different cooling scenarios. Further details on the cooling scenarios provided in the Supplementary Information.

indicate the volume of freshwater consumed by each pathway, for each additional GW of capacity added (equivalent to a medium-large power station).

For further analysis we tested different cooling scenarios (#1–10) to identify where the most effective reductions in freshwater consumption can be achieved compared to the 2050 baseline projections (#0) presented in Section 3.1. For both coal (#1–4) and combined cycle gas turbines (#5–8) with carbon capture and storage, the following 5 scenarios were tested:

- 50% reduction in freshwater capacity (transferred to tidal water) (1 and 5);
- 50% relative increase in hybrid cooling on freshwater capacity (2 and 6);
- 100% of freshwater capacity with closed loop cooling (3 and 7);
- 100% of freshwater capacity with hybrid cooling (4 and 8).
- Additionally, two scenarios where all cooling, for both coal and combined cycle gas turbines, was either closed loop or hybrid (9 and 10).

Presented in Fig. 7, the greatest reductions were achieved by either reducing the proportion of coal with carbon capture capacity on freshwater by 50% (from 39% to 19.5% with the remainder on tidal water) or by using hybrid cooling on all the freshwater-based coal with carbon capture capacity. Similar reductions were achieved with the same measures for combined cycle gas turbines (CCGT) although absolute reductions were smaller given the lower water intensity of CCGT. Finally we evaluated potentially worst and best-case scenarios – respectively whereby all freshwater capacity was either closed loop (18–21% increase) or hybrid cooling (20–23% decrease). On this basis, for a fixed quantity of freshwater available it would be possible to support 41% more thermoelectric capacity if using hybrid cooling over closed loop.

3.3. Carbon and water intensity

Fig. 8 (left) plots the average consumptive water intensity of thermoelectric capacity on freshwater. Fig. 8 (right) plots both 'carbon dioxide intensity' ($MTCO_2$/TWh) and 'consumptive freshwater intensity' in ML/TWh of the six pathways averaged over the whole capacity of the grid. Whilst all the electricity pathways modelled are expected to significantly reduce the carbon intensity of generation with an aim of meeting the statutory carbon budgets, there has not yet been any in-depth investigation into changes in water intensity for UK energy pathways.

Considering only the capacity on freshwater, Fig. 8 (Left) shows that in all cases (except CP2-NUC), intensity of freshwater consumption increases through a switch to coal and gas with carbon capture and storage by a range of 24–62%. The ratio between coal and gas is the key determinant in the water intensity as can be noted by the labels.

When we take into account all electricity generation (i.e. including renewables), emissions intensities all reduce as intended, in fact achieving negative figures through use of bioenergy with carbon capture and storage. For cooling, the levels of freshwater consumed per unit electricity generated vary from 11 to 468 ML/TWh in 2050 over 2010 levels of 311. Despite the water intensity of carbon capture plants being considerably higher than current capacity (as shown in Fig. 8 left), higher levels of nuclear and renewables bring the overall grid average down. The level of nuclear power also has an indirect inverse effect on consumption, as higher proportions of nuclear power displace

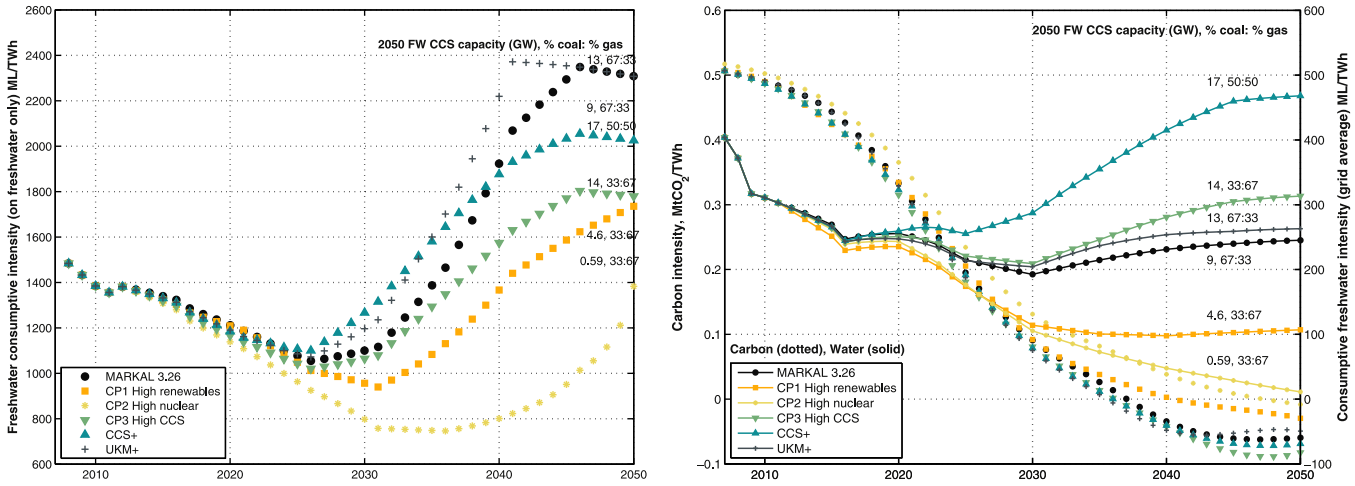


Fig. 8. (Left) – Non-tidal surface water consumption intensity (ML/TWh) averaged over FW capacity only, shows that as capacity is replaced the average water intensity increases, due to CCS equipment. (Right) Dotted lines show 'grid' carbon intensity in $MtCO_2$/TWh (equivalent to gCO_2/kWh), solid lines show freshwater consumption intensity in ML/TWh, averaged over all the capacity in the grid.

freshwater capacity and lower the overall freshwater intensity. Where freshwater use is reduced due to higher levels of nuclear power, tidal water use is significantly increased. Considered together, 2050 consumption intensity for fresh and tidal water differs greatly between CP2-NUC and CCS+ with 350 and 939 ML/TWh, respectively. However, despite having the highest intensity, the CCS+ pathway balances this across both fresh and tidal water whilst CP2-NUC is particularly water-intensive on tidal water only. Considering tidal intensity alone, all pathways increase from 333 to the range of 339–471 besides CP1-REN whose intensity decreases to 190 ML/TWh. Total water intensity in 2050 for all sources including sea water was consistent across all pathways ranging from 1002 to 1116 ML/TWh over a 2010 value of 830, besides the CP1-REN pathway whose final intensity was 507 ML/TWh.

4. Discussion

Current water use by the electricity sector is substantial in volume and critical to its operation, yet pressures of population growth, climate change and hydrological variability will complicate the issue further even if water use in 2050 remains at current levels. Our results have shown a mixture of trends, depending on the perspective of analysis.

4.1. Changes in cooling methods and sources

Freshwater abstractions will reduce if all the remaining open loop cooling is replaced by closed loop or hybrid configurations. This will bring benefits through reduction of thermal pollution and ecological impacts, but will also, in the majority of cases result in higher consumptive losses. Freshwater consumption will depend primarily on the level of carbon capture and storage (CCS) capacity installed, and subsequently on whether it is gas or coal. Pathways with more coal will have higher freshwater usage, which in the 'cost-optimised' pathways (UKM-326 and UKM+) will be 69% more water intensive per unit electricity output than current levels. If water resources are limited, less capacity (than at present) will be able to use freshwater and hence more will shift to tidal and sea water use. If low flows are experienced, not only will the coal plant be more vulnerable to the water scarcity due to higher requirements, but its water consumption and downstream impacts would be twice that of a similar gas plant. Therefore, whilst the headline result of Fig. 8 (right) indicates freshwater consumption across the grid as decreasing or staying at current levels, we must be wary that at the plant level the intensity of freshwater consumption will increase substantially with the use of CCS (Fig. 8 (left)).

Given this increase in water intensity and limited abstraction licenses, the future is unlikely to see an increase in the level of capacity on freshwater, but an increase in absolute consumption is possible. Besides the generation offset by renewables, we can expect higher levels of capacity on tidal and coastal locations. Both abstraction and consumption will increase substantially, primarily through the use of once through nuclear power but also additional CCS capacity (Fig. 4).

4.2. Carbon capture and storage

For freshwater, the analysis shows that a gradual switch to closed loop and hybrid cooling reduces abstraction volumes substantially whilst maintaining high levels of consumptive use. Most significantly, the intensity of freshwater consumption increases with the level of coal capacity with carbon capture and storage (CCS) whilst thermal discharges switch from water bodies to the air. Reducing abstractions should reduce vulnerability to low flows (Förster and Lilliestam, 2009), whilst bringing benefits to local environments by minimising thermal pollution and fish entrainment. However, high levels of consumption could increase the risk of low flows and we expect the Government's Roadmap for carbon capture and storage deployment (DECC, 2012e) to exacerbate this issue. The Roadmap explicitly specifies clustering in order to reduce the costs of CO_2 compression and transport infrastructure and has identified, with good reason, clusters of high point-source emissions around which CCS infrastructure and high-carbon industry can develop. Such sites may contribute to and be vulnerable to localised water shortages, increasingly so due to the higher water use intensity. The River Trent, which supports eight stations totalling approximately 11.1 GW capacity (3.0 GW on freshwater, 8.1 on tidal water) with a further 3.6 GW approved for construction on freshwater, could come under considerable water stress when CCS infrastructure is installed and water use intensity doubles. One of the largest rivers in the UK, the Trent still has water available for licencing, but only under 'hands-off flow' conditions that would prevent abstraction for the lowest 30% of flows during a dry year (EA, 2008d). Yet CO_2 pipelines along this corridor will inevitably attract further power station development. In summary, and similarly concluded by Naughton et al. (2012), if CCS development is to occur in series or clusters, water abstractions and cooling provisions should be

evaluated as such (and not as single plants), before CO_2 infrastructure is constructed.

4.3. Coastal locations

The greater the need to protect inland water resources for agriculture and public water supply, whilst maintaining levels of environmental quality, the greater the pressure will be to shift thermoelectric generation towards the coast. Most tidal and sea water sites afford developers the use of direct cooling, which combined with greater cooling efficiency, offers both capital and operational cost reductions and has been identified as the *Best Available Technology* for large coastal and estuarine power stations (EC JRC, 2001). The scale of increases presented by pathways UKM-326, UKM+ and CP2-NUC, between 148% and 399%, will require careful management of the effects of fish entrainment and thermal pollution in marine and estuarine environments. Whilst not beyond current engineering expertise, it may complicate the planning process when sites are in close proximity or near sensitive environments. We note a recent case where a 2099 MW combined cycle gas plant commissioned in 2012 on a legacy site in a *Special Area of Conservation* at Pembroke, Wales, was under considerable pressure to use closed loop cooling yet a once through system was authorised by the Environment Agency and consented by the Department for Energy & Climate Change (DECC) (ENDS Report, 2009). This elicited a European Commission letter of infringement to DECC regarding non-compliance of numerous articles in the EU's Habitats, Environmental Impact Assessment (EIA), Nitrates and Integrated Pollution Prevention and Control (IPPC) Directives (ENDS Report, 2012; European Commission, 2012). Coastal locations are also vulnerable to storm surges and coastal flooding, with the greatest risks in the UK on the east coast where carbon capture clusters have already been identified. However, the costs of flood protection may be offset against the savings from not building cooling towers.

4.4. Nuclear power

Nuclear plants in the UK use open loop cooling with abstraction in the order of 65 m^3/s per reactor, resulting in substantial ecological impacts, despite careful management via intake and outfall structures (EA, 2010). A very high nuclear capacity, such as the 75 GW in CP2-NUC (20% more than France at present), may require a highly distributed configuration across the UK or alternatively, clusters of reactors and acceptance that local effects on the environment would be concentrated. Even the 31 GW of capacity in UKM-326 would require 10 sites of 2×1.6 GWe reactors, yet the UK Government's Strategic Siting Assessment authorised only 8 suitable sites in the National Policy Statement (DECC, 2011d). Identification of further sites is possible, yet probably not without compromise; a study by Atkins (2009) for DECC identified only 3 additional sites *worthy of further consideration* having assessed 270 areas in England and Wales in addition to a further 82 historical sites that had already been ruled out by energy companies. Of the 270, in excess of 80% were ruled out due to *potential adverse impacts to internationally designated sites* of ecological importance. Ambitious proliferation of nuclear power will only happen through compromising at least one of the existing selection criteria.

4.5. Trade-offs, location choice and cooling methods

The assumptions and distributions on cooling sources and technologies, designed to be realistic and to reduce the freshwater abstractions without excessively abstracting from tidal and sea water environments, may not always be available to other water-scarce or landlocked countries undergoing electricity transitions. With limited availability of water abstraction licences in the UK, power station location choice will become increasingly important and contentious. Our assumptions about the distribution of capacity over different sources and the cooling methods are based on the legacy of the current configuration, planned capacity and expectation that the large majority of generators will continue to use the most commercially efficient cooling technologies permitted by regulation.

That said, we have noticed three plants on tidal waters using hybrid cooling (Uskmouth, Wilton, Connah's Quay), a choice usually made for plume abatement and public acceptability, not lack of water. Thus, the benefits of legacy site redevelopment, such as existing grid connections, land ownership and local workforce appear in these observed cases to outweigh the additional costs of hybrid cooling or alternative of finding more suitable greenfield sites elsewhere. This is a trend we expect to continue and corroborated by Schoonbaert (2012).

We have tested additional cooling scenarios to explore potential water use reductions in the sector. Both reduction in freshwater coal capacity (by 50%) and universal use of hybrid cooling for coal and combined cycle gas with carbon capture have the potential to reduce freshwater consumption in the range of 20–42% for all pathways. Reduction in capacity on freshwater would inevitably mean a shift to greater tidal and sea water cooled capacity, which as discussed may increase risks to local ecology unless more costly closed or hybrid loop cooling is used. Alternatively, freshwater capacity could use higher levels of hybrid cooling, with yet again higher capital and operational costs to the generators and ultimately consumers. We have assumed hybrid operation equivalent to 35% dry cooling and 65% wet cooling (see Table 3 and S7) in such a way that dry cooling would be employed mostly during summer and autumn months when water is usually most scarce. This would increase the resilience of the electricity sector to low flows whilst leaving water available for other uses but at an estimated cost of 4–7% higher fuel input and an equivalent increase in greenhouse gas emissions per power station.

4.6. Opportunities for the UK energy sector and the global context

The Energy Bill, going through UK Parliament as this paper goes to press will grant subsidies for low-carbon thermoelectric generation with indirect implications for water use by the electricity sector. It will make nuclear and carbon capture-enabled generation increasingly competitive with renewables, thus, the potential for long-term lock-in of water intensive electricity generation is a distinct possibility facilitated by the proposed legislation.

The pathways tested all meet the 2050, 80% emissions reduction targets and come close to or succeed in achieving the defeated 2030 decarbonisation target of 50 gCO_2/kWh, an amendment recommended by the Committee on Climate Change (CCC, 2013), the House of Commons Energy and Climate Change Select Committee (ECC, 2012) and supported by a long list of large businesses and non-governmental organisations (FOE UK, 2013). It is clear from Fig. 8 that up to the 2030s, water use performance in all pathways and by all measures improves in line with rapid decarbonisation. Up to this point, renewables increase their share whilst older coal, gas and nuclear plant are decommissioned and more affordable deployment of new nuclear and carbon capture-equipped generation begins to take shape. It is in the 2030s that water security of the UK could be in the balance as the water intensity of the pathways diverges; coal and gas plants would be forced to shut down if they do not adopt carbon capture and storage (CCS) yet this will increase their water intensity. Hence we

see that decarbonisation policy at first plays an important role in reducing the water intensity of the sector, yet beyond 2030 will play a pivotal role depending on what generation capacity emerges. If CCS and nuclear power are deployed on wider scales, water intensity will rapidly increase. Unless more hybrid or air cooling is employed, developers will be forced to choose between using limited freshwater supplies or increasing abstraction from tidal and sea water, both of which could be problematic for the environment.

Worth a mention is the possibility of using combined heat and power (CHP) to reduce the cooling requirements of power plants by supplying waste heat to industrial, commercial and domestic users through district heating. Uptake in the UK is currently very low, probably due to the penalty on electricity production (Mackay, 2009). The additional penalty induced by CCS, is probably why it is only specified somewhat indirectly, in the UKM-326 pathway. Other long-standing barriers, such as long-term reliable customers, also need to be overcome (Foxon et al., 2005; Kalam et al., 2012).

We conclude that the current path dependency of the system, particularly facilitated by the aforementioned delays in carbon capture and nuclear deployment, sets the UK on a sustainable pathway that is reducing emissions as well as dependency on water resources. It is only the fruition of new nuclear and carbon capture and storage schemes in the pathways analysed, that reinstates the high dependency on water for cooling, which will come under increasing pressure from population growth and climate change.

These findings are widely applicable to the wider world, of which some 67% of generation is fossil-fuelled thermoelectric (International Energy Agency, 2009). Macknick et al. (2012b) report broadly similar trends of reduction in freshwater abstractions and rising consumption, in a similar study for the U.S., as well as similar findings concerning pathways with high penetrations of renewables. Whilst decarbonisation of the electricity sector is essential to mitigating anthropogenic greenhouse gas emissions, national strategies for the roll out of carbon capture and storage retrofits, if and when it becomes commercially viable, will need to strongly consider impacts on water resources. Coal power, responsible for 40% of global generation and widely used in China and India, is approximately twice as water and carbon intensive as combined cycle gas plants, with the performance well modelled by (Zhai and Rubin, 2010; Zhai et al., 2011) and the water impacts of Chinese coal use investigated by Pan et al. (2012). We also reiterate that this analysis has not considered the water use impacts of fossil fuel extraction and production, which is thought to be substantial worldwide and could become increasingly important in this UK context if domestic shale gas extraction takes off (Entrekin et al., 2011).

5. Conclusions

We have shown that whilst some electricity pathways present opportunities to simultaneously reduce water dependency and carbon emissions, others increase the dependence on water resources.

- In cases with high levels of nuclear and carbon capture and storage, abstraction and consumption, respectively, increase to levels that far exceed current use. With high levels of nuclear, abstractions of tidal and seawater can be expected to increase substantially, in the CP2-NUC pathway up to 6 times the current levels.
- Even though the volume of seawater abstracted is inconsequential, the evidence examined indicates a lack of suitable sites for wide scale nuclear power if negative environmental impacts are to be avoided.

The research has also shown a range of possible changes in the absolute volumes of freshwater consumption, however:

- All-round significant increases in the intensity of freshwater consumption are due primarily to carbon capture and storage technology.
- Pathways with high levels of coal with carbon capture will be the most water intensive. We expect the intensity of this consumption to have negative localised environmental impacts, exacerbated by the clustering of plants with carbon capture.
- Significant reductions in freshwater consumption are possible through wide scale use of hybrid cooling, which would increase the level of freshwater resources available, for either the electricity sector or other uses. Hybrid cooling would however marginally increase cost and emissions, but also security of supply, by enabling the use of air-cooling during low flows when abstractions may be prohibited.

We have shown that up to 2030 good progress is made on both decarbonisation and water intensity:

- It is the capacity developed post-2030 that will determine whether pathways exploit the inertia of this progress or revert to water-intensive but low carbon generation.
- Our findings show that the usage of high levels of carbon capture and storage and nuclear will bring environmental risks related to water use that will require trade-offs between emissions, cost and the environment.
- Pathways with low levels of nuclear and carbon capture, such as CP1-REN, minimise these risks, the benefits of which should be accounted for.

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Appendix A. Supplementary information

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