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Electricity generation and cooling water use: UK pathways to 2050☆

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ABSTRACT

Thermoelectric generation contributes to 80% of global electricity production. Cooling of thermoelectric plants is often achieved by water abstractions from the natural environment. In England and Wales, the electricity sector is responsible for approximately half of all water abstractions 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 thermoelectric 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.

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