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Quantification and regional comparison of water use for power generation: A California ISO case study

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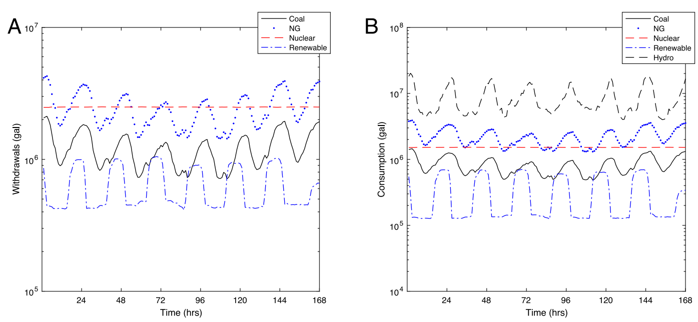
HIGHLIGHTS

- Water use for power generation quantified by generation mix using factors in gal/MWh.
- Generation under different balancing authorities is compared on an hourly basis.
- Overall water consumption and withdrawals calculated over one week in California ISO.
- Uncertainty is quantified according to water use factors obtained from literature.
- This method can assist with controlling electrical power use based on water use.

GRAPHICAL ABSTRACT



- Total water withdrawals(A) and consumption (B) for different power generation fuel types over one week during the summer (19-26 August 2015).

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ABSTRACT

Analysis of water use for power generation has, in the past, focused on large geographical regions and time scales. Attempting to refine this analysis on the time and spatial scales could help to further understand the complex relationships involved in the energy–water nexus, specifically, the water required to generate power. Water factors for different types of plants and cooling systems are used from literature in combination with power generation data for different balancing authorities to model water use as a function of time based on the fuel mix and power generated for that region. This model is designed to increase public awareness of the interrelation between the energy consumed and water use that can be taken into account when making decisions about electrical energy use. These results confirm that areas with higher renewable energy penetration use less water per unit of power generated than those with little or no renewable technologies in the area, but this effect is heavily dependent on the distribution of the types of renewable and conventional generation used.

1. Introduction

Water is essential for thermoelectric power generation, and electrical power is used to treat and distribute water, in what is called the energy–water (or electricity–water) nexus (Scott et al., 2011; Cook et al., 2015; Bazilian et al., 2011; Sovacool and Sovacool, 2009). Water is used for cooling, removing waste heat in a power generation cycle, and the electricity sector is second only to agriculture in water use within the United States (''USGS: Thermoelectric Power Water Use in the United States'' 2014). Water shortages and occurrences of drought have been increasing in recent years, especially in the arid western US, with California facing some of the most extreme water scarcity (California Natural Resources Agency, 2016). The amount of water used for each unit of electrical power

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will vary based on the grid's generation mix as well as method of cooling at a given climate and hour of the day. Water is considered to be withdrawn when it is diverted from a source and immediately returned to that source after use, water is consumed when it is not returned after use. Plants with once-through systems generally withdraw large quantities of water but have low water consumption while plants with closed circuit-cooling with cooling towers withdraw less but consume a lot more. One way of preserving water for power systems would be to not use water but rather air in what is termed dry cooling. However, this method is more expensive to implement and is not as efficient (Peer et al.). Another proposed way would be to increase the cost of water in order to encourage more frequent use of less water intensive power systems (Sanders et al.). In the case of California, the need for water conservation is a growing concern as drought continues to strain water resources in the area, and therefore, the water use in the power sector needs to be considered on a regional scale in order to know how to best allocate resources.

Quantifying water use on a regional scale can be useful when considering resource allocation or electrical generator dispatch, and can be used to increase public awareness of how much water is used in connection with power consumption in people's day to day lives. Leading thinkers at the energy–water nexus have identified a shift in perception that clarifies the relationship between these two interconnected resources as a critical need for conservation and environmental protection (Webber, 2016). Providing information about water use tied to electricity use could help to encourage conservation motivate water-concerned individuals to cut down on electrical power usage.

Water usage for power varies with the power generation mix, depending on: the fuel used by power plant, its efficiency, cooling technology, and ambient conditions. A group of researchers at the US Department of Energy's National Renewable Energy Laboratory have compiled a range of water withdrawal and consumption factors for different fuel technologies and cooling types based on power plants across the country (Macknick et al., 2011). Power generation systems typically include coal, natural gas, nuclear, and renewable technologies while the cooling systems range from once-through systems and cooling towers to dry cooling. These values relate water use to power generation in gallons of water consumed or withdrawn per megawatt-hour. Many of these water factors found by Macknick et al. can vary widely across a range of potential values for water use (Macknick et al., 2011). They are used here to give the maximum and minimum values as well as the median for each power system and cooling type considered.

This range of water factors introduces a great deal of uncertainty when assessing overall water use for a region of the power grid. Water use can vary based on the temperature of that water, with more water flow needed to remove the necessary amount of heat when the water's temperature is high (Koch et al., 2014; Kyle et al., 2013). Temperature differences can also disrupt plant operations, which results in less power being generated at any one time (Koch et al., 2014; Kim and Jeong, 2013; Linnerud et al., 2011). For example, a water intake temperature increase of only 3 °C can reduce the power output by 500 GWh/year for plants with once through systems, and 50 GWh/year for plants with closed circuit cooling (Koch et al., 2014). Even temperature shifts in the diurnal cycle could alter the water factors of certain plants.

The US Geological Survey (USGS) currently reports water use for power generation on the state level and only once every few years ("USGS: Thermoelectric Power Water Use in the United States" 2014). Increasing the temporal and spatial resolution associated with these calculations can also increase understanding of the relationships between water and power. This analysis will focus on the geographical area of at the level of balancing authorities, who coordinate between power generation facilities and power supply to the electrical grid. Furthermore, calculations here are made on an hourly time scale. While the balancing areas are large, it is difficult to attribute a specific generation mix at smaller scales, and reliable power generation data is reported on at least hourly scales for many of these areas. Fig. 1 ("FERC: Industries—RTO/ISO" 2016) shows a map of balancing authorities in the US These authorities are responsible for power generation and distribution in their given area, although they can trade and distribute power outside that region ("Glossary—US Energy Information Administration (EIA)" 2016). For example, power generated by the MISO region may end up being transferred and used in the PJM region. This paper focuses on the CAISO (California Independent System Operator) region as a case study due to the region's frequent reporting of generation data and the state's significant concerns about water availability. CAISO covers most of the geographical area of the state of California, as shown in orange in Fig. 1. A similar analysis with other balancing authorities can be conducted using the same methodology, allowing for comparisons between the generation mix in each region.

Here, overall water use for power generation will be modeled on a regional scale for a specific balancing authority area, more specifically in the CAISO region. Water use factors found by Macknick et al. (2011) are combined with generation data from the balancing authority to find an estimate of the total water used per megawatt hour for that region, in a specific hour. The full range of water factors (minimum to maximum) will be evaluated in this paper in order to show the potential spectrum of overall water use. By using these regional coefficients, this methodology can be used to describe how much water a specific facility or process is using indirectly based on its electrical power consumption.

2. Methods

Water usage in a power plant can depend on many factors including the cooling system that is used, weather, as well as the region the plant occupies. For this model, it is assumed that all power systems used closed circuit cooling with cooling towers. This assumption is warranted since the state of California water resource control board put in place a new regulation in 2010 that limits the amount of water withdrawn for once-through cooling systems, which withdraw much more water than other cooling systems and can be especially harmful to marine wildlife, and encouraging the modification of existing once-through systems to closed circuit cooling (California State Water Resources Control Board, 2016). This will also provide a minimum basis for the amount of water being used to generate power. Since this is not the case for many other regions, the authors will incorporate once-through systems into the model before the source code is released to the public.

Macknick et al. have compiled withdrawal and consumption numbers that represent the water used by the plant per unit of energy generated (gal/MWh) for each generation system and cooling type that will be used in coming up with a total water usage in a given area. Table 1 verifies that these water factors can be applied to the study area by taking three plants for each cooling system, once-through and cooling towers, and comparing the withdrawal and consumptions factors compiled by Macknick, et al. to those calculated using power generation data and water use data reported by EIA in 2015 (EIA). Water factors were calculated based on water usage data available from EIA.

It can be seen from Table 1 that, with the exception of the nuclear plant, all plants fit within the expected range of water factors reported by Macknick et al. Concerning the nuclear plant, its withdrawal number for the year is exceptionally large for that year considering that the withdrawal factor the previous year was