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

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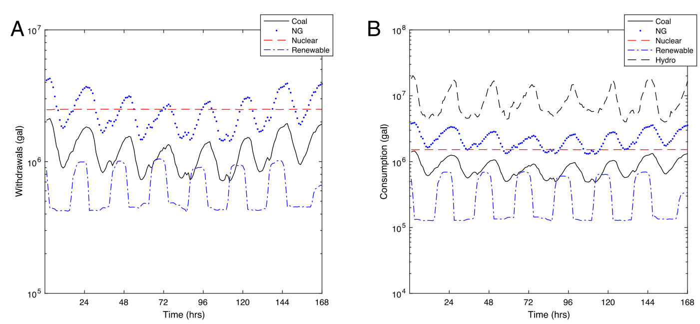
HIGHLIGHTS

- 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

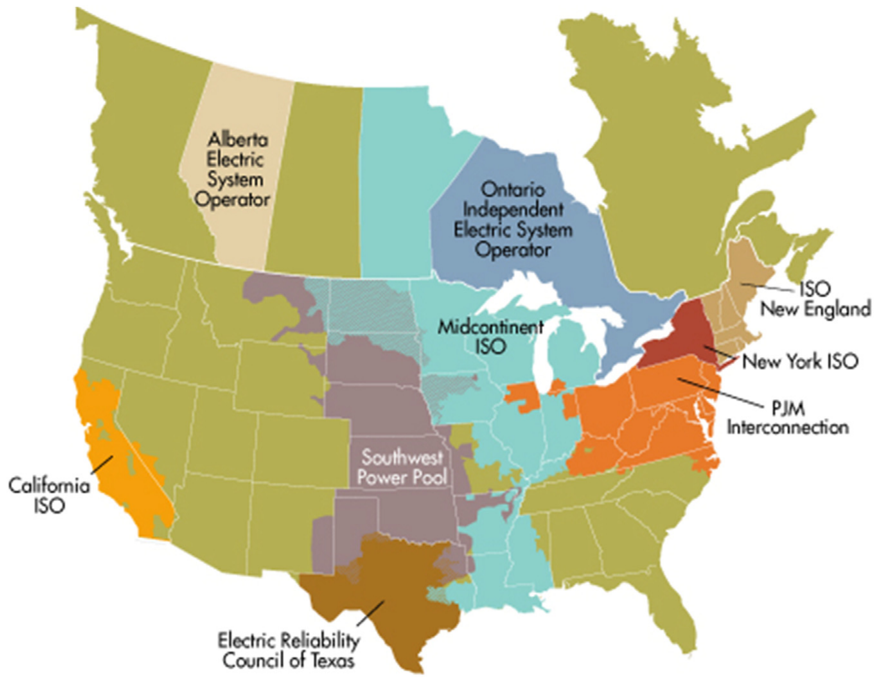

Fig. 1. Service regions for independent system operators with CAISO shown in orange (California Independent System Operator Corporation, 2016a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Comparison of withdrawal factors (WF) and consumptions factors (CF) with the withdrawal and consumptions factors reported by Macknick et al. (MWF and CWF respectively) for three plants of each cooling type. Water factors units are gal/MWh and capacity is in MW.

Plant name	Capacity	Fuel type	WF	CF	MWF	MCF
Cooling tower technology						
Mountainview generating station	1037	NG	197	154	150–283	130–300
Valley (CA)	691	NG	241	205	150–283	130–300
Etiwanda generating station	24	NG	1 137	962	950–1460	662–1170
Once-through systems						
Diablo canyon	2323	NUC	166 724	–	25 000–60 000	100–400
Dynegy moss landing power plant	2802	NG	19 418	–	10 000–60 000	20–100
Haynes	2425	NG	54 122	–	10 000–60 000	20–100

37,160 gal/MWh which does fit within NREL's range. Drought in California was more severe 2015 with low reservoir levels which may be the reason for the exceptionally high factor that year (NCEI). As discussed above, limited water availability can have a large impact on plant cooling systems.

In order to analyze the amount of water being used for power, it is necessary to first know how much power is being generated in a specific region and by what type power system. This is accomplished using an online API called WattTime (WattTime, 2016). WattTime provides open data on many balancing authorities in the United States including fuel mix data and carbon emissions data on an hourly and/or a five-minute basis. The fuel mix data is broken down into components of thermal, solar, wind, hydro, solar thermal, etc. depending on what is being used for generation in that area. The data for the CAISO region is broken up into thermal, nuclear, natural gas, and various types of renewable forms of energy generation such as solar, hydro, and geothermal. The term "thermal" here refers to those plants that produce their energy thermoelectrically. Since it is unclear how much of the thermal generation is divided into coal, natural gas, and nuclear power, it becomes necessary to break down the thermal generation using the EPA's power profiler ("How Clean Is the Electricity I Use?—Power Profiler | Clean Energy | US EPA" 2016). Based on data compiled by the EPA, out of the total power produced by thermoelectric generation, roughly 10% was produced by coal and 90% by natural gas in the WECC California sub region. However, the consideration of power generation units' contributions by percentage of total electrical generation (on a yearly basis) will introduce significant uncertainty, particularly at smaller, sub-yearly time scales, because the percentage of power generation at any given time is determined by the CAISO market (CAISO 2016b).

The next step is to verify the quality of the given data. This is done using a statistical analysis. Each point of the data is plotted as a function of the data point before to show how the data varies within the dataset. This was done using the BPA region due to the large quantity of data points provided, updating their power generation every five minutes. This data, taken from two different weeks in the summer and winter, is converted to hourly data and is plotted in Fig. 2 for each fuel mix. In this case, $Y(i)$ represents power data at time step i. A linear trend is observed in each of the data sets with no more than one outlier in a few of the plots. This shows that the data is of good quality and can be used in the analysis. There were some points in the data that were either nonexistent or contained no value; these were dealt with by a simple linear interpolation. For the CAISO region, this was a negligible concern, happening less than 0.1% of the time.

The model was built using MATLAB, an engineering computing software, which takes in data from WattTime and gives the overall

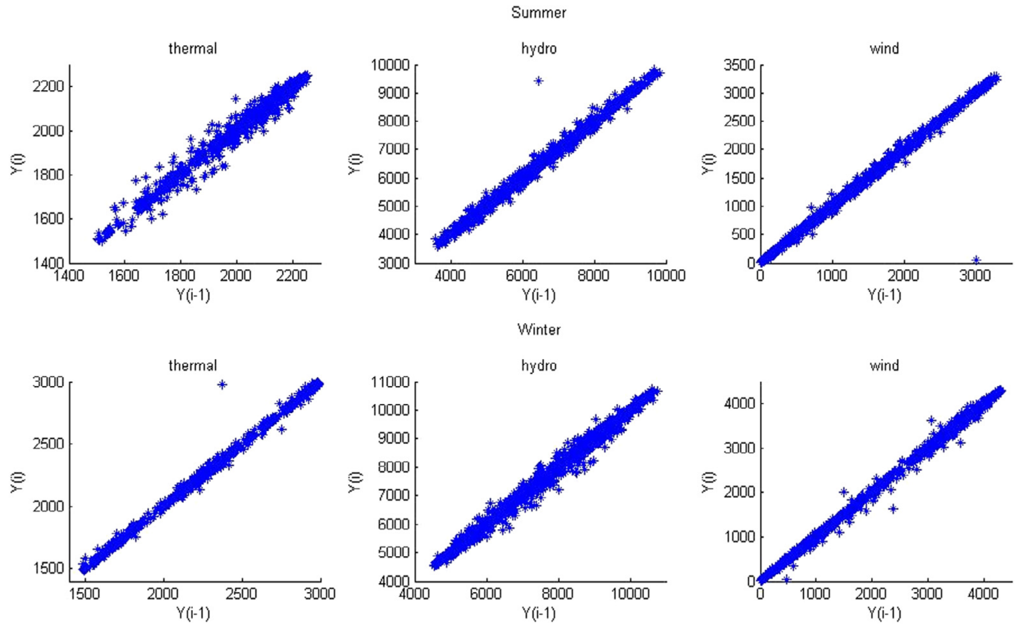

Fig. 2. Statistical analysis of data provided by WattTime for each power system dataset for one week of summer and winter.

water usage per megawatt hour based on the fuel mix at the given time. The process is illustrated in the below analysis.

Let x be the area or balancing authority where the data is taken, and i be the generation fuel type of the area x at time n. The total generation of each power plant type is divided by the total generation in that hour to produce a weighting factor (WF) as shown in the equation below.

$$WF_i^n(x) = \frac{P_i^n(x)}{\sum_{i=1}^{N} P_i^n(x)} \tag{1}$$

where P is the power produced by generation fuel type i at time n, where N is the total amount of different generation types. A weighting factor is generated for each power generation facility at each hourly time step. These factors are then multiplied by Macknick's withdrawal and consumption factors, defined as MW and MC respectively, for each generator, i, and added together at each time step, n, to come up with a total water use factor at each hour for both withdrawals and consumption as shown below.

$$W^n(x) = \sum_{i=1}^{N} WF_i^n(x) * MW_i \tag{2}$$

$$C^n(x) = \sum_{i=1}^{N} WF_i^n(x) * MC_i \tag{3}$$

where W and C are the withdrawal and consumption factors in gal/MWh at time n. These water numbers can then be multiplied by total hourly energy use in a building or city to estimate the amount of water being withdrawn and consumed at each hour of the day. This can be done for each specified balancing authority x such as BPA, CAISO, ISONE, MISO, or ERCOT depending on the data available.

3. Results and discussion

Hourly data was taken for the CAISO region during the summer and winter seasons for one week in August of 2015 and February of 2016. The results are shown in Figs. 3–5. Fig. 3 shows the average weighted water factors, in gallons per megawatt hour, throughout the week. It also shows the large range at which these water factors can fluctuate which is due to the large range of water factors observed for each individual plant fuel type. This means that there is some related uncertainty introduced when determining how much water is being used as a function of power consumption.

Fig. 2 shows the overall water withdrawals and consumption in the summer and winter months based on the power production values from WattTime and the water factors from Macknick et al. (2011). The water use can be seen to fluctuate more in the summer possibly due to the greater accessibility of renewable forms of energy during that time. This plot uses overall energy data to calculate water use over time, but the water factors can also be applied to building energy data to see how much that water is associated with the power being used in that building. This can be useful in order to increase awareness of where water is being used and can also be valuable in times of water shortages when considering what resources can be reduced in order to save water. Reducing water consumption from power use often leads to reduced emissions from plants as well. Typically, the more power is generated at a given time, the more greenhouse gases and other pollutants are released into the atmosphere; however, the relationship between power generation, water use, emissions, and other environmental impacts is complex and often involves trade-offs between desired environmental outcomes (Peer et al., 2016). This model should be used in conjunction with a similar model incorporating emissions resulting from power generation to evaluate whether decisions affecting power generation units would benefit both water conservation and emissions reductions.

Withdrawals and consumption are broken down by generation type in Fig. 5. This illustrates the power plant fuel types that are using the most water. It can be seen that in both summer and winter, the most amount of water being consumed is from hydroelectric plants. This is to be expected because while water passing through a hydro plant is not considered to be withdrawn, hydro plants can consume large amounts of water from the added evaporation due to creating a large reservoir (Mekonnen and Hoekstra, 2012). The green line in Fig. 5 represents the water used by all renewable forms of energy. Renewable energy, despite its growing popularity and accounts for almost 30% of power generated in the CAISO region (see Fig. 6), uses the least amount of water with most of the water used is the result of geothermal

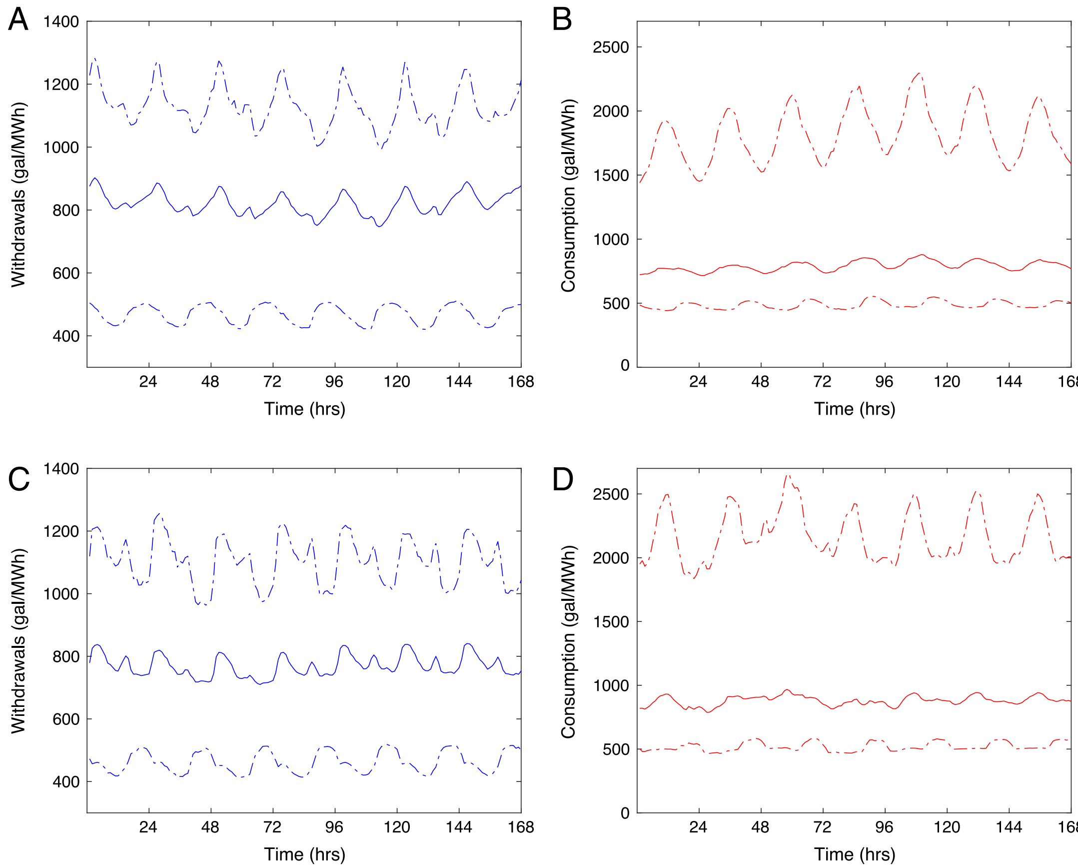

Fig. 3. (A) Summer withdrawal factors. (B) Summer consumption factors. (C) Winter withdrawal factors. (D) Winter withdrawal factors.

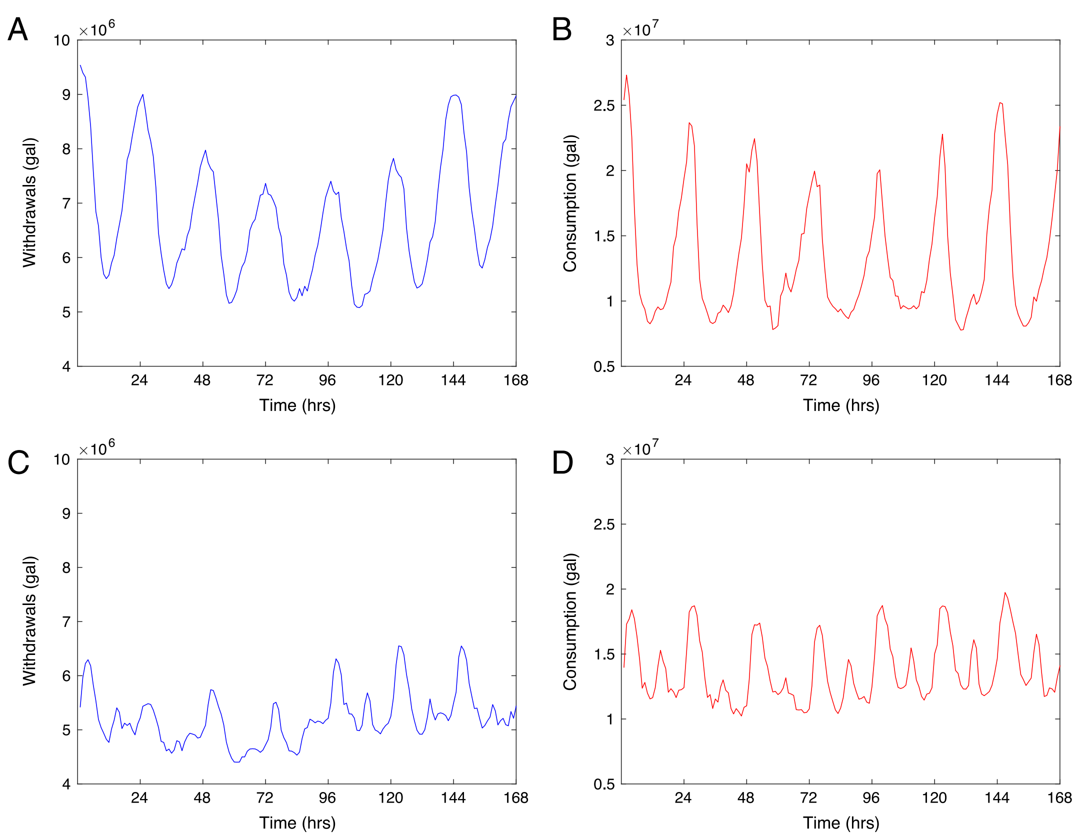

Fig. 4. (A) Summer total withdrawals. (B) Summer total consumption. (C) Winter total withdrawals. (D) Winter total consumption.

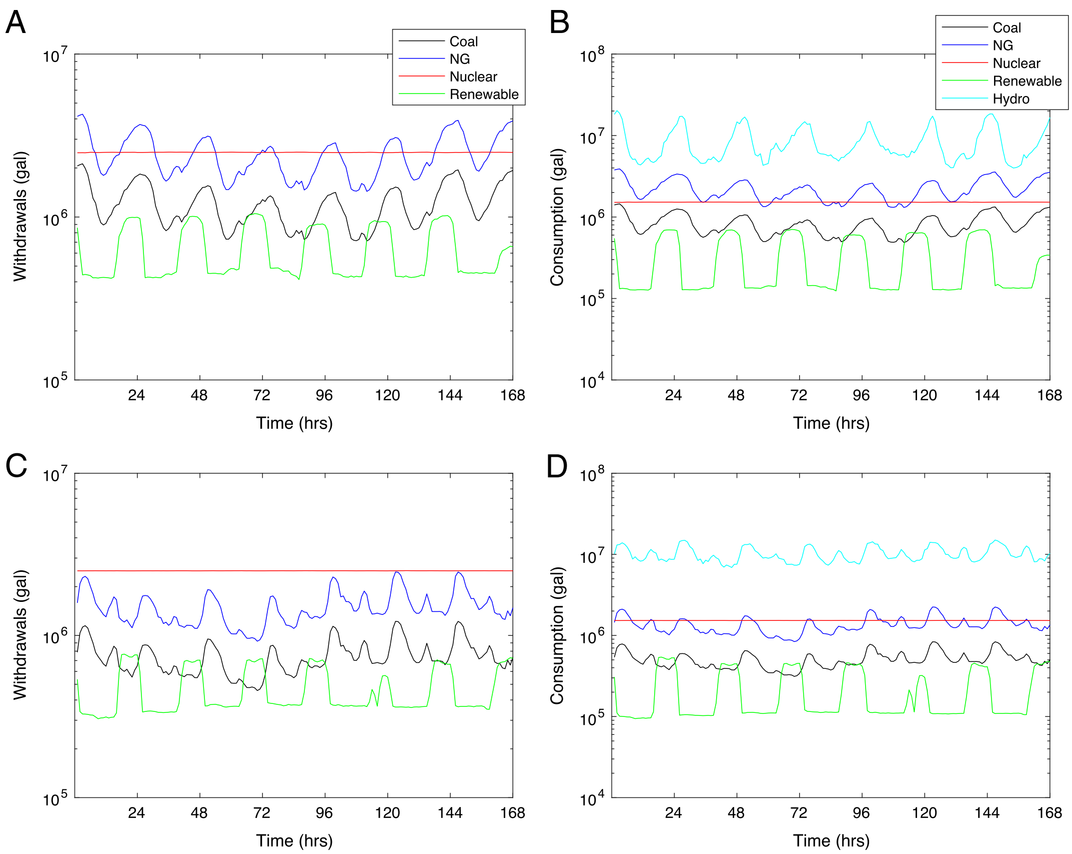

Fig. 5. (A) Summer withdrawals by generation type. (B) Summer consumption by generation type. (C) Winter withdrawals by generation type. (D) Winter withdrawals by generation type. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

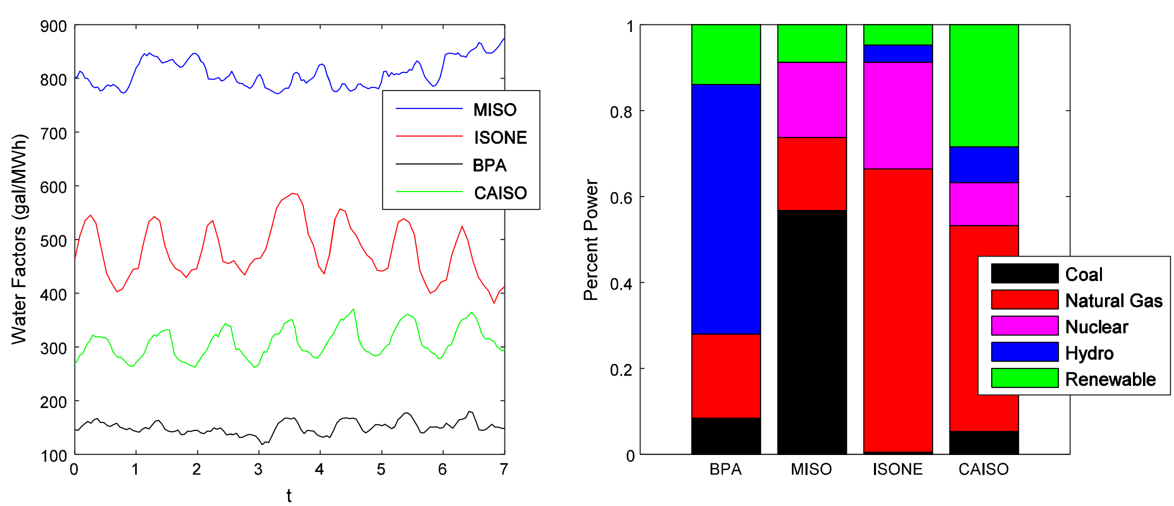

Fig. 6. Water factors for each balancing authority in the month of August 2015 (left). The average amount of each fuel type used by each balancing authority in August (right).

and solar thermal power generation. These systems can still use as much water as conventional thermoelectric generating systems though it is greatly reduced in the case of geothermal (Macknick et al., 2011). In contrast, solar PV and wind energy use almost no water (IRENA, 2015).

4. Conclusion

This analysis results in a new method for perceiving water use as related to energy consumption. The water consumption and water withdrawals made for power generation were quantified according to the generation mix using factors in gal/MWh. Water withdrawals and consumption were simulated down to an hourly time scale in order to illustrate changes in water use throughout the day, focusing on two weeks during summer and winter for the California ISO. Uncertainty in these calculations is based on the range of expected values found in the literature, and is illustrated along with the withdrawal and consumption values to illustrate the magnitude of uncertainty associated with this method. Water usage from power in regions with greater renewable power generation penetration has also been compared to water use in regions with less renewable energy in the generation mix.

Although there is significant uncertainty when relating water use to power generation, this uncertainty may be quantified and was presented here along with the water withdrawal and consumption estimates. This can be used to better understand how water use will change as a result of changes in the generation mix; and is critical to understanding how power production affects the water supply on a regional scale. More detailed information on the power plants in a specific region will help to reduce this uncertainty; when the specific cooling technology used, ambient conditions, and thermodynamic operating conditions of the plants are considered, the range of potential values for water consumption and withdrawals attributed to those plants are smaller. Future work by the authors will address reducing uncertainty with the water use predictions, and investigating the impacts of renewable power generation integration on water use in a given region.

When an individual or facility manager could see how much water is being used due to their own power consumption, this information can be used for education and conservation. Using less power, rather than only limiting municipal water usage, helps to protect water resources as well. This work provides a simplified method for quantifying the amount of water savings with a given amount of electricity savings. Water usage from power should also be considered more thoroughly during the handling of water shortages, just as with agricultural or other public uses. Quantifying of this water use could further aid in the decision making process when water allocations are made.

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