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# Characterizing cooling water source and usage patterns across US thermoelectric power plants: a comprehensive assessment of self-reported cooling water data

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E-mail: [peerr@usc.edu](mailto:peerr@usc.edu)**Keywords:** energy-water nexus, power plant cooling, electricity generation, cooling towersSupplementary material for this article is available [online](#)

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## Abstract

This study characterizes cooling water sources (by type and quality) and cooling water usage rates in thermoelectric power plants across the US based on data reported by power plant operators to the Energy Information Administration (EIA) for the year 2014. Geospatial distributions of water usage by specific cooling technologies and water sources confirm trends towards wet recirculating cooling systems, dry cooling and reclaimed water usage in the power sector, especially in more water constrained locations. Results include a database of water withdrawal and water consumption rates for 672 unique power plants organized by fuel, prime mover and cooling system classification, expanding available data records by an order of magnitude from previous analyses. While median calculated rates are generally comparable to values reported in the literature for most cooling technologies, results suggest that water usage rates at power plants with unique locations or operating conditions might not be accurately characterized by averages, especially in the case of once-through cooled facilities. Despite previous criticisms of EIA cooling water data, improvements in form instructions, reporting methods, and cooling system definitions have markedly improved the quality and usability of cooling water data records in recent years.

## Introduction

Approximately 86% of US power production is generated in thermoelectric power plants that require water at sufficient quantities and temperatures for cooling [1]. Water use for power generation is reported in terms of water withdrawals and water consumption, which are defined as the total volume of water removed from a source (river, reservoir, ocean, etc.) and the volumetric subset of withdrawn water that is not returned to the source (i.e. consumed via evaporative losses), respectively [2–7]. Nationwide, almost half (45%) of annual US water withdrawals and about 3% of total US water consumption is dedicated to cooling thermoelectric power plants [8].

The water requirements of power plants can vary significantly across different facilities and are influenced by characteristics such as cooling technology, fuel type, prime mover, pollution controls, and ambient climate [6, 7, 9]. Cooling system configuration is the most

significant characteristic governing a power plant's water use. Open-loop (or once-through) cooling systems withdraw large volumes of water, used once to condense steam exiting a steam turbine, while closed-loop (or recirculating) cooling systems withdraw smaller volumes per unit of generation by recirculating water continuously, at the expense of higher water consumption rates [6, 7]. Differences in the combustion (or conversion) characteristics of different primary energies (i.e. coal, natural gas, uranium, solar, etc.), as well as the prime mover technology used for conversion, also influence the efficiency, and thus the water requirements, of transforming primary energy into finished electricity [8]. A facility using a steam turbine to convert primary energy into electricity, for example, typically has higher water requirements than a combined-cycle facility that combines a steam turbine with combustion turbines to increase the efficiency of electricity generation [10, 11]. Additionally, pollution controls for existing fossil-fueled generators typically

require auxiliary systems that introduce parasitic power losses and additional water requirements for operation [12]. Climatic variables such as air and water temperatures, streamflow, precipitation, and occurrence of extreme events can also impact the availability and/or required volumes of cooling water for power generation [13–23].

While these general trends are understood, there exist only a few vetted datasets that detail the operational water requirements of US power plants. The lack of data availability surrounding water use at thermoelectric power plants was highlighted in 2009 by the Government Accountability Office [24]. Macknick *et al.* compiled one of the first reviews of cooling water use rates (i.e. cooling water volume per electrical energy output) based on reported values from primary literature sources [25, 10]. This compilation of water use rates has been central to most recent studies evaluating cooling water use at the operational phase of power production [22, 26–42]. It characterizes power facility cooling water consumption and withdrawal rates based on fuel, cooling system, and prime mover configuration for a small sample of generators (on average four facilities per technology classification) reflecting the best available data at the time of publication [10]. Another recent report published by the US Geological Survey (USGS) estimated the water consumption and withdrawal rates for a large set of power plants based on heat budget models. While the USGS dataset represents a statistically significant sample size of power plants, water usage rates do not reflect the unique configurations of each individual power plant and are not reported by fuel or prime mover [38].

Although self-reported cooling water data by power plant operators are collected and published annually from the Energy Information Administration (EIA), these data have been criticized for poor data quality and inconsistent reporting across US generation technologies [33, 10]. Furthermore, the data are difficult to use in practice as generation data are reported by unit specific prime mover, while water use data are collected and reported according to a cooling water system identification number. Since power plants often have multiple fuels, cooling systems, and/or prime movers, these data, although large in number, are not straightforward to analyze, and therefore, have not been used in many studies to date [25, 10, 33]. Despite recent efforts by the EIA to improve data quality, no analysis has been completed to re-assess self-reported values since the 2008 data were analyzed by Averyt *et al.* [33].

Although there has been a growing body of analyses exploring the cooling water requirements of the power sector in the peer-reviewed literature across various energy futures [22, 26–29, 32, 34, 40, 43], these studies lean almost exclusively on published water usage rates based on a small subset of power plants. Additionally, little analysis has been done to characterize emerging

trends such as the expansion of dry-cooled and recirculating tower cooled power generation or the use of alternative sources of cooling water, such as reclaimed water from municipal and industrial wastewater treatment facilities. Given growing concerns regarding the water usage of power plants, an updated and expanded investigation is needed.

The purpose of this study is to systematically analyze 2014 self-reported cooling water data published by the EIA in terms of plant-by-plant water usage rates, cooling water source type and quality, and geospatial trends in power plant cooling by watershed. The resulting vetted database of the cooling water characteristics of hundreds of power plant facilities is available in full in the SI document, offering the research community a statistically significant and geographically diverse database of plant-specific cooling water data for US power plants.

## 1. Methodology

EIA Forms 923 [1] and 860 [44] were used to characterize the cooling system and cooling sources for each power generator in 2014. These forms are sent to operators at US power generation facilities of 1 MW or greater that are connected to a regional power grid [45]. EIA Form 860 Schedule 6D details each cooling system by type, ID number, operational characteristics and annual cooling water usage data. Thermoelectric generators are prompted to characterize their cooling water sources in terms of four type (i.e. surface water, groundwater, plant discharge water or other) and five quality (i.e. brackish water, freshwater, reclaimed water, saline water or other) classifications, respectively. Cooling data in EIA Form 923 Schedule 8D were used to cross-check information and identify cooling system and water source when data were missing. In cases when a generator reported no cooling source in Schedules 8D or 6D, specific cooling source names (e.g. 'Colorado River' or 'wells') reported in the EIA Form 860 Schedule 2 were manually analyzed and recorded into the prescribed type and quality classifications. Generators with missing cooling technology and/or cooling source data records were generally small facilities. (Full details regarding data cleaning and assumption assignments for missing data are available in the SI [stacks.iop.org/ERL/11/124030/mmedia](http://stacks.iop.org/ERL/11/124030/mmedia)). The data available in the 2014 self-reported EIA surveys outnumbers previous data records by an order of magnitude for common generating technologies, such as steam-fired, tower-cooled coal and natural gas facilities.

Operational water use rates were also calculated using cooling water data collected through EIA Forms 923 [1] and 860 [44]. Each data record in Form 923 Schedules 3A & 5A, which provide information on annual primary energy consumption by fuel type and electricity output, was compared to 860 Schedule 8D based on power plant identification number. Each

power plant identification number associated with a facility using one type of fuel, one type of prime mover (plus all combined-cycle facilities), and one type of cooling system was filtered into a sub-set of generators, which were assigned a code designating fuel type, prime mover type, cooling system type, and combined heat and power (CHP) status. To increase the generation available for analysis, power plants that generated over 95% of their annual generation from coal or natural gas in steam or combined cycle facilities were also added to this filtered sub-set. Although these facilities generated up to 5% of their electrical output using other fuels, the impact on cooling water was assumed to be minimal. Only coal, natural gas, and nuclear generation facilities were considered in the water use rate analysis due to data availability constraints for other types of generation facilities.

Generators reporting multiple fuels, prime movers or cooling systems made some data difficult to synthesize. Although EIA Form 923 Schedule 6A associates Boiler ID to Cooling ID for a selection of generators, most generators were not included in this form. Thus, for most power plants with multiple fuels, prime movers, and/or cooling systems, there was no way to disaggregate water use by fuel and configuration (e.g. linking the specific cooling system to the specific prime mover system). Therefore, these facilities are omitted from the final filtered water usage rate dataset. In total, the dataset of generators represented roughly 86% of total 2014 US thermoelectric, water-cooled generation.

The filtered data records were processed by dividing annual cooling water withdrawals and consumption by total annual power generation to determine a final water withdrawal and consumption rate, respectively. The Appendix Instructions detailed in Form 923 Schedule 8D were followed to determine water consumption in recirculating cooled facilities, which was defined as the volumetric difference between water withdrawals and water discharges [46]. This calculation was only performed on recirculating facilities that reported values for water withdrawal and discharge, but not for consumption. Generally, these facilities were cooled using recirculating pond(s)/canal(s). Outliers were detected using a modified Z-score, based on methods described by Iglewicz and Hoaglin [47]. Although reported zero-values would not be considered outliers if the absolute value of the Z-score was less than 3.5, a thermal generation unit requires some amount of cooling fluid (i.e. water in wet cooled systems and air in dry cooled systems) to reject heat during operation. Thus, generators with wet cooling systems that reported zero-values or no cooling water data were discarded from the final filtered dataset. Confidence intervals were used as an alternative to standard deviation to describe the probable bounded region within which the true values of the cooling water estimates were located [48].

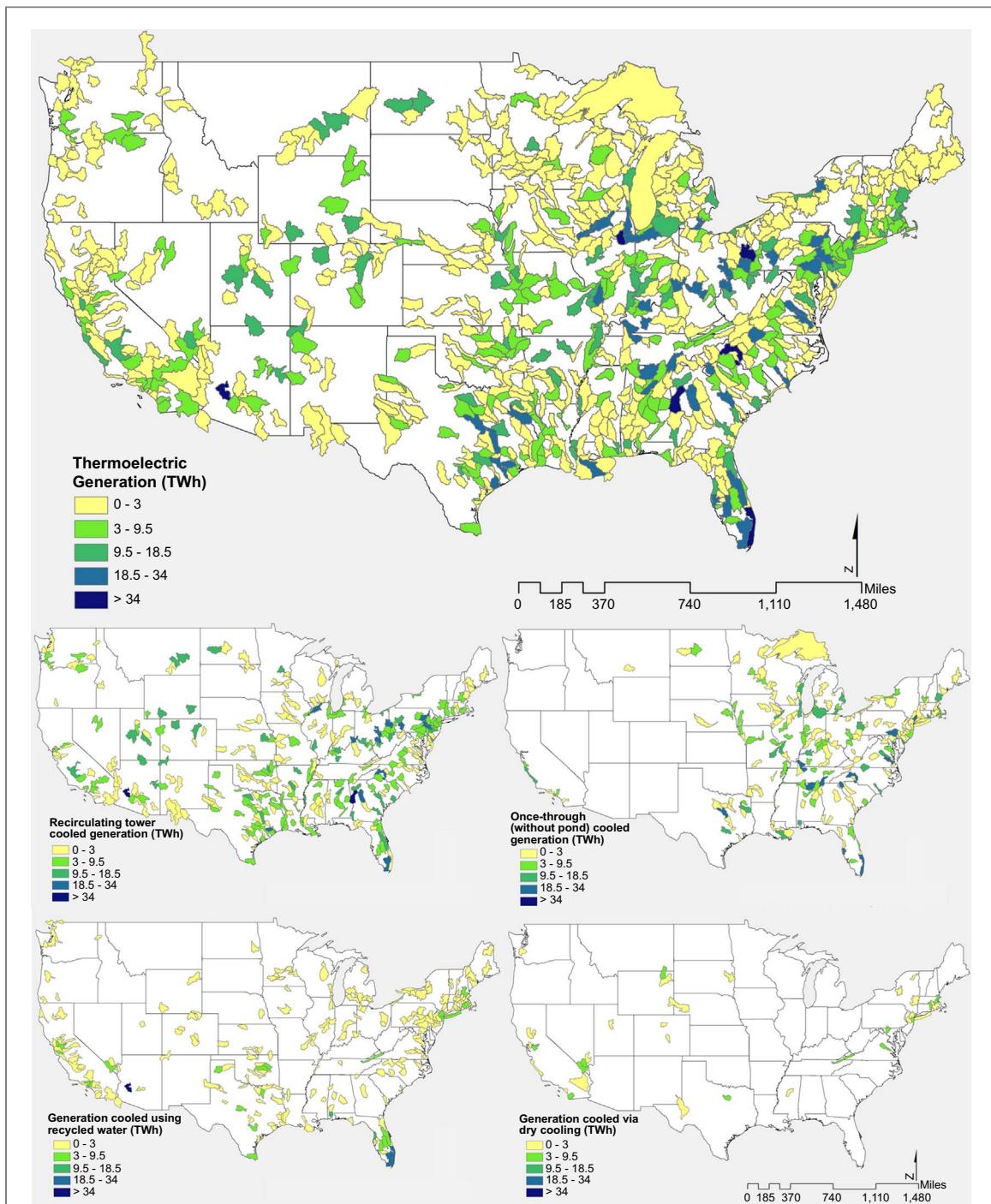
**Table 1.** Cooling system technologies were characterized for all 2014 US electricity generators reporting to the EIA (listed from most to least water withdrawal intensive, on average). Eighty-six percent of this generation was produced in thermoelectric power facilities requiring a cooling system. Wet recirculating tower cooling systems are now utilized more than any other type of cooling system.

Cooling System Type	2014 Generation (billion kWh)	Generation
No Cooling	564 $\pm$ 28.2	13.8%
Dry (air) cooling System	116 $\pm$ 5.92	2.84%
Hybrid: recirculating with forced draft cooling tower(s) with dry cooling	8.29 $\pm$ 0.414	0.203%
Hybrid: recirculating with induced draft cooling tower(s) with dry cooling	8.80 $\pm$ 0.527	0.215%
Recirculating with Induced Draft Cooling Tower	1400 $\pm$ 72.9	34.2%
Recirculating with Natural Draft Cooling Tower	501 $\pm$ 25.5	12.2%
Once through with Cooling Ponds	105 $\pm$ 6.56	2.57%
Recirculating with Cooling Ponds	326 $\pm$ 16.8	7.97%
Once through without cooling pond(s) or canal(s)	1064 $\pm$ 55.1	26.0%
Total	4093	100%

## 2. Results and Discussion

Table 1 summarizes total 2014 US power generation by cooling system. Over half of all thermoelectric power generation was cooled with wet recirculating cooling towers, while about 42% was produced in facilities utilizing once-through cooling or some type of cooling pond. Dry-cooled facilities generated nearly 3% of total US thermoelectric generation, nearly three times previous estimates in the literature [2]. Nevada, California and New York represented approximately 16%, 15%, and 13% of total US dry-cooled generation, respectively (figure 1). Much of California's coastal generation seen in figure 1 recently switched from once-through cooled facilities using saline water to dry cooled facilities using reclaimed water because of new regulations [49]. The average cooling system in-service year for power plants listing their primary cooling technology as once-through without cooling ponds, induced draft cooling towers, or dry cooling was 1963, 1988, and 2004, respectively, confirming the general shift towards lower withdrawal systems over time [44].

While fresh surface water represents the majority of US cooling water, reclaimed water is used to cool nearly 6% of thermoelectric generation (See table 2). These facilities are generally located near big cities where effluent from wastewater treatment or industrial facilities is abundant. Although reclaimed water is often utilized within dry cooled generation facilities, this trend is not captured in table 2 since dry-cooled facilities were not consistent in reporting a cooling source of water versus air. However, some of this geospatial coupling is observed in figure 1 by



**Figure 1.** Total 2014 generation (top) and total generation by each respective cooling technology/source are aggregated in each map across each HUC-8 watershed. Once-through cooled facilities are concentrated in the eastern US and coastal regions where water is generally abundant. Water constrained locations typically use recirculating cooling towers, which avoid large water withdrawals at the expense of higher water consumption. Dry cooled generation and generation cooled with reclaimed water have expanded in recent years, lowering both freshwater consumption and withdrawals compared to other cooling systems.

comparing the HUC-8 subbasins on the lower two maps in the figure, especially in California. Power plants using saline or brackish surface water are generally older once-through facilities, as water with high total dissolved solids causes fouling in cooling towers.

The geospatial distributions of water withdrawals and water consumption in figure 2 reflect cooling system configurations. Once-through cooled facilities that require large flow rates are typically located on larger rivers or the coasts, where water availability is

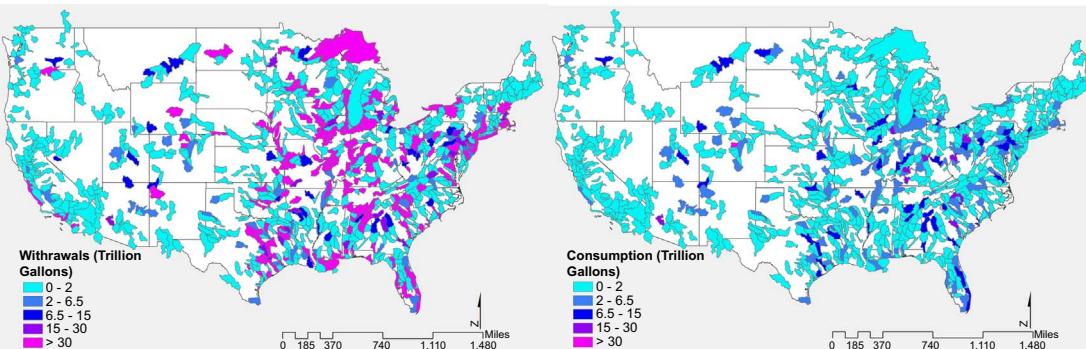
high. Thus, most once-through cooled capacity is located in the water-rich eastern US (figure 1).

Median, minimum, and maximum water use rates (table 3), in addition to full statistical distributions (figure 3), were characterized for all available technology configurations considered in this study. The number of power plants analyzed in each category,  $n$ , reflects the total number of data points,  $n_T$ , less outliers,  $n_o$ , and zeroes,  $n_z$  (i.e.  $n = n_T - n_o - n_z$ ) (table 3). In total, 644 water

**Table 2.** Cooling sources were characterized for all US 2014 electricity generators reporting to the EIA. Nearly 75% of US generation produced in power facilities requiring cooling utilized fresh surface water.

Water Source	Source Type	2014 (billion kWh)	Generation
Surface Water	Freshwater	2626 $\pm$ 170	64.2%
	Brackish	141 $\pm$ 8.37	3.44%
	Saline	162 $\pm$ 8.09	3.96%
Groundwater	Freshwater	230 $\pm$ 29.2	5.63%
	Brackish	3.36 $\pm$ 0.168	0.082%
	Saline	4.33 $\pm$ 0.217	0.106%
Plant Discharge	Recycled	3.92 $\pm$ 0.196	0.096%
	Other	6.17 $\pm$ 0.309	0.151%
	Recycled	202 $\pm$ 11.7	4.94%
Other	Freshwater	10.9 $\pm$ 0.544	0.266%
	Saline	0.250 $\pm$ 0.012	0.006%
	Other	22.7 $\pm$ 1.32	0.553%
Dry-cooled	Dry-cooled <sup>a</sup>	116 $\pm$ 5.41	2.84%
No Cooling	No Cooling	564 $\pm$ 28.2	13.8%
Total		4093	100%

<sup>a</sup> Although dry-cooled facilities consume approximately 10% of a wet-recirculating tower facility [8], generators were not consistent in reporting cooling water sources, so their water sources are not classified in this table.



**Figure 2.** Total cooling water withdrawal and consumption volumes utilized by thermoelectric power generators in 2014, aggregated here by HUC-8 watershed, reflect cooling system technology trends.

withdrawal rates and 499 water consumption rates (including all non-zero and non-outlier values) were calculated in this analysis, representing data from a total of 672 unique power plants. The majority of non-reporting facilities were smaller than 1000 MW or had low net generation in 2014 (figure 4). Larger plants that were excluded from this analysis were mostly power plants using both coal and natural gas. Approximately 92%, 90%, and 85% of total nuclear, coal, and natural gas-fired generation in 2014, respectively, was classified with a single prime mover, fuel, and cooling system and reported non-zero and non-outlier values for either cooling water withdrawals or consumption. Collectively, these plants represent 86% and 84% of once-through and recirculating cooled generation in 2014, respectively.

The influence of fuel, prime mover, and cooling system on cooling water usage rates are evident in figure 3. The difference between water withdrawal rates for different cooling systems differed by up to three orders of magnitude, while the difference between consumption rates was typically within one

order of magnitude. Generally, once-through cooled facilities reported the highest water withdrawal rates, while the recirculating tower-cooled facilities reported higher consumption rates, in comparison. A regression analysis was performed to investigate the role of generation unit efficiency on water usage. Results did not show a strong correlation between average water withdrawal and consumption rates and monthly average heat rate. However, results were very dependent on accurate monthly primary fuel usage, generation and volumetric water usage data; even small margins of error in reporting would be expected to weaken the regression analysis. (Full details of this regression analysis are available in the SI document.) Additionally, the influence of CHP and pollution controls on water usage rates were evaluated but data were not sufficient to draw meaningful conclusions.

Results of the EIA data analysis were compared to published cooling water usage rates in recent years. Calculated median water withdrawal and consumption rates for most recirculating tower-cooled facilities were comparable to values presented by Macknick *et al* [25, 10]

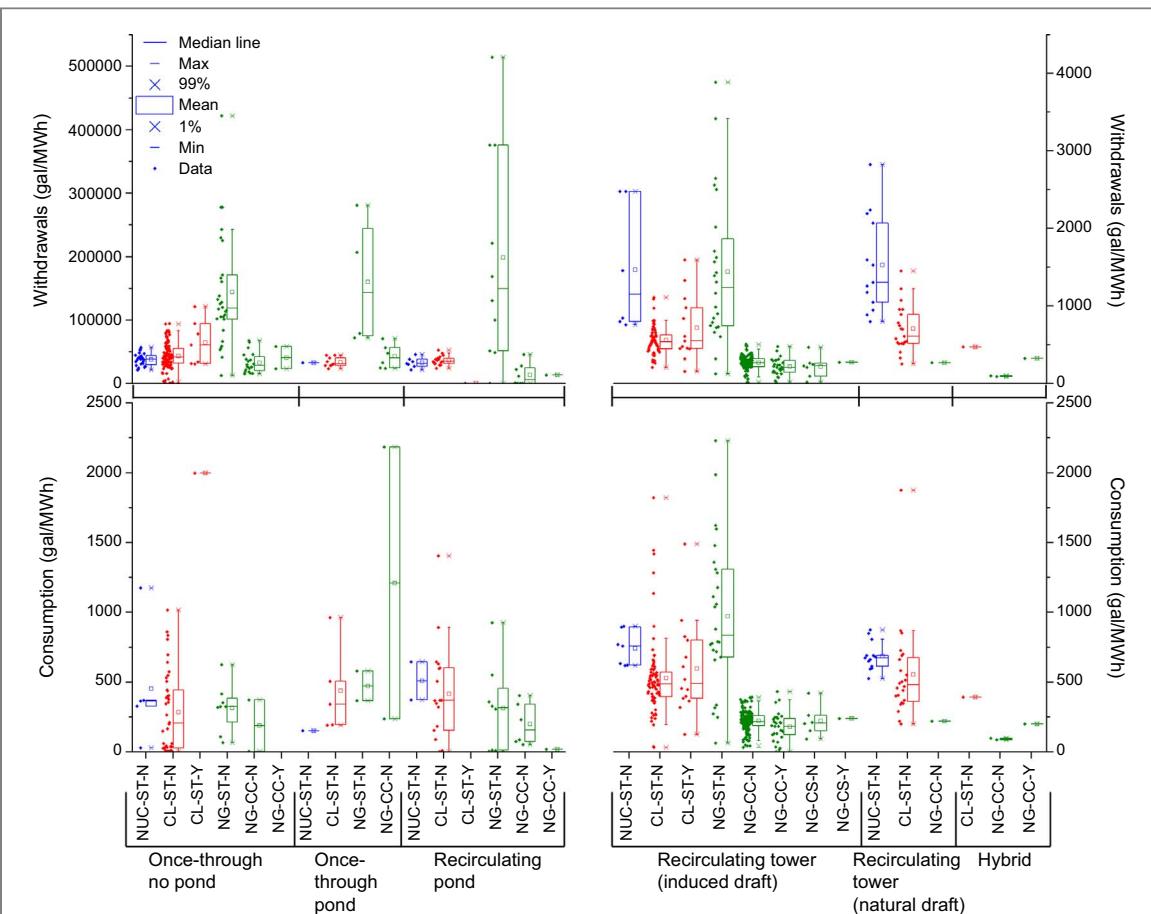
**Table 3.** Water withdrawal and consumption factors for electric generation units in the US based on calculations using self-reported cooling water data from 2014 EIA forms 923 and 860 [1, 44]<sup>a</sup>.

Cooling System	Fuel	Prime Mover	CHP Status	Water Withdrawal (Gal/MWh)								Water Consumption (Gal/MWh)							
				Median	Min.	Max.	<i>n</i>	<i>n<sub>z</sub></i>	<i>n<sub>o</sub></i>	<i>n<sub>T</sub></i>	Median	Min.	Max.	<i>n</i>	<i>n<sub>z</sub></i>	<i>n<sub>o</sub></i>	<i>n<sub>T</sub></i>		
Once through with ponds	Nuclear	Steam	N	32,375	32,375	32,375	1	0	0	1	151	151	151	1	0	0	1		
	Coal	Steam	N	30,469	23,365	44,626	10	1	0	11	340	190	962	5	0	6	11		
	Natural Gas	Steam	N	142,753	71,708	280,729	4	0	0	4	472	365	579	2 <sup>b</sup>	0	2	4		
	Natural Gas	Combined Cycle	N	40,092	24,119	70,320	6	0	0	6	1,209	235	2,184	2 <sup>b</sup>	0	4	6		
Once through without ponds	Nuclear	Steam	N	37,924	21,214	56,713	28	2	0	30	363	28	1,176	5	1	24	30		
	Coal	Steam	N	41,106	566	94,298	112	7	0	119	204	0.1	1,016	42	2	75	119		
	Coal	Steam	Y	60,940	30,840	120,963	7	0	0	7	1,997	1,997	1,997	1	0	6	7		
	Natural Gas	Steam	N	118,490	12,488	421,489	30	7	0	37	325	65	623	8	1	28	37		
	Natural Gas	Combined Cycle	N	28,007	15,099	67,341	20	1	1	22	188	2.4	373	5	0	17	22		
	Natural Gas	Combined Cycle	Y	40,930	23,524	58,335	2	0	0	2	-	-	-	-	-	-	-		
Recirculating ponds	Nuclear	Steam	N	31,589	21,642	45,427	7	0	0	7	509	372	645	2 <sup>b</sup>	0	5	7		
	Coal	Steam	N	35,338	24,143	52,364	18	4	0	22	368	0.3	1,403	18	1	3	22		
	Coal	Steam	Y	27	27	27	1	0	0	1	-	-	-	-	-	-	-		
	Natural Gas	Steam	N	149,449	2.6	513,781	10	0	0	10	317	4.9	924	8	0	2	10		
	Natural Gas	Combined Cycle	N	6,037	74	45,575	8	1	0	9	158	53	404	6	0	3	9		
	Natural Gas	Combined Cycle	Y	13,149	13,149	13,149	1	0	0	1	18	18	18	1	0	0	1		

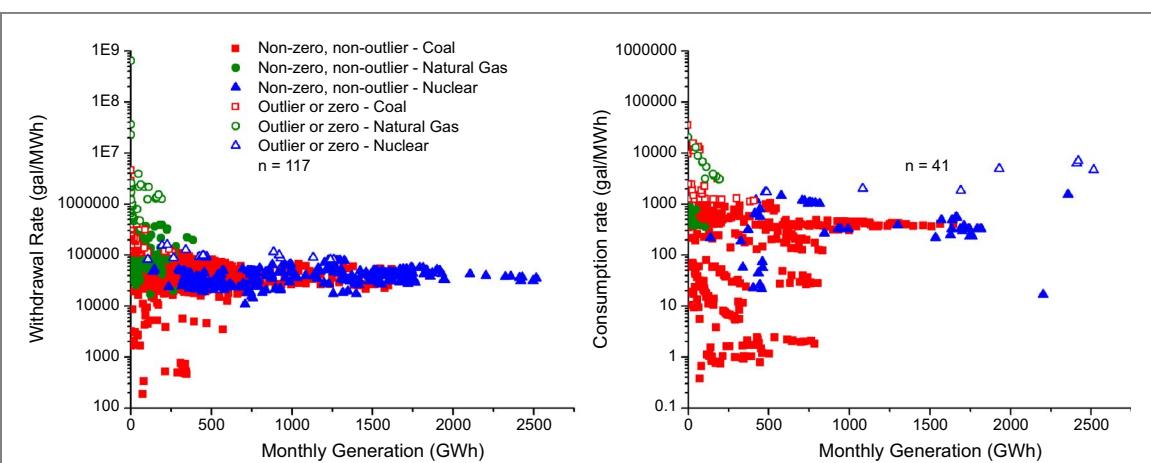
Recirculating Tower (induced draft)		Nuclear	Steam	N	1,150	758	2,475	6	1	0	7	758	617	899	7	0	0	7
		Coal	Steam	N	539	205	1,106	71	14	0	85	487	31	1,820	82	3	0	85
		Coal	Steam	Y	546	152	1,594	13	3	0	16	487	126	1,489	14	1	1	16
		Natural Gas	Combined Cycle	N	265	15	508	156	18	5	179	217	30	392	152	19	8	179
		Natural Gas	Combined Cycle	Y	207	14	478	28	3	2	33	183	1.0	432	29	2	2	33
		Natural Gas	Combined Cycle Single Shaft	N	227	19	466	7	1	0	8	205	93	420	6	1	1	8
		Natural Gas	Combined Cycle Single Shaft	Y	273	273	273	1	0	0	1	238	238	238	1	0	0	1
Recirculating Tower (natural draft)		Nuclear	Steam	N	1,304	795	2,821	13	1	0	14	672	525	873	13	1	0	14
		Coal	Steam	N	607	249	1,451	21	3	0	24	404	198	1,875	24	0	0	24
		Natural Gas	Steam	N	1,235	124	3,883	24	3	1	28	833	64	2,229	26	1	1	28
		Natural Gas	Combined Cycle	N	267	267	267	1	0	0	1	218	218	218	1	0	0	1
Hybrid		Coal	Steam	N	470	470	470	1	0	0	1	392	392	392	1	0	0	1
		Natural Gas	Combined Cycle	N	93	87	98	2 <sup>b</sup>	0	1	3	92	86	98	2 <sup>b</sup>	0	1	3
		Natural Gas	Combined Cycle	Y	325	325	325	1	0	0	1	200	200	200	1	0	0	1

<sup>a</sup>  $n$ : number of data points, excluding outliers and zero-values;  $n_z$ : number of data points reporting zero-values;  $n_o$ : number of data points classified as outliers according to calculated modified Z-scores (see supplementary information for full table including outliers.);  $n_t$ : total number of data points. Median, minimum, and maximum values reflect  $n$  filtered values. Facilities with multiple cooling systems, prime movers, and/or fuels are not included in the final filtered dataset.

<sup>b</sup> Median reflects average of Min and Max values.



**Figure 3.** Distributions of 644 water withdrawal rates and 499 water consumption rates, characterized by cooling system, fuel and prime mover configuration, represent data from a total of 672 unique power plants (excluding power plants reporting outliers and zero-values). Box-and-whisker plots showcase the quartile distribution of data (points shown to the left of the plots) for each generating technology analyzed. Minimum, maximum, and median values are identified on box-and-whiskers as horizontal lines; mean values are identified as hollow squares. **Fuel:** Coal (CL), Natural Gas (NG), Nuclear (NUC); **Prime Mover:** Steam Turbine (ST), Combined Cycle (CC), Combined Cycle Single-Shaft (CS); **Combined heat and power (CHP):** Yes (Y), No (N)



**Figure 4.** Monthly average water usage rates versus monthly generation for the subset of once-through cooled generation units suggest that older units with low capacity factors located on large bodies of water often report very high water withdrawal and/or consumption rates.

and heat budget models from the USGS [38]. There were also a large amount of data available for recirculating tower cooled facilities, increasing the value of the resulting distribution. (Quantitative comparisons to previous studies are available in the SI document.)

Calculated water usage values for once-through facilities were also similar to previous analyses;

however, there were cases in which calculated water withdrawal and/or consumption rates were one or more orders of magnitude higher than expected. Figure 4 illustrates the distribution of calculated monthly withdrawal and consumption rates versus monthly generation for once-through cooled generation units considered in the analysis. Calculated water

use rates for a subset of these generators were markedly higher than values reported in prior review and heat budget studies. In general, these generators with water withdrawal or consumption rates characterized as outliers (shown with hollow shapes in figure 4) had low capacity factors, were constructed pre-1970 and were located on large bodies of water (e.g. rivers with very fast flow such as the Mississippi River or the Pacific Ocean). Thus, these high water use rates were most likely driven by large incoming flows of water used to cool small amounts of generation in infrequent intervals. This insight points to the importance of considering water usage on a plant by plant basis, as averages might not correctly characterize water usage at power plants with unique locations or operating conditions. Such underestimations could lead to an underestimation of ecosystem impacts associated with high flow rates (i.e. through entrainment or entrapment) or thermal pollution. Most once-through cooled natural gas steam cycle generators, in particular, had calculated values withdrawal rates larger than 100,000 gal/MWh, which were far higher than previous studies.

Water withdrawal rates for generating units using recirculating pond/canal or once-through pond/canal cooling systems were generally much greater than values reported by Macknick *et al* [10] and Diehl and Harris [38], whereas reported non-zero consumption rates were similar in value. Diehl and Harris (2014) make a clear distinction between recirculating and once-through cooling ponds or canals. They define a once-through pond system as a large reservoir, typically located within a large watershed that receives enough natural runoff to maintain normal flow rates, while a recirculating pond system is typically within a smaller watershed with little to no runoff [38]. Once-through systems would be expected to have higher withdrawal rates and lower consumption rates than recirculating systems based on this distinction. However, the calculated median water use rates from EIA data for all generating systems using ponds/canals do not show noticeable differences between open-loop and recirculating systems. Although the EIA provides an 'Appendix for Schedule 8D' [46] to plant operators to supplement 923 instructions, there are evident inconsistencies in reported cooling system definitions.

### 3. Conclusion

This study characterized US cooling water usage trends in 2014 based on self-reported cooling water data from thermoelectric power generation units, published in EIA's 2014 923 and 860 forms. Results indicate that shifts in the power sector toward wet recirculating cooling towers, dry cooling, and reclaimed water use in recent years. Water withdrawal and water consumption rates were calculated according to fuel, prime mover, and cooling system classification for 672 unique power

plants, which is an order of magnitude larger than available water usage rates published in the literature based on real power plant data. While some reported data are incomplete or erroneous, results suggest that water usage rates at power plants with unique locations or operating conditions might not be accurately characterized by 'average' facilities. Although characteristics such as power plant efficiency, and consequently, pollution controls and combined heat and power configurations would be expected to affect the water usage of power plants, the 2014 EIA dataset analyzed was not sufficient to draw meaningful conclusions about these characteristics, so future research should be dedicated to analyzing the impacts of more complex power plant configuration on cooling water usage.

Water withdrawal and consumption rates calculated for power plants cooled with wet recirculating towers in this analysis were particularly close to values presented in the literature and calculated in heat budget models [10, 25, 38], suggesting that there is a good understanding of the water requirements of recirculating cooling systems. Calculated water withdrawal and/or consumption rates for some technologies were one or more orders of magnitude higher than estimates in the literature, notably natural gas steam cycle facilities with once-through cooling. These high water use rates could be the result of large incoming flows of cooling water used for small amounts of generation in infrequent intervals. This new insight highlights the need for building a more robust understanding of the cooling water usage of power plants with unique locations and/or operating conditions.

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### References

- [1] US Energy Information Administration 2015 2014 Form EIA-923 Data *Technical Report*
- [2] Feeley T J, Skone T J, Stiegel G J, McNemar A, Nemeth M, Schimmoller B, Murphy J T and Manfredo L 2008 *Energy* **33** 1–11
- [3] Sovacool B K 2009 *Energy Law J.* **30** 11–52
- [4] Stillwell A S, Clayton M E and Webber M E 2011 *Environ. Res. Lett.* **6** 034015
- [5] Macknick J, Sattler S, Averyt K, Clemmer S and Rogers J 2012 *Environ. Res. Lett.* **7** 045803
- [6] King C W, Stillwell A S, Twomey K M and Webber M E 2013 *Nat. Resour. J.* **53** 117–215
- [7] Sanders K T, Blackhurst M F, King C W and Webber M E 2014 *Environ. Sci. Technol.* **48** 7128–34

[8] Sanders K T 2015 *Environ. Sci. Technol.*

[9] Scanlon B R, Reedy R C, Duncan I, Mullican W F and Young M 2013 *Env. Sci. Tec.* **47** 11326–34

[10] Macknick J, Newmark R, Heath G and Hallett K C 2012 *Environ. Res. Lett.* **7** 045802

[11] Sanders K T and Webber M E 2012 *Environ. Res. Lett.* **7** 034034

[12] Rochelle G T 2009 *Science* **325** 1652–4

[13] Sieber J 2013 *Clim. Change* **121** 55–66

[14] Mukheibir P 2013 *Clim. Change* **121** 67–78

[15] Vine E 2012 *Clim. Change* **111** 75–99

[16] Kopytko N and Perkins J 2011 *Energy Policy* **39** 318–33

[17] Department of Energy 2013 U.S. energy sector vulnerabilities to climate change and extreme weather Tech. rep. Department of Energy (<http://energy.gov/sites/prod/files/2013/07/f2/20130710-Energy-Sector-Vulnerabilities-Report.pdf>)

[18] Mideksa T K and Kallbekken S 2010 *Energy Policy* **38** 3579–85

[19] Khan I, Alam F and Alam Q 2013 *Energ. Policy* **61** 1460–70

[20] Sathaye J a, Dale L L, Fitts G a, Koy K, Lewis S M and de Lucena A F P 2011 Estimating Risk to California Energy Infrastructure from Projected Climate Change *Tech. rep.* California Energy Commission (<http://emp.lbl.gov/sites/all/files/lbnl-4967e.pdf>)

[21] Sathaye J A, Dale L L, Larsen P H, Fitts G A, Koy K, Lewis S M and de Lucena A F P 2013 *IEEE Power Energy Mag.* **11** 32–45

[22] Yates D and Miller K A 2013 The International Journal of Climate Change: Impacts and Responses vol 4

[23] Harto C, Yan Y E, Demissie Y, Elcock D, Tidwell V C, Hallett K, Macknick J, Wigmosta M and Tesfa T 2011 Analysis of drought impacts on electricity production in the Western and Texas Interconnections of the United States *Technical Report*

[24] United States Government Accountability Office 2009 ENERGY-WATER NEXUS: improvements to federal water use data would increase understanding of trends in power plant water use ENERGY-WATER NEXUS Highlights *Technical Report*

[25] Macknick J, Newmark R, Heath G and Hallett K C 2011 A review of operational water consumption and withdrawal factors for electricity generating technologies *Technical Report*

[26] Meldrum J, Nettles-Anderson S, Heath G and Macknick J 2013 *Environ. Res. Lett.* **8** 015031

[27] Tidwell V C, Moreland B D, Zemlick K M, Roberts B L and Passell H Water as a constraint for new thermoelectric generation in the WECC *Technical Report*

[28] Tidwell V C, Kobos P H, Malczynski L A, Klise G and Castillo C R 2012 *J. Water. Res. Pl.* **138** 491–501

[29] Cooley H, Fulton J and Gleick P 2011 Water for energy: future water needs for electricity in the Intermountain West *Technical Report*

[30] Yates D, Meldrum J, Flores-Lopez F and Davis M 2013 *Environ. Res. Lett.* **8** 035042

[31] Yates D, Meldrum J and Averyt K 2013 *Environ. Res. Lett.* **8** 045005

[32] Tidwell V C, Malczynski L a, Kobos P H, Klise G T and Shuster E 2013 *Environ. Sci. Technol.* **47** 8940–47

[33] Averyt K, Macknick J, Rogers J, Madden N, Fisher J, Meldrum J and Newmark R 2013 *Environ. Res. Lett.* **8** 015001

[34] Clemmer S, Rogers J, Sattler S, Macknick J and Mai T 2013 *Environ. Res. Lett.* **8** 015004

[35] Kyle P, Davies E G, Dooley J J, Smith S J, Clarke L E, Edmonds J A and Hejazi M 2013 *Int. J. Greenhouse Gas Control* **13** 112–23

[36] Zemlick K, Tidwell V C, Roberts B L and Castillo C R 2013 *J. Contemp. Water Res.* **13** 95–105

[37] Faeth P 2014 The impacts of EPA's Clean Power Plan on electricity generation and water use in Texas *CNA Technical Report*

[38] Diehl T and Harris M 2014 Withdrawal and consumption of water by thermoelectric power plants in the United States, 2010 *U.S. Geological Survey Scientific Investigations Report* **2014-5184**

[39] Baker J, Strzepek K, Farmer W and Schlosser C A 2014 *J. Am. Water Res. Assoc.* **50** 1289–303

[40] Bracken N, Macknick J, Tovar-hastings A, Komor P, Gerritsen M and Mehta S 2015 Concentratin solar power and water issues in the U.S. Southwest *Technical Report* March Western States Water Council

[41] Mouratiadou I, Biewald A, Pehl M, Bonsch M, Baumstark L, Klein D, Popp A, Luderer G and Kriegler E 2016 *Environ. Sci. Pl.* **64** 48–58

[42] DeNooyer T A, Peschel J M, Zhang Z and Stillwell A S 2016 *Applied Energy* **162** 363–71

[43] Ou Y, Zhai H and Rubin E S 2016 *Int. J. Greenhouse Gas Control* **44** 249–61

[44] US Energy Information Administration 2015 2014 Form EIA-860 Data *Technical Report*

[45] US Energy Information Administration 2014 FORM EIA-923 POWER PLANT OPERATIONS REPORT INSTRUCTIONS

[46] US Energy Information Administration 2013 2013 Form EIA-923 Instructions Appendix for Schedule 8D *Technical Report*

[47] Iglewicz B and Hoaglin D 1993 *How to Detect and Handle Outliers Volume 16 of ASQC Basic References in Quality Control: Statistical Techniques* ed Mykytka E F (ASQC Quality Press) p 87

[48] National Institute of Standards and Technology and SEMATECH 2012 *Standard and Expanded Uncertainties Engineering Statistics Handbook* ch 2 ([www.itl.nist.gov/div898/handbook/](http://www.itl.nist.gov/div898/handbook/))

[49] ICF Jones & Stokes, Global Energy Decisions and Trask M 2008 Electric grid reliability impacts from regulation of once through cooling in California *Technical Report*