

Water Consumption Factors for Electricity Generation in the United States

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Abstract

In many regions of the United States, water availability is of concern due to growing demand and limited supply. In these regions, water is also an essential resource for most power generation technologies. Thermal power plants, which generate 87% of the total electricity in the United States, typically require a large amount of water for cooling purposes. Depending on types of cooling technology and prime movers, water loss or “consumption” through evaporation vary significantly. Hydropower plants with reservoirs “consume” large amount of water through evaporation due to the typically large surface area of the reservoir. Because water consumption rates vary by region due to different climate conditions, regional variation of water consumption due to hydropower generation should be considered. The objective of this study is to estimate the water consumption factor (WCF) for electricity generation, which is defined as the water consumed per unit of power generation (e.g., gallons of water per kWh of generated electricity). In particular, this study evaluates the variation in WCF by region. For hydropower, water consumption from hydropower reservoirs is calculated using reservoir’s surface area, state-level water evaporation data, and background evapotranspiration. Note that water consumption in multipurpose reservoirs is allocated to hydropower generation based on the share of the economic benefit of power generation among benefits from all other purposes (e.g., irrigation, flood control, navigation, etc.) Thus, the balance of water consumption is allocated among all other purposes based on their estimated economic benefits. For thermal power plants, the WCFs by types of cooling technology and prime mover are estimated. Because cooling technologies and prime mover types vary by region, the WCF for thermal power generation also exhibits regional differences. The WCFs from hydropower and thermal power generation are aggregated to the national-level and also to each North American Electric Reliability Council (NERC) utility region. The national average WCF for electricity is estimated at 0.58 gal/kWh considering the average U.S. electricity generation mix in 2015. At a facility-level, the WCFs of thermoelectricity and hydropower are 0.33 and 4.4 gal/kWh, respectively, while the shares of thermo- and hydro-power generation are 87% and 6.3%, respectively. The WCFs have been implemented in the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET[®]) model developed by Argonne National Laboratory. GREET is a life cycle analysis tool that evaluates energy use and emissions, as well as water consumption on a life cycle basis. This study allows researchers to analyze lifecycle water consumption for various energy production and conversion pathways. While the economic benefits approach was employed to allocate WCF to hydropower generation in multipurpose reservoirs, other approaches for estimating the hydropower WCFs are subjects for future analysis and updates to the GREET model.

1 Introduction

Demand for water grows rapidly with population growth, which requires more water resources for drinking, cooking, sanitation, food production, and power generation (Burnett et al. 2014). However, it is expected that there would be a steady drop in fresh surface water availability (Seager et al. 2013), and climate change may influence the water cycle through increased evaporation (Bartos and Chester 2015; Qaddumi et al. 2009). Therefore, competition over water resources between various demands may result in stress over water availability in affected regions.

The power generation sector is a major water consumer, and it is projected that demand for electricity generation will grow over time due to increases in population and energy use per capita (EIA 2016). As a result, water security became one of the biggest challenges to sustainability for hydropower and thermal power generation (i.e., fossil-based and nuclear power generation). Hydropower dams generate electricity by converting gravitational potential energy from flowing water into electricity using hydraulic turbines, and typically require an extensive volume of water to be stored in a reservoir. In the meanwhile, water is evaporated from the reservoirs resulting in loss or consumption of water. Water consumption is defined as water that is lost, i.e., that does not return to its original source in a given region. This is in contrast to water “withdrawal”, which represents the amount of water withdrawn for a given purpose, regardless of whether it is lost or returned to its original regional resource. Thermal power plants accounted for 87% of total power generation in the United States in 2015 (EIA 2016) and required a large amount of water for cooling purposes. The United States Geological Survey (USGS) estimated cooling water at power plants as the largest sector of water withdrawal with 45% of total withdrawals in 2010 (Maupin et al. 2014). While most of the withdrawn water is returned to the water body, a smaller portion is considered consumed, mainly due to evaporation, which depends on the employed cooling technologies at the power plant level.

Water cannot be substitute by other resources for cases such as irrigation, drinking, and sanitation. However, there are cooling technology options in power generation sectors which lead to reduced water consumption. This is particularly important for reliability of power generation in areas where water resources are limited. For example, California had to burn more natural gas to generate electric power because hydropower was roughly halved during the drought of 2007–2009 (Christian-Smith et al. 2011). Also, several southwestern thermoelectric power plants were forced to reduce or stop power generation due to limited available cooling water resources (Kimmell and Veil 2009; van Vliet et al. 2012).

Life cycle analysis (LCA) is a method that evaluates the environmental impacts of any product, including power generation, and covers all stages of the product’s lifetime. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET[®]) model developed by Argonne National Laboratory is used to systematically evaluate the life cycle energy use, greenhouse gas (GHG) emissions, and criteria air pollutant emissions associated with various fuel production pathways and vehicle technologies. The GREET model was recently expanded to include water consumption as an additional environmental sustainability metric. To determine the water consumption on a life cycle basis, it is essential to construct a water consumption inventory of every process along the product’s life cycle. Because electricity is one of the key resources used for other products’ pathways, it is important to evaluate water consumption for the power generation sector. Furthermore, considering the large difference in water availability and water consumption by region, regional analysis is essential for the water LCA.

This study aims to quantify water consumption for electricity generation and calculate water consumption factors (WCFs), which are defined as water consumption per unit of electric energy generation. For hydropower, regional climate differences that influence the WCFs of hydropower generation are mainly

discussed. For thermoelectricity, water consumption varies by types of cooling technologies and prime movers. Because the share of cooling technologies varies by region, it is expected that the WCFs of thermoelectricity also exhibit similar variation. The regional and national WCFs of various electricity generation technologies are implemented in the GREET model to facilitate the evaluation of the life cycle water consumption associated with the various end use of electricity.

2 Methodology

2.1 Definitions of Water Consumption

First, the definitions of fresh water and water consumption in this study should be clarified. On a global scale, water is not limited; it is rather the most abundant resource. However, available water resources for most end uses are constrained because water on earth is mostly seawater, which is not directly accessible by inland areas or end uses that require fresh water. Thus, available water resources, in general, mean freshwater which can be directly used for various purposes such as public water supply, irrigation, power generation.

There are two terminologies that commonly refer to water use: water withdrawal and water consumption. Water withdrawal represents the amount of water uptake from a surface or ground water source. Generally, there are three causes of water consumption: evaporation, incorporation into products, or degradation to insufficient quality for future use (Lampert et al. 2015). However, degradation of water quality can usually be treated in waste water treatment plants and recycled for reuse. In such case, degradation of water quality with use is not considered as water loss or consumption.

In this study, only freshwater is regarded as a water resource that is impacted by consumption. Water consumption is different from water withdrawal, because withdrawn water can be used multiple times unless it is consumed. In order to investigate the amount of water consumed for power generation, a WCF is defined as water consumption per unit of generated electricity (gal/kWh).

2.2 WCFs of Hydropower Generation

2.2.1 Water Consumption in Hydropower Dams

Although hydropower plants convert the gravitational potential energy of flowing water into electricity, the water keeps its quality as it merely flows through the hydraulic turbines. Such water can also be used for other downstream applications such as irrigation or water supply. Therefore, direct water use for hydropower generation is not considered consumed. However, when reservoirs store a large amount of water for the power generation purpose, stored water is evaporated from the surface. This portion should be accounted as consumed water because it becomes unavailable for other uses in the same water resource region.

Previously, the National Renewable Energy Laboratory (NREL) evaluated a national-level WCF for hydropower in the United States as 18.2 gal/kWh (Torcellini et al. 2003). That study aggregated the water evaporation from individual reservoirs using yearly averaged pan evaporation data and divided the annual evaporation by annual power generation. In 2012, Intergovernmental Panel on Climate Change

(IPCC) reported operational water consumption for hydropower varies from zero for run-of-river (ROR) hydropower plants, which do not employ reservoirs, up to 55.2 gal/kWh by referencing five data sources (Fthenakis and Kim 2010; Gleick and others 1993; LeCornu 1998; Mielke, Anadon, and Narayanamurti 2010; Torcellini et al. 2003). Bakken et al. (2013) reviewed previous approaches of evaluating hydropower water consumption and pointed out a methodological error. The authors mentioned that background evapotranspiration should be subtracted from the estimated water evaporation to account only for the amount of water consumption caused by anthropogenic actions. In this report, we use the methodology suggested by Bakken et al. (2013).

Figure 1 shows how reservoir construction changes water consumption in a given region. Before a dam is built, water consumption is primarily caused by evapotranspiration which represents water consumed through both direct evaporation and plant transpiration from the land (Sanford and Selnick 2013). This evapotranspiration is regarded as background water consumption when there is no reservoir. Once dam construction is finished, the area becomes a reservoir filled with water. In this case, water is consumed due to the increased evaporation from the reservoir surface area. Therefore, it is required to estimate the water evaporation from the reservoir and the background evapotranspiration in the same region in order to calculate the net water consumption caused by dam construction.

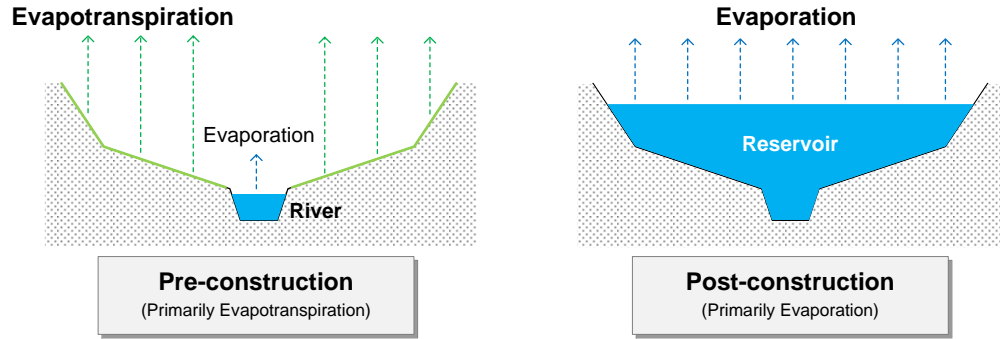


Figure 1. Water Loss Before and After Hydropower Reservoir Construction

2.2.2 Water Consumption by Region

First, annual water evaporation (cm/year) is estimated to calculate the amount of water evaporated from each reservoir. Because water evaporation varies by region due to different climate conditions such as temperature, precipitation, humidity, solar radiation, and the wind, state-level water evaporation is needed. Water evaporation can be estimated through pan evaporation data which measures the depth of consumed water in a standardized pan. National Weather Service (2016) reports daily pan evaporation measured at stations distributed nationwide. After screening the data from the measured daily pan evaporation for 2010–2015, averaged annual state-level pan evaporation has been calculated. The reported data shows that five states do not have evaporation stations. Also, other five states show inconsistent evaporation results compared to those of neighboring states and/or large fluctuation over the years. In order to supplement pan evaporation data, other sources of data are used for these states. For example, the National Weather Service (Farnsworth and Thompson 1983) measured pan evaporation during 1956–1970; this data source is used for Alabama, Georgia, Rhode Island, and Utah. For Alaska, data from Desert Research Institute (DRI) (2016) is used. For the remaining five states (Minnesota, New Hampshire, Vermont, West Virginia, and Delaware), pan evaporation is estimated by averaging data from neighboring

states that are subject to similar climate conditions. Table 1 shows the developed annual pan evaporation data by state.

Natural evaporation from reservoirs does not exactly match with the measured pan evaporation. When pan evaporation is measured, water is contained in a small pan installed above ground. Therefore, additional water evaporation is caused by heat exchange with surrounding walls. In order to compensate for this effects, lake evaporation is estimated by multiplying pan evaporation data with a coefficient of 0.75 (DRI 2016). Lake evaporation data at state-level is presented in Figure 2 and Table 1. The results show that southwestern states have the highest evaporation rates due to their tropical and dry climate conditions.

As mentioned earlier, to evaluate water consumption caused by dam construction, background evapotranspiration needs to be subtracted from evaporation. Due to lack of measured evapotranspiration data nationwide, a regression equation developed by Sanford and Selnick (2013) is used, which combines watershed water-balance data with meteorological data for 1971-2000, and related evapotranspiration with climate data. As a result, evapotranspiration (ET) at a certain location in the United States can be estimated using mean annual daily temperature (T_m), mean annual daily maximum temperature (T_x), mean annual daily minimum temperature (T_n), and mean annual precipitation (P). Eq. (1) represents the regression equation:

$$ET = \frac{\tau \Delta P}{\tau \Delta + \Pi} \quad (1)$$

where, $\tau = (T_m + T_o)^m / ((T_m + T_o)^m + a)$, $\Delta = (T_x - T_n) / ((T_x - T_n) + b)$, and $\Pi = (P / P_o)^n$. The fitted values are 13.735°C, 505.87 cm, 2.4721, 1.9044, 10,000, and 18.262 for T_o , P_o , m , n , a , and b , respectively (Sanford and Selnick 2013). Calculated annual evapotranspiration by state is shown in Figure 2 and Table 1. Note that temperature and precipitation data are all from National Centers for Environmental Information (NCEI) (NOAA 2016). Estimated evapotranspiration results show that the values along the Gulf Coast and in Florida are the highest because of the large amount of rainfall and warm temperatures, while the arid southeastern California area has the lowest evapotranspiration due to its low rainfall and dry conditions.

Table 1. Pan Evaporation, Lake Evaporation, Evapotranspiration, and Water Consumption by State

State	Pan Evaporation (cm/yr)	Lake Evaporation (cm/yr)	Evapotranspiration (cm/yr)	Water Consumption (cm/yr)
AL ^a	129	97	85	12
AK ^b	37	28	26	0
AZ	260	195	26	169
AR	114	85	79	6
CA	250	188	42	145
CO	212	159	29	130
CT	57	43	64	0
DE	84	63	68	0
FL	213	160	87	73
GA ^a	164	123	81	42
HI	230	173	84	88
ID	108	81	29	52
IL	93	70	62	8
IN	110	83	65	18
IA	114	85	58	28
KS	173	130	58	72
KY	113	85	72	12
LA	149	112	87	25
ME	53	40	53	0
MD	84	63	69	0
MA	36	27	59	0
MI	90	67	53	14
MN ^c	96	72	49	23
MS	113	85	85	0
MO	150	113	70	43
MT	113	85	32	53
NE	182	136	52	84
NV	265	199	20	178
NH ^c	55	41	35	7
NJ	97	73	65	7
NM	396	297	31	266
NY	90	67	61	6
NC	219	164	77	87
ND	95	71	40	32
OH	144	108	63	45
OK	176	132	74	59
OR	164	123	60	62
PA	64	48	64	0
RI ^a	91	68	65	3
SC	135	102	79	22
SD	120	90	45	45
TN	130	98	78	20
TX	302	227	65	162
UT ^a	143	107	32	75
VT ^c	55	41	56	0
VA	133	100	72	28
WA	132	99	62	37
WV ^c	181	136	68	68
WI	72	54	54	0
WY	150	112	34	79

^a Farnsworth and Thompson (1983)^b Desert Research Institute (2016)^c Pan evaporation data have been averaged using neighboring states due to insufficient or inconsistent data

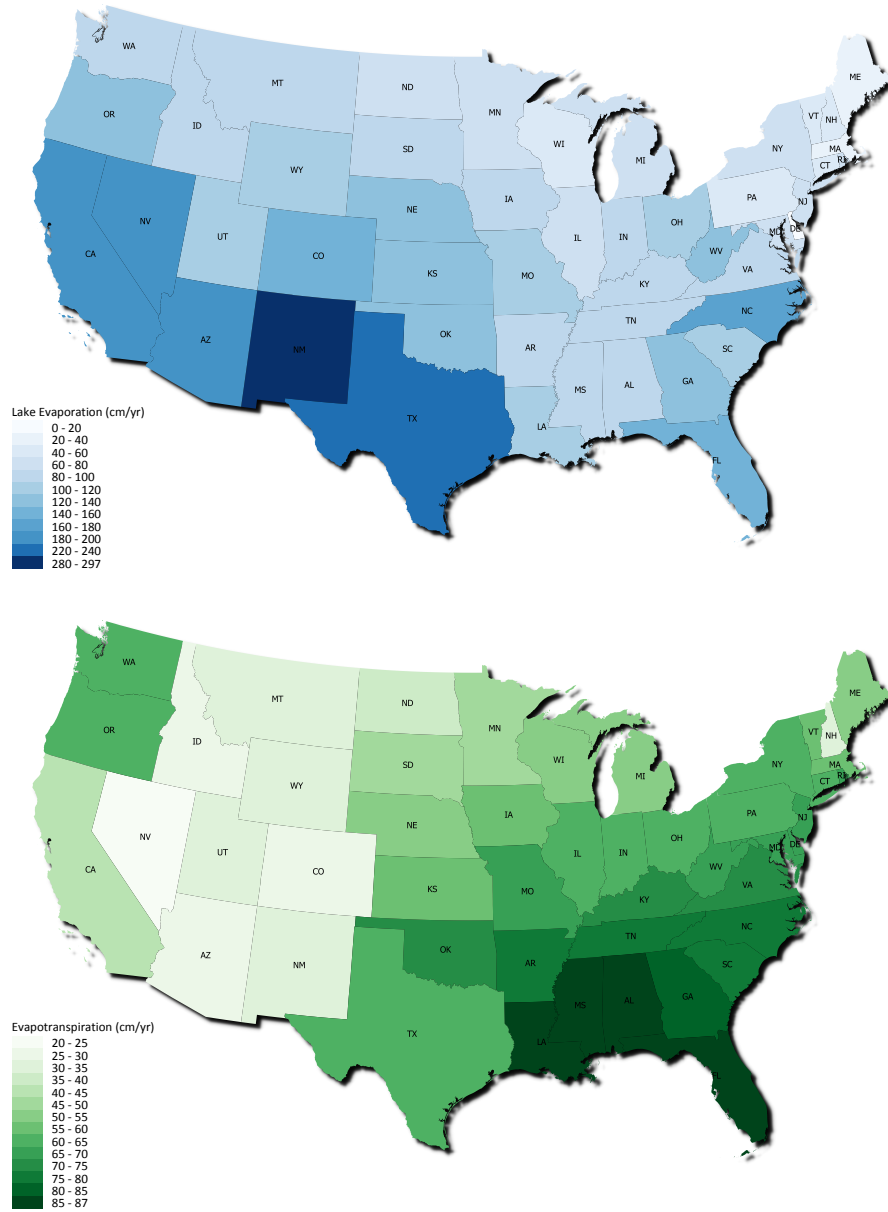


Figure 2. State-level Annual Lake Evaporation and Evapotranspiration (cm/yr) in the United States

As explained earlier, annual state-level water consumptions caused by increased water surface area are calculated as the differences between the evaporation and the evapotranspiration, and the results are shown in Figure 3 and Table 1. In cases where the water evapotranspiration rate is higher than the water evaporation, it is assumed that water consumption is negligible. Annual water consumption at each hydropower reservoir can be calculated using these state-level water consumption values along with reservoirs' surface area data.

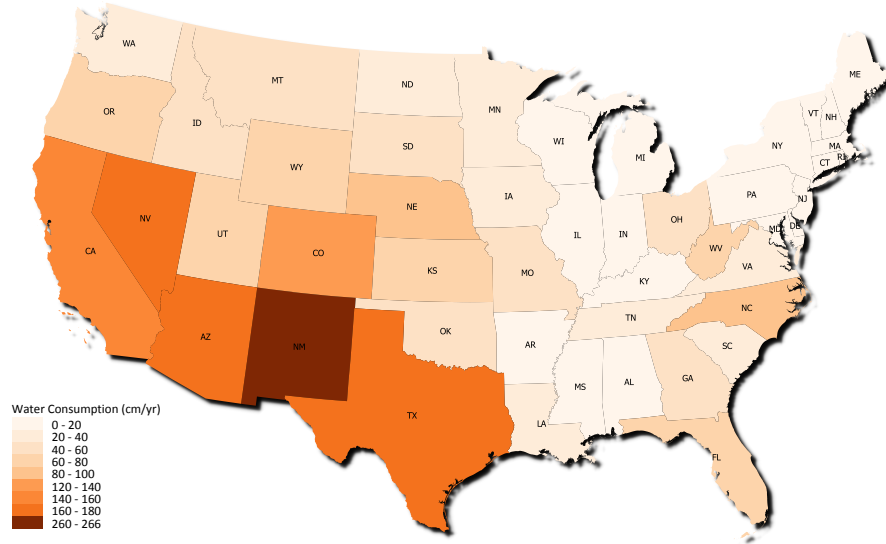


Figure 3. State-level Annual Water Consumption due to Evaporation (cm/yr) in the United States

2.2.3 Data Sources and Data Processing

In order to estimate the water consumption from each hydropower reservoir, surface area data are needed. National Inventory of Dams (NID) listed by Army Corps of Engineers (2010) includes data for dams in the United States. The inventory has 8,119 dams in total, and lists the location, reservoir surface area, and purposes of each dam. The amount of consumed water from a reservoir can be simply calculated by multiplying the increment in surface area due to dam construction and the corresponding state-level water consumption (cm/yr) estimated above. It is assumed that the surface area before dam construction is negligible compared to the huge reservoir area so that the surface area data in the NID are directly used. Among the NID data, there are some dams with possibly wrong surface area, which have been corrected by incorporating other data sources as in Table 2.

Because the NID do not include power generation data, additional data need to be incorporated. US EPA (2015) publishes the Emissions & Generation Resource Integrated Database (eGRID) every year to provide information on GHG emissions associated with power generated in the United States. This includes information and data of each power plant such as capacity, types of power generation, plant location, and annual power generation. The eGRID includes a total of 1,365 hydropower plants which generated 270 TWh in 2012. In order to calculate the WCFs of hydropower dams, the two data sets—the NID and the eGRID—have been merged based on the names and the proximity of the plants calculated using the location information from each data set. After data processing, 85% of the dams in the United States that generate hydropower are matched between the NID and the eGRID data sets, and data of these 539 dams are used for WCF calculation. Figure 4 summarizes the data sources and the processes of calculating the hydropower WCF. Note that water consumption associated with dam construction is excluded in this analysis because it is negligible compared to the water consumption during operation (Mekonnen, Gerbens-Leenes, and Hoekstra 2015).

Table 2. List of Dams with Corrected Surface Area

	Power Generation (MWh) in 2012	Surface Area Corrected (acres)	
		From	To
Rovert Moses – Niagara ^a	13,373,029	0	1,900
Diablo ^b	935,630	0	910
Yale ^c	702,744	0	3,800
Thurmond Lake Dam ^d	310,391	0	71,100
Utah Power & Light – Cutler ^e	50,408	0	9,700
Lake Summit Dam ^f	19,953	0	290
Turner Shoals Dam ^d	10,999	0	438
Red Bridge Dam ^g	10,690	0	25
Zumbro Lake ^h	7,550	0	600
Sugarloaf ⁱ	5,195	0	780
Wachusett Reservoir Dam ^g	4,100	0	4,135
Chief Joseph Dam ^k	12,480,327	8,400	0
The Dalles Lock and Dam ^k	7,805,592	11,200	0
Lower Monumental Lock and Dam ^k	2,520,051	6,590	0
Lower Granite Lock and Dam ^k	2,417,376	8,900	0
Bonneville ^k	5,549,149	20,600	0
Little Goose Lock and Dam ^k	2,302,381	10,025	0
John Day Dam ^k	10,445,910	55,000	0
McNary Lock and Dam ^k	5,803,559	38,800	0
Lay ^k	349,824	13,700	0

^a New York Power Authority (2016)^b National Park Service (2011)^c Federal Energy Regulatory Commission (2006)^d Lakes Online (2016)^e Audubon (2016)^f Lake Summit Property Owners Association (2016)^g Energy and Environmental Affairs (2016)^h Minnesota Department of Natural Resources (2016)ⁱ Recreation.gov (2016)^j USBR and USACE (2001)

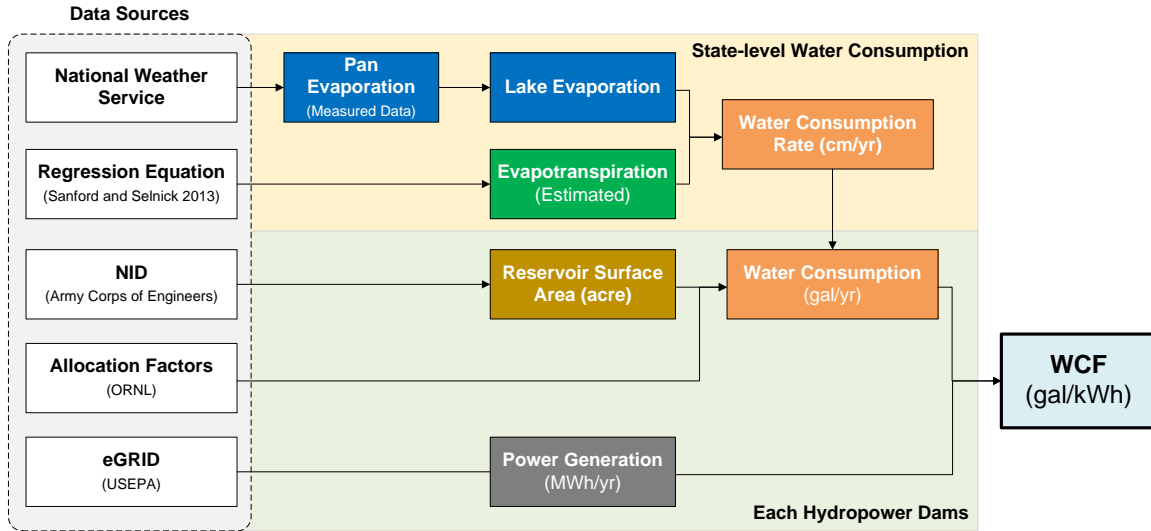


Figure 4. Data Sources and Calculation Processes of WCFs for Hydropower

2.2.4 Water Consumption Allocation in Multipurpose Hydropower Dams

When dams are built they are usually not designed to only generate electricity but also to serve other purposes (e.g., flood control, irrigation, and navigation). Also, there are many cases where hydropower systems are added to existing non-power generation dams to improve revenue (Hadjerioua, Wei, and Kao 2012). Therefore, it is not appropriate to allocate all of the water consumption solely to hydropower generation in these cases. The NID specifies the purposes of dams to include hydropower generation, irrigation, flood control, navigation, water supply, recreation, fire protection, fish and wildlife, debris control, and others. It has been found that hydropower is not a major purpose of dam construction. Among 8,119 dams in the NID, only 1,211 dams (15% by number) include hydropower as one of their purposes, which means the majority of dams and reservoirs serve purposes other than hydropower generation. Dams for hydropower alone (dedicated dams) are only 4% (298 dams) of the total number of dams, while the rest, 11% (913 dams) are multipurpose dams that serve other purposes while also generating electricity. There are some dams called ROR, which do not need reservoirs, but use natural river flow to generate electricity. Therefore, there is no water consumption caused by power generation from these dams, and they need to be separately classified along with dedicated (to hydropower) and multipurpose dams.

There have been discussions on allocation of water consumption to hydropower for multipurpose dams. IPCC commented that allocation schemes for multipurpose reservoirs can significantly influence the results (Edenhofer et al. 2011). However, Bakken et al. (2013) found only one study allocating water consumption to hydropower in a multipurpose dam among all previously published papers for the water footprint of hydropower. Pasqualetti and Kelley (2008) evaluated economic values of hydropower, recreation, agriculture, and municipal supply for Lake Powell Dam located on the border between Utah and Arizona. They allocated 55% of water consumption to hydropower based on the share of economic values of each purpose.

There are many allocation schemes in LCA studies, and proper approaches are chosen among energy allocation, volume or mass allocation, market value allocation, and displacement or substitution, depending on the types of main products, co-products, and by-products. However, it is difficult to apply the same schemes to multipurpose dams because often each purpose is vastly different from any of the other

purposes. Recently, Bakken et al. (2016) analyzed water consumption for four multipurpose hydropower dams in India, Egypt, and Spain using four different allocation methods – volume allocation, energy allocation, economic allocation, and explicit prioritizing. They concluded that volume allocation is the most robust approach citing that the economic allocation method may incur additional uncertainties. They also pointed that cost-efficient functions may take a higher burden than those generating the least benefits.

However, the volume allocation method also has several critical drawbacks. It might be straightforward to estimate the volume used for some purposes such as power generation, water supply, and irrigation because they have physically distinct volume usage. But it is subjective to use the same definition of “volume” for other purposes such as navigation, flood control, and recreation because of the volume for each of these purposes is not distinct. For these purposes, allocation varies significantly depending on the definition of the volume of water used for the specific purpose. For example, Bakken et al. (2016) used two totally different definitions of water volume for flood control. They used volumes available for storage of inflow for Aswan High Dam in Egypt as proposed by the International Commission of Large Dams, but for Mularroya Dam in Spain, they used 20% of the total storage capacity. Similarly, the volumes used for navigation and recreation purposes are difficult to evaluate since there is no consensus regarding the definitions of the volume for these purposes. Most of all, these approaches might fail to obtain national or state-level WCFs due to insufficient data on these volumes.

Oak Ridge National Laboratory (ORNL) recently collected data of hydropower dams from three agencies—The U.S. Bureau of Reclamation (USBR), The U.S. Army Corps of Engineers (USACE), and The Tennessee Valley Authority (TVA), which accounted for 42% of the total installed hydropower capacity in the United States. Based on the data, they quantified economic benefit for each purpose (Hadjerioua et al. 2015). Economic benefits indicate how dams are currently utilized, which makes it possible to compare the relative importance of each purpose in terms of monetized values. The economic benefit of hydropower over total economic benefits from all purposes can be regarded as the allocation factor of hydropower. This approach is less controversial considering that dams would be constructed only when there are demands, and people or municipalities are willing to pay for that.

Table 3 shows the allocation factors of hydropower based on the economic benefit evaluated by ORNL. They categorized allocation factors in terms of hydropower capacity and the number of purposes. The values indicate relative burdens that hydropower needs to take, which vary from zero to one. One means that water consumption from reservoirs is totally allocated to hydropower, while zero represents there is no water consumption by hydropower generation. Table 3 shows that the higher the number of purposes, the fewer burdens to hydropower because the burdens are shared by other purposes. Reservoirs with four or more purposes are classified into one category because additional purposes may not have significant impacts and the ORNL’s report showed slight disproportion for the dams with five purposes.

In general, hydropower dams with high capacity tend to have higher allocation factors than low and mid-size capacity hydropower dams. It is mainly because the revenue from power generation is dominant for high capacity hydropower dams. Also, for dams with low to mid-size capacity, recreation tends to have high economic benefits because those dams are more likely to be located near metropolitan areas than massive hydropower dams. The revenue of recreation takes the majority of the evaporation burden, which explains why hydropower in low and mid-capacity dams have low allocation factors. Using the allocation factors in Table 3, water consumption for hydropower generation in each multipurpose reservoir is calculated. It should be noted that the dams with a capacity greater than 500 MW generated more than a half of hydroelectricity in 2012, and they are dominant for determining overall allocation factors.

Table 3. Allocation Factors of Hydropower Based on Economic Benefits (Hadjerioua et al. 2015)

Capacity (MW)	Number of purposes			
	1	2	3	4 or more
<100	1.000	0.444	0.171	0.130
100~500	1.000	0.545	0.264	0.196
>500	1.000	0.973	0.594	0.131

2.3 WCFs of Thermoelectricity Generation

2.3.1 Water Consumption in Thermal Power Plants

National Renewable Energy Laboratory (NREL) evaluated national water consumptions for thermoelectricity generation in the United States as 0.47 gal/kWh in 2003, using a USGS's water consumption estimates and EIA's net power generation data (Torcellini et al. 2003). Later, NREL collected WCFs by power generation technologies from the literature (Macknick et al. 2011), but the reported values may not be representative of the average WCF for the examined categories because each group included only a small sample. USGS also estimated water use at thermoelectric plants using linked heat and water budgets models, and the results were compared to EIA-reported water use (Diehl and Harris 2014; Diehl et al. 2013). To avoid uncertainties of reported estimates, they calculated evaporation from reported energy budget. These studies, however, have not evaluated the WCFs for electricity generation by region.

Power generation in thermal power plants mainly converts thermal energy input (heat) into electricity. Most thermal power plants use water to generate steam, which operates turbines to produce electricity. While the heat for boiling water can be obtained from various sources such as fossil fuel combustion or nuclear reaction, the concepts of generating thermoelectricity are basically the same regardless of energy sources. Once the steam is exhausted from the turbine, it is condensed and recirculated to the boiler. Cooling water is typically used to dissipate the waste heat from the turbine exhaust in the condenser.

Water evaporation per unit power generation due to cooling mainly depends on the power plant energy efficiency and employed cooling technology. According to the second law of thermodynamics for heat engines, only a portion of heat input from fuel combustion is converted into electricity in thermal power plants, while the rest has to be rejected, which is largely determined by the plant energy efficiency. Thus, the amount of heat rejected per unit power generation can be calculated using the plant energy efficiency. For cooling technologies that employ water to reject heat to the environment, the amount of heat rejected to the water is a direct function of the energy conversion efficiency. Note that, prime movers employing steam turbine and combined cycle have different energy efficiencies. The combined cycles typically have much higher energy conversion efficiency than steam turbine cycles, and thus reject less heat to the environment.

Given the amount of heat to be dissipated, water consumption varies depending on types of cooling technologies. There are three major cooling technologies – once-through (or single-loop), recirculating (or closed-loop), and dry cooling. Some power plants may use two or more types of cooling technologies. The once-through cooling takes a large amount of water from a near water body, and the cooling water goes through heat exchangers to cool down and condense the hot steam exiting from turbines. The heated cooling water is then discharged to the water body usually back to its withdrawn source. The discharging cooling water temperature is slightly higher than that of the withdrawal due to the large heat capacity and flow rate

of cooling water, which leads to negligible amount of water evaporation during the cooling process. On the other hand, the recirculating cooling system has a closed-loop which circulates a relatively smaller amount of cooling water. The recirculating cooling system uses towers (natural or mechanical draft cooling tower) or ponds to dissipate the heat absorbed in the condenser by evaporating a portion of the cooling water to the atmosphere. The deficiency due to the evaporation is compensated by withdrawing “makeup” water. In other words, the once-through cooling system dissipates the heat through a small increase in the temperature of cooling water, while the recirculating cooling system experiences large increase in water temperature that is released to the environment through a subsequent evaporation process that involves phase change of cooling water and results in significant water loss or consumption. Dry cooling technologies use air instead of water to cool the steam, which does not include any water consumption but usually incur higher energy and economic burdens.

Figure 5 shows how the trend of the cooling technologies employed in thermal power plants varied over time. This classifies 1,560 cooling systems that are operational in 2014 based on the starting year of service (EIA 2015a). It shows dominance of recirculating cooling systems starting mid-1970s, with large reduction in installations of once-through cooling systems. According to Mielke et al. (2010), the relative capital cost for recirculating and dry cooling are 1.5 and 9.6 times higher compared to the once-through cooling. Once-through cooling technology was dominant in the beginning because power plants had an easy access to use a large amount of cooling water. The trend has changed because of awareness and concerns over thermal pollution caused by heated effluent of once-through cooling systems that threatened aquatic ecosystems. In 1972, Section 316(b) of the federal Clean Water Act (CWA) was enacted, requiring that cooling systems reflect the best technology available (BTA) to minimize environmental impact. However, it was reversed in 1977, and for about 20 years state authorities issued permits on a case-by-case basis. In 1995, EPA entered into a consent decree, and regulations were phased in starting 2001, which identified recirculating cooling in general as the BTA for new facilities. These historical regulation changes explain the trend in Figure 5.

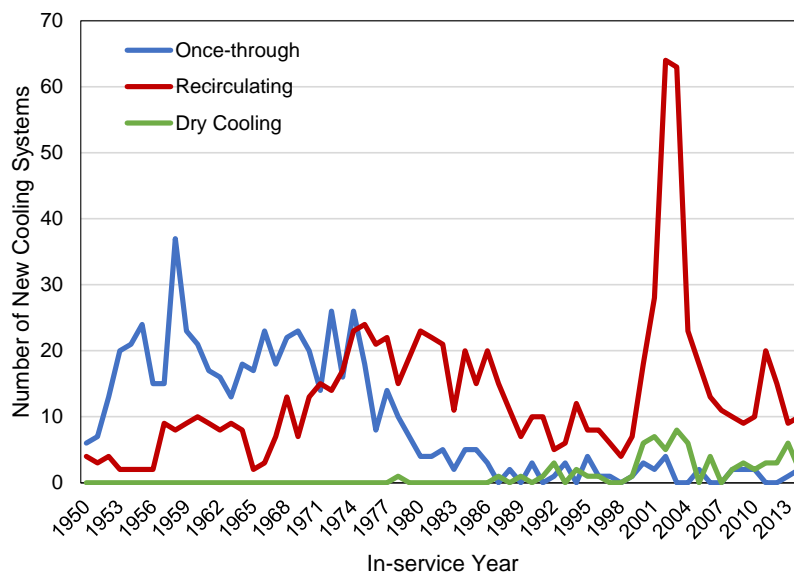


Figure 5. Number of New Cooling Systems with respect to In-service Year for Various Cooling Technologies Employed by Systems that are Operational in 2014 (Data from EIA-860)

Although the regulations led the changes in cooling system technology installations, there were still many power plants with once-through cooling technology because the BTA does not restrict it to a recirculating cooling technology. Existing plants are required to equip cooling systems that achieve environmental protection of aquatic species, equivalent to recirculating cooling. Based on EIA-860, the recirculating cooling system is dominant for most southern and western states, while northern and eastern states use of once-through is more prevalent. The differences in the use of cooling technologies by region result in differences in their water use for power generation.

For the once-through cooling systems, the difference between the withdrawal and the discharge is regarded as water consumption. Though the discharged water is not reused at a facility-level, it can be used downstream of the power plant because no significant degradation of the water quality is incurred during heat exchange process. There might be small increase in loss of water to evaporation after the cooling water is returned to the water body due to increased temperature, but it is assumed to be negligible. It should be noted that there are some once-through cooling systems with cooling towers or ponds. They cool down the discharge to minimize environmental thermal impacts. In this case, the water consumption can be estimated in the same manner of the once-through cooling system without cooling towers or ponds. For recirculating cooling with a cooling tower, the system withdraws a small amount of makeup water to compensate for the water loss due to evaporation. Similarly, the recirculating cooling systems with ponds withdraw makeup water from near water body to maintain the water level of the cooling ponds. Therefore, the makeup water can be regarded as water consumption for the recirculating cooling.

2.3.2 Data Sources and Data Processing

First, water consumption at the facility-level has been examined. EIA-923 (EIA 2015b) includes data of power generation technologies, cooling technologies, water withdrawal and water consumption along with other general information on the power plants. EIA-860 (EIA 2015a) includes information regarding cooling tower and cooling ponds. Because EIA-923 does not specify whether or not once through cooling employs cooling towers, EIA-860 is used to reclassify power plants with once-through cooling technology.

The original EIA data includes a total of 3,380 thermal power plants, which produced 3,600 TWh in 2014. The data are processed for the analysis as summarized in Table 4. Data used in this analysis covers 63% of power generation by the thermal power plants in EIA-923. Major data rejections are data with incomplete information regarding the type of employed cooling technology. In order to investigate the WCF associated with a specific cooling technology and prime mover, plants with multiple cooling technology options cannot be used, and are therefore eliminated. Additionally, cooling systems of 15 power plants needed reclassification, mostly by adding a category of once-through cooling that uses cooling tower, which is not listed in EIA-923. With the help of EIA-860, 11 power plants are categorized into once-through with a tower, while four misplaced plants are re-categorized after a careful investigation.

After the data processing, power plants are classified into six categories based on cooling technologies and prime movers: (1) once-through cooling without a pond or a tower, (2) cooling with a pond (steam turbine), (3) cooling with a pond (combined cycle), (4) cooling with a tower (steam turbine), (5) cooling with a tower (combined cycle), and (6) dry cooling. For once-through cooling without a pond or a tower, steam turbine and combined cycle power plants are classified in the same category because there is minor difference between them with respect to negligible water consumption. The once-through cooling systems with a pond or a tower have water consumption similar to recirculating cooling technology. Overall,

cooling water consumption depends on targeted cooling temperature; this is true for a cooling pond or a cooling tower. Because there are only few plants with once-through using a pond or a tower, and they all have similar level of water consumption, they are aggregated with the recirculating cooling systems.

Table 4. Data Processing (EIA-923)

	Number of thermal power plants	Power generation in 2014 (TWh)
Original data	3,380	3,600
Data eliminated		
- Plants without cooling technology information	2,510	237
- Plants with multiple cooling technologies	64	309
- Plants with multiple prime movers	198	546
- Erroneous data	59	234
Data used for analysis	549 (16%)	2,274 (63%)

2.3.3 Non-freshwater Use

In order to meet the cooling water demands in a limited water availability environment, alternative water sources are considered. Thermal power plants do not necessarily have to use high-quality freshwater for cooling purposes. The processed data show that many plants, which contribute 21% of the total reported power generation, utilize non-freshwater (i.e., reclaimed water, brackish water, and saline water) for cooling. Using non-freshwater leads to some technical design and operational issues such as corrosion, scaling, and biofouling, which may require additional pretreatment to mitigate these challenges (Stillwell and Webber 2014; Satpathy et al. 2010). However, these measures cost about 1–2% of electricity revenue (Walker et al. 2012), while the economic feasibility largely depends on the distance between power plants and the water sources, as well as the price of water when applicable (Stillwell and Webber 2014).

Based on the earlier definition of water consumption, thermoelectric power plants using reclaimed water, brackish water, and saline water have zero fresh water consumption. It is expected that these resources can reduce freshwater consumption significantly. Figure 6 shows the locations of power plants which use non-freshwater for cooling, while the relative size of circles in the figure indicates amount of power generation. Figure 6 shows that these power plants are mostly located along the coast due to easy access to seawater. However, there are some inland power plants that use reclaimed water, especially where freshwater resources are not sufficient.

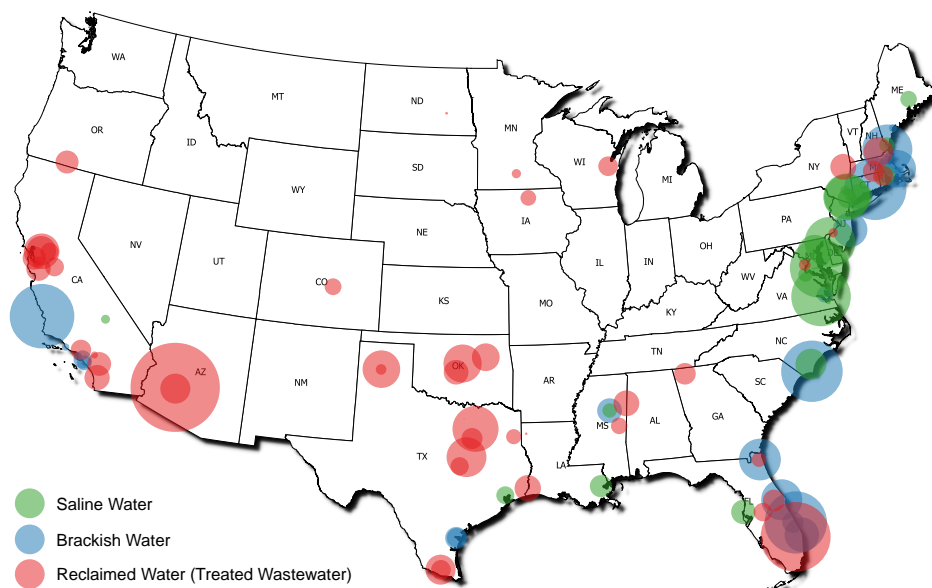


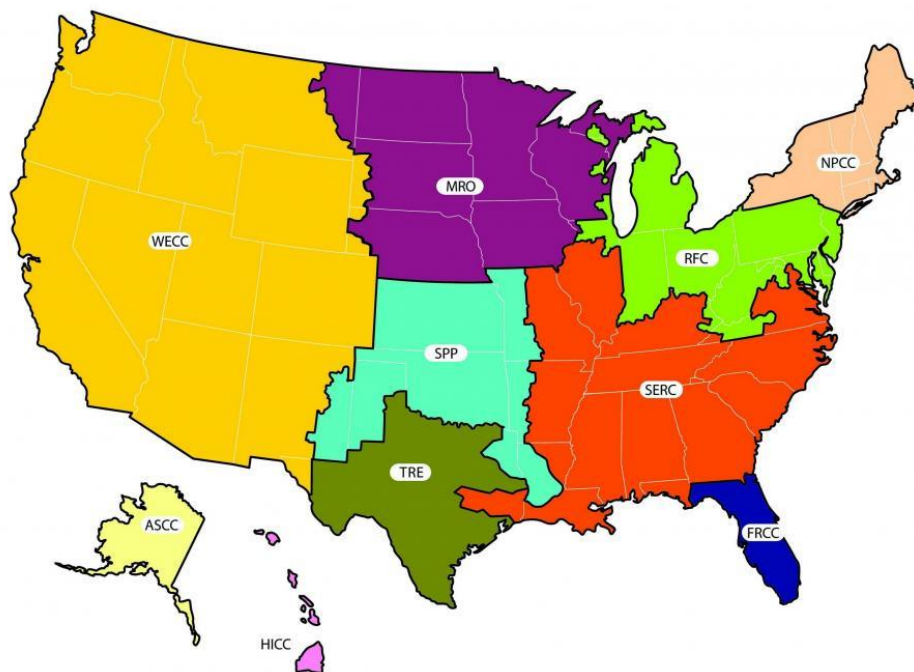
Figure 6. Power Generation using Cooling Water from Reclaimed Water, Brackish Water, and Saline Water

2.3.4 Regional Analysis

Electricity can be generated through various pathways; it may be generated from fossil or nuclear sources, or through the conversion of water potential energy, solar, and wind energy. Because each region has different electricity generation mix, electricity generation in the different region has different environmental impacts. In the United States, the North American Electric Reliability Council (NERC) utility regions typically represent bulk-power systems that are interconnected facilities and systems for electricity energy transmission network and system reliability (16 US Code 8240) as shown in Figure 7. Therefore, it is of interest to examine the WCFs for power generation by NERC region. There are eight regional entities: (1) Midwest Reliability Organization (MRO), (2) Northeast Power Coordinating Council (NPCC), (3) Reliability First Corporation (RFC), (4) SERC Reliability Corporation (SERC), (5) Southwest Power Pool, RE (SPP), (6) Western Electricity Coordinating Council (WECC), (7) Florida Reliability Coordinating Council (FRCC), and (8) Texas Reliability Entity (TRE).

It is expected that there are differences in water consumption in power plants by region, mainly caused by different types of cooling systems and prime movers. Figure 8 shows the power generation share by types of cooling technologies and prime movers for each NERC region. The WECC region, where water availability is a major concern, mostly uses recirculating cooling systems.

The WCFs by NERC region can be estimated using two methods. First, the WCFs by cooling technologies and prime movers can be estimated using the cooling technology shares for that region as shown in Figure 8. However, when the actual water consumption and power generation data are available by regional units, the WCFs can be calculated more accurately. Where data are available, the WCFs from the actual values are used by default.



This is a representational map; many of the boundaries shown on this map are approximate because they are based on companies, not on strictly geographical boundaries.
USEPA eGRID2010 Version 1.0 December 2010

Figure 7. Geographic Coverage of NERC Region (US EPA 2016)

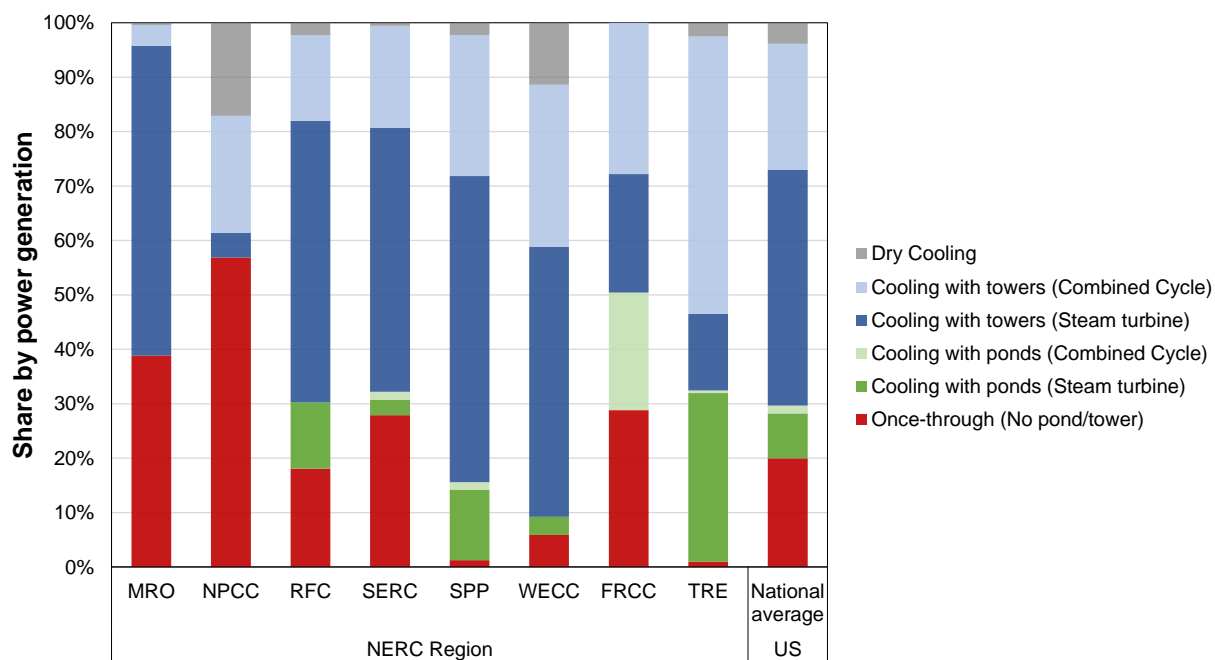


Figure 8. Power Generation Share by Cooling Technology for each NERC Region

3 Results and Discussions

3.1 WCFs of Hydroelectricity

Table 5 shows the national weighted average WCF for hydroelectricity in the United States, which is 4.4 gal/kWh. As mentioned earlier, ROR dams do not have reservoirs, which incur zero water consumption. There is a total of 15 ROR dams contributing about 22% of total hydropower generation, and these dams reduce the national WCF by generating power without water consumption. Dedicated dams consume 150 million gallons of water to support 11% of U.S. hydropower generation, which results in the WCF for 5.7 gal/kWh. Multipurpose dams contribute 66% of total hydropower generation while contributing 96% of total water consumption. If hydropower receives all of the water consumption burdens (i.e., none of the other purposes receive any burden), the WCF for hydropower generation from multipurpose dams is estimated at 24.4 gal/kWh. This is 4.3 times higher compared to dedicated dams.

When the allocation factors from ORNL are applied to individual multipurpose dams, and are subsequently aggregated to the national level, hydropower becomes only responsible for 24% of water consumed in multipurpose reservoirs. This leads to a WCF for multipurpose dams of 5.7 gal/kWh. It is interesting to note that the allocated WCF for multipurpose dams is equal to the WCF for dedicated dams, suggesting that WCF for dedicated dams can be used as a surrogate for WCF of multipurpose dams, especially when allocation data are not available.

Table 5. National Average WCF for Hydroelectricity in the United States

	No. of dams	Power Generation (TWh)	Total Water Consumption (million gals)	Allocated Water Consumption (million gals)	WCF (gal/kWh)	Allocated WCF (gal/kWh)
ROR	15	50.6	0	0	0	0
Dedicated	128	26.4	150	150	5.7	5.7
Multipurpose	396	153.0	3,731	869	24.4	5.7
Total	539	230.1	3,880	1,018	16.9	4.4

In Figure 9, the hydropower WCFs at the state-level are presented. The red circles indicate locations of hydropower generation, while the relative size of the circles shows annual hydropower generation. The figure indicates that WCFs in the southern states are much higher compared to those in the northern states, consistent with water evaporation data in Figure 3. We note that the scale associated with WCF in Figure 8 is not linear, mainly to accommodate the large variation in WCF between states. The magnitude of the WCFs of most southern states is much higher compared to northern states, even when considering the high water consumption rates in these states shown in Figure 3. This implies that the high WCFs in the southern states is not entirely attributed to the climate conditions in these states.

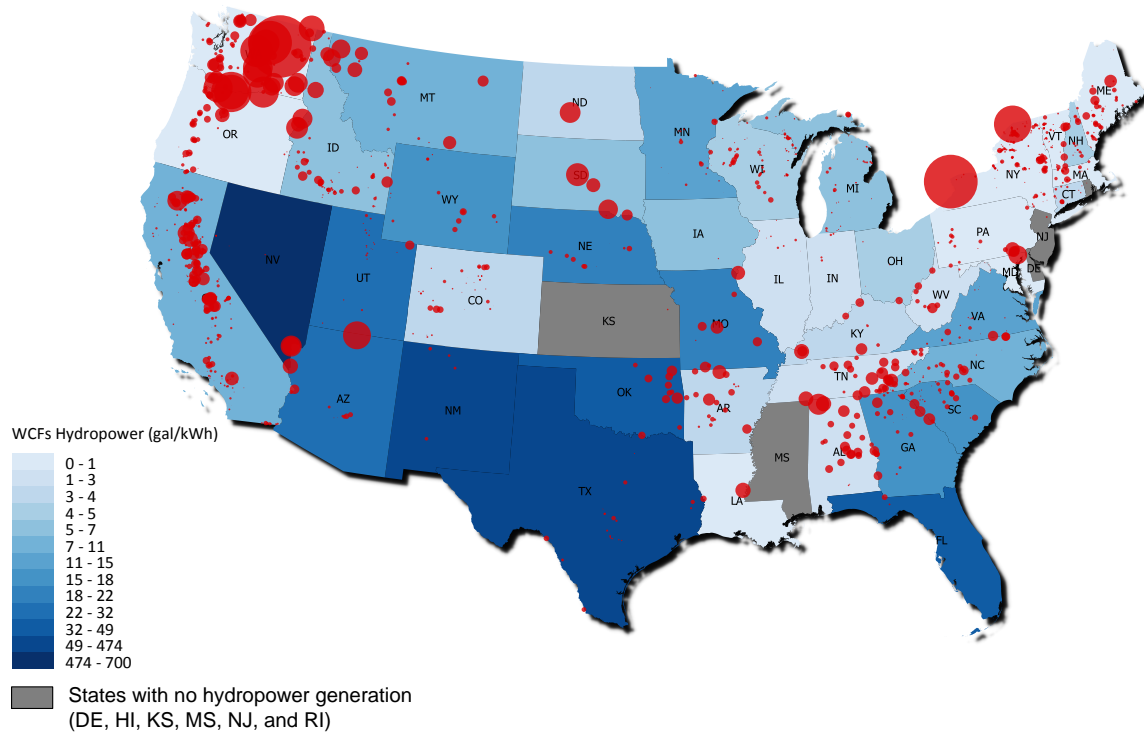


Figure 9. Hydropower Generation and WCFs by State (gal/kWh)

Water consumed in hydropower plants mainly depends on climate conditions as earlier discussed. In addition to that, a capacity factor is an important parameter which influences the WCFs of hydropower plants. Water consumption in hydropower is not directly related to power generation, but rather it is related to water storage. Because annual water consumption is determined by climate conditions and reservoir surface area, water consumption from a reservoir is independent of whether or not power is generated.

Capacity factor represents actual power generation as a percentage of capacity of power generation, which is a measure of actual generated electricity from hydropower plant compared to its potential capacity. Thus the capacity factor value varies on a scale from zero to one; where one represents continuous operation at maximum generation output throughout the year, while zero means there is no generation throughout the year. Figure 10 shows state weight averaged capacity factors of the hydropower dams. It shows that, in general, southern states have relatively lower capacity factors compared other regions, which combined with the high water evaporation rates in these states represent the major factors impacting the large variation in the WCFs between states, previously shown in Figure 9. Possible reasons for the large variation in hydropower capacity factor by region include differences in hydrologic conditions and water demands for competing uses (Uría-Martínez, O'Connor, and Johnson 2015). However, investigating the variation of capacity factor is beyond the scope of this study.

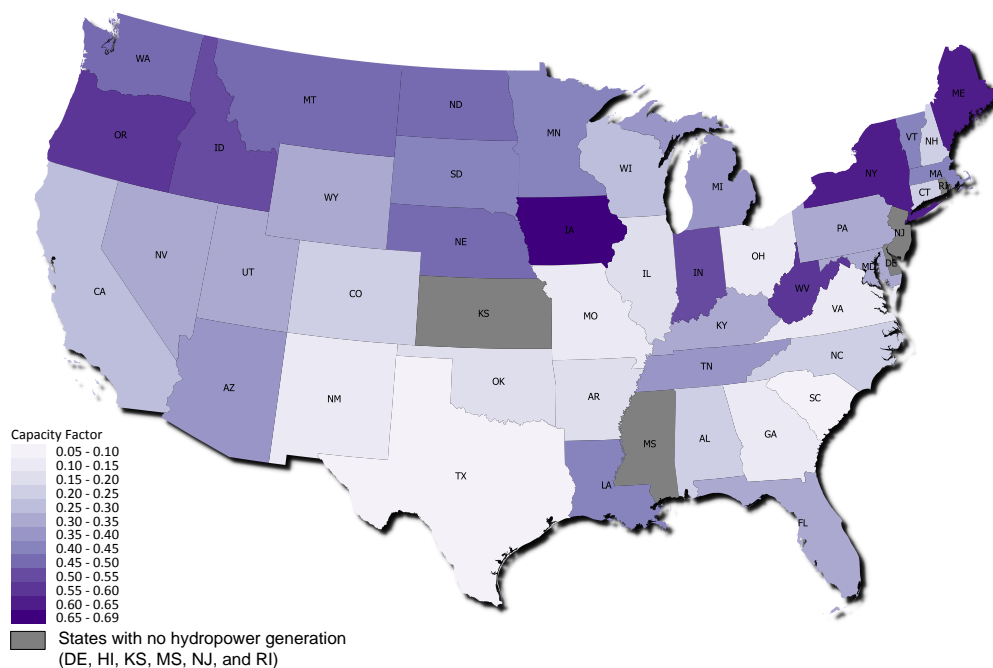


Figure 10. Capacity Factors of Hydroelectric Plants by State

Figure 11 shows the WCFs of hydroelectricity by NERC region. The light blue bars indicate the WCFs for hydroelectricity, while the light gray bars represent water consumption allocated to all other purposes. Similar to state-level data, Figure 10 shows that WCF for hydropower varies significantly by NERC region. In particular, the WCFs for TRE and FRCC are much higher at 315 and 48 gal/kWh, respectively, compared to other NERC regions. This is because these regions cover southern states where water evaporation rates are high, and capacity factors are low.

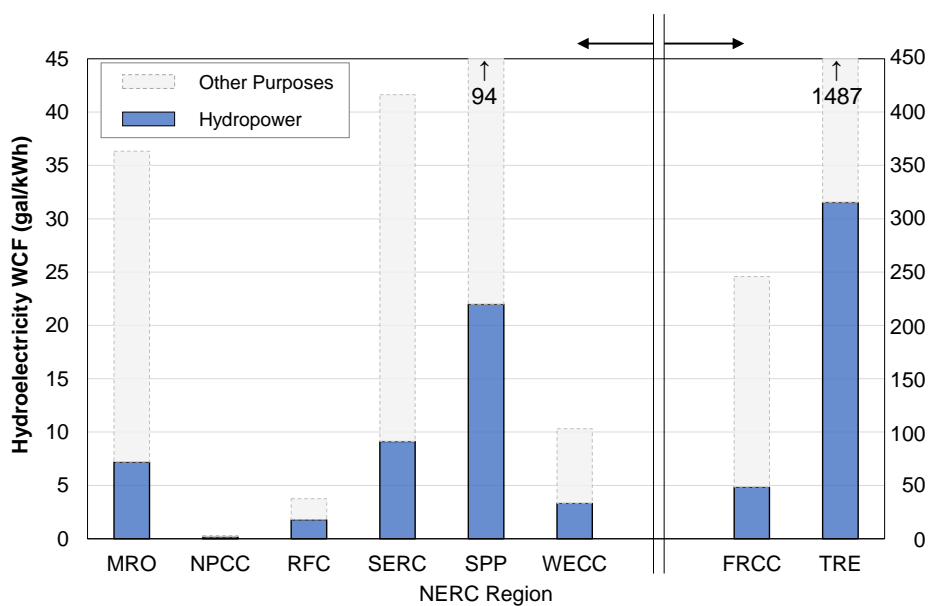


Figure 11. WCFs for Hydropower by NERC Region

3.2 WCFs of Thermoelectricity

3.2.1 WCFs by Cooling Technologies and Prime Movers

Figure 12 shows the weighted average WCFs of six thermoelectricity generation categories based on their cooling technologies and prime movers. Each WCF is calculated from total water consumption divided by total power generation. The error bars indicate the distribution of WCF for each prime mover/cooling technology combination, while the corresponding low end and the high end represent 25% and 75% percentile, respectively. For the dry cooling and the once-through cooling without ponds and towers, both the low end and the high end are all zero WCFs, which is why the error bars are not shown. The gray bars indicate non-freshwater use which contribute power generation without water consumption.

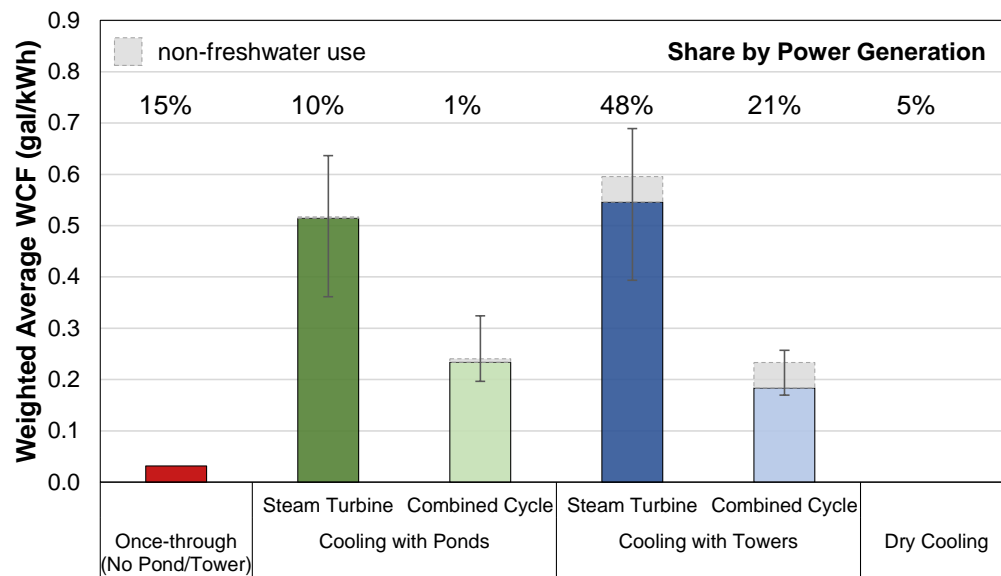


Figure 12. WCFs by Cooling Technology and Prime Mover

First, we investigate the WCFs of thermoelectricity by prime movers. The power generation energy efficiencies for conventional steam turbine and combined cycle plants are approximately 33% and 50%, respectively. As mentioned earlier, thermal energy to be rejected per unit power generated mainly depends on the power plant energy efficiency. Higher energy efficiency implies less waste energy, and thus less cooling demand and less evaporation losses, and also implies increased power generation output. Combined, less evaporation losses and more generated electricity work in the same direction of decreasing WCF. Figure 12 shows this trend. For the recirculating cooling, WCF is not significantly impacted by whether cooling ponds or cooling towers are employed as long as the prime mover is the same. For steam turbine power plants, the WCFs are estimated at 0.52 and 0.60 gal/kWh for cooling with a pond and cooling with a tower, respectively, while the WCFs for combined cycle plants are estimated at 0.24 and 0.23 gal/kWh, for cooling with a pond and cooling with a tower, respectively.

Once-through cooling systems result in negligible water consumption, and most power plants equipped the once-through cooling without ponds or towers usually report zero water consumption.

However, 17 among 125 power plants in this category specified water consumption, which is why the WCF for the once-through cooling is 0.03 gal/kWh, not exactly zero.

Note that, among power plants using non-freshwater in Figure 6, around 42% of their power generation use once-through cooling without pond/tower. From a water consumption point of view, there is no gain of using non-freshwater for these facilities because the WCF for the once-through without pond/tower is negligible. On the other hand, power plants with a cooling tower or a pond reduce freshwater consumption by the amount of non-freshwater use. Despite the fact that the recirculating systems consume more water than the once-through cooling systems, it is inevitable to avoid shifting from once-through to other types of cooling technologies due to regulations. Given this fact for granted, water consumption can be reduced by increasing the efficiency of the power plants, or by using non-freshwater resources.

3.2.2 WCFs of Thermoelectricity by Region

Table 6 shows the aggregated water consumption and the power generation in thermal power plants in the United States. The data used for this aggregation are based on data in Table 4. Table 6 shows that power plants using freshwater for cooling represent 79% of total power generation, while dry cooling and cooling with non-freshwater shares are 4% and 17%, respectively. When considering power generation technologies that use only freshwater for cooling, their aggregate average WCF is estimated at 0.42 gal/kWh. However, when dividing the annual fresh water consumption by the total annual power generation (using freshwater and non-freshwater), the national average WCF for thermoelectricity becomes 0.33 gal/kWh. Note that the WCF for power generation that uses cooling with non-freshwater is estimated at 0.20 gal/kWh, which is mainly because of large use of once-through cooling along the coastline.

Table 6. National Average WCF for Thermoelectricity in the United States

	No. of Plants	Power Generation (TWh)	Water Consumption (billion gallons)	WCF (gal/kWh)
Cooling with freshwater	403	1,806 (79%)	756	0.42
Dry cooling	36	87 (4%)	0	0
Cooling with non-freshwater	110	380 (17%)	76 ^a	0.20 ^a
Overall	549	2,274	756 ^b	0.33 ^b

^a non-freshwater use

^b freshwater use only

Figure 13 shows the regional differences in the WCFs of thermoelectricity by NERC region. The main driver for these differences is the power generation technology shares in each region, provided in Figure 8. The regions with high recirculating cooling share have higher WCF. For example, SPP has only 1.3% of once-through cooling without pond/tower by power generation, which is the lowest share of that cooling technology among all NERC regions. Consequently, SPP has the highest WCF among all NERC regions at 0.58 gal/kWh, without considering the gain in WCF from non-freshwater use. On the contrary,

NPCC has the highest share of once-through cooling without pond/tower, 57%, and thus has the lowest WCF at 0.07 gal/kWh. Non-freshwater use reduces the WCF, especially for the regions located along the coastline such as WECC and FRCC.

Table 7 shows the thermoelectricity WCFs by NERC region as calculated from the technology shares in Figure 8 and the WCFs in Figure 12.

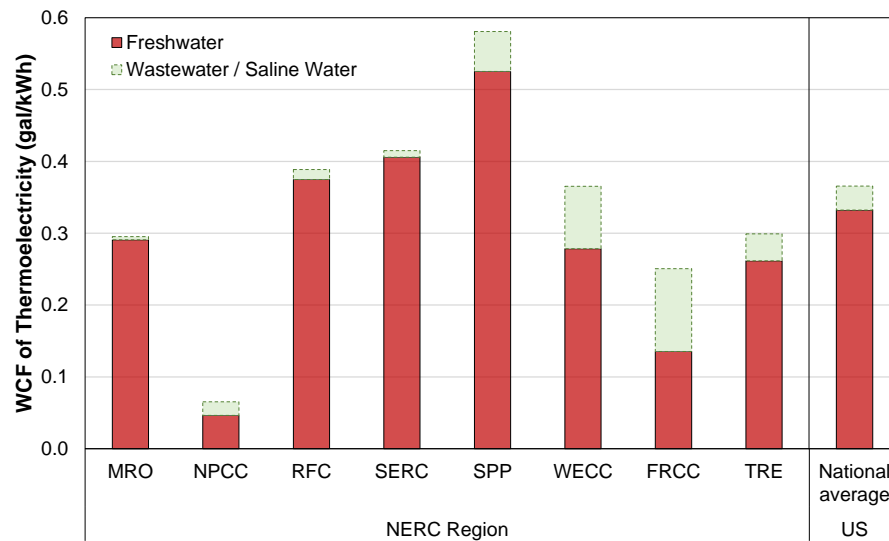


Figure 13. WCF for Thermoelectricity by NERC Region Calculated from Actual Water Use and Power Generation Data

Table 7. WCF for Thermoelectricity by NERC Region Calculated from Technology Shares

	MRO	NPCC	RFC	SERC	SPP	WECC	FRCC	TRE	US
Steam Turbine									
Once-through no pond/tower	39%	92%	21%	35%	2%	10%	43%	1%	27%
Cooling with a pond	0%	0%	15%	4%	18%	6%	0%	68%	12%
Cooling with a tower	61%	8%	63%	61%	80%	82%	57%	31%	61%
Dry cooling	0%	0%	1%	0%	0%	3%	0%	0%	1%
Combined Cycle									
Once-through no pond/tower	33%	8%	4%	0%	0%	0%	20%	1%	4%
Cooling with a pond	0%	0%	0%	7%	0%	0%	35%	1%	5%
Cooling with a tower	61%	51%	87%	90%	92%	76%	45%	93%	80%
Dry cooling	6%	41%	9%	3%	8%	24%	0%	5%	12%
Thermoelectricity WCF (gal/kWh)									
Steam turbine	0.34	0.07	0.43	0.36	0.53	0.48	0.32	0.52	0.40
Combined cycle	0.12	0.10	0.16	0.18	0.17	0.14	0.17	0.17	0.16

3.3 WCFs for Electricity Generation

In order to calculate the WCF for total electricity generation, including thermos- and hydro-power generation, the overall electricity generation technology mix should be considered. Table 8 shows the electricity generation mix by NERC region in 2015 (EIA 2016). The WCFs of geothermal, wind, and solar PV are set at 1.2, 0.001, and 0.045 gal/kWh, respectively (Lampert et al. 2015).

Table 8. Electricity Generation Mix by NERC Region in 2015 (EIA 2016)

		Thermo-electricity	Hydropower	Geothermal	Wind	Solar PV
NERC	MRO	77%	5.2%	0%	18%	0%
	NPCC	83%	13%	0%	2%	0%
	RFC	96%	1.1%	0%	2%	0%
	SERC	96%	3.4%	0%	0%	0%
	SPP	82%	1.8%	0%	15%	0%
	WECC	66%	22%	2%	7%	3%
	FRCC	98%	0.7%	0%	0%	0%
	TRE	90%	0.2%	0%	10%	0%
US national average		87%	6.3%	0%	5%	1%

Figure 14 represents the overall electricity WCFs by NERC region, which is calculated by multiplying the WCF for each generation type and the power generation share in the region. Due to its high WCFs, hydropower generation significantly influences the overall WCFs despite its small power share. In the United States, the aggregate average WCF for electricity generation is estimated at 0.58 gal/kWh, with thermoelectricity and hydropower generation equally contributing to that WCF as shown in Figure 13. Note that most hydroelectricity is generated where WCFs are low as shown in Figure 9. For TRE and FRCC with much higher hydropower WCFs, their impact on WCF at the NERC regional level is limited due to the small hydropower shares in these regions (0.3% and 0.7% for TRE and FRCC, respectively).

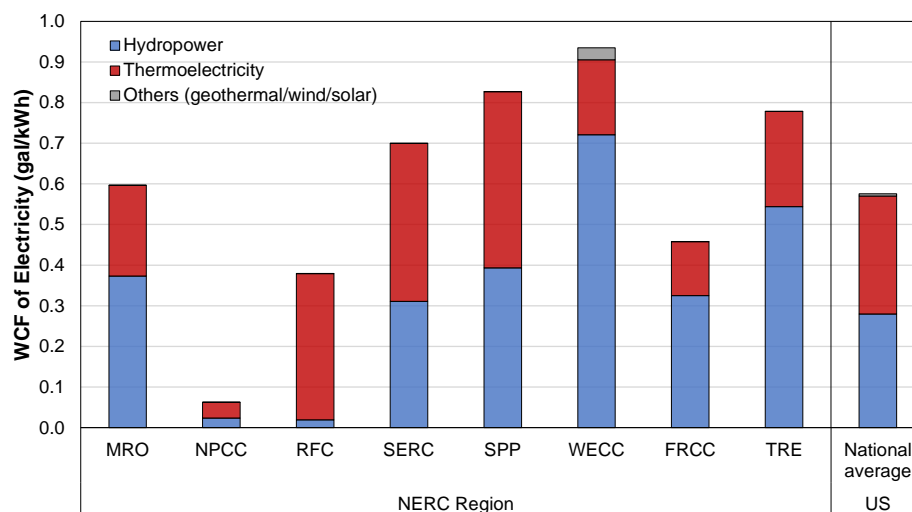


Figure 14. WCFs (gal/kWh) for Electricity Generation by NERC Region

4 Conclusions

In this study, the WCFs for electricity generation have been investigated. Water is critically important for thermal power and hydropower generation, and they require large amount of water for their operation. It has been found that WCF varies significantly by power generation technology, cooling technology, and by region.

Our analysis estimated the national average WCF for electricity generation at 0.58 gal/kWh, with equal contribution from thermoelectricity and hydropower generation, despite the much smaller share of hydropower generation in the national average generation mix. In 2015, the thermoelectricity and hydropower generation contribute 87% and 6.3% of total electricity generated in the United States, respectively. The national average WCF for thermoelectricity generation is estimated at 0.33 gal/kWh, while the corresponding WCF for hydropower generation is 4.4 gal/kWh.

For thermal power plants, the historic use of cooling technologies trends from once-through to recirculating due to regulations of discharging water temperature. Considering that the recirculating cooling involves higher water consumption compared to once-through cooling, alternative ways of cooling should be considered. Dry cooling and non-freshwater are alternatives to the conventional cooling technologies as they do not involve freshwater consumption for power generation. While hydropower is regarded as non-polluting generation technology, it may result in significant water loss to evaporation if reservoirs are employed, especially in regions where evaporation rates are high and the generation capacity factor is low. In this study, increasing the number of purposes served by a dam/reservoir results in reduced water consumption burden on hydropower by allocating a portion of the water evaporation to the other purposes. However, the allocation method is a source of uncertainty and requires further investigation.

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