Regional water consumption for hydro and thermal electricity generation in the United States

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HIGHLIGHTS

- Regional water consumption for electricity generation in the US is evaluated.
- Water consumed for thermoelectricity depends on plant efficiency and cooling system.
- Water consumed by multipurpose dams is allocated by each purpose's economic benefits.
- Water evaporation from hydropower reservoirs varies by region significantly.

ARTICLE INFO

ABSTRACT

Water is an essential resource for most electric power generation technologies. Thermal power plants typically require a large amount of cooling water whose evaporation is regarded to be consumed. Hydropower plants result in evaporative water loss from the large surface areas of the storing reservoirs. This study estimated the regional water consumption factors (WCFs) for thermal and hydro electricity generation in the United States, because the WCFs of these power plants vary by region and water supply and demand balance are of concern in many regions. For hydropower, total WCFs were calculated using a reservoir's surface area, state-level water evaporation, and background evapotranspiration. Then, for a multipurpose reservoir, a fraction of its WCF was allocated to hydropower generation based on the share of the economic valuation of hydroelectricity among benefits from all purposes of the reservoir. For thermal power plants, the variations in WCFs by type of cooling technology, prime mover technology, and by region were addressed. The results show that WCFs for electricity generation vary significantly by region. The generation-weighted average WCFs of thermoelectricity and hydropower are 1.25 (range of 0.18–2.0) and 16.8 (range of 0.67–1194) L/kWh, respectively, and the generation-weighted average WCF by the U.S. generation mix in 2015 is estimated at 2.18 L/kWh.

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1. Introduction

Demand for freshwater grows rapidly with population growth for agriculture, municipal use, and power generation [1]. On the other hand, it is expected that freshwater availability would steadily decrease [2], and climate change may deteriorate the situation even further [3,4]. Therefore, competition over water resources among various demands may result in stressing these resources in world regions.

One of the major water demands is energy production [5]. Many energy production technologies require a significant amount of

cooling and process water (e.g., steam). Also, biomass farming for biofuels (e.g., corn and soybean) requires irrigation in some regions. Hydropower generation requires a large storage reservoir, which loses a large amount of water to evaporation. Demand for energy is expected to grow in the future due to increases in population and energy use per capita [6]. Thus, water consumption to satisfy the growing demand for energy will increase, unless the freshwater consumption of water-intensive energy technologies is lowered substantially.

Two terms are commonly used to refer to water use in a given process—water withdrawal and water consumption. Water withdrawal represents the amount of water uptake from a surface or groundwater source. Water consumption, however, refers to the amount of water that becomes unavailable for other uses in the same water resource in a region. For example, water discharged from facilities is not considered to be consumed, since it is usually

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treated and becomes available for future use in the same region. Generally, there are three major causes of water consumption: evaporation, incorporation into products, and degradation to a quality not appropriate for future use [7]. While water is one of the most abundant resources on the earth, available water generally refers only to freshwater, because freshwater is a limited resource and can be directly used for various purposes for the survival of humanity. In this study, only the consumption of freshwater was considered, and a water consumption factor (WCF), defined as freshwater consumption per unit of a functional unit (e.g., L/kWh, if electricity is generated), was used. Thus, saline and brackish water use were excluded from the scope of this analysis.

Because water consumption associated with energy production occurs at every stage of an energy product's life-cycle, a life-cycle analysis (LCA; a systematic accounting of water consumption during a life-cycle of an energy product) needs to be conducted to estimate and compare the water consumption of conventional and new energy technologies. Such information will be valuable for evaluating the sustainability of future energy supply and demand in various regions. A comprehensive and thorough LCA of water consumption can also identify the key factors affecting water consumption in an energy product pathway so that efforts can be made to reduce the water consumption of energy technologies.

This study investigated electricity generation, since it consumes a significant amount of water and is associated with various energy conversion pathways. Thermal power plants and hydropower reservoirs are two major water consumers in the electricity generation sector. There have been efforts to evaluate water consumption for electricity generation. For water consumption for hydropower, the National Renewable Energy Laboratory (NREL) evaluated a national-level WCF for hydropower in the United States as 68.9 L/kWh [8], and the Intergovernmental Panel on Climate Change (IPCC) [9] reported that water consumption for hydropower varies from 0 to 209 L/kWh by referencing five data sources [8,10–13]. NREL also evaluated national water consumptions for thermoelectricity generation in the United States as 1.8 L/kWh [8], and studied further to evaluate the ranges of technology-based WCFs by collecting WCFs from the literature [14]. However, the reported values may not be representative of the average WCF for the examined categories because each group included only a small sample. The U.S. Geological Survey (USGS) also estimated water use at thermoelectric plants using linked heat and water budgets models [15,16].

This study aimed to address two major issues in water LCA. First, regional variations in WCFs have yet to be evaluated in detail, which is an important factor for further regional impact analysis due to differences in water supply and demand by region [17,18]. For example, previous studies focused on specific plants or specific technologies, which do not provide variations in water consumption by region [8,10–16]. Even though the LCA study by Lampert et al. [19] generated regional WCFs for electricity generation, they used estimated national average WCFs for hydropower plants and thermoelectric plants and applied these WCFs for each power plant uniformly. Thus, the regional variations in Lampert et al. [19] were based on the regional differences in technology shares and generation mixes. Instead, the first goal of this study is to investigate regional parameters such as climate conditions and cooling technology of individual plants and estimate the water consumption using plant-level water consumption and power generation data. The water consumption rates from individual plants were then aggregated to evaluate U.S. average and regional WCFs.

The second goal of this study is to develop a systematic and objective method to allocate water consumption in multipurpose dams to hydropower. When estimating the water consumption for hydroelectricity generated from multipurpose dams, previous studies typically allocated all water consumption burdens to

hydropower only [20], which leads to much higher WCFs for multipurpose hydropower dams compared to the dams designed to serve for hydropower only. This is because multipurpose dams are designed to have large reservoirs, in general, so as to be able to serve for other purposes. Therefore, it is inappropriate to allocate all water consumption to hydropower alone for multipurpose hydropower dams. To address the gap, this study allocated water consumption from multipurpose reservoirs to hydropower generation based on the economic value of hydropower generation relative to the total economic benefits from all purposes served by each reservoir.

2. Methodology

Depending on the type of driver of power generator, electric power plants can be categorized as thermal (using heat from nuclear fission or combustion of natural gas, coal, oil, or biomass), hydro, solar, wind, and geothermal power plants. Among them, two major water consumers include hydropower plants with large water storage reservoirs and thermal power plants [19].

2.1. WCFs for hydropower generation

Hydropower plants convert the change in gravitational potential energy of flowing water into electricity using hydraulic turbines. The water discharged from the turbines is not considered "consumed," because such water can be used for other downstream applications. However, when reservoirs store a large amount of water for power generation, stored water is partially consumed by evaporation, which may not be available for further use in the same region.

2.1.1. Water consumption in hydropower dams

Bakken et al. [20] reviewed previous approaches of evaluating hydropower water consumption and maintained that background evapotranspiration should be subtracted from the water evaporation to account for the avoided water consumption caused by dam construction. 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 [21]. This evapotranspiration is regarded as background water consumption when there is no reservoir built. Once the dam construction is completed, the background area becomes a reservoir filled with water. In this case, more water is evaporated from the reservoir surface area compared to the evapotranspiration water loss before the dam was built. The difference is used to calculate the net water consumption caused by dam construction in each region. In this study, we used the methodology suggested by Bakken et al. [20].

2.1.2. Water consumption by region

First, regional annual water evaporation (cm/yr) was estimated to calculate the amount of water evaporated from reservoirs in each U.S. region. Water evaporation varies by region due to different climate conditions such as temperature, precipitation, humidity, solar radiation, and wind condition. Water evaporation was estimated through pan evaporation data, which measure the depth of consumed water in a standardized pan. The National Weather Service reports pan evaporation measured daily at stations distributed nationwide [22]. After screening the data from the measured daily pan evaporation for 2010–2015, the pan evaporation data were averaged by state, since the measured data are limited, both temporally and spatially. The data can be updated if higher-resolution pan evaporation data are available for each state or smaller regions within states. For states without sufficient data,

additional resources were incorporated [23,24]. To compensate for additional water evaporation caused by heat exchange through surrounding walls when the pan evaporation is measured, lake evaporation was estimated by simply multiplying pan evaporation data with a coefficient of 0.75 [25]. Note that there are many parameters that influence the coefficient, such as types of pan and climate conditions, which lead to spatial and temporal variation [25–29]. Since it was out of the scope of this study to evaluate the pan coefficient, a fixed mid-value of a national coefficient range was used [25]. In general, southwestern states have the highest evaporation rates due to their subtropical and dry climate conditions.

For evapotranspiration, a regression equation developed by Sanford and Selnick was used [21]. They combined watershed water-balance data with meteorological data for 1971–2000, and correlated evapotranspiration with climate condition. As a result, evapotranspiration at a given state in the United States can be estimated using temperature and precipitation data obtained from the National Oceanic and Atmospheric Administration [30]. Detailed information can be found in the Supplementary Material. Estimated evapotranspiration results showed 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.

Annual state-level water consumptions caused by increased water surface area in reservoirs, shown in Fig. 1, were calculated as the differences between the evaporation and the evapotranspiration in each state. In the few cases where the water evapotranspiration rate was higher than the water evaporation, it was assumed that water consumption due to dam construction is negligible. As shown in Fig. 1, southwestern regions of the United States have high annual water consumption. Annual water consumption at each hydropower reservoir can be calculated using these state-level water consumption values along with reservoirs' surface area data.

2.1.3. Data sources and data processing for surface area and electric generation of reservoirs

To estimate the water consumption from each hydropower reservoir, surface area data are needed. The National Inventory of Dams (NID) listed by the U.S. Army Corps of Engineers (USACE) [31] includes data for dams such as their location, reservoir surface area, and purposes of each dam in the United States. The amount of consumed water from a reservoir can be calculated by multiplying the increment in surface area due to dam construction and the corresponding state-level water consumption (cm/yr) estimated above. It was assumed that the water surface area before dam construction is negligible compared to the large reservoir area, and thus the surface area data in the NID were used directly.

Because the NID does not include power generation data, the U.S. Environmental Protection Agency's (EPA's) Emissions & Generation Resource Integrated Database (eGRID) was also used [32]. This includes data from each power plant such as capacity, types of power generation, plant location, and annual power generation. To calculate the WCFs of hydropower dams, the NID and the eGRID were merged. After data processing, 85% of the dams in the United States that generate hydropower were matched between the NID and the eGRID data sets, and these were used to calculate the WCF for hydropower. Note that water consumption associated with dam construction was excluded in this analysis because it is negligible compared to the water consumption during operation [33].

2.1.4. 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 [31]. Also, there
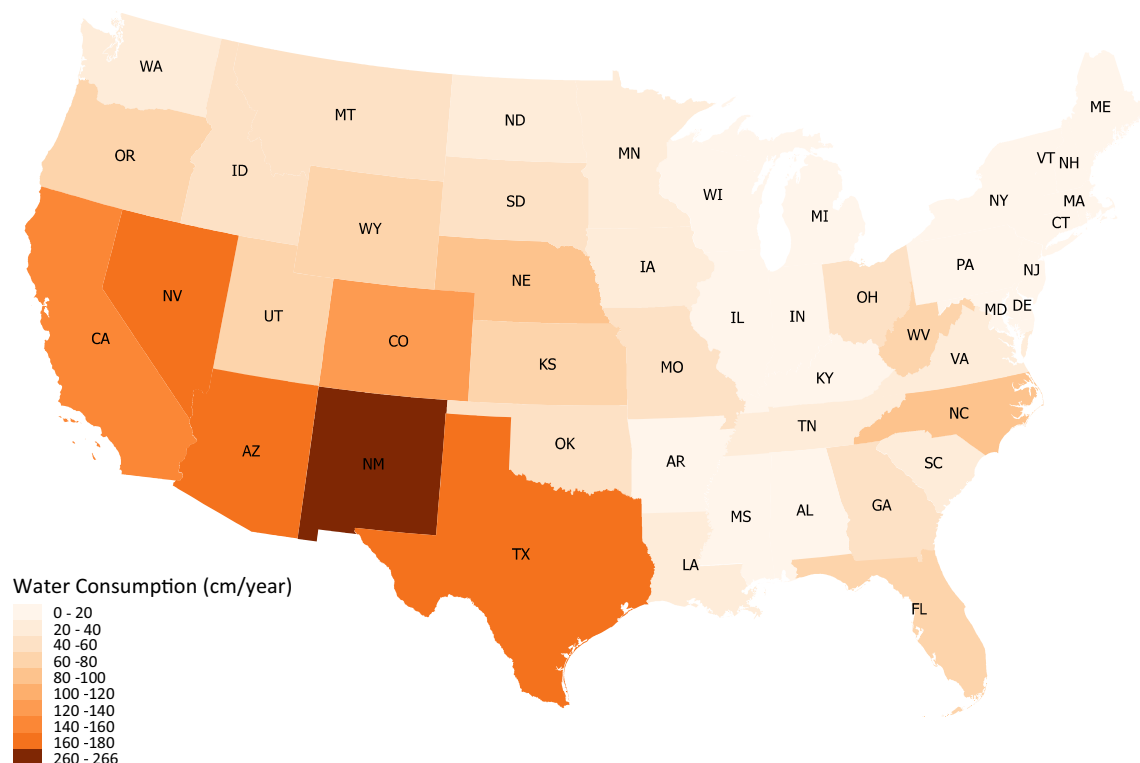
Fig. 1. State-level annual water consumption due to evaporation (cm/yr) in the United States (Data sources: [21–25,30]).

are many cases in which hydropower systems are added to existing non-power generation dams to improve revenue [34]. Therefore, it is not appropriate to allocate all of the water consumption solely to hydropower generation for multipurpose dams.

The NID specifies the purposes of dams, including hydropower generation, irrigation, flood control, navigation, water supply, recreation, fire protection, fish and wildlife, and debris control [31]. It has been found that hydropower is not a major purpose of dam construction, since only 15% of all dams in the NID, by number, include hydropower as one of their purposes. This means that the majority of dams and reservoirs serve purposes other than hydropower generation. Dams for hydropower alone (dedicated dams) are only 4% of the total number of dams, and the rest, 11%, are multipurpose dams that serve other purposes while also generating electricity. Run-of-river (ROR) dams do not need reservoirs, but use natural river flow to generate electricity. Therefore, there is no water consumption caused by power generation from ROR dams; thus they need to be classified separately, along with dedicated and multipurpose hydropower dams.

There have been discussions about the allocation of water consumption to hydropower for multipurpose dams. The IPCC pointed out that allocation schemes for multipurpose reservoirs can significantly influence the results [9]. However, Bakken et al. [20] found that only Pasqualetti and Kelley [35] allocated portions of water consumption to hydropower in multipurpose dams, while all other previously published papers on the hydropower water footprint attributed total water consumption to hydropower. Recently, Bakken et al. [36] analyzed water consumption for four multipurpose hydropower dams using four different allocation methods—volume allocation, energy allocation, economic allocation, and explicit prioritizing; they concluded that volume allocation is the most robust approach. The volume allocation method, however, inconsistently treated those purposes without distinct water consumptions (e.g., flood control, navigation, and recreation) among the four dams that Bakken et al. examined [36]. For example, when accounting for water consumptions for flood control, the total volumes available for storage of inflow were used for the Aswan High Dam in Egypt, while only 20% of the total storage capacity was used for the Mularroya Dam in Spain.

To allocate the water consumptions among all purposes for the 2873 multipurpose dams in the United States [31], an allocation method that treats all multipurpose dams on a consistent basis is required. As mentioned earlier, the volume allocation cannot consistently handle various purposes. Moreover, even when a distinct volume of water can be used for a single purpose, that volume can also be used for other purposes (e.g., a given volume of discharged water can be used for hydropower generation, irrigation, and domestic water supply). In such cases, it is challenging to allocate the shared volume consistently. The energy allocation is not applicable to most multipurpose dams, as many of the purposes serve non-energy-related services. The explicit prioritizing of services is challenging since priorities can change over time and are unique to each dam.

Oak Ridge National Laboratory (ORNL) recently published a report estimating the economic benefits of multipurpose hydropower reservoirs using data collected from three agencies—the U.S. Bureau of Reclamation (USBR), USACE, and the Tennessee Valley Authority (TVA), which accounted for 42% of the total installed hydropower capacity in the United States [37]. ORNL noted that hydropower is just a part of an integrated system of multiple purposes, but many non-energy-related benefits are overlooked when evaluating multipurpose hydropower dams. To address this issue, ORNL estimated the economic benefit for each purpose; its detailed methods are summarized in the Supplementary Material. The economic benefit of hydropower over the total economic benefits from all purposes can be regarded as the allocation factor for hydropower. In this study, allocation factors based on economic benefits were used, as it facilitated evaluating the relative benefits of employed purposes in terms of monetized values. We acknowledge that the economic benefits for each purpose can vary over time; however, using economic benefit for allocation of water consumption provides a consistent basis for allocation of water consumption among the large number of hydropower dams in the United States.

Table 1 shows how ORNL 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 0 to 1. One means that water consumption from reservoirs is completely allocated to hydropower, while zero represents no water consumption allocated to hydropower generation. Table 1 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 as one category, because additional purposes beyond four have less significant impacts, although ORNL's report did show a 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. This is mainly because the revenue from power generation is dominant among all purposes for high-capacity multipurpose 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 burden.

Using the allocation factors in Table 1, water consumption for hydropower generation in each multipurpose reservoir can be allocated based on the number of purposes and the hydropower capacity. It should be noted that the dams with a capacity greater than 500 MW generated more than a half of the hydroelectricity in 2012 [32], and they dominate in the determination of the overall allocation factors for hydropower generation.

2.2. WCFs for thermoelectricity generation

Thermal power plants may employ a steam power cycle that feeds water to boilers and generates high-enthalpy steam, which subsequently expands in turbines to produce mechanical power that is converted to electricity in a generator. Cooling water is typically used to condense the steam exhaust from the turbine and feed it to the boiler feedwater pumps to complete the power cycle. Water loss to evaporation during the cooling processes is considered as water consumption. Water loss to evaporation per unit electricity generation depends on the power plant energy efficiency and the employed cooling technology. According to the second law of thermodynamics for heat engines, only a portion of heat input from fuel combustion can be converted into mechanical energy, while the rest has to be rejected to the environment. The amount of heat rejected per unit of power generation can be calculated using the plant energy conversion efficiency. Note that combined-cycle technologies for power generation have higher

Table 1
Water consumption allocation factors of hydropower based on economic benefits [37].

Capacity	Number of purposes			
(MW)	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

energy conversion efficiencies than simple steam or gas turbine cycle technologies, and thus reject less heat to the environment with less water loss to evaporation.

Water consumption in thermal power plants also varies depending on the cooling technology employed. 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. Once-through cooling withdraws a large amount of water from an adjacent water body, feeds it to a heat exchanger to remove the heat rejected by the power cycle, and discharges it back to the water body. Due to the large volume of water withdrawal for cooling and the high heat capacity of water, its temperature rise in the heat exchanger is usually small, resulting in negligible water loss to evaporation due to cooling. On the other hand, a recirculating cooling system employs a closed loop that circulates a relatively smaller amount of cooling water. The recirculating cooling system uses a cooling tower or a pond to dissipate the heat absorbed in the condenser by evaporating a portion of the cooling water to the atmosphere. The deficiency in cooling water due to the evaporation is compensated by withdrawing makeup water. Dry-cooling technologies use air rather than water for the cooling process of the power cycle, resulting in no water consumption. However, they usually incur higher energy and economic burdens compared to cooling-water technologies because of the large heat exchange surface area and fan power requirements.

While this study focuses on the WCFs, the feasibility of water withdrawal could be a limiting factor for determining the types of cooling technology, which leads to regional variation in cooling technology share. Thus, a water withdrawal factor (WWF), defined as water withdrawal per unit of electric power generation, for each type of cooling technology is also discussed. Note that "diversion" in Energy Information Administration (EIA)-923 [38] data was used to estimate the WWFs of cooling with a pond or a tower when withdrawal is not specified, because it refers to water withdrawal in this system boundary.

2.2.1. Water consumption in thermal power plants

The EIA reported that the cooling technologies employed in thermal power plants varied over time [39]. It showed the dominance of recirculating cooling systems starting in the mid-1970s, with a large reduction in installations of once-through cooling systems. According to Mielke et al. [13], the relative capital cost for the recirculating and dry-cooling technologies is 1.5 and 9.6 of the once-through cooling technology, respectively. This explains why the once-through cooling technology was dominant in the early stage, because power plants had easy access to a large amount of cooling water.

The trend has changed because of concerns over thermal pollution caused by the heated effluent of once-through cooling systems that threatens 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 state authorities issued permits on a case-by-case basis for about 20 years [40]. In 1995, the EPA entered into a consent decree, and regulations were phased in starting in 2001, which identified recirculating cooling in general as the BTA for new facilities. These historical regulation changes explain the trend.

Although the regulations led to changes in cooling system technology installations, there are still some power plants operating with once-through cooling technology because the BTA requirement did not restrict the choice to a recirculating cooling technology. Existing plants are required to equip cooling systems that achieve a degree of environmental protection of aquatic species equivalent to recirculating cooling. Based on EIA-860 [41], the

recirculating cooling system is currently dominant for most southern and western regions, while the use of once-through cooling is more prevalent in northern and eastern regions of the United States. The differences in the use of cooling technologies by region result in differences in their WCFs for power generation.

For the once-through cooling systems, the difference between withdrawal and discharge is regarded as water consumption. There might be a small increase in the loss of water to evaporation after the cooling water is returned to the water body due to a small increase in temperature, but it is assumed to be negligible. We note that there are few once-through cooling systems that employ cooling towers or ponds to cool discharged water in order to minimize environmental thermal impacts. 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, recirculating cooling systems with a pond withdraw makeup water from nearby water bodies to maintain the water level of the cooling ponds. Therefore, the makeup water can be regarded as water consumption for recirculating cooling.

2.2.2. Non-freshwater use

In order to meet cooling-water demands, alternative water sources can be considered. Data show that plants which contribute 17% of the total reported power generation utilize non-freshwater (i.e., reclaimed water, brackish water, and saline water) for cooling. Based on the earlier definition of water consumption, thermoelectric power plants using non-freshwater have zero freshwater consumption. Therefore, it is expected that these resources can reduce freshwater consumption significantly, although at increased expense due to the reduced effectiveness of heat exchange and the life of heat exchangers. While power plants using non-freshwater are mostly located along the U.S. coast due to easy access to seawater, there are some inland power plants that use reclaimed water, especially where freshwater resources are not sufficient.

There are economic, technical, and environmental drawbacks that limit the use of non-freshwater for cooling purposes [42]. The Electric Power Research Institute (EPRI) calculated that the costs of degraded water are 1.5–2.5 and 1.1–1.2 times higher than those of freshwater at inland plants and coastal plants, respectively, with the range capturing the impact of variation in the quality and proximity of the water source [43]. Also, using non-freshwater may lead to technical design and operational challenges such as corrosion, scaling, and biofouling, which may require additional pretreatment to mitigate these challenges [44,45]. Non-freshwater used for cooling may also have unfavorable environmental impacts [42,43]. In general, when non-freshwater is used, cooling ponds are not favorable because managing non-freshwater in the cooling ponds to meet environmental regulation requirements is challenging.

For power plants using saline water, the once-through cooling system is dominant, representing 89% of power generation with saline water cooling. Considering that the power generation share with once-through freshwater cooling is only 15% of the total power generation with freshwater cooling, it is clear that water availability plays an important role in determining the cooling technology for power generation. Unlike saline water, discharging reclaimed water or brackish water is subject to many restrictions, which is why recirculating with a cooling tower is dominant for brackish water cooling (76%).

2.2.3. Data sources and data processing for thermal electric power plants

Water consumption at the facility level has been investigated using EIA-923 [38], which includes data concerning power generation technologies, cooling technologies, water withdrawal, and

water consumption, along with other general information on the power plants. Because EIA-923 [38] does not specify whether once-through cooling employs cooling towers, EIA-860 [41], which includes information about cooling towers, was used to reclassify power plants with once-through cooling technology.

The original EIA data include the information that thermal power plants produced 3600 TW h in 2014 [38], and the processed data used for 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 and water consumption.

Power plants in this study were classified into six categories based on the employed cooling technology and prime mover technology: (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 were classified in the same category because there is a 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. Because there are only a few plants with once-through cooling using a pond or a tower, and they all have a similar level of water consumption, they were aggregated with the recirculating cooling systems.

2.2.4. Regional analysis

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 the electricity energy transmission network and system reliability (16 *United States Code* 8240). There are eight regional entities as shown in Fig. 2: (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, Regional Entity (SPP); (6) Western Electricity Coordinating Council (WECC); (7) Florida Reliability Coordinating Council (FRCC); and (8) Texas Reliability Entity (TRE). In this study, the WCFs for power generation were examined by NERC region because electricity is easily transmitted within a region.

3. Results

3.1. Regional WCFs for hydroelectricity

3.1.1. Unallocated WCFs for hydroelectricity

As in Table 2, ROR dams contribute about 22% of total hydropower electricity generation in the United States. These dams generate power without water consumption because they do not employ reservoirs. Dedicated hydropower dams consume 567 million liters of water to support 11% of U.S. hydropower electricity generation, which results in a WCF of 21.4 L/kWh. Multipurpose dams contribute 67% of total hydropower generation, while contributing 96% of total water consumption by all reservoirs that generate hydropower. If hydropower receives all of the water consumption burdens, the WCF for hydropower generation from multipurpose dams is estimated at 92.3 L/kWh. Overall, the WCF for hydropower electricity generation is estimated at 63.8 L/kWh, including ROR, dedicated hydropower dams, and multipurpose hydropower dams.

Table 2 also includes power generation and water consumption in hydropower dams by NERC region, and the WCFs were calculated correspondingly. The results show that there is significant regional variation. For example, TRE and FRCC have much higher WCFs than other NERC regions at 5627 and 931 L/kWh, respectively, while NPCC and RFC consume only 1.2 and 14.2 L/kWh, respectively.

Differences in climate conditions are among the major causes of the regional variation in the WCFs. As shown in Fig. 1, water consumption in the arid southwestern regions is much higher than in the northeastern regions due to high evaporation conditions and
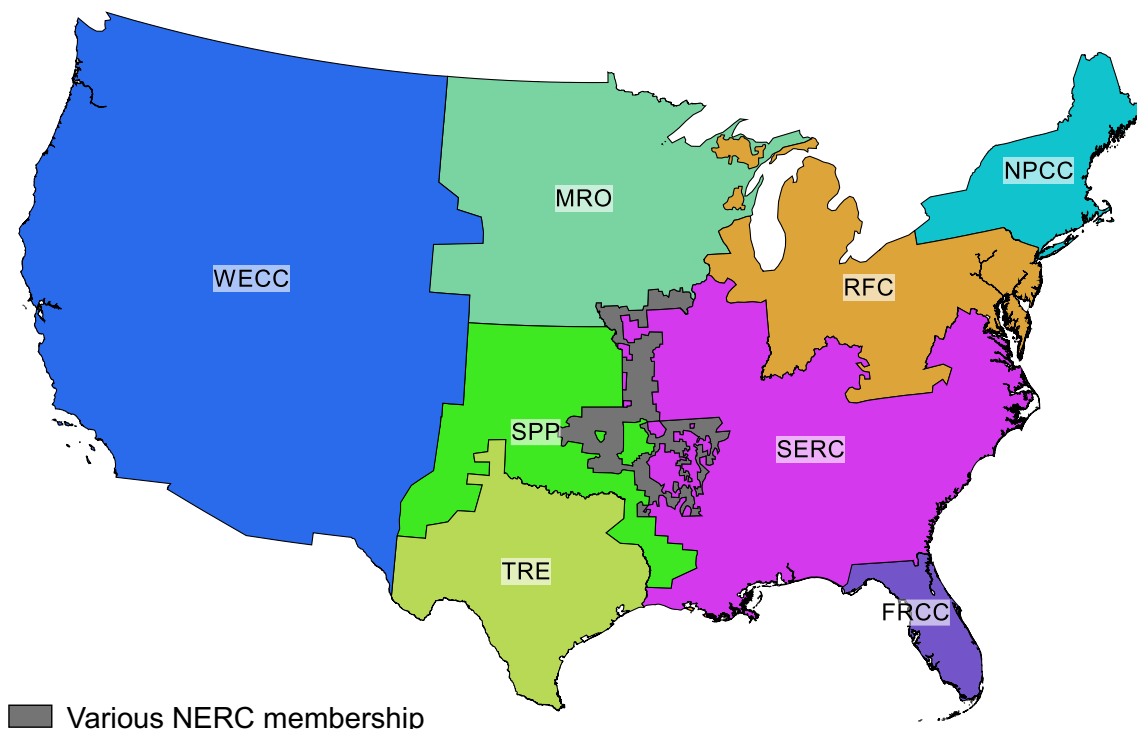

Fig. 2. The North American Electric Reliability Council region map [46].

Table 2
Unallocated WCF for hydroelectricity in the United States by NERC region.

Region		Power generation in 2012 (10^6 kWh)			Water consumption[b] (10^6 L)		Unallocated WCF (L/kWh)			Capacity factor (%)
		ROR	Dedicated	Multipurpose	Dedicated	Multipurpose	Dedicated	Multipurpose	Overall	
NERC	NPCC	0.02	14.6	10.5	4.0	25.2	0.27	2.4	1.2	59
	RFC	0.2	0.2	5.2	20.3	59.1	84.0	11.5	14.2	35
	WECC	49.4	7.8	102.5	290	5945	37.3	58.0	39.1	46
	MRO	–	0.2	12.3	23.7	1687	133	138	138	45
	SERC	1.0	2.9	19.1	227	3406	78.5	178	158	24
	SPP	–	–	2.9	–	1021	–	357	357	17
	FRCC	–	–	0.2	–	140	–	931	931	31
	TRE	–	–	0.3	–	1838	–	5627	5627	9
U.S.[a]		50.6 (22%)	26.4 (11%)	153.0 (67%)	567 (4%)	14,122 (96%)	21.4	92.3	63.8	42

[a] Hydropower generation in Alaska is included.
[b] Pan evaporation data of 2010–2015 were used [22].

the dependence of water consumption for hydropower on climate conditions. However, the large variation in WCF by region in Table 2 cannot be fully explained even by considering climate conditions. For example, while the weighted average water consumption rate of TRE in Fig. 1 is only 28 times higher than that of NPCC, the WCF of TRE is 4850 times higher than that of NPCC.

The main reason for the large regional variation in the WCFs than in the water consumption rate is that water consumption by hydropower (the numerator of WCF) is not directly related to power generation (the denominator of WCF). The annual generation of hydropower depends largely on hydrologic conditions and the volume of water discharged, rather than the size of the reservoir (a key factor for water consumption) [47]. In this respect, a capacity factor that represents the actual electric energy generated by a hydropower plant as a percentage of its designed maximum generation capacity is an important indicator that manifests in the WCF of each hydropower plant, since the stream flow and the size of the reservoir are key design factors for generation capacity [34,48–50].

Table 2 presents the capacity factors of the hydropower dams calculated using the eGRID data [32], which show that southern regions in general have relatively lower capacity factors compared to other regions. Possible reasons for the large variation in hydropower capacity factor by region include differences in hydrologic conditions [47]. Considering that the design capacity of a hydropower dam is typically set by assessing stream flow, hydropower dams are likely to be overdesigned where seasonal and interannual flow changes are high. Hydropower may also conflict with other purposes. Where water scarcity is an issue, storing water in the reservoir could be more important than generating power. Purposes such as navigation and recreation require water to be stored for their operation, and, if irrigation is included as one of the purposes, power generation could be limited by the release schedule for irrigation. There might be other factors, but investigating the variation of the capacity factors of hydropower dams was beyond the scope of this study.

3.1.2. Allocated WCFs for hydroelectricity

When the allocation factors in Table 1 are applied to individual multipurpose dams and are subsequently aggregated to the national level, hydropower becomes responsible for only 23% of total water evaporation in multipurpose reservoirs. This leads to a WCF for multipurpose dams of 21.5 L/kWh, and the allocated national weighted average WCF for hydroelectricity becomes 16.8 L/kWh, as in Table 3.

Shares of types of dams are important to allocating water consumption to hydropower in a given region. Table 3 explains the trend of allocation factors by NERC region. Where the number of purposes is relatively few, the allocation factors for multipurpose

hydropower dams are high. For example, NPCC has the highest allocation factors, as most multipurpose hydropower dams have only two purposes. On the other hand, the other regions have lower allocation factors, since a much smaller share of multipurpose dams in these regions have only two purposes. Note that the allocation factor for a multipurpose dam decreases significantly as the number of purposes increases from 2 to 3, as shown in Table 1. Overall allocation factors consider dedicated dams along with multipurpose dams, which are higher than the multipurpose allocation factors, depending on the power generation share between dedicated and multipurpose hydropower dams, as seen in Table 2. The results show that the allocated WCFs for hydropower dams by NERC region vary from 0.67 to 1194 L/kWh.

All of these factors together (i.e., water consumption rate, capacity factor, and allocation factor) impact the WCFs for hydropower by NERC region. While the water consumption rates and capacity factors are influenced by regional conditions, the allocation factors are determined by the power generation shares, as in Table 3, which do not show a regional trend.

3.2. Regional WCFs for thermoelectricity

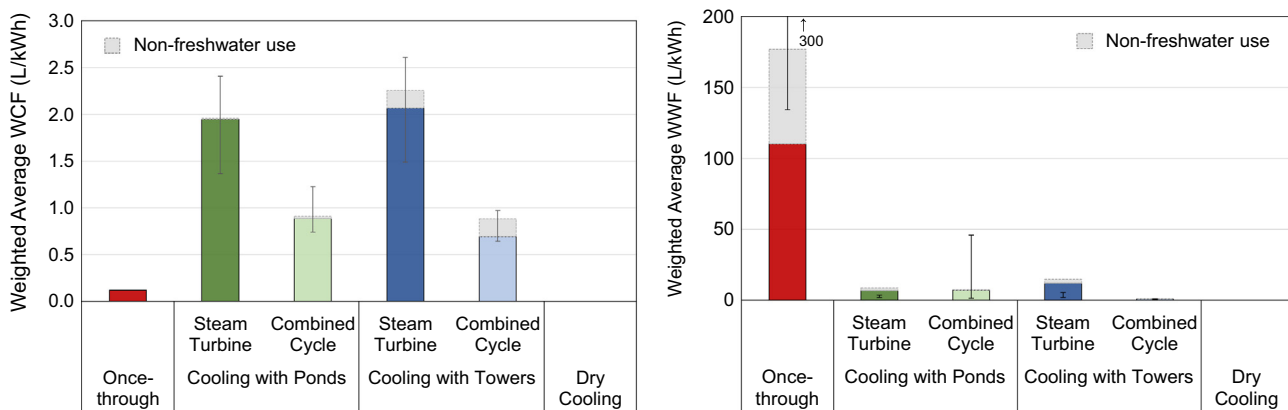#### 3.2.1. WCFs by cooling technologies and prime movers

Fig. 3 shows the weighted average WCFs and WWFs of six thermoelectricity generation categories based on their cooling technologies and prime movers. The error bars indicate the distribution of facility-level WCFs, and the corresponding low and high end of the bars represent the 25% and 75% percentile, respectively. For the WCFs of dry cooling and once-through cooling, both the low end and the high end of the WCF are zero, which is why the error bars are not shown. The gray bars indicate non-freshwater use, which contributes power generation without freshwater use.

The power generation energy efficiencies for steam turbine and combined-cycle power plants are approximately 33% and 50%, respectively [51]. As mentioned previously, the thermal energy to be rejected per unit of power generation mainly depends on the energy efficiency of the power plant. Higher energy efficiency implies less waste energy and increased power generation output. Thus, power plants with higher efficiency require less cooling demand, which results in less evaporation losses. As in Fig. 3, combined cycles have lower WCFs than those of steam turbine cycles, due to higher power generation efficiency. For cooling with a pond or a tower, the WCF is not significantly impacted by whether a cooling pond or a tower is employed, as long as the prime mover is the same. For steam turbine power plants, the WCFs were estimated at 1.96 and 2.25 L/kWh for cooling with a pond and cooling with a tower, respectively, while the WCFs for combined-cycle plants were estimated at 0.91 and 0.88 L/kWh, for cooling with a

Table 3
Power generation shares by number of purposes of multipurpose dams, allocation factors, and allocated WCF by NERC region.

Region		Power generation share by number of purposes			Allocation factor	Allocated WCF (L/kWh)[a]	
		2	3	4 or more	Multipurpose	Multipurpose	Overall
NERC	NPCC	95%	3%	2%	51%	1.2	0.67
	RFC	32%	53%	16%	29%	3.4	6.7
	WECC	29%	17%	53%	29%	16.8	12.6
	MRO	13%	2%	85%	19%	25.6	27.2
	SERC	18%	26%	56%	17%	29.7	34.5
	SPP	15%	10%	75%	23%	83.2	83.2
	FRCC	4%	0%	96%	20%	183	183
	TRE	19%	23%	58%	21%	1194	1194
U.S.		30%	18%	52%	23%	21.5	16.8

[a] Allocation factors were calculated using power generation data in 2012 [32] and ORNL's facility-level allocation factors [37].

Fig. 3. WCFs and WWFs by cooling technology and prime mover.

pond and cooling with a tower, respectively. Note that no regional trend was found within the same cooling technology and prime mover category unlike evaporation from hydropower reservoirs, because cooling-water evaporation depends highly on cooling-water temperature change rather than climate conditions.

Once-through cooling systems result in negligible water consumption, and most power plants equipped with once-through cooling without ponds or towers reported zero water consumption [38]. However, 17 among 125 power plants in this category specified very small water consumption, which is why the WCF for once-through cooling is 0.12 L/kWh, not exactly zero.

As expected, the trend between cooling technologies is totally opposite for the WWFs. Without considering the gain from non-freshwater use, the WWF of once-through cooling was estimated at 177 L/kWh, which is much higher than that of cooling with a pond or a tower, which ranged from 1.21 to 14.6 L/kWh.

For once-through cooling, using non-freshwater significantly reduces the WWF, but does not provide any benefit from a water consumption point of view, because the WCF for once-through cooling is also negligible. On the other hand, power plants with a cooling tower or a pond reduce freshwater consumption by the amount of non-freshwater use. Power plants with cooling towers reduce WCFs by 8.3% and 21% for steam turbine and combined cycle, respectively, by using non-freshwater. However, power plants using non-freshwater typically do not use ponds, as mentioned earlier, which is why reductions in freshwater use are negligible in these cases.

Regulations on thermal power plants' cooling stimulated the shift from once-through to other types of cooling technologies, although recirculating systems consume more water than once-

through cooling systems. Given this fact, freshwater consumption for thermoelectricity can be reduced by increasing the power generation efficiency or using non-freshwater resources.

3.2.2. WCFs for thermoelectricity by region

Table 4 shows the aggregated water consumption and the power generation in thermal power plants in the United States. 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 was estimated at 1.58 L/kWh. However, when dividing the annual freshwater consumption by the total annual power generation (freshwater and non-freshwater cooling and dry cooling), the national average WCF for thermoelectricity becomes 1.25 L/kWh. Note that the WCF for power generation that uses cooling with non-freshwater was estimated at 0.75 L/kWh, which is mainly because of the large use of once-through cooling along the coastline.

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. Fig. 4 shows the power generation shares by types of cooling technologies and prime movers for each NERC region. It shows that where water availability is a major concern (i.e., TRE, SPP, and WECC), recirculating cooling systems are dominant, while northeastern regions still have a quite high share of once-through cooling. This is because once-through cooling systems require a large amount of water withdrawal, as shown in Fig. 3, which is not feasible where water availability is of concern.

Table 4
National average WCF for thermoelectricity in the United States.

Cooling type	No. of plants	Power generation in 2014 (10^9 kWh)	Water consumption in 2014 (10^9 L)	WCF (L/kWh)
Cooling with freshwater	402	1804 (79%)	2846	1.58
Dry cooling	36	87 (4%)	0	0
Cooling with non-freshwater	110	380 (17%)	286[a]	0.75[a]
Overall	548	2272	2846[b]	1.25[b]

[a] Non-freshwater use.
[b] Freshwater use only.

Fig. 5 shows WCFs for thermoelectricity by NERC region. The red and gray bars represent freshwater and non-freshwater consumptions, respectively. The main driver for the regional variation is the power generation technology shares in each region, as shown in Fig. 4. The regions with high recirculating cooling shares have high WCFs, and the regions with high once-through cooling shares have low WCFs, due to the differences in facility-level WCFs in Fig. 3. For example, SPP has only 1.3% of once-through cooling by power generation. Consequently, SPP has the highest WCF (2.20 L/kWh) among all NERC regions, without considering the gain in WCF from non-freshwater use. While TRE also has a similar level of once-through cooling share at 1.0%, the WCF is as low as 1.13 L/kWh due to its high share of combined cycles. In contrast, NPCC has the highest share of once-through cooling, 57%, and the lowest WCF at 0.25 L/kWh.

Non-freshwater use reduces the WCF, especially for the regions located along the coastline. For example, reductions in WCF for thermoelectricity due to non-freshwater use in the FRCC, NPCC, and WECC regions were estimated at 46%, 29%, and 24%, respectively, while the national average reduction is 9%.

3.3. Regional WCFs for electricity generation

The electricity generation technology was considered to calculate the WCF for average electricity generation, including thermal and hydro-power generation. Fig. 6 shows the electricity generation share in 2015 [6] and the overall WCFs for electricity by NERC region. Other than thermoelectricity and hydroelectricity, the WCFs for electricity generated from geothermal, wind, and solar photovoltaic were set at 4.5, 0.004, and 0.17 L/kWh, respectively
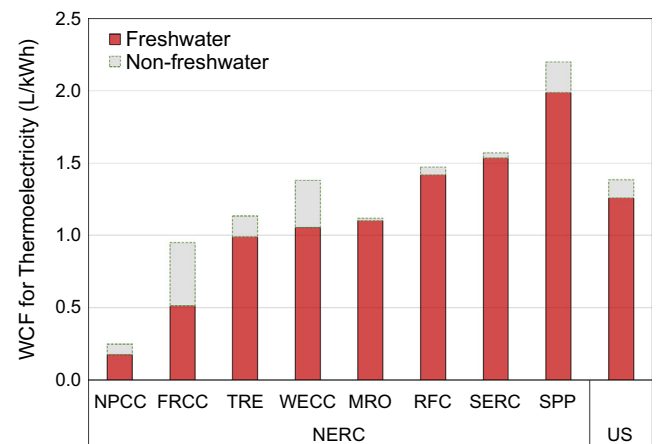

Fig. 5. WCF for thermoelectricity by NERC region calculated from actual water use and power generation data.

[7]. The results exclude non-freshwater use in thermal power plants and water consumption allocated for other purposes in multipurpose dams.

Despite its small power generation share, hydropower significantly influences the overall WCFs due to its high WCF. In the United States, the average WCF for electricity generation was estimated at 2.18 L/kWh, with thermoelectricity and hydropower generation almost contributing equally to that WCF, as shown in Fig. 6. Note that most hydroelectricity in the United States is generated where WCFs for hydropower are relatively low. For example, although TRE and FRCC have much higher hydropower WCFs
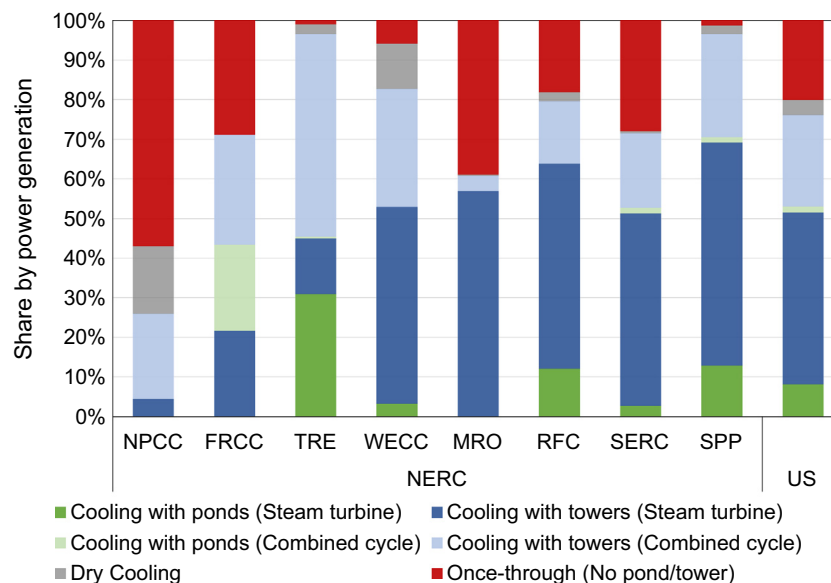

Fig. 4. Power generation share by cooling technology for each NERC region.

WCF for Electricity (L/kWh)

WECC 3.54 — Others 0.70, Hydroelectricity 2.73
MRO 2.26 — Thermoelectricity 0.84, Hydroelectricity 1.41
NPCC 0.24 — Thermoelectricity 0.15, Hydroelectricity 0.09
SPP 3.13 — Thermoelectricity 1.64, Hydroelectricity 1.49
RFC 1.43 — Thermoelectricity 1.36, Hydroelectricity 0.07
SERC 2.65 — Thermoelectricity 1.47, Hydroelectricity 1.18
US 2.18 — Thermoelectricity 1.10, Hydroelectricity 1.06
TRE 2.95 — Thermoelectricity 0.89, Hydroelectricity 2.06
FRCC 1.73 — Thermoelectricity 0.50, Hydroelectricity 1.23

Legend:
- Thermoelectricity
- Hydroelectricity
- Others (geothermal / solar / wind)

Power Generation Share

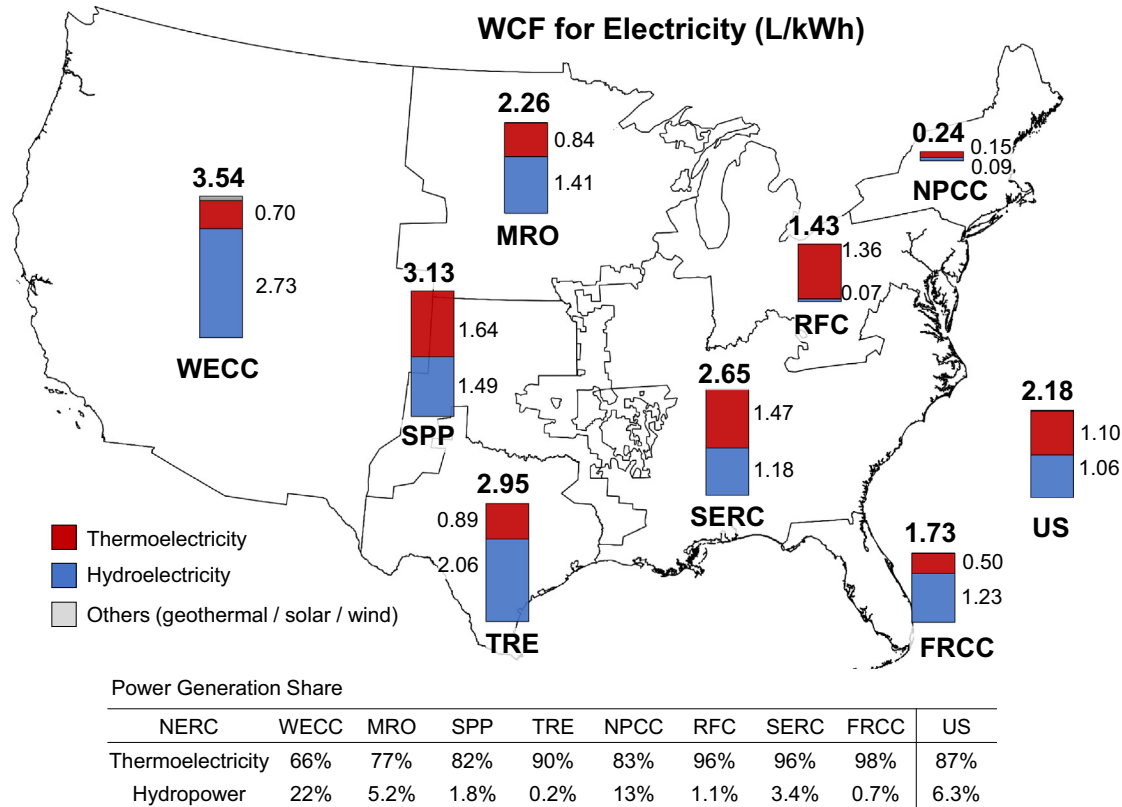| NERC	WECC	MRO	SPP	TRE	NPCC	RFC	SERC	FRCC	US
Thermoelectricity	66%	77%	82%	90%	83%	96%	96%	98%	87%
Hydropower	22%	5.2%	1.8%	0.2%	13%	1.1%	3.4%	0.7%	6.3%

Fig. 6. WCFs for electricity generation by NERC region.

at 1194 and 183 L/kWh, respectively, their impact on the WCF at each region is limited due to small hydropower shares (0.2% and 0.7% for TRE and FRCC, respectively). On the other hand, while the WCF for hydropower in WECC is only 12.6 L/kWh, the high hydropower generation (22%) in this region has a more significant impact on the national electricity WCF.

In water-stressed regions, we found that the share of once-through cooling that has almost zero water consumption is very low due to the limited availability of water resources (Fig. 4). However, Fig. 6 shows that water-stressed regions (e.g., WECC and TRE) have relatively lower thermoelectric WCFs than the national average, which demonstrates the efforts of reducing freshwater consumption by using technologies with less WCFs or non-freshwater use. Also, high shares of wind and solar power generation indirectly reduce the WCF by lowering the share of thermo-electricity generation.

It is possible for thermal power plants to reduce water consumption by implementing less water-intensive technologies. However, water consumption for hydropower is mostly determined by climate and hydrology conditions, not by technologies. As discussed previously, cooling technologies in thermal power plants will continue to shift from once-through to recirculating, which possibly increases water consumption in thermal power plants. Also, climate change and corresponding water availability issues are expected to increase the WCF for hydropower in the future [3,4]. However, several factors may decrease water consumption for electricity. First, the share of solar and wind power generation is projected to increase from 5.4% in 2015 to 17.5% in 2040 [6]. Since they involve a negligible amount of water consumption [7], their increased shares can lower water consumption for power generation. In addition, the share of the natural gas combined cycle that has high power generation efficiency

and reduced water consumption for cooling processes is also expected to increase, while other types of thermal power plants decrease [6].

4. Conclusions and discussion

Water is critically important for thermal and hydro electricity generation since they consume large amounts of water. In this study, the regional WCFs for electricity generation have been investigated using primary data sources at the generator level. While hydropower is regarded as an emission-free generation technology, it may result in significant water loss due to evaporation from reservoirs. Especially in regions where evaporation rates are high and capacity factors are low, the amount of water consumed by hydropower generation is significantly high. The WCF for hydropower shows high WCFs in arid U.S. southwestern regions. For multipurpose dams, we allocated water consumption based on economic valuation of different purposes of dams. At the national level, this allocation resulted in 23% of water consumption to hydropower in multipurpose dams, and the rest to other purposes. The allocated national average WCF for hydropower was estimated at 16.8 L/kWh.

Thermal power plants require a huge amount of water for cooling purposes, and the water consumed during cooling processes varies with power plant efficiency and employed cooling technologies. In order to quantify the regional variation, this study evaluated cooling water consumption by NERC region. For thermal power plants, cooling with non-freshwater or dry cooling also reduces freshwater consumption. The national average WCF for thermoelectricity generation was estimated at 1.25 L/kWh, including these reductions. Regional variation is caused mainly by types of prime movers and cooling technologies.

Using U.S. regional power generation mixes, we estimated the national average WCF for U.S. electricity generation at 2.18 L/kWh, which is from thermoelectricity and hydropower generation (1.10 and 1.06 L/kWh, respectively). Due to its high WCF, hydropower generation plays an important role for the overall electricity WCF, even with a small electric share (6.3% in 2015) [6]. Note that water consumption for electricity generation varies by region significantly, due to the power generation mixes and the parameters that influence water consumption at a facility level.

Freshwater availability is an important global concern, and the interrelationships among water issues and energy issues are now being addressed [52]. As discussed, in order for thermal power plants to reduce freshwater consumption, they need to increase power plant efficiency, to use non-freshwater such as saline, brackish, and reclaimed water, or to use a less water-intensive cooling technology. Regarding the cooling technology of thermal power plants, however, there is a trade-off between water consumption and withdrawal. Once-through cooling needs a large amount of water withdrawal with negligible water consumption, while recirculating cooling has relatively higher water consumption with a small amount of water withdrawal. Thus, the use of once-through cooling can be limited by water availability in water-stressed regions, which increases water consumption. Also, cooling technologies have gradually shifted to the recirculating technologies that consume more water due to regulations that limit the use of once-through cooling technology. Dry cooling also can be an alternative to conventional cooling technologies, but it may have economic and operating issues.

Unlike water consumption in thermal power plants, water consumption for hydropower is largely determined by climate and hydrology conditions, not by hydropower technologies. As the allocation scheme for water consumption to hydropower in multipurpose dams has a profound impact on the WCF of hydropower, further investigation of an appropriate allocation method is needed.

Our study investigated regional water consumption for electricity generation in the United States. It is expected that the results of this study will be valuable for comprehensive LCA of water consumption for various pathways that use electricity. Especially, regional WCFs for electricity generation can be studied further for impact analyses that consider water availability and demand in each region. Note that the same methodology can be used for other countries and regions if regional data are available. In addition, it is expected that this study will contribute to further regional impact analysis. Because each region has unique water supply and demand (i.e., water stress) conditions, the relative impact of water consumption can vary significantly by region depending on water availability in each region. This is a subject for future research and further analysis.

Acknowledgements

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.05.025.

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