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

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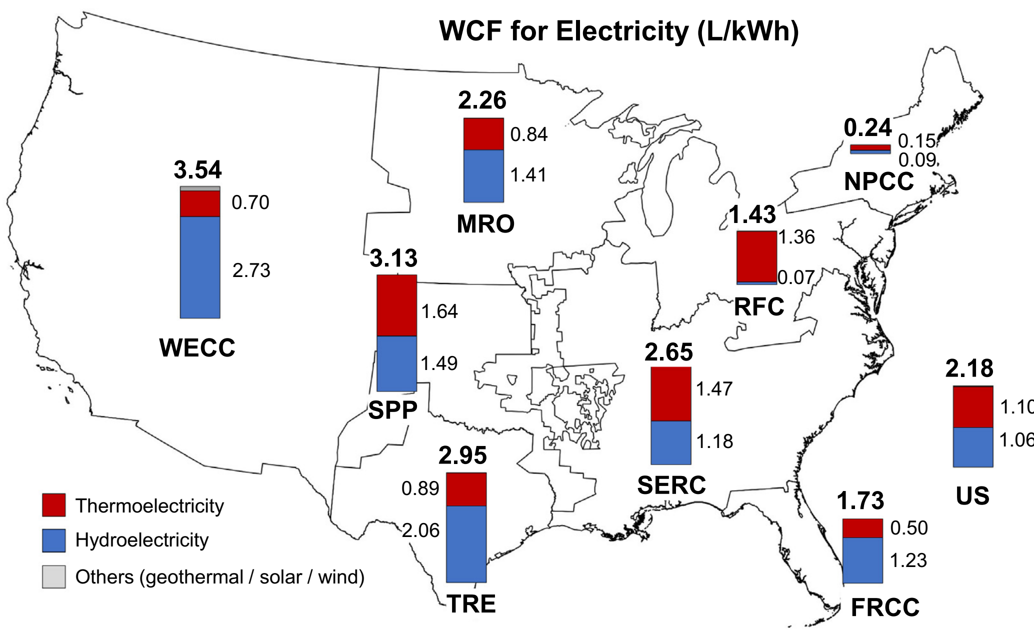
HIGHLIGHTS

- 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.

GRAPHICAL ABSTRACT



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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

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Allocation
Regional analysis

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.

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 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),