Opportunities for Robustness of Water Footprints in Electricity Generation

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Key Points:

• Current practices of water footprints in the energy sector are limited with static values.
• Seasonal assessments of water footprints for electricity will enhance robustness of the metric.
• Opportunities exist to explore utility of pairing sub-annual assessments of footprints with forecasts for improved decision-making.

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Abstract

Water resources are required for cooling of thermoelectric power plants and in the production of hydroelectricity. Scarcity of water resources impacts the ability to generate electricity in grids across the globe. There is extensive literature and research on the electricity-water nexus, spanning hydrology, policy, and energy sectors. Existing research often focuses on quantifying a static relationship and rarely accounts for expectations of annual, seasonal, and sub-seasonal water variability in nexus research. This omission leaves an important, unanswered question in the field: how can the water footprinting framework be operationalized in the electricity-water nexus with hydroclimatic forecasts? Building off the work by Chowdhury et al. (2021), we comment on the opportunities for climate-informed, seasonal or sub-annual assessments of the electricity-water nexus to facilitate decision-making.

Plain Language Summary

Water footprints are a tool to assess the impacts of electricity generation on the local environment. However, studies assessing this relationship often generalize the amount of water consumed by electricity generation to a single number throughout a year. Global climate phenomenon shape water resources availability at monthly and annual time scales. To increase robustness and usability of the water footprint metric for decision-making, there are opportunities for sub-annual assessments to be paired with forecasts, enhancing the utility of water footprints for electricity. We expand on the work by Chowdhury et al. (2021) and discuss the impacts of climate phenomena on water availability and the subsequent impact to the production of electricity.

1 Introduction

Climate change is expected to intensify global atmospheric phenomena, such as ENSO, which will destabilize the water cycle and increase uncertainty in the availability of water resources on regional and watershed scales (Trenberth, 2011; Huntington, 2006). As a result, infrastructure and other resources that depend on reliable access to water resources are impacted, such as food and energy. Sectoral dependence on water resources can lead to cascading failures when water is scarce (Gerlak et al., 2018). One such example is the relationship between electricity and water, which is often termed the electricity-water nexus. Water resources are consumed in the cooling of thermoelectric power plants and in the production of hydroelectric power. Chowdhury et al. (2021) investigate this nexus of resources and determine how energy production variability is explained by ENSO climate patterns within the Mekong River basin in Southeast Asia. Greenhouse gas emissions and costs of operating the electricity grid respond to ENSO-driven fluctuations in water availability. In drought years, operational costs and resultant greenhouse gas emissions rise due to the reduced availability of hydroelectric power generation capacity (Chowdhury et al., 2021). The authors, in their analysis, place dams and thermoelectric power plants in a broader context, focusing on understanding the variable hydrologic patterns of the region, and how they drive temporal water availability.

The work by Chowdhury et al. (2021) facilitates an interesting discussion on the role of water resources management in electricity production and subsequent greenhouse gas emissions under hydrologic uncertainty. Chowdhury et al. (2021) compliment work regarding the electricity sector in California, which showed the 2012–2016 drought in California caused an estimated increase of carbon emissions by 10-33% compared to predrought conditions (Gleick, 2015; Hardin et al., 2017; Kern et al., 2020). The drought in California resulted in reduced water availability, which impacted the production of hydroelectricity and forced increased reliance on carbon intensive fuel-based generation. This clear link between electricity’s demand on water and resultant impacts on greenhouse gas emissions requires management to meet the goals of the Paris Accords. Ad-
Additional droughts are often accompanied by higher temperatures, leading to reduced efficiency in power plants (Lubega & Stillwell, 2018). As a result, Miara et al. (2017) determine that 99% of power plants in the United States will show some reduction in available capacity due to climate change, with significant regional disparities. Further, including ENSO and other global climate phenomena into electricity-water nexus studies offers insights into joint management of the two resources (Voisin et al., 2018). Water resources and electricity demand are seasonally constrained and variable. These seasonal fluctuations in the relationships are further constrained by thermal pollution policy (Lee et al., 2020). The confluence of the aforementioned issues suggest that identifying and accounting for seasonal and interannual hydroclimate patterns, driven by global atmospheric phenomena, are crucial when evaluating the electricity-water nexus and making decisions (Gaudard et al., 2018).

However, commonly used metrics in the energy-water nexus include water footprints (Hoekstra et al., 2011). Water footprints describe the amount of water consumed in the generation of a product and can also be discussed as water use intensities or consumption per unit (typically megawatt-hour) of electricity. Often, these water footprints are treated as static variables, without regard to in-season or expectant drought concerns. While water footprints in other sectors, such as agriculture, naturally account for seasonality, as a function of growing seasons, electricity water footprints are generally not seasonally adjusted. Therefore, they are limited in their utility for planning, forecasting, and decision-making. In this commentary, we suggest an opportunity to enhance the robustness of the water footprint metric through coupling with global climatic phenomenon, water availability, and forecasting practices; see Figure 1. The pairing of climate change and hydrologic forecasts helps predict water availability at the seasonal scale which then dictates constraints on electricity demand and subsequent water footprints.

Chowdhury et al. (2021) highlight the fact that water scarcity, driven by ENSO, explains power production variability, illuminating the reality that climatology-based assessments can be useful. Additionally, because there is usually an opportunity cost as-
sociated with consumptive water use, intra-annual variability in water resources should be considered in decision-making. Improved robustness of water footprints, which measure water consumption, can be informed by expectations of availability, especially where consumption alternatives exist and generation of greenhouse gas emissions are regulated. By coupling skillful hydroclimate forecasts with footprint frameworks, decision-makers can account for water use as a function of greenhouse gas emissions, water use efficiency, and make scarcity-based decisions prior to expected anomalous hydrologic conditions.

2 Electricity-Water Nexus

Climate change and reduced water availability inhibit the production of electricity. Higher temperatures increase peak-load demands for space conditioning, while also reducing the thermal capacity of transmission lines (Ke et al., 2016). Additionally, climate change increases ambient temperatures that, as a result, increase the temperature of cooling water, reducing efficiency of power plants across the globe. For more information, Sanders (2015) provides a comprehensive review on the electricity-water nexus. A recent study projects 6.3-19% and 4.4-16% decrease in capacity of power plants due to climate change in Europe and US, respectively based on simulated river flows and daily temperatures (Van Vliet et al., 2012). Miara et al. (2017) estimate that 99% of power plants in the US show some reduction in available capacity associated with climate change. The number of regions experiencing power reductions due to water stress is expected to increase across Europe, particularly in the Mediterranean (Behrens et al., 2017). Hydroelectric power is also highly determinant on water availability within a region. Studies on the vulnerability of hydroelectricity to a changing climate span globally including, the Mekong River Basin (Chowdhury et al., 2020, 2021), Zambezi River Basin (Yamba et al., 2011), Yangtze River Basin (Zhong et al., 2020), Colorado River Basin (Kopytkovskiy et al., 2015), and others.

Despite the clear relationships between electricity generation and water resources, there is still a need to integrate the two sectors for decision-making (Sanders, 2015). For example, water availability is not generally considered as part of the United Kingdom’s energy strategy (Byers et al., 2014). With a business-as-usual case across the United States, demands for water in the power sector are expected to increase 30% over a 20-year planning horizon (Tidwell et al., 2016). These water demands become a constraint to electricity generation and transmission and could drive the use of non-fresh water sources for power plant cooling, such as reclaimed water (Barker & Stillwell, 2016). There are several regional examples of water-for-electricity across the globe. Water consumption of thermoelectric power plants in Spain is projected to increase 25% by 2030 from a 2005 baseline (Carrillo & Frei, 2009). In the United States, water consumption rate has remained relatively constant, while increased electricity demand has increased overall water demands (Peer & Sanders, 2018). Enhanced analysis of the electricity-water nexus within the scope of climate change and global climate phenomena offer opportunities for better decision-making of utilities under future water availability concerns.

3 Water Footprints and Seasonality

A common metric to evaluate the impact of energy on the water sector is the concept of water footprints. Water footprints are a life-cycle metric that accounts for the water consumed along the supply chain of a product (Allan, 1998; Hoekstra & Chapagain, 2006, 2008; Hoekstra et al., 2011). The water footprint framework establishes both blue (surface and groundwater), green (rainfall), and grey water footprints (volume needed to assimilate pollutants). Water footprints are generally described at the annual scale for energy systems (Chini & Stillwell, 2018; Okadera et al., 2015; Zhang et al., 2020) with a few exceptions. For instance, recent studies of the electricity grid in Europe investigated the virtual trade of water footprints between countries at a monthly scale (Chini
& Stillwell, 2020) and at a finer resolution to identify impacts of COVID-19 lockdowns (Roidt et al., 2020). Additionally, monthly grey water footprints (that account for thermal pollution) were analyzed for thermoelectric power generation in the United States (Chini et al., 2020). However, even within these intra-annual studies, static water footprint factors of electricity are assumed.

Therefore, the opportunity of water footprints exists in moving away from a static water footprint for electricity. Instead these water footprints can be informed based on their seasonal and long-term variability. To increase the utility of water footprints, there is a need to investigate seasonality of water footprints both for thermoelectric and hydroelectric power (Gaudard et al., 2018). Understanding the seasonal cycles of water footprints for electricity would facilitate pairing with season-ahead forecasts and climate models to determine the risk of electricity generation to water consumption demands. Disaggregated or seasonally adjusted water footprints would also enable greater understanding of regulatory impacts from thermal pollution that are often seasonally adjusted (Logan & Stillwell, 2018). For example, Liu et al. (2017) identifies an increased need for thermal pollution variations in the United States with climate change. Finally, Chowdhury et al. (2021) identified that Thailand imports nearly 90% of the electricity production of Laos. As electricity is often exchanged across country (Chini & Stillwell, 2020; Peer & Chini, 2020) or regional (Chini et al., 2018) boundaries, consumption of electricity indirectly impacts the water availability in another location. The coupling of exchanged water footprint models with informed seasonal assessments of the water impacts of electricity allows finer resolution of coupled resource decision-making.

Establishing these seasonal assessments of water footprints for electricity are not without their challenges. For example, in determining the water consumption of hydroelectricity, it is often difficult to attribute across multiple purposes or uses of the reservoir (Grubert, 2016; Bakken et al., 2017). Additionally, data are often limited on a global scale with many global analyses relying on data from the United States (Spang et al., 2014). Therefore, before water footprints can be coupled holistically with climate change and global climate phenomena, there is still work to be completed in identifying seasonal variations of electricity’s water demand.

4 Global forcings and seasonal hydroclimatological variability: From Forecasts to Footprints

Combinations of antecedent global atmospheric phenomena and local conditions have proven skillful in the prediction of the hydroclimate and streamflow at various spatiotemporal resolutions, from global (Zimmerman et al., 2016) to regional (J. Delorit et al., 2017), and the subseasonal to seasonal scales (Robertson et al., 2015). Only recently have these forecasts been coupled with sectoral economic models, decision support tools, agent-based social simulators, and robust optimization frameworks as a means of translating skill to operational value (Giuliani et al., 2020; J. D. Delorit et al., 2019; Ziervogel et al., 2005; Anghileri et al., 2016). Hydroclimate forecasters explore tradeoffs between forecast lead and model skill, to maximize the value of information provided to stakeholders.

The focus on coupling forecasts with decision models has contributed to a number of interdisciplinary studies, and the establishment of several nexuses, including that of food-energy-water (D’Odorico et al., 2018). Hydroclimate forecasts have been primarily applied to reservoir operating policies for agriculture, flood control, and municipal water supply (Alexander et al., 2019; Yang et al., 2020; J. D. Delorit & Block, 2020). Typically water’s value in nexus discourse is expressed in economic or non-economic demand terms, e.g., profit, flood losses avoided, unsatiated water demand. The success of these efforts, and evidence of forecast uptake by decision-makers point to the operational value of these models.
Hydroclimate or streamflow forecasts have been applied to electricity generation and water footprinting, but are minimal outside of hydropower, likely because water is considered a complementary input, e.g., cooling (Okadera et al., 2014; Peer & Sanders, 2016; Chowdhury et al., 2020). However, given the relevance of footprinting to electricity-generation and associated greenhouse gas emissions, expressing the value of hydroclimate forecast information in the water footprint of energy production could aid in (1) overcoming climatology-based water factor assumptions, (2) informing water-intensive electricity generating policy, and, ultimately, (3) leaning forward on the objectives of the Paris Accords.

5 Opportunities for the Water Footprints in the Electricity Sector

Future iterations of the water footprint of electricity should seek to enhance the robustness of the metric’s decision-making capabilities. We suggest two opportunities for future assessments of the electricity-water nexus. (1) Increase the temporal resolution of water footprints using non-static seasonal or sub-annual values to better facilitate correlations with natural hydrologic cycles. (2) Incorporate climate models and forecasting to footprint metrics at the seasonal or sub-annual scale to increase robustness of water footprints as a decision-making tool. In conclusion, we end with this question: what opportunities are available with skillful forecasts of water footprints in the electricity sector?

Data Availability

Data were not used, nor created for this research.

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