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The water consequences of a transitioning US power sector

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HIGHLIGHTS

- Shifts in cooling water use due to recent US power sector transitions are studied.
- New natural gas combined cycle units have significantly reduced water withdrawals.
- Increases in dry cooling and reclaimed water have reduced freshwater use for cooling.
- Troubling trends include increases in groundwater for power plant cooling.
- Changes in cooling water usage vary significantly across watersheds.

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ABSTRACT

The US power sector is in a state of transition, prompted by significant shifts in technological innovations, energy markets, regulatory structures, and social pressures. As the electricity generation fleet changes, so too does the spatial & temporal distribution of the cooling water requirements for power plants. However, to date, these impacts have yet to be quantified. This study uses power plant-specific fuel consumption, generation, and cooling water use data to assess changes in the water withdrawn and consumed by thermoelectric power plants across 8-digit Hydrologic Unit Code (HUC-8) watersheds between 2008 and 2014. During this period, a few prominent trends are noted, including transitions in generation from coal-fired steam to natural-gas combined cycle units, from once-through cooling to wet recirculating towers and dry cooling systems, and from traditional fresh and saline surface cooling water to reclaimed water and groundwater sources. Total US cooling water withdrawals and consumption volume decreased from 2008 to 2014. The average water withdrawn per unit of electrical output decreased over this time, while changes in water consumption rates stayed relatively flat. Changes in water use at the watershed scale were unevenly distributed, as some water-scarce regions experienced increases in cooling water usage for thermal power plants, while others experienced significant water reductions and environmental benefits, especially where coal-fired generation was retired or retrofitted. The results from this study underscore the importance of evaluating water withdrawals and consumption at local spatial scales, as the water extraction, water quality and environmental health consequences of power plants on downstream users are non-uniform.

1. Introduction

Recent shifts in resource availability, economics, environmental policy and public opinion have prompted large transitions in the US electricity generation fuel mix [1,2]. Between 2005 and 2015, domestic natural gas production increased by almost 40% largely due to advances in horizontal drilling and hydraulic fracturing techniques used for US shale gas extraction, putting downward pressure on natural gas fuel costs and prompting large investments in natural gas-fired generation units [3]. This growth in natural gas-fired generation, as well as renewable electricity in recent years, has reduced the competitiveness of coal-fired and nuclear power plants in many US regions.

These technological and market transformations across the power sector have translated into environmental consequences that have yet to be quantified. Although a growing body of literature has addressed the emissions ramifications of increasing natural gas-fired and decreasing coal-fired generation [4,2,5,6], much less analysis in the literature has been dedicated to assessing how recent fuel transitions in the power sector have affected US water availability or water quality at the national level.

Recent studies have analyzed the cooling water tradeoffs that follow more general shifts in fuel use [7–9], pollution controls [10–14],

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cooling system technologies [15–18], environmental fees [19], and generator dispatch order [20–22]. Grubert et al. (2012) completed a detailed comparison of the water intensity of natural gas and coal extraction, cooling for electricity production, and emissions controls at fossil-fueled power plants in Texas using the peer-reviewed literature and government data. The researchers note that the efficiency benefits of switching coal-fired power plants to natural gas combined cycle offer the potential for a 60% reduction in annual freshwater consumption, even given the water-intensity of hydraulic fracturing for the natural gas fuel [7]. Stillwell et al. (2011) assessed the reduction in water diversions for thermal power plant cooling in Texas from switching traditional once-through cooling systems to alternatives such as recirculating towers or dry cooling using a water availability model from the Texas Commission on Environmental Quality. The authors noted potential reductions in annual diversions up to 700 million m^3 from switching from coal-fired to natural gas-fired combined cycle power plants, which could contribute to increased stream flow and reduced water stress along the Texas Gulf in particular [15]. Another study by Tidwell et al. (2014) assessed the transition of the whole US thermoelectric fleet to alternative cooling water sources (dry cooling or wet cooling using reclaimed water) to achieve zero freshwater withdrawals using a custom algorithm incorporating cost models, geographic proximity to water resources, and resource availability. The results suggest that retrofits could be beneficial in the East by reducing plant vulnerabilities to thermal discharge limits and in the West by reducing freshwater consumption during times of drought or reduced water availability [18]. Similarly, a case study by Stillwell and Webber (2014) investigated the potential of utilizing reclaimed water as a cooling source for thermoelectric power plant cooling in Texas using a geospatial multi-criteria analysis. They found that over 60% of thermoelectric capacity in the state is located within 25 miles of a reclaimed water source and could be feasibly retrofitted to help alleviate water availability concerns [23].

A recent body of work has also evaluated the long-term water use impacts of various electricity futures. In 2008, the Department of Energy (DOE) completed a report estimating the volumes of freshwater required to meet future electricity demand based on five scenarios defined in the US Energy Information Administration's (EIA) 2008 Annual Energy Outlook forecast. With the exception of the business-as-usual scenario (i.e. no changes), all case studies showed decreases in water withdrawals and increases in water consumption for thermoelectric cooling, largely due to transitions away from once-through cooling and towards recirculating cooling [24]. Clemmer et al. (2013) modeled low-carbon electricity futures through 2050 using the Regional Energy Deployment System (ReEDS) model developed by the National Renewable Energy Laboratory (NREL) to calculate changes in national and regional cooling water use, finding that investments in energy efficiency and renewable energy technologies resulted in considerable water savings over other technology-based investments, such as carbon capture and sequestration [25]. Another study modeled changes in cooling water usage using a GAMS optimization model to estimate water withdrawals and consumption at thermoelectric, non-thermoelectric, and dry-cooled facilities based on energy portfolio scenarios developed by NREL for high renewables penetration and a scenario retrofitting all existing wet cooling systems to recirculating cooled systems through 2050. The study found that significant water withdrawal and consumption reductions are achieved under the high renewable energy scenario, while only water withdrawal reductions are achieved in the second scenario but at the expense of increased water consumption [26]. In another study that evaluates changes in the electricity fleet through 2095 using an integrated assessment model (GCAM) to investigate the electric sector's global water demand, water withdrawals remained relatively constant over the five scenarios examined (i.e. three climate change futures and two strategic technology improvement scenarios), mainly due to the retirement of once-through cooling systems [27]. The water use implications of a global 2 °C warming policy (by end of century) were analyzed by Fricko et al. (2016) using a global integrated assessment model. The authors found that noticeable reductions in water withdrawals are achieved if large transitions toward recirculating cooling systems occur, but water consumption increased for all electricity futures analyzed [28]. On a smaller spatial scale, the influence of 2 °C of warming, prolonged drought, and population growth on water use until mid-century in the southwestern US showed a continued or increased reliance on fossil fuels in the business as usual and Annual Energy Outlook scenarios, leading to greater water stress. Conversely, carbon policy, renewable energy integration, and increased energy efficiency led to decreased water stress and carbon emissions [29].

Despite the large changes that have occurred to the US generation fleet recently, no study to the authors' knowledge has evaluated the cooling water tradeoffs resulting from these transitions at the national scale. This research fills this knowledge gap by evaluating how recent shifts in thermoelectric power generation affected the spatial and volumetric distribution of US cooling water withdrawals and consumption between 2008 and 2014.

2. Methodology

Self-reported data by power plant operators from EIA forms 923 [30,31] and 860 [32,33] were used to characterize US power plants and their respective generation units in the years 2008 and 2014. Power plant operators are required to complete these forms for all plants of 1 MW capacity or greater that are connected to a regional power grid [34].

EIA Form 860 details power plant locations (i.e. latitude and longitude), as well as power plant cooling system information including cooling system ID number and cooling water source type (i.e. surface water, groundwater, plant discharge water, etc.). In some cases, cooling water source type data were missing, but information was available on the physical source (i.e. wells, rivers, ocean, etc.), which enabled an adequate estimation of cooling water source type for many of these plants. Information on cooling water quality (i.e. freshwater, reclaimed water, saline water, etc.) was only available for 2014 power plants. Although all power plant operators are required to report generation, fuel use, and boiler information for generating units with capacity 1 MW or greater, they are not explicitly required to report volumetric water usage via the EIA 860 form unless they have a capacity of 100 MW or greater. While annual cooling water usage data in 2014 were relatively abundant, these data for 2008 are considerably less complete [32,33,30,31]. In addition, there is no streamlined methodology imposed upon power plant operators for data collection to ensure consistent reporting of water use. Consequently, many facilities use different methodologies for measuring water withdrawals, consumption, diversions, and discharge [35].

EIA Form 923 details electricity generation unit technology, fuel type, combined heat and power (CHP) status, and annual generation for operational units at each US power plant. When applicable, this form was also used to cross-check and identify missing cooling system and water source data from the EIA 860 form. Each unit operating at a thermoelectric power plant requiring a cooling system was categorized by fuel type, generation technology, CHP status, cooling technology, and cooling water source type. Full details of this categorization procedure are documented in Peer and Sanders (2016) [36].

Plant-specific cooling water consumption and withdrawal factors (i.e. rates in gallons/MWh) calculated by Peer and Sanders [36] using EIA's 2014 water usage data were applied to power plants based on generator technology (i.e. fuel type, prime mover type, and cooling system type) when all units within the plant reported a single fuel, prime mover, and cooling system. These water use factors were applied consistently to power plants that were operating in both 2008 and 2014 and/or only in 2014 (i.e. new power plants). The Union of Concerned Scientists' (UCS) vetted database of 2008 water use at thermal power