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LETTER

Quantification of the water-use reduction associated with the transition from coal to natural gas in the US electricity sector

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Abstract
The transition from coal to natural gas and renewables in the electricity sector and the rise of unconventional shale gas extraction are likely to affect water usage throughout the US. While new natural-gas power plants use less water than coal-fired power plants, shale gas extraction through hydraulic fracturing has increased water utilization and intensity. We integrated water and energy use data to quantify the intensity of water use in the US throughout the electricity’s lifecycle. We show that in spite of the rise of water use for hydraulic fracturing, during 2013–2016 the overall annual water withdrawal (8.74 × 10^10 m^3) and consumption (1.75 × 10^9 m^3) for coal were larger than those of natural gas (4.55 × 10^10 m^3, and 1.07 × 10^9 m^3, respectively). We find that during this period, for every MWh of electricity that has been generated with natural gas instead of coal, there has been a reduction of ~1 m^3 in water consumption and ~40 m^3 in water withdrawal. Examining plant locations spatially, we find that only a small proportion of net electricity generation takes place in water stressed areas, while a large proportion of both coal (37%) and natural gas (50%) are extracted in water stressed areas. We also show that the growing contribution of renewable energy technologies such as wind and solar will reduce water consumption at an even greater magnitude than the transition from coal to natural gas, eliminating much of water withdrawals and consumption for electricity generation in the US.

1. Introduction
The advent of hydraulic fracturing fundamentally transformed the electric power sector of the US, allowing natural gas to displace coal as a major energy source in the electricity sector. While in the 2000s the share of electricity generated with coal was more than three times the fraction generated by gas (52% coal, 16% natural gas), in 2015 natural gas overtook coal as the primary electricity generating resource. In 2016, natural gas was up to 32% while coal was 30% of the energy sources for the US electricity sector (figures S1 and S2 is available online at stacks.iop.org/ERL/14/124028/mmedia) [1]. Since 2000, only 58 new coal-fired generators with a combined capacity of 19 300 MW have come online, while 3075 new natural gas generators with a combined capacity of 333 000 MW (of which 1231 were natural gas combined cycle (NGCC) generators with total capacity of 225 000 MW) have been installed [2, 3].

Despite the shift in source of energy generation, a majority of electricity generation in the US still derives from water- cooled systems. Approximately 40% of the total water withdrawn in the US is used for cooling thermal power plants [4]. The large volume of water utilized by this sector, compounded with climate change, growing population, degradation of water quality, as well as other factors, may exacerbate future water availability problems [5–7]. Reduced water availability could also have important implications for reliability of the electric power sector, as suggested by 18 episodes from 2000 to 2015, when coal plants were unable to generate electricity because of insufficient or high-temperature water supplies [8, 9]. In almost all incidents the curtailments happened in the summer months during drought periods.
The literature examining the water-energy nexus over the past decade has grown substantially, with a focus on electricity generation constraints due to impacts of climate change and water stress [5, 9–16]. Assuming the same electricity generation profile of today, it has been estimated that water consumption in the southwest US will increase 3%–7% by 2095 [17]. However, rapid changes in the electricity sector, including increased utilization of wind and photovoltaic energy, along with retrofits of thermal plants with dry cooling systems, suggests that water consumption could rather decrease by up to 50% [17].

Recent reports examining the threats that climate change pose to the future US economy highlight the reduction in CO₂ emissions that could be achieved by decommissioning coal plants [8, 12, 17–20]. Nonetheless, with natural gas becoming the predominant energy source for the electricity sector, the intensification of shale gas production in the US, and the significant increase in the intensity of water consumption of this process [21], raises questions about the implications of the transition from coal to natural gas on water availability.

Here, we examine water-use changes derived from the ongoing transition from coal to natural gas in the US electricity sector, taking into account the intensification of water use for hydraulic fracturing and shale gas extraction. We analyzed historical energy and water-use data to quantify the water intensity of coal relative to natural gas for different power generation and cooling technologies, and in this way examined the water-footprint of systems with different shares of both natural gas and coal. While other studies have quantified the water intensity of power generation [22–24], and the water intensity of the transitioning US power sector [25–27], this study, for the first time integrates these components, in addition to extrapolating the long-term water impacts under different future generation scenarios. This study also includes critical water components from the upstream (i.e. mining, hydraulic fracturing) processes. The water intensity of electricity generation reflects the amount of water directly and indirectly consumed or withdrawn throughout the life-cycle of electricity, divided by the amount of net electricity generation in a plant (m³ MWh⁻¹), and it includes water use at both the power plant and at all upstream processes. At the power plant level, water withdrawn is water taken out of a reservoir for cooling and plant operation purposes, while water consumption is the difference between withdrawal and discharge volumes, reflecting losses due to evaporation, leakage, or recharge to the deep subsurface. Upstream of the power plant, energy production uses water directly in coal mining, drilling, hydraulic fracturing, transportation, and refinement of coal and natural gas, while also indirectly using water as a product embedded in the fuels and electricity used in these upstream processes. In addition to the evaluation of the water footprint of electricity generated with natural gas and coal, we examine the effects of the evolution of power plant cooling technologies including one through recirculating, and dry cooling, showing that from 2013 to 2016 both total water consumption (TWC) and withdrawal volumes for electricity generation in the US have decreased despite constant electricity net generation.

2. Methodology

2.1. Data collection

Forms EIA 860 and EIA 923 were downloaded from the EIA website for 2013–2016 [2, 3]. Previous years were available, but data quality concerns prevented them from being used in this analysis [22, 25]. Wide ranges on median values reported here (figure S3) are likely caused by variations in plant operations, cycling and idling [28]. Summary of data values for downloaded years match well with other literature values, providing confidence in the results reported in this study (see tables S1 and S2) [22, 24].

2.2. Data organization

Plant technology was classified based on EIA 860, form 3_1_Generator_Y20XX using a combination of ‘Prime Mover’ and ‘Energy Source 1.’ For generators using coal as the primary energy source, generators were classified as ‘subcritical,’ ‘supercritical,’ or ‘ultra-supercritical’ based off of columns in 3_1_Generator_Y20XX indicating these fields. Integrated gasification combined cycle coal plants were identified by their fuel source, coal-derived synthesis gas, ‘SGC.’ Natural gas plants were divided into combined cycle, steam turbine, and combustion turbine. Because combustion turbines do not use water as part of a steam cycle, they were not included in this analysis, except in scenarios where total net generation was quantified. Plants burning both coal and natural gas in many cases used different cooling towers for their natural gas burning equipment than for their coal burning equipment. In cases where natural gas and coal plants used the same cooling tower, water consumption and withdrawal were divided based on their proportion of net generation. Finally, while plants may use alternative sources of water with fresh ground and surface water accounting for approximately 70% of total water withdrawals (TWWs) and the remainder of water coming from brackish or saline water, we do not distinguish between water source in this study [22].

In this study we did not include several lifecycle components including the water footprints of plant zoning and construction, in addition to the water footprints for the manufacturing of plant parts, mining equipment, and transportation equipment. We also did not include pond cooling as a distinction within once through and recirculating plants. While pond cooling systems can operate similarly in either once
through or recirculating systems, we classified these based on their overarching once through or recirculating distinction [23]. Carbon capture and storage (CCS) is a technology that is being considered in a number of regions across the United States. CCS systems can greatly increase the water consumption and withdrawal for plants using the technology [12, 23, 26, 29, 30]. Currently the adoption of CCS is not widespread, so in this study we did not include estimates of any potential CCS additions. Finally, we did not consider water use for coal ash and wastewater management associated with coal mining and natural gas extraction.

2.3. Upstream and total water use calculations

In order to calculate the overall life-cycle water use of electricity generated from coal and natural gas, we estimated the water intensity of the processes that are upstream of the power plants, which include mining, drilling, transportation and processing of coal and natural gas. To this end, we used data from the Unit Process Library provided by the National Energy Technology Laboratory (NETL), which presents a life-cycle inventory of both energy and material movements from cradle to gate and grave for a number of industrial processes [31]. We accounted for direct (i.e. water physically used in the processes) and indirect water used (water used to generate the electricity and diesel fuel to operate machinery that are inputs to the processes). We define the water use derived from the combination of all of these processes as upstream water consumption (UWC, in cubic meters, tables S1–4, equations below and see supplemental data file).

Upstream water consumption and water withdrawal intensity were calculated using a combination of indirect and direct water uses in the mining, processing, and transportation of coal and natural gas. Because there was no distinction between water consumption and water withdrawal within the datasets utilized in this project, we assume that in all upstream processes, water consumption is equal to water withdrawal. Because of this assumption, actual upstream withdrawal and consumption could differ slightly from estimated values reported in this study. For coal, the following equation describes the upstream water use:

\[
UWC_{\text{Coal}} = WCCM_{\text{mt}} \times VC_{\text{mt}} + WCCC \times VC_{\text{Total}} + CTT \times VC_{\text{Total}} + E_p \times VC_{\text{Total}} \times EI + VC_{\text{Total}} \times VD_{\text{Total}} \times VC_{\text{Total}} \times EI + VD_{\text{Total}} \times DF \times EI,
\]

where WCCM is water consumption from coal mining for both surface and underground mines (mt = surface or underground) in m³ kg⁻¹ coal, VC is the volume of coal sent to power plants originated from surface and underground mines (mt, tables S1–4), WCCC is water consumption from cleaning coal (WCCC) in m³ kg⁻¹ coal, CTT is water consumption for transportation of coal (CTT) in m³ kg⁻¹ coal.

Indirect water use is calculated by multiplying \(E_p\), the electricity used in each upstream processes (MWh kg⁻¹ coal) by the water intensity for electricity generation of the electricity grid (m³/MWh⁻¹) calculated using an input-output model to iterate the additions of upstream processes to power plant level water consumption and withdrawal. \(V_D\) is the diesel fuel used onsite to power mining and transportation equipment (in kg diesel kg⁻¹ coal), \(DI\) is the water intensity for diesel fuel extraction (m³ of water per kg diesel) and \(DF\) is the electricity requirement for a petroleum refinery (MWh kg⁻¹ diesel).

Similarly, for natural gas, we repeated this calculation:

\[
UWC_{\text{NG}} = WCNG_{\text{DrillType}} \times VNG_{\text{DrillType}} + VD_{\text{Total}} \times VNG_{\text{Total}} \times DI + VD_{\text{Total}} \times DF \times EI + E_p \times EI \times VNG_{\text{Total}}
\]

where the water consumption for natural gas generation is split up between offshore, onshore conventional, and onshore unconventional (shale gas) drilling. Further, due to recent increasing trends in water use for hydraulic fracturing (unconventional natural gas drilling), we further split WCNG_{DrillType} up by year. Indirect consumptive processes included diesel used for well construction \(V_D_{\text{Total}}\) (kg diesel/MCF NG) and electricity for well drilling, liquid separation, compression, and pipeline transport.

Plant level water consumption and withdrawal was determined from the downloaded EIA data and was added to UWC to calculate the TWC and TWW respectively:

\[
TW(C \lor W) = \text{PlantLevel}(C \lor W) + UWC_{\text{NG/Coal}}
\]

Alternative water sources are beginning to be utilized for some of these upstream processes including the reuse of hydraulic fracturing fluids and produced water in subsequent wells [7, 32]. Despite this, we did not distinguish between fresh, saline, and reclaimed water for upstream processes in this study.

3. Results and discussion

3.1. Water use for fuel extraction, processing and transportation: volume and intensity

By adding the direct and indirect water consumption estimates for fossil fuel extraction, transportation and refinement, we estimate upstream water consumption of coal as 0.60 m³ MWh⁻¹, while natural gas upstream processes consumed 0.18 m³ MWh⁻¹ in 2016 (figure 1, tables S3, S5). From 2013 through 2015 water consumption intensity for coal upstream processes increased before falling in 2016 (from 0.60 m³ MWh⁻¹ in 2013 to 0.66 m³ MWh⁻¹ in 2015 and back down to 0.60 m³ MWh⁻¹ in 2016), while the water consumption intensity of natural gas upstream processes increased only by 0.03 m³ MWh⁻¹ (from 0.15 m³ MWh⁻¹ in 2013 to 0.18 m³ MWh⁻¹ in 2016,
The water withdrawal intensity for coal and natural gas both decreased from 2013 to 2016 (3.59 m$^3$ MWh$^{-1}$ in 2013 to 3.29 m$^3$ MWh$^{-1}$ in 2016 for coal, and from 2.03 m$^3$ MWh$^{-1}$ in 2013 to 1.80 m$^3$ MWh$^{-1}$ in 2016 for natural gas, figure 2). Because we included both direct (water use for the process) and indirect (water used to produce the electricity used in fuel extraction) water consumption and withdrawal in our estimates, values of upstream water consumption and withdrawal are higher than those previously reported (table S5) [4, 24]. Calculations for the upstream processes can be seen in the Methods section and SI.

3.2. Water use for power plant operations: volume and intensity
In 2016, coal combustion accounted for 30% of the total US electricity generation, while natural gas accounted for 34% (figures S1 and S2) [11]. Nonetheless, given that the water-consumption intensity of natural gas is lower than that of coal, the total volume of water consumed at coal-fired power plants ($1.75 \times 10^9$ m$^3$) was almost twice as much as the water consumed at coal natural gas power plants ($1.07 \times 10^9$ m$^3$) (figures 1, 2) [2, 3]. Moreover, during the 2013–2016 period, the gap between water use efficiency of coal compared to natural gas widened; as the water consumption intensities of coal-fired power plants did not change through time, those of natural

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**Figure 1.** Water consumption and withdrawal intensities (top) and volumes (bottom) broken down by the upstream and at plant water use processes. Percentage values in upper charts reflect the proportions of the water intensity in the upstream processes relative to the water intensity of cooling thermoelectric plants. Upstream processes such as mining and transportation play a significant role in the water consumption, while representing only a small proportion of water withdrawals.

**Figure 2.** Total plant level water consumption (A) and water withdrawal (B) volumes of electricity generated with coal (gray) and natural gas (red) in the United States from 2013 to 2016. Future projections were calculated by multiplying 2016 consumption intensity (C) and 2016 withdrawal intensity (D) by EIA estimates for reference case electricity generation from 2017 through 2030 (11). These values are based on integrating water use intensities for both power plant cooling upstream water use for the extraction of the fossil resources. Solid lines (in panels (C) and (D)) replicate the EIA’s reference case scenario for the electricity mix in the US, while dash lines replicate the EIA’s $15 \text{ carbon allowance scenario in which coal generation decrease by 69% while natural gas generation increases by 30% from 2016 to 2030}$ (11).
gas plants decreased. Likewise, the withdrawal intensity of coal-fired plants increased and those of natural gas plants decreased. The average water consumption intensity for coal power plant operations (i.e. the average volume of water (m$^3$) consumed by power plants to generate 1 MWh of energy) has slightly dropped, from 1.41 m$^3$/MWh$^{-1}$ in 2013 to 1.35 m$^3$/MWh$^{-1}$ in 2015 (figure 1). Over that same time period, the average water consumption intensity for natural gas generation decreased from 1.26 m$^3$/MWh$^{-1}$ to 0.78 m$^3$/MWh$^{-1}$. Water withdrawal intensity for coal increased from 67.20 m$^3$/MWh$^{-1}$ in 2013 to 70.56 m$^3$/MWh$^{-1}$ in 2016, while withdrawal intensity for natural gas has decreased from 52.42 m$^3$/MWh$^{-1}$ in 2013 to 33.07 m$^3$/MWh$^{-1}$ in 2016 (figure 1). Values reported in this study compare favorably with those published in previous studies (table S6).

The total volume of water consumed for cooling coal plants has been steadily declining since 2014, due to the significant reduction in electricity generation from this fuel (figures 1, 2, S1). Over the same time period, TWC for cooling natural gas plants has also decreased, reflecting the addition of newer, more efficient NGCC plants to replace older steam turbine fueled NG plants and retiring coal plants (figure 2). The reduced water intensity of natural-gas fired power plants, together with the replacement of a number of once through cooled coal plants with combined cycle natural gas plants using recirculating water-cooling systems, have caused a decline in water consumed and withdrawn to generate electricity from 2014 through 2016 (see Supplement Information for description of the different types cooling systems) [27]. Finally, we find that if all the electricity generated with coal plants in 2016 (1.24 × 10$^{10}$ MWh) had been generated with natural gas using the average natural gas water intensity for 2016, that would have resulted in reductions of as much as 1.30 × 10$^{9}$ m$^3$ of water consumption and 4.83 × 10$^{10}$ m$^3$ of water withdrawal (figure S4).

3.3. Combined power plant and upstream water consumption and withdrawal

Taking the upstream estimates together with the average volume of water used at power plants in 2016, we find that upstream water consumption accounts for 30% of the TWC intensity of coal-fired electricity, while representing only 19% of TWC intensity for natural gas. Due in large part to the intensification of hydraulic fracturing and shale gas extraction during this period [21], UWC of natural gas increased from 11% of total natural gas water consumption in 2013 to 19% in 2016. We find that combined upstream and at plant processes for coal-fired electricity has been responsible for 2.49 × 10$^{9}$ m$^3$ of water consumption in 2016, down from 3.20 × 10$^{9}$ m$^3$ in 2014. Upstream coal processes in 2016 represent 30% (7.41 × 10$^{8}$ m$^3$) of the total consumption, while plant operations represent 69% (1.75 × 10$^{9}$ m$^3$). In comparison, natural-gas fired electricity in 2016 accounted for 19% (2.49 × 10$^{8}$ m$^3$) of total water consumed (1.32 × 10$^{9}$ m$^3$), which increased from 2013 (1.68 × 10$^{9}$ m$^3$, figure 1). In 2016, average water consumption at natural-gas fired power plants was lower than in 2013 (figures 2, 1.41 × 10$^{9}$ m$^3$ in 2013 to 1.07 × 10$^{9}$ m$^3$ in 2016), however, the increase in upstream consumption most likely from the intensification of hydraulic fracturing [21], slightly offset this reduction (figure 1). Withdrawals for coal were down from 1.13 × 10$^{11}$ m$^3$ in 2014 to 9.15 × 10$^{10}$ m$^3$ in 2016, while the withdrawals for cooling natural gas plants in 2016 (4.80 × 10$^{10}$ m$^3$) were lower than estimated in 2013 (6.11 × 10$^{10}$ m$^3$), despite an increase from 2014 to 2015 (figure 1). Upstream processes made up a much smaller portion to TWWs (from 4% to 5% for both coal and natural gas). For every MWh of electricity generated in 2016, the conversion to natural gas from coal results in a reduction of 1.05 m$^3$ for water consumption and 38.98 m$^3$ for water withdrawal.

3.4. Projections of future water use

To predict future water use in the United States, we compared several scenarios (which can all be explored using the supplemental data sheet). Future electricity net generation was taken from the 2018 EIA annual energy outlook [11], which estimates the breakdown of primary fuel type in the US through 2030. In the EIA’s reference case scenario, coal and natural gas proportions and net generation (in MWh) in the mix will remain constant for the next 15 years (figure 2) [26]. If one assumes that coal and natural gas water consumption and withdrawal intensities (in m$^3$/MWh$^{-1}$) remain as calculated for 2016, we project steady unchanged plant level volume water consumption and withdrawals through 2030 (figure 2) [11]. In addition to this ‘business as usual’ scenario, the trend of replacements of old coal-fired subcritical power plants with NGCC should continue into the future and will result in an even larger water consumption and withdrawal reductions (see supplemental information). To capture the current trend in power generation, we used a second scenario from the 2018 EIA annual energy outlook, which has an estimate of future coal production, where a $15 carbon allowance fee is instituted [11, 26]. This scenario has a 69% decrease of coal generation from 2016 to 2030, while natural gas generation increases by 30% (figure 2) and is the closest EIA scenario to the actual observed trend between 2013 and 2016. Keeping water consumption and withdrawal intensities at 2016 levels, we estimate that by 2030, 1.83 × 10$^{9}$ m$^3$ water consumption and 6.71 × 10$^{9}$ m$^3$ water withdrawal will be reduced with respect to the reference scenario. We further estimate that a scenario of which 100% of coal-fired power plants were replaced with natural gas combined cycle power plants with recirculating cooling would result...
in a reduction of \(4.72 \times 10^{10}\) m\(^3\) per year of water withdrawals, and \(1.28 \times 10^9\) m\(^3\) of water consumption (figure S4). For comparison, these water savings are respectively equivalent to 232% and 6% of the total water use for the industrial sector in the US in 2015 \((2.04 \times 10^{10}\) m\(^3\) per year) [33]. These reductions would occur if water withdrawal and consumption for upstream processes account as in 2016, for less than 19% of the water used throughout the life-cycle of natural-gas fired electricity, which makes the total life-cycle water intensity of electricity from natural gas less than half of the intensity of electricity from coal (figure 2). The water benefits from this transition could be lower given that shale gas is becoming the major source of natural gas in the US (55% of shale natural gas use in 2016, up from 40% in 2013 [34]), and that water consumption intensity for hydraulic fracturing is increasing every year [21], but nonetheless would still be significant. If we assume that 2016 production were fueled entirely by shale gas, upstream water consumption would increase by 27% (from \(2.49 \times 10^8\) m\(^3\) to \(3.17 \times 10^8\) m\(^3\)).

### 3.5. Relationships between water use for energy and water stress

We evaluated regional water consumption and withdrawals for 2016 and compared them with estimates of water stress indicators across the US [14]. Water stress index levels were taken from the Aqueduct Water Stress Projections from WRI and can range from low (<10% of watershed water inputs are used) to extremely high (>80% of watershed water inputs are used). We find that both cooling technology in thermoelectric plants and their location in the US are favorable with respect to the goal of avoiding exacerbation of water stress. Thanks in part to the Clean Water
Act (316b) [35, 36], the majority (70%) of power plant generation in all regions is cooled through recirculating systems (figure 3) [14], and most of electricity generation takes place in areas deemed to have relatively low water stress. Currently, there is only marginally more net generation from natural gas than coal in high and extremely high water-stressed areas (1.56 × 10^8 MWh natural gas versus 1.42 × 10^8 MWh coal), with most plants being cooled using recirculating technology. Natural gas water consumption for plant operations in high and extremely high stress areas was 1.31 × 10^8 m³, accounting for only 11.6% of TWC for coal.

In contrast, a larger proportion of upstream water consumption for coal is located in water stress areas; 37% of coal mined in the US was extracted via surface mining in high or extremely high stressed areas, which infers upstream water consumption of 3.06 × 10^8 m³ out of 7.41 × 10^8 m³ TWC for coal in the US (41%, figure S5, table S7) [14, 37]. In contrast, about 50% of natural gas is generated in shale gas basins located in high or extremely high stressed areas, which has water consumption of 58% (1.45 × 10^8 m³ relative to 2.49 × 10^8 m³) of the total upstream water consumption for natural gas in the US (figures S6 and S7, table S8) [14, 21, 38]. If 100% of current natural gas generation was fueled by unconventional shale gas, and assuming that 44% of shale gas is generated in areas that are under high or extremely high-water stress, up to 1.38 × 10^8 m³ out of 3.17 × 10^8 m³ (43%) would be consumed in water stressed areas.

4. Future directions

Water intensity of electricity could increase if pollution control or carbon capture and sequestration (CCS) techniques are implemented to reduce emissions from fossil fuel plants [17, 26, 29, 30]. Previous studies of the water impacts of CCS implementation, have estimated an increase of 0.50 m³ MWh⁻¹ in water consumption and 0.73 m³ MWh⁻¹ increase in water withdrawal for supercritical pulverized coal plants at 40% carbon capture, and a 0.16 m³ MWh⁻¹ increase in water consumption for an NGCC plant at 40% carbon capture [29]. One of the mechanisms that could greatly reduce the water footprint of thermoelectric generation is switching from wet (once through and recirculating) to dry cooling plants. Switching from wet to dry cooling however is expensive with capital costs estimates of $83 million for a dry cooling system in a 600 MW gross NGCC plant versus $29 million for a wet cooled system [40]. Dry cooling systems also reduce plant efficiency and raise coal/natural gas resource consumption, which introduces a trade-off between increased carbon emissions and water use [40].

While the focus of this study is on the transition from coal to natural gas, the rising importance of renewable electricity sources such as wind and solar cannot be ignored. From 2013 through 2016, solar net generation has increased by 299% (from 9 million MWh in 2013 to 36 million MWh in 2016, figure S8), while wind net generation has increased by 35% (from 168 million MWh in 2013 to 226 million MWh in 2016, figure S8). Combined, solar, wind, and geothermal accounted for 7% of total net electricity generation in the United States in 2016, up from 5% in 2013 [1] and continues to increase through 2019. In 2019, the electricity generated by renewables energy became equal to that of fossil fuels [39].

Water consumption intensity for geothermal (0.86 m³ MWh⁻¹) is similar to the lifecycle water consumption intensity for natural gas [4]. Other studies have estimated a wider range of water consumption for geothermal (0.02–1.9 m³ MWh⁻¹) [23]. In contrast, solar photovoltaic (PV) and wind powered generation have much lower water consumption intensities. Water consumption and withdrawal for solar PV and wind generation use water for panel and blade washing, while the bulk of water use for geothermal electricity comes from steam fields, reservoir augmentation, and in some cases also cooling [4]. Grubert and Sanders (2018) [4] have estimated lifecycle water consumption for solar PV of 0.02 m³ MWh⁻¹, while wind has a lifecycle water consumption 0.001 m³ MWh⁻¹ (table 1). Combined, renewable electricity generation consumed 1.4 × 10^7 m³ of water in 2016 with the majority of that water coming from geothermal. Because there is no cooling involved with renewable generation (aside from solar thermal and some geothermal technologies), the water withdrawal intensities are similar to consumption intensities. This means that if renewable electricity generation replaces coal generation, the water consumption savings will be even greater than the transition to natural gas demonstrated in this study, while water withdrawals will be negligible compared to those of coal and natural gas (from 0.03 to 0.86 m³ MWh⁻¹ for renewables versus 34.8 m³ MWh⁻¹ for natural gas and 73.8 m³ MWh⁻¹ for coal, table 1). The widespread installation of renewable energy sources would therefore result in important and even more significant reductions in water intensity of US electricity.
Table 1. Comparison of 2016 water consumption intensities and water withdrawal intensities associated with natural gas, coal, nuclear, geothermal, solar, and wind [4].

| Energy source                | Lifecycle water consumption intensity of electricity generation (m$^3$/MWh$^{-1}$) | Lifecycle water withdrawal intensity of electricity generation (m$^3$/MWh$^{-1}$) | Source                  |
|------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-------------------------|
| Natural gas combined cycle (once through) | 0.22                                                                          | 87.43                                                                        | This study              |
| Natural gas combined cycle (recirculating) | 0.98                                                                          | 2.79                                                                         | This study              |
| Coal subcritical (once through) | 1.36                                                                          | 173.02                                                                       | This study              |
| Coal supercritical (once through) | 0.96                                                                          | 153.29                                                                       | This study              |
| Coal IGCC (recirculating)     | 1.92                                                                          | 5.20                                                                         | This study              |
| Coal subcritical (recirculating) | 2.51                                                                          | 5.80                                                                         | This study              |
| Coal supercritical (recirculating) | 2.12                                                                          | 6.49                                                                         | This Study              |
| Coal ultrasupercritical (recirculating) | 2.18                                                                          | 5.19                                                                         | This study              |
| Nuclear plant                | 2.00                                                                          | 93.60                                                                        | Grubert (2018)          |
| Wind                         | 0.001                                                                         | 0.001                                                                        | Grubert (2018)          |
| Solar                        | 0.02                                                                          | 0.04                                                                         | Grubert (2018)          |
| Geothermal                   | 0.86                                                                          | 0.86                                                                         | Grubert (2018)          |

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Data availability statement

Any data that support the findings of this study are included within the article.

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