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Research papers

Retirement of US fossil fuel-fired power plants will increase water availability

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ABSTRACT

Nearly two-thirds of fossil fuel-fired electricity generation capacity in the United States is expected to reach its typical end of life by 2035. While the closure of fossil fuel-fired power plants will help advance decarbonization goals, the cessation of water use for fossil fuel-fired power plant cooling - the largest water user in the US - will also impact the nation's water resources. We assess when, where, and how much water will be made available upon the expected retirement of the nation's nearly one thousand fossil fuel-fired power plants by combining a lifespan-based model of fossil fuel-fired generator retirements for the US fossil fuel-fired electricity generation fleet with a national-scale hydrologic model. We show that annual water withdrawals and consumption of fossil fuel-fired power generators will be significantly curtailed (85 % and 68 % reduction, respectively) by 2035 if these generators follow their typical retirement timeline. Most rivers with fossil fuel-fired power plants diverting and/or discharging water will have a net increase in annual streamflow after plant retirement (maximum decrease of 2 %, maximum increase of 57 % by 2050), with the most pronounced increases occurring in the summer months. The retirement of fossil fuel-fired power plants will lead to a large relative change (>5%) in streamflow at least one month per year by 2050 in 31 subbasins. The retirement of power generators was shown to produce noticeable streamflow impacts up to hundreds of kilometers downstream. By the retirement of the last US fossil fuel-fired power generator, 2.6 billion m^3 of water that was once consumed by these power plants could be made available for other uses. In addition to the global benefits of reduced greenhouse gas emissions, the notable increases in streamflow and water availability in many US rivers due to the retirement of fossil fuel-fired power plants could benefit local water users and ecosystems.

1. Introduction

Fossil fuel-fired power plants will need to close or radically alter their operations for rapid decarbonization in response to climate change (Pfeiffer et al., 2016; The White House, 2021; Tong et al., 2019; Williams et al., 2021). United States fossil fuel-fired power plants are aging, with over 70 % of capacity expected to reach a typical fuel- and prime mover-specific lifespan by 2035, President Biden's target date for decarbonizing the electricity sector (Grubert, 2020b). In addition to the primary policy target of decarbonization, closing fossil fuel-fired power plants stops other ongoing impacts of plant operations, notably including air pollution (Giang and Selin, 2016; Grubert, 2020b; Henneman et al., 2019; Hertwich et al., 2014; Tessum et al., 2019). Another major dynamic related to fossil fuel-fired power plant closure, though, is cessation of water use (withdrawal and consumption) for fossil fuel-fired power plant needs, most significantly, cooling (Dieter et al., 2018; Grubert and Sanders, 2018; Lohrmann et al., 2019; Lubega and Stillwell, 2019; Macknick et al., 2012a; Macknick et al., 2012b; Madden et al., 2013; Peer et al., 2019; Peer and Sanders, 2016; 2018).

More water is withdrawn in the US to produce electricity than any other economic sector (Dieter et al., 2018). The portion of the withdrawn water not evaporated by the power plant will return to a waterbody or be held on site for reuse. The fraction of water withdrawn from a waterbody that is consumed varies by power plant and is primarily related to the cooling technology used. Water consumption related to fossil fuel-fired power plants is significantly less than withdrawals (Marston et al., 2018); yet these power plants' water consumption have important implications on water availability (Wang et al., 2017; Lee

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et al., 2020).

Fossil fuel-fired power plants can be a major contributor to water stress (Averyt et al., 2011; 2013). Climate change and population growth will further strain already stressed watersheds (Brown et al., 2019), accentuating the large, spatially concentrated water withdrawals by fossil fuel-fired power plants. The impact of fossil fuel-burning power plants' water withdrawals and consumption is particularly pronounced in the summer (De La Guardia et al., 2022). Water withdrawals and consumption by power plants typically peaks in the summer due to higher evaporative potential and large electricity demands (Miara et al., 2018), which often coincides with peak water use by other sectors and a low flow period for many rivers. A reduction of water consumption by fossil fuel-burning power plants could make water available to meet new or growing water demands or be set aside to meet environmental water needs.

This research combines a lifespan-based model of fossil fuel-fired generator retirements for the US fossil fuel-fired electricity generation fleet (Grubert, 2020b) with a national-scale hydrologic model to determine when, where, and how much water will be made available upon the expected retirement of the nearly one thousand fossil fuel-fired power plants across the US that rely on water for cooling. We resolved generator-level annual water consumption and withdrawal records to a monthly timestep and then determined how a change in streamflow due to retirement of a fossil fuel-burning power plant will impact local and downstream water availability. While previous studies have assessed changes in water use by the electric sector under different scenarios (e.g., Ackerman and Fisher, 2013; Cameron et al., 2014; Macknick et al., 2012a; Macknick et al., 2012b; Tidwell et al., 2013; Liu et al., 2015; Peer and Sanders, 2018; Fulton and Jin, 2021), they do not capture the spatially- and temporally-important hydrologic details afforded by our coupled modeling approach. We show in this study that the impact of fossil fuel-fired power plants on water availability can be seen locally but also propagate downstream through the hydrologic network. Furthermore, streamflow impacts vary significantly by subbasin, month, and in response to temporal climate variability, which demonstrates the importance of the refined spatial and temporal resolution of our study.

2. Methods

Annual water withdrawals and consumption, water source, and lifespan for each fossil fuel-fired generator were estimated using the model and data described in Grubert (2020b), which assumes fossil fuel-fired generators retire upon reaching their 2018 fuel- and generation technology-specific average lifespan. This model projects future US fossil fuel-fired electricity generation and several socioenvironmental attributes (emissions, water use, labor requirements) by assuming that generators continue to operate at their 2018 output levels until they reach a typical lifespan. Annual freshwater withdrawals and consumption for each generator were resolved to the monthly timestep and to the eight-digit Hydrologic Unit Code (HUC8 or subbasin level) to be used by the national-scale hydrologic model that simulates the hydrologic impact of abstractions from surface water and groundwater sources at the monthly time step for each HUC8 subbasin in the contiguous United States. Data preparation and model integration are detailed below.

2.1. Monthly water withdrawal and consumption estimates

Estimated generator-level water consumption from Grubert (2020b) uses an annual timestep, whereas the hydrologic model used in this study uses a monthly timestep. We project water consumption through 2075 to include the typical lifespan of all existing fossil fuel-fired generators [indexed to 2018 in Grubert (2020b)] and any currently under construction, to facilitate model updates. Accordingly, this work downscales projected 2018–2075 annual average water consumption for power plants with at least one fossil fuel-fired generator operable as of 2018 to the monthly level, reflecting two major dynamics that are relevant for evaluating water consumption in context. Namely, 1) power generation seasonality and 2) evaporative water intensity seasonality. Our approach is necessary due to a lack of accurate, comprehensive - subannual water use records (Chini and Delorit, 2021). The Energy Information Administration (EIA), which is the primary federal agency for collecting, analyzing, and distributing energy data, has published estimated monthly water withdrawals and consumption at the boiler level since 2014 (EIA 2022). However, these data are neither accurate nor complete for the needs of this work. For 2020, EIA data show zero water withdrawal for 40 %, and zero water consumption for 50 %, of the 926 plants for which we model ongoing water use as of 2020. These entries are often clearly incorrect, for example, with entries of zero water withdrawal for plants with nonzero water consumption. Despite these data discrepancies that we would expect to contribute to an overall underestimate, EIA estimates for water withdrawals and consumption for our modeled plant population are a factor of ten higher than our modeled estimates, which are consistent with other published aggregate data. For the universe of plants EIA models (which includes non-fossil plants), EIA-estimated 2020 thermoelectric water withdrawal is approximately-five times, and estimated 2020 thermoelectric water consumption is approximately-five times, that estimated by USGS for 2015 (Dieter et al., 2018). Potential explanations include inconsistent definitions (e.g., reporting total cooling flow volumes inclusive of recirculation, rather than withdrawals from a water body), multiple counting due to complex relationships between boilers and cooling systems, and misreports. As such, we model projected monthly water withdrawal and consumption using physical relationships, contributing consideration of seasonal generation and evaporative capacity (Wang et al., 2017; Lee et al., 2020; Fulton and Jin, 2021). We describe these dynamics, and the modeling approach, below. Data and calculations are included in this work as the Supplementary Data File.

Annual generator-level water consumption is assigned to US power plants that had at least one fossil fuel-fired generator operable as of 2018 in the EIA 860 database (EIA, 2021a). This assignment proceeds by aggregating estimated fossil fuel-fired generator annual water consumption to the plant level based on the Plant ID field for each year between 2018 and 2075 (inclusive), by which point all fossil fuel-fired US generators will have reached mean age-on-retirement for their type (Grubert, 2020b). A power plant's water withdrawals and consumption revert to zero upon retirement. Generators are assumed to run at modeled 2018 levels (i.e., with modeled 2018 annual water consumption), so for each year, the model used in this work assigns generator-level water consumption to a plant if the generator has not yet passed its modeled closure date (Grubert, 2020b). Plants that had no generators with water consumption as of 2018, which were essentially all air-cooled natural gas and oil-fired combustion generators, were discarded from this analysis. Removing these 2,005 plants with no 2018 modeled water consumption left 976 plants accounting for 640 GW of US 2018 fossil nameplate capacity, out of a total of 840 GW.

Power generation seasonality is incorporated to reflect that power generation is not consistent throughout the year: electricity demand (and thus generation) is typically highest in summer, then winter, in the United States, in part because of the major contribution of heating and cooling demand and because air conditioning (summer cooling) is essentially entirely electrified while winter heating is not (EIA, 2013). As such, most US electricity systems are summer peaking, although we caution that decarbonization-motivated electrification (Williams et al., 2021) is expected to alter these relationships over the projection period of this study. This study therefore assumes two alternatives for power generation seasonality: a) 2019 fleet-average seasonality for steam fossil generation (coal, distillate fuel oil, and natural gas) (EIA, 2021b), and b) no seasonality (that is, monthly generation is assigned assuming equal generation for every day). Steam fossil generation is bundled across fuel resources to avoid false precision: seasonality for these resources is similar enough to support the coarse analysis in this study. That is, even historical annual generation patterns vary interannually (e.g., due to weather and maintenance cycles) and across generators (e.g., due to variable regional contexts), and expected major changes to the electricity sector suggest that past performance might not be a good predictor of future operational patterns. Given that generation is often higher during summer when water resources are more stressed in much of the US, capturing the dynamic of higher water consumption during periods of high summer electricity demand was deemed to be sufficiently relevant for evaluating water quantity impacts that the 2019 pattern is included illustratively. These two alternatives are illustrated in Fig. 1, with the steam coal- and natural gas-trends shown separately for context.

As with power generation seasonality, evaporative water intensity seasonality can be highly variable across contexts. Evaporative water intensity seasonality reflects the point that higher water temperatures are associated with higher evaporative potential, such that a unit of heat input to a unit of cooling water in a cold January month results in less evaporative water consumption than would occur with the same units of heat input and cooling water in a warm July. Our first-order analysis includes two illustrative scenarios of evaporative water intensity seasonality: i) average evaporative seasonality as calculated using the evaporation model from Diehl et al. (2013) for a sample of USGS temperature sites with complete monthly data (Segura et al., 2015), and ii) the most extreme evaporative seasonality from that same sample of sites, where the most extreme is defined as the seasonality at the site with the highest difference between minimum and maximum evaporative potential.

Evaporative seasonality is calculated using Diehl's Model of Forced Evaporation from a Water Surface (FEWS v3.104) (Diehl et al., 2013), using all default parameters except natural water temperature, T, in degrees Celsius, to calculate the output metric "evaporated gallons per MWh thermal condenser duty" by month and on average over the course of a year. Due to this work's interest in the seasonality pattern rather than estimated water consumption per unit of generation (because of access to plant-level annual water consumption records), monthly evaporation was normalized by average annual evaporation to give a monthly evaporative potential value in percent (Equation (1)):

$$evaporative\ potential_m = \frac{evaporated\ gallons\ per\ MWh\ thermal\ condenser\ duty_m}{evaporated\ gallons\ per\ MWh\ thermal\ condenser\ duty_y} \quad (1)$$

where m is month and y is year. Calculated thusly, the monthly evaporative potential is invariant to dry bulb, wet bulb, and plant characteristics as implemented in FEWS v3.104. Under the FEWS v3.104 model, evaporative potential is a function of the monthly natural water temperature (we hold other model parameters at their default values).

USGS water temperature sites were taken from Segura et al. (2015), noting that stream water temperature data are sparse and thus difficult to obtain for sites that are directly relevant for power plant intakes. Here, we use the 62 sites for which a full set of monthly average water temperature data were available, shown in Fig. 2 alongside power plants with at least one fossil fuel-fired generator operable as of 2018. As such, the sites used for this analysis are not representative of sites supplying power plant cooling water. They are, however, highly validated with high quality temperature records and thus considered suitable for this first-order analysis.

Average evaporative seasonality is the simple average of monthly evaporative potential (Equation (2)) across the 62 sites for which a full

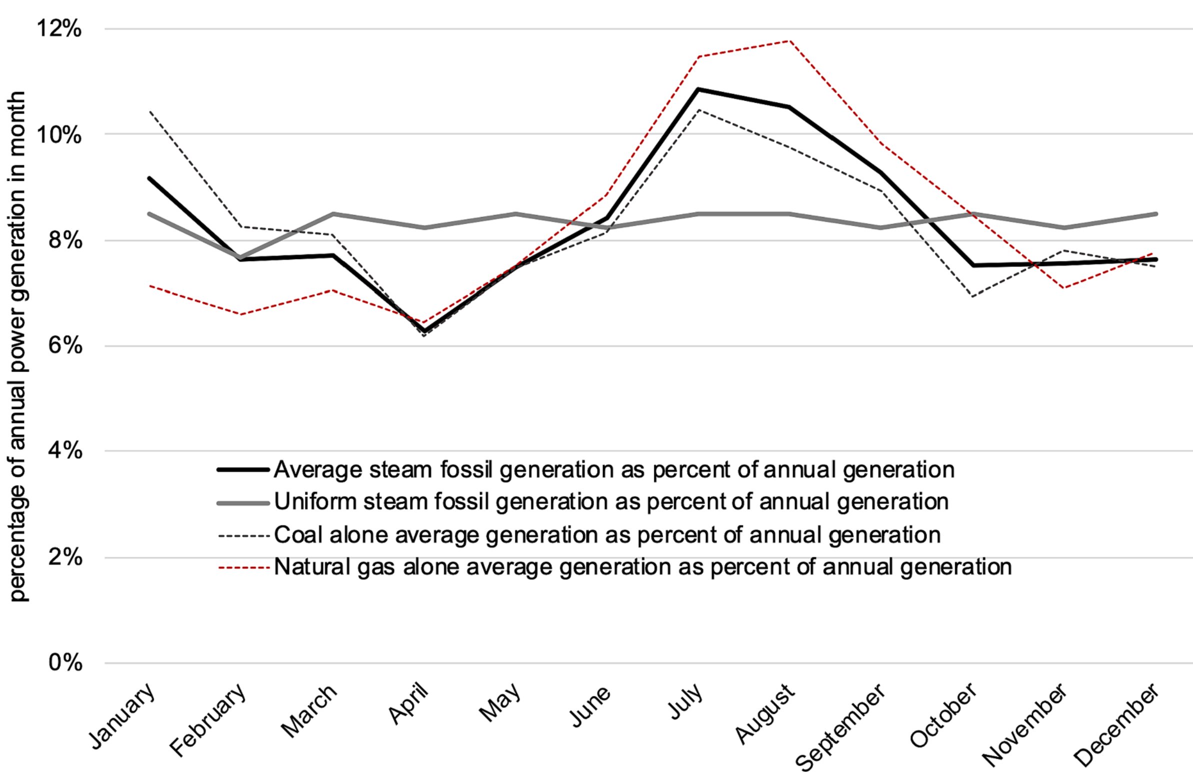

Fig. 1. Seasonal power generation profiles.

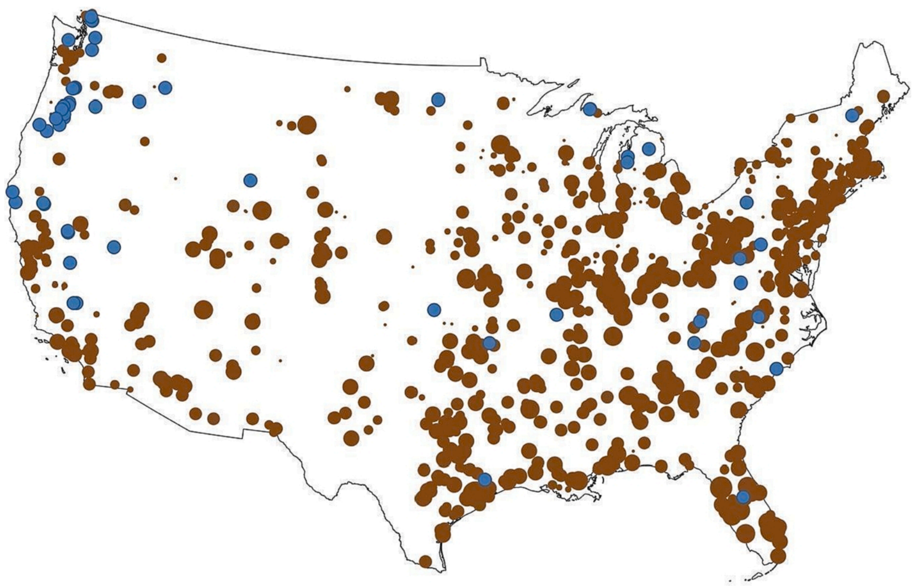

Fig. 2. Power plants (brown; scaled by nameplate fossil capacity) and stream temperature sites (blue) included in this analysis.

set of monthly average water temperature data were available. No location weighting of water temperature seasonality was attempted for this first-order analysis because a meaningful weighting metric reflecting variable conditions at the power plants of interest was not available. Instead, we assess two evaporative seasonalities within this analysis (see Fig. S1 for a visual depiction) to test sensitivity: the average, and the extreme seasonality profile from site 5057000, on the Sheyenne River in eastern North Dakota. W.

$$water\ \ consumption_m = water\ \ consumption_y \times \frac{\frac{generation_m}{generation_y} \times \frac{evaporative\ \ potential_m}{evaporative\ \ potential_y}}{\sum_m \left(\frac{generation_m}{generation_y} \times \frac{evaporative\ \ potential_m}{evaporative\ \ potential_y}\right)} \quad (2)$$

Monthly water consumption (January 2018 through December 2075) at point-of-generation was estimated by combining power generation and evaporative seasonalities with annual estimates of water consumption as follows (Equation (2)), where m is month and y is year

In the equation above, the combined seasonality estimate (seasonal generation multiplied by seasonal evaporative potential in a given month) is renormalized by the sum of the combined monthly seasonality estimates to ensure total water consumption for the year is preserved. See the Supplementary Data File for more details. Fig. 3 shows the four profiles (two approaches to estimating generation seasonality combined

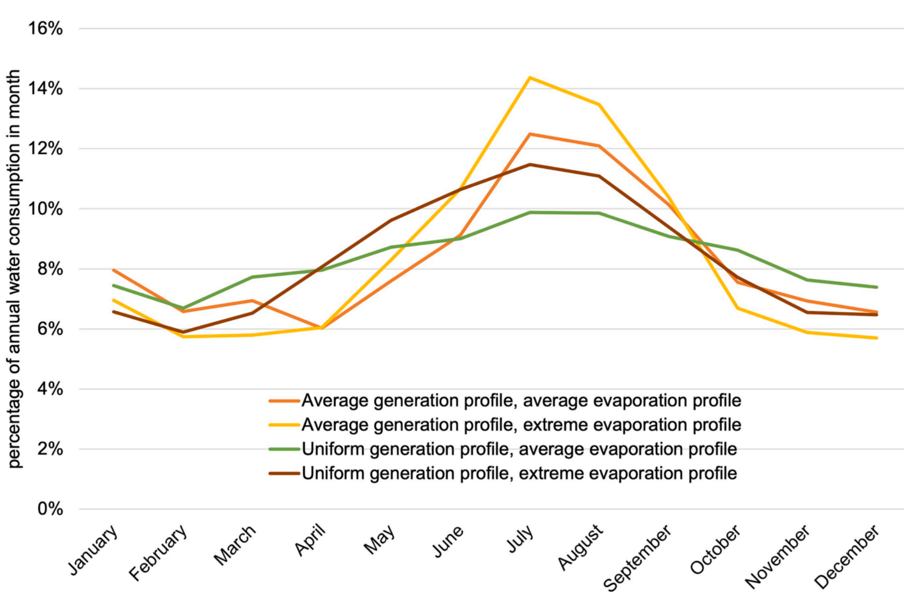

Fig. 3. Monthly share of annual water consumption implied by power generation and evaporative potential seasonalities used in this analysis.

Table 1
Evaporative and generation seasonality scenarios.

Alternative	Description
Average evaporation profile	Average evaporative seasonality as calculated using the evaporation model from Diehl et al. (2013) for a sample of USGS stream temperature sites with complete monthly data (Segura et al., 2015).
Extreme evaporation profile	The evaporative seasonality with the largest difference between minimum and maximum evaporative potential based on USGS stream temperature records.
Average generation profile	Fleet-average seasonality (yr. 2019) for steam fossil generation (coal, distillate fuel oil, and natural gas).
Uniform generation profile	Monthly generation is assigned assuming equal generation for every day (i.e., no seasonality).

with two approaches to estimating evaporative potential seasonality) used in this analysis.

Pairings of the two generation and two evaporative seasonality profiles yield four different seasonality scenarios (Table 1). Different combinations of generation and evaporation scenarios for fossil fuel-fired power plants generated very similar projected streamflow estimation at the subbasin level (Fig. S2). Considering the negligible impact of evaporation and generation scenario on streamflow estimation, we used average evaporation combined with average generation throughout our analysis. The evaporation and generation scenarios have no bearing on annual water withdrawal and consumption estimates of this study, only the partitioning of annual water use estimates to each month.

2.2. National-scale hydrologic model

The effects of the fossil fuel-fired power plant water use scenarios on streamflow were assessed using the Water Supply Stress Index (WaSSI) hydrologic model developed by the US Department of Agriculture Forest Service (Caldwell et al., 2012; Sun et al., 2011). WaSSI has been extensively tested through comparison to observed flows at US Geological gauging sites and comparison to other models (Caldwell et al., 2012; Li et al, 2020; Schwalm et al, 2015; Sun et al., 2015). The WaSSI model estimates monthly streamflow for each of the 2,099 HUC8 subbasins in the contiguous US by computing the watershed water balance as affected by climate, land use, soil properties, and topographical characteristics, and then accumulating streamflow through the river network. Importantly, WaSSI accounts for and enables assessment of streamflow impacts due to human water abstractions (Marston et al., 2020; Richter et al., 2020).

As our purpose is to isolate the effect of fossil fuel-burning power plant retirements on streamflow, we hold other water uses, such as irrigation and public supply, static around recent levels (Marston et al., 2018; Marston et al., 2020). Likewise, we evaluated the effects of the retirement scenarios on streamflow using a common climate time period to isolate the effect of the scenarios from potential climate changes. Many regions have seen fundamental shifts in their hydrology since the start of the century (Barnett et al., 2008; Sagarika et al., 2014). Therefore, we selected the 2001–2015 period for analysis and report the impact of plant retirements on the average monthly flow regime during that time. In addition, we evaluated streamflow impacts during a historically wet year (1993), dry year (1963), and recent year (2015).

Generator-level projections of monthly water withdrawals and consumption between 2018 and 2075 were aggregated within each HUC8 subbasin to match the spatial resolution of WaSSI. Our water use model accounts for the water withdrawal source (e.g., river, natural lake, aquifer, ocean) and disposal location of return flows since they have implications on both current and future hydrologic conditions upon plant retirement. When assessing streamflow impacts, fossil fuel-fired power plants that either withdraw from or discharge to a river, or both, were included. Among the 976 power plants analyzed in this study, more than half (573) source their water directly from or discharge to a river, or both. While previous studies assess the effect of future power plant operations, our modeling approach is unique in that it accounts for the displacement of water availability impacts to downstream subbasins through the river network.

2.3. Limitations

For fossil fuel-fired generators, seasonality is driven by electricity demand (and increasingly, electricity demand net of generation from power plants utilizing flow resources like wind and solar) rather than by resource availability. For example, solar power plants have a clear and inherent seasonality reflecting longer day length in the summertime (EIA, 2021b), whereas the higher historical summer generation from coal and natural gas plants is due to dispatching these resources in response to load. One major implication for this study is that these generation profiles might change in response to dynamic fuel mixes (e.g., increased solar penetration) and dynamic demand (e.g., from electrification of residential heating). Further, these generation profiles might change in ways that vary by region, due to variation in climate, climate policy, and other factors. As such, results should be interpreted with the understanding that these projected changes to water resource consumption by fossil fuel-fired power plants reflect anticipated conditions absent climate policy or climate change. Similarly, water evaporation profiles do not reflect future climatic conditions, notably changing heat and humidity relationships. As with the original model (Grubert, 2020b), the assumption of constant 2018 output and impacts for all future years a generator is expected to operate is intended as a coarse proxy for a counterfactual scenario without strong climate policy and other retirement forcing functions, noting that the assumption of constant output over time has historically been a reasonable simplification at the fleet level (Grubert, 2020a) but likely overestimates future coal plant outputs and underestimates future natural gas plant outputs (Grubert, 2020b), even assuming history is a good predictor of the future, which it might not be. This study evaluates the hydrologic and water availability impacts of expected fossil fuel-burning power plant retirements; the assessment of replacement and new electricity generation facilities on water availability is left for future studies.

3. Results and discussion

3.1. Impact of fossil fuel-fired generators' retirement on volumetric water use

The 976 US fossil fuel-fired power plants that we analyzed withdrew 58.4 billion m^3 of water from surface water and groundwater sources in 2018 to produce 2.43 billion MWh of electricity. The water withdrawals of these 976 power plants exceeded the 148,000 US public water systems' 2015 water withdrawals by over 4.5 billion m^3 (Dieter et al, 2018). Evaporative cooling at fossil fuel-fired power plants consumed around 4.5 % of the withdrawn water, thus making this water unavailable for downstream use. By the time the last generator reaches typical retirement age (2066), a decrease in water consumption related to evaporative cooling will make an additional 2.64 billion m^3 of fresh surface water available nationwide.

Analysis based on the retirement of fossil fuel-fired generators predicts a sharp decline in water withdrawals and consumption within the next two decades and a complete cessation of water use by existing fossil fuel-fired generators by the year 2066 (Fig. 4). Water withdrawals from fossil fuel-fired power plants are expected to decline more quickly than water consumption. Nearly 64 % of 2018 electricity generation and 50 % of the fossil fuel-fired power plants will be at retirement age between 2018 and 2035; yet, these plant retirements will lead to an 85 % reduction in water withdrawals (from 58.4 billion m^3 to 8.6 billion m^3; Fig. 4). Within the same timeframe, consumptive water use of fossil fuel-fired electricity generation will decrease by 68 %, from 2.6 billion m^3 to

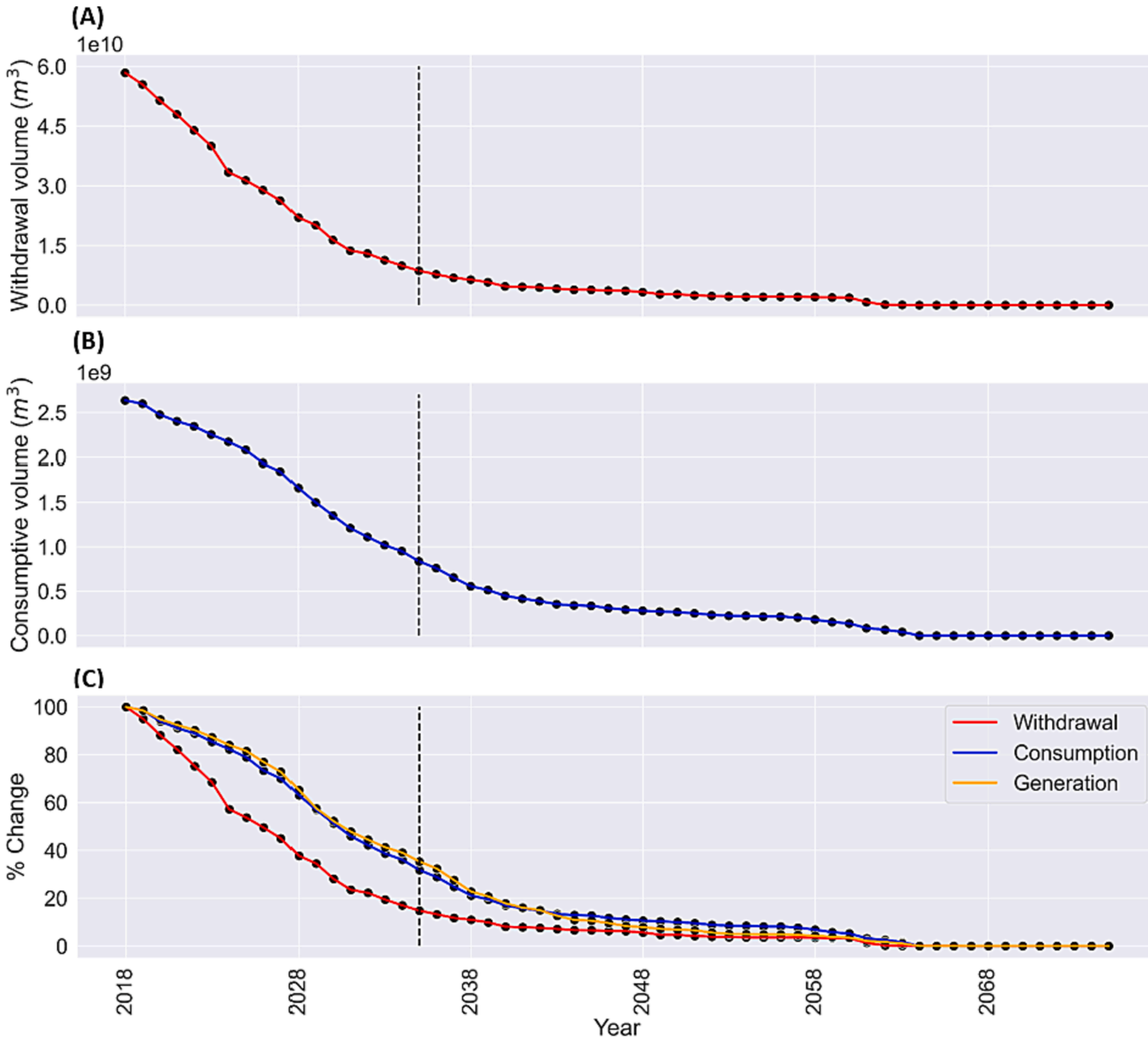

Fig. 4. National estimates of trends in volumetric water withdrawal (A) and consumption (B) for fossil fuel-fired electricity generation. The percent reduction in water withdrawals, water consumption, and fossil fuel-fired power plants between 2018 and 2075 is shown in panel (C). The black dashed line represents the year 2035, President Biden's target date for decarbonizing the electricity sector. The expected decline in water withdrawals and consumption will result from the retirement of fossil fuel-fired power generators.

0.84 billion m^3. The disproportionate reduction in water withdrawals compared to water consumption in the near term reflects more retirements of power plants that employ once-through cooling technology, which has significantly larger water withdrawals relative to consumption compared to recirculating cooling technology.

Almost all hydrologic regions (HUC2) will see a faster decline in water withdrawals than water consumption by 2035 (Fig. 5). The retirement of fossil fuel-fired power plants in the Missouri River region, which is the hydrologic region with the largest withdrawals by volume and whose power plants largely use once-through cooling systems, will reduce water withdrawals by 94 % by 2035. The water-stressed Rio Grande and Upper Colorado will see reductions in water withdrawals and consumption greater than 85 % of 2018 rates by 2035. Water withdrawals by fossil fuel-burning power plants in the Upper and Lower Colorado regions will decline by a combined 238 million m^3 by 2035. While seemingly a large volume of water, this reduction in water withdrawals only amounts to 1.3 % of the total water allocated to the Upper and Lower Colorado region states. There will be a similar decrease in water consumption (163 million m^3 or 69 % of the reduction in withdrawals) within the Colorado River region due to prevalence of recirculating cooling technology in the region. Regional estimates of trends in water withdrawal and consumption aggregated by HUC2 hydrologic regions are shown in Fig. S3.

3.2. Impact of fossil fuel-fired power plant retirements on streamflow

Among the 352 HUC8 subbasins where fossil fuel-fired power plants withdraw from and/or discharge to a river, these power plants withdrew more than 1 % of total 2001–2015 mean annual natural streamflow in 111 subbasins and consumed more than 1 % of total annual streamflow in 24 subbasins under 2018 levels of water use (Fig. 6A and 6D). Annual water withdrawals and consumption of fossil fuel-fired power plants constituted more than 25 % of natural streamflow in 25 and 3 subbasins, respectively, in this scenario. Surface water withdrawals in six subbasins and water consumption in two subbasins surpassed total annual natural streamflow within the subbasin under this scenario. Such anomalies occurred when the cooling water is withdrawn from and discharged to a reservoir for repeated use (e.g., Thomas Hill Lake in Little Chariton subbasin, Lake Sakakawea in Lake Sakakawea subbasin, Jim Bridger reservoir in Bitter subbasin), water is diverted from an adjacent large

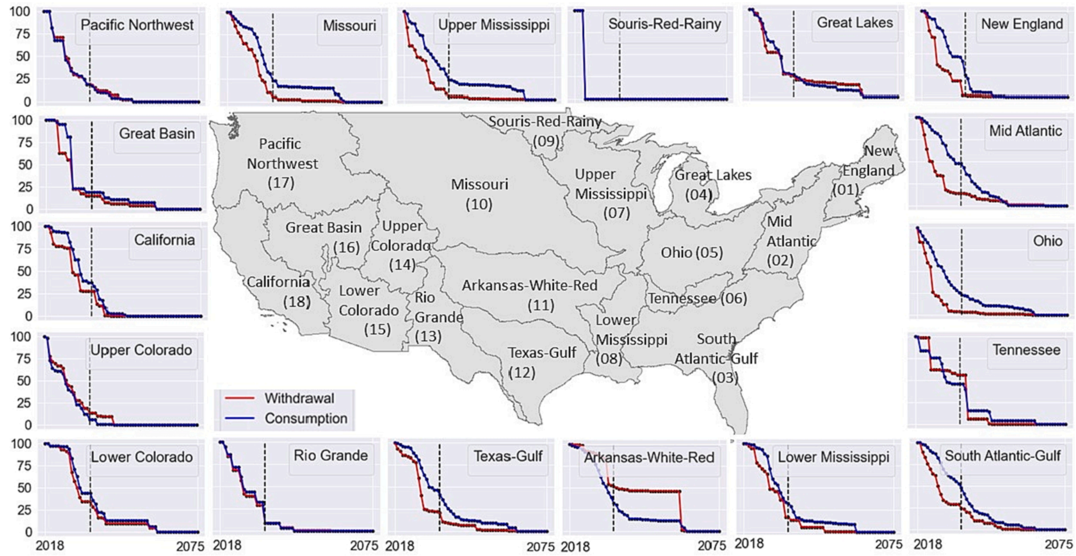

Fig. 5. Regional (HUC2) percent change in the volume of water withdrawn (red line) and consumed (blue line) in electricity production by fossil fuel-fired generators between the year 2018 and 2075. The dashed lines denote the year 2035.

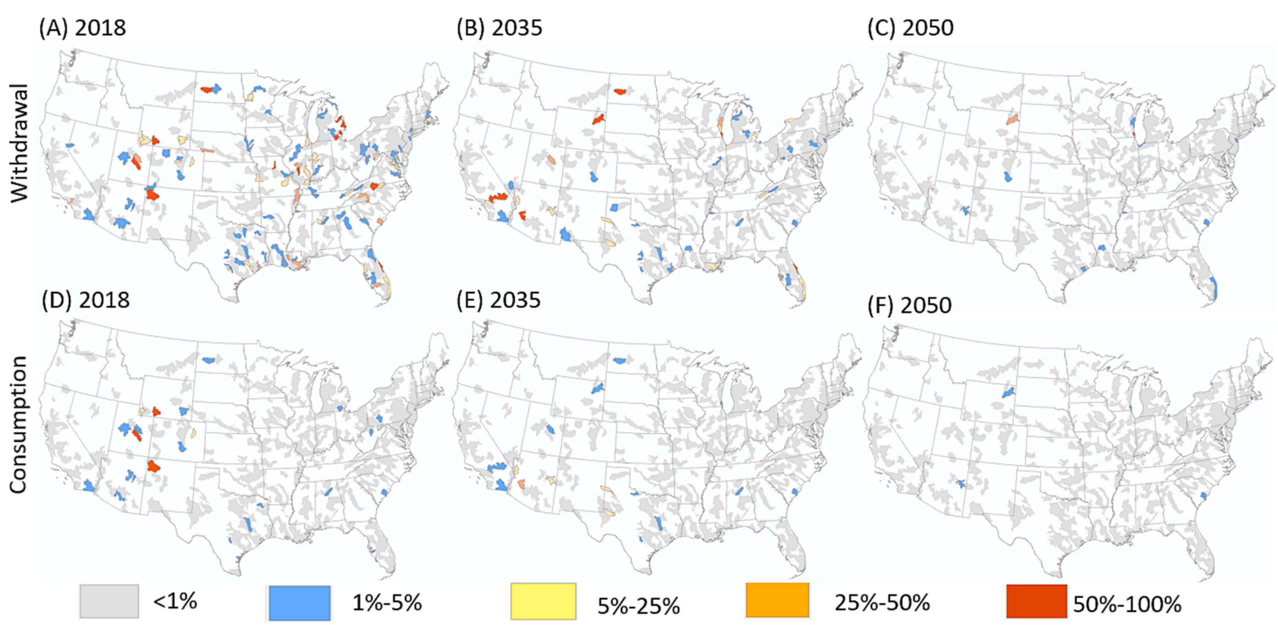

Fig. 6. Ratio of fossil fuel-fired power plants' water withdrawal (top) and consumption (bottom) in 2018, 2035, and 2050 to compared to average (2001–2015) natural streamflow conditions. Subbasins without a fossil fuel-fired power plant are shaded gray. Fossil fuel-fired power plants in the majority of the subbasins withdraw and consume only a small portion of the available water within the subbasin. Around 5% subbasins were identified to withdraw more than 1% of the streamflow available within the subbasin.

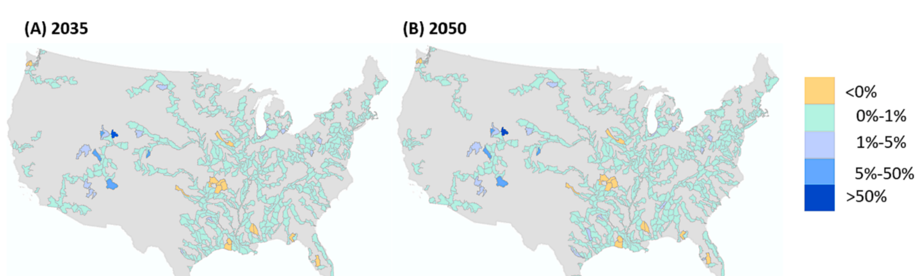

Fig. 7. Subbasin-level percent change in streamflow due to the retirement of fossil fuel-burning power plants between 2018 and 2035 (A) and 2050 (B). Streamflow in most subbasins will be unaffected by fossil fuel-fired power plants retirement (subbasins shaded gray) since fossil fuel-fire burning power plants are not located in most subbasins and water savings in many cases are insignificant compared to streamflow. Most of the impact of fossil fuel-fired power generation on streamflow will occur by 2035.

water body (e.g., Cape Canaveral Power Plant diverts from the Indian River near the subbasin outlet), or water is transferred from a nearby subbasin to supply power plant(s) (e.g., Middle San Juan to Chaco subbasin, Raisin to Ottawa-Stony subbasin). The number of subbasins with more than 1 % of its annual streamflow withdrawn in 2018 reduces from 111 to 50 by 2035 and to 13 by 2050 (Fig. 6B and 6C).

All 352 subbasins with fossil fuel-fired power plants that withdrawal from or discharge to a river will experience changes to streamflow due to the retirement of 573 fossil fuel-fired power within these subbasins. For power plants using once-through cooling technology, the vast majority of water withdrawals return to the water source, thereby minimizing their individual impact on downstream flow volumes (though an end of thermal water pollution associated with the retirement of power plants will likely have an impact on downstream water temperatures; Miara et al., 2018). Almost one-fourth (512) of the 2,099 subbasins in the US will experience a net increase in streamflow due to the retirement of fossil fuel-fired power plants, while 0.8 % (16) subbasins experience a net decrease in streamflow. Most subbasins with plant retirements will experience a small increase (<1%) in annual streamflow due the cessation of water consumption by fossil fuel-fired power plants (Fig. 7).

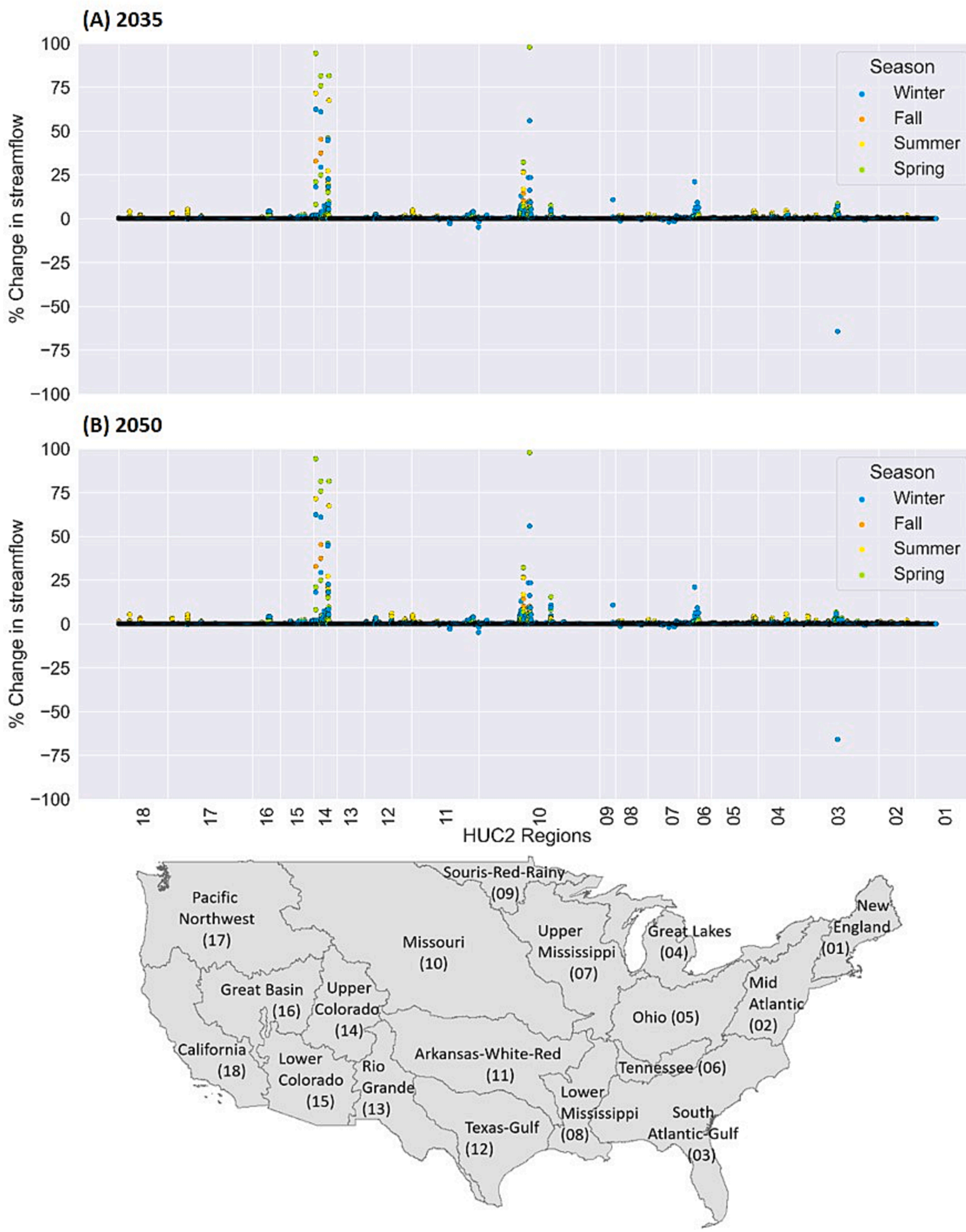

Fig. 8. Impact of fossil fuel-fired power plants retirement on monthly streamflow for 2035 (A) and 2050 (B) compared to 2018. The majority of subbasins are expected to experience little change in streamflow. Several subbasins in the Missouri and Upper Colorado regions will experience a notable change in streamflow for some months of the year. The majority of subbasins are expected to experience little change in streamflow, which is shown by the clustering of dots around zero.

Less than one percent of subbasins will see a slight decrease in streamflow when a major portion of generation is supported by non-surface water cooling and return flows are discharged to a nearby river. The remaining 1,571 subbasins will have a negligible or no change in streamflow due to the retirement of fossil fuel-fired power plants.

Changes in streamflow due to the retirement of fossil fuel-burning power plants vary by month. Generally, both the maximum volumetric and percent increase in monthly streamflow will occur during the summer (July-September), which is when most existing power plants withdrawal and consume the most water. The minimum volumetric and percent increase in streamflow occurs during the spring (April-June) when power plant water use is typically lower and streamflows are naturally higher. Subbasins in the Missouri River region and the Upper Colorado River region will experience the highest gains in monthly streamflow relative to natural streamflow levels (Fig. 8). Nearly-two dozen subbasins within these two larger regions will experience over a 5 % increase in monthly streamflow by 2035 compared to 2018 conditions. The largest volumetric increases in both annual and summer streamflow are predominately in eastern rivers, however (Fig. S4).

Changes in streamflow due to power plant retirements have a greater impact on water availability in subbasins with less naturally available streamflow. While some subbasins in the Missouri and Upper Colorado River regions will see a large relative increase in streamflow compared to 2018 levels, many of these subbasins have little streamflow to begin with. Thus, while the absolute volume of streamflow made available upon the retirement of power plants is relatively small (averaging less than 6 million m^3, annually) compared to flow at the outlet of the Missouri River and Upper Colorado River, it comprises a large portion of total streamflow within these subbasins. In comparison, several subbasins in the Ohio River region and South Atlantic-Gulf region will see a large volumetric increase in streamflow (averaging 37 million m^3), but this volume only represents a negligible percentage of streamflow for these water abundant regions. Fig. S4 shows the location and magnitude of expected streamflow gain during the summer months (mean of July-September) in 2035 and 2050 compared to 2018 due to the retirement of fossil fuel-fired power plants.

We identified 31 subbasins where the gain in streamflow due to the retirement of fossil fuel-fired power plants will lead to a large relative change (>5%) in streamflow at least one month per year by 2050 (Fig. 9). Many of these 31 subbasins will see a large volumetric increase in streamflow (more than 10 million m^3). Streamflow in subbasins within the Upper Colorado and Texas Gulf regions will observe the greatest gains in streamflow, particularly during the summer season. Some subbasins, while experiencing a large relative increase in already low streamflow, will only have a small increase in streamflow magnitude. Notably, many of the 31 subbasins with large changes in streamflow between 2018 and 2050 are hydrologically connected, such as subbasins along the Platte River, Mississippi River, and Yampa River.

Retirement of fossil fuel-fired power plants not only has impacts on streamflow within the subbasin where the power plant is located, but plant retirements can create notable impacts to streamflow in downstream subbasins. As an example, the Comanche Generating Station located in the Upper Arkansas subbasin in the Arkansas-White-Red Region is among the largest water consuming (36th) fossil fuel-burning power plants in the US. The retirement of the Comanche Generating Station will make 14.5 million m^3 (1.5 % of annual streamflow) water available locally, including 1.0 million m^3 (8.0 %) during the low-flow month of February. Likewise, immediately downstream, the Upper Arkansas-Lake Meredith subbasin will experience a 1.3 % increase in annual streamflow and a 6.4 % increase during the low-flow month of February. Annual streamflow will remain above 1 % of pre-plant retirement conditions for over 500 km downstream, reflecting the nonlocal water availability impacts of fossil fuel-fired power plant retirement.

The retirement of fossil fuel-burning power plants has a larger impact on streamflow during exceptionally dry periods compared to wet or average years. Fig. S5 shows the impact of the retirement of fossil fuel-fired power plants on streamflow under conditions matching those from a historically wet year (1993), dry year (1963), and recent year (2015). During a year similar to 1963 when many streams had low flow

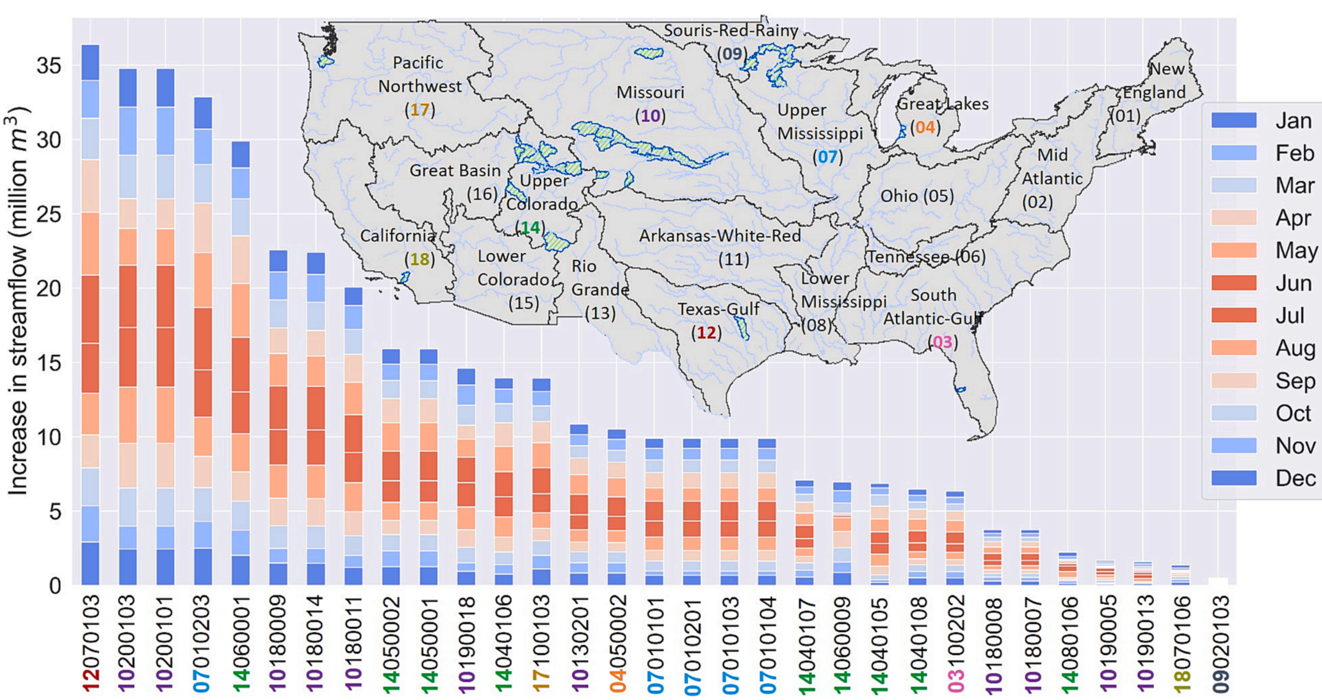

Fig. 9. HUC8 subbasins where at least one month of the year will gain more than 5% of its average (2001–2015) natural streamflow by 2050 due to the retirement of fossil fuel-fired power plants. The inset shows the locations of the subbasins of interest. Subbasins in Upper Mississippi, Missouri, and Upper Colorado regions are expected to see large volumetric and percent increases in streamflow. The first two digits of the listed HUC8 correspond to the HUC2 numbers shown in the map inset. A large portion of the volumetric gain in streamflow will occur during the summer months.

conditions, 102 subbasins would have a >5 % gain in streamflow at least one month per year by 2050 (compared to 31 subbasins under average flow conditions). The number of subbasins with more than 1 % of its annual natural streamflow withdrawn by fossil fuel-fired power plants under a low-flow scenario reaches 65 by 2035 and to 21 by 2050 (compared to 50 and 13, respectively, for average flow conditions).

4. Conclusions

This study reveals changes in US water availability and streamflow due to the retirement of fossil fuel-fired power plants. Through the coupling of a lifespan-based model of fossil fuel-fired generator retirements and a hydrologic model, we show that water withdrawals and consumption of fossil fuel-fired power generators will be significantly curtailed (85 % and 68 % reduction, respectively) by 2035 if generators retire upon reaching average retirement age. Most rivers with fossil fuel-fired power plants diverting or discharging water will have a net increase in annual streamflow, with the most pronounced increases occurring in the summer months. The retirement of these power generators can produce noticeable impacts on streamflow volumes up to hundreds of kilometers downstream. By the retirement of the last fossil fuel-fired power generator in 2066, 2.6 billion m^3 of water that was once consumed by these power plants will be made available for other uses. While most of this water will be made available in the eastern US, the retirement of fossil fuel-burning power plants in the western US will make a large contribution to streamflow in dozens of water-limited subbasins.

The retirement of fossil fuel-fired power plants provides an opportunity to meet the unmet water demands of other water users, including the environment. Even in areas not facing water stress, our results could inform water storage allocations (e.g., flood storage) and other water resources management decisions. In the eastern US, water supply benefits will be minimal in most basins under average flow conditions but could have larger benefits during drought. However, a reduction in thermal pollution caused by plants discharging heated return water to water bodies will have wide-ranging environmental benefits (Miara et al., 2018; Logan and Stillwell, 2018). In water stressed basins within the western US, we show that the retirement of fossil fuel-fired power generators will make nontrivial amounts of water available. Given the high value of water in these regions, it is likely these water rights will be sold to support new urban development or other high-value uses. If the water rights of retired power plants are sold to downstream water users, the increase of instream flows between the power plant and new user can create co-benefits by improving ecosystem health along the way (Kendy et al., 2018).

At least 50 fossil fuel-fired power plants fulfill their water demand by damming rivers (EIA 2021a; 2021b). Once these power plants are retired, hundreds of millions of cubic meters of reservoir storage allocated for these power plants may be reallocated to other purposes, such as irrigation or public water supplies, or to buffer the effects of a new climate regime. In some cases, dam removal may be a viable option, thereby allowing a return of the natural streamflow regime and an unimpeded corridor for fish and sediment. Disinvestment and deferred maintenance at fossil fuel fired-power plants in response to both expectations of future climate action and competition from low-cost, low emissions electricity generation sources could pose major challenges for ensuring regular maintenance of power plant-owned dams. Government agencies should devise plans to ensure the retirement of power plants does not lead to unmaintained water infrastructure to avoid dam failure and catastrophic flooding, as was the case in 2020 with a hydropower dam (Edenville Dam) in central Michigan.

For over a century and a half, society has harnessed rivers to generate electricity. While rivers will continue to play a role in electricity production for the foreseeable future, that role will likely be diminished as other natural resources that do not depend on rivers – namely, solar and wind – play an increasingly larger role in electricity generation. Economic and regulatory headwinds centered on making electricity more affordable and less carbon intensive will have the incidental impact of making the electricity sector less water dependent, which will benefit other water users and the environment.

Data availability

Data and model output needed to replicate or extend this study are provided as supplementary files. The supplementary materials include: i) generator-level, annual and monthly water withdrawals and consumption; ii) generator-level electricity generation and retirement year; and iii) monthly streamflow conditions for each HUC8 subbasin under different flow scenarios for 2018, 2035, and 2050.

CRediT authorship contribution statement

Md Abu Bakar Siddik: Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Emily Grubert:** Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Peter Caldwell:** Formal analysis, Writing – review & editing. **Landon T. Marston:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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