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Water Impacts of a Low-Carbon Electric Power Future: Assessment Methodology and Status

Haibo Zhai · Edward S. Rubin

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Abstract Water is an integral element of energy production. Future US energy production will increasingly be driven by the need to mitigate climate change, posing complex water challenges. The water impacts of electricity generation in a carbon-constrained future have been a subject of active research. This paper reviews technologies and regulatory policy options for low-carbon electricity generation, including systems that use fossil fuels with carbon capture and storage, renewables such as wind, solar, and biomass, and nuclear energy. We also review cooling technologies in support of thermoelectric power generation, report and discuss current assessment methods and results on water use for low-carbon energy production, and identify adaptive approaches that could reinforce resilience for low-carbon electricity generation. Some recommendations are made for future research.

Keywords Future · Low-carbon · Electricity generation · Cooling · Water use · Impacts · Coal · Natural gas · Carbon capture and storage · Renewable energy · Nuclear · Regulations · Policies

Introduction

Water is an integral element of energy production. Along with US population and economic growth, the demand for energy, especially electricity, continues to grow; this, in turn, may increase water use for energy production. Future US

electricity generation will increasingly be driven by the need to mitigate climate change, posing complex water challenges for the electric power industry, water resource management, and policy or decision makers. The challenges may also vary by location. Thus, the water impacts of electricity generation towards a low-carbon energy future have been receiving growing attention. Low-carbon resources considered for electricity generation include fossil fuel with carbon capture and storage (CCS), renewables such as wind, solar and biomass, and nuclear energy. The overall objective of this paper was to review and discuss the state-of-the-art assessment methodology and results on this subject. Specifically, we review technologies and regulatory policy options for low-carbon electricity generation as well as cooling technologies employed for thermoelectric power plants, report and discuss current assessment methods and results on water use for energy production using low-carbon resources, and identify adaptive approaches that help secure water use for electricity generation in a carbon-constrained world.

Technologies, Regulations, and Policies for Low-Carbon Electricity Generation

A transition from carbon-intensive fossil fuels to low-carbon resources and technologies for electricity generation has increasingly been considered as one of the most important approaches for climate change mitigation. In this transition, CCS could play a key role in deeply cutting carbon dioxide (CO₂) emissions from fossil-fuel-fired power plants. However, the CCS implementation would significantly increase plant water use due to the large amount of additional cooling water required for the capture process [1]. Driven by low gas prices and new supplies from shale gas production, a shift from coal to natural gas for electricity generation may facilitate the transition to a low-carbon energy future. Increasing the use

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of renewables and nuclear power will help to decarbonize the electric power sector [2•, 3]. The generation mix of a carbon-constrained energy future will be determined largely by resource availability and cost of electricity generation, and be shaped by low-carbon regulations and policies. Table 1 summarizes the costs of major power generation systems [4, 5].

Regulations and policies are drivers needed to limit CO₂ emissions from the power sector and to incentivize innovations and technological changes, as well as market establishment for low-carbon energy technologies. In September 2013, the US Environmental Protection Agency (EPA) issued a new proposal that sets up separate performance standards for limiting CO₂ emissions from new coal- and gas-fired electric generating units (EGUs) [6]. Compliance with the current proposal would require approximately 40–50 % CO₂ capture for new coal-fired EGUs, varying with power-plant designs [7]. Once these new source performance standards come into effect, Section 111(d) of the Clean Air Act requires the EPA to establish carbon pollution standards for existing power plants.

Table 1 Cost of electricity and water use for different power generation systems

Plant type	Capacity factor (%) ^a	Average cost of electricity generation (\$/MWh) ^a	Water use based on wet cooling tower when applicable (gallon/MWh) ^b	
			Water withdrawal	Water consumption
Dispatchable technologies				
SC PC	85 ^c	58.9 ^c	582–670	445–594
SC PC-CCS	85 ^c	106.5 ^c	1,098–1,157	815–907
IGCC	80 ^c	74.0–81.3 ^c	358–605	318–439
IGCC-CCS	80 ^c	105.6–119.4 ^c	479–742	522–604
NGCC	87	64.4	150–283	130–300
NGCC-CCS	87	91.3	487–544	378–407
Nuclear	90	96.1	800–2,600	581–845
Geothermal	92	47.9	5–361	5–361
Biomass	83	102.6	500–1,460	480–965
Non-dispatchable technologies				
Wind	35	80.3	0	0
Wind-offshore	37	204.1	0	0
Solar PV	25	130.0	0–5	0–5
Solar thermal	20	243.1	725–1,109	725–1,109
Hydro	53	84.5	1,425–18,000	1,425–18,000

SC PC supercritical pulverized coal, CCS carbon capture and storage, IGCC integrated gasification combined cycle, NGCC natural gas combined cycle, PV photovoltaic

^a Source of data: US Energy Information Administration [4]

^b Source of data: Macknick et al. [12•]

^c Source of data: National Energy Technology Laboratory [5]

Thus, the EPA proposed a flexible Clean Power Plan that sets up state-specific emission goals in order to reduce nationwide carbon pollution from the power sector by 30 %, from 2005 levels, in 2030 [8]. States have the flexibility to choose how to meet the goals, especially through programs that encourage heat rate improvement for fossil fuel power plants, increased utilization of natural gas combined cycle (NGCC) plants, renewable energy, and energy efficiency. In addition, other regulatory and policy options have been considered to promote low-carbon energy production, including CO₂ emission budgets, CO₂ emission prices or taxes, cap-and-trade programs, or the combination of the multiple options.

Cooling Technologies for Thermoelectric Power Plants

Water is used in thermoelectric power plants, mainly for the purpose of cooling. In contrast, in photovoltaic (PV) and wind power plants, water is used occasionally for cleaning or washing, which is negligible. In general, cooling technologies can be classified into two types: wet and dry cooling, which use water and air, respectively, as the cooling fluid to dissipate exhaust heat. The combination of wet and dry cooling is called a ‘hybrid cooling system’. Wet cooling technologies mainly include once-through cooling systems and closed-loop cooling ponds and towers, whereas dry cooling technologies include air-cooled condensers. Once-through cooling systems withdraw a large amount of cool water from a source via intake structures and then discharge the heated water directly back into the source. Once-through cooling systems produce adverse environmental impacts at both the intake and the outlet, but are relatively inexpensive compared with closed-loop cooling systems. In comparison between wet cooling towers and ponds, cooling ponds require a larger amount of land but less operating power and capital costs [9]. Different from wet cooling systems, dry cooling systems have no direct water use, but require more operating power, space, and capital costs than those of wet towers [10].

The EPA issued regulations on cooling intake structures under Section 316(b) of the Clean Water Act to minimize adverse environmental impacts [11]. The regulations promote the switch from once-through cooling to wet cooling towers or ponds since they are considered as ‘best technology available’ for meeting the requirements. Among various power plants, coal plants with CCS and concentrating solar power (CSP) plants using wet towers have the highest water consumption intensities, whereas non-thermal renewable plants such as PV and wind have the lowest water consumption. Nuclear plants with once-through cooling have the highest water withdrawal intensities, whereas non-thermal renewable energy technologies have the smallest values. Table 1 also presents water-use factors for different generation systems using wet cooling towers where applicable. Compared with wet cooling, the

water use for dry cooling is negligible. More details of plant water use are available in the review by Macknick et al. [12•].

Energy-Water Assessment Approaches

The water demand for regional low-carbon energy production is often estimated as the product of regional electricity generation projections multiplied by power-plant water-use factors. Thus, we first review current approaches that are employed to estimate plant-level water-use factors and regional electricity generation for alternative low-carbon energy futures.

Plant-Level Water-Use Factors

Three major approaches are reported to estimate plant water-use factors in gallons per megawatt-hour, including utility survey, top-down approach, and bottom-up approach.

- *Survey forms* Survey forms collected by the US Energy Information Administration (EIA) from individual utilities, such as EIA-767, EIA-860, and EIA-923, are used to derive water-use factors [3, 13•, 14]. However, this approach is based on the data of current generation systems and does not account for the differences between the current and future generation fleets.
- *Top-down approach* Average water-use factors are estimated based on the total water use divided by the total power generation in an energy-generating region. The US Geological Survey reports total generation and water use for thermoelectric plants at the county level by water type (fresh vs. saline), source (surface water vs. groundwater), and cooling technology [9]. However, no distinction is made for the type of plants using the same cooling technology. The water-use factors used for regional assessments often remain constant.
- *Bottom-up approach* Water-use models are developed based on fundamental mass and energy balances for thermoelectric power plants [1]. Thus, this kind of water-use model can explain variability by power plant and cooling system designs in plant water use [1]. Once probabilistic distribution functions are assigned to input variables under uncertainty, stochastic simulation can be carried out to yield the probabilistic range of plant water use and estimate the likelihood of a specific outcome.

Macknick et al. conducted a review that summarizes plant-level water-use factors available from the literature for a range of electricity generation and cooling systems [12•]. This review reveals that currently reported water-use factors are inconsistent, and have high uncertainties. The water-use factors adopted in the literature are estimated mainly on an annual national average basis without quantification of uncertainties.

The water-use estimates derived from survey data cannot sufficiently account for the variability by either location or season, which can exceed 15 % [2•, 12•]. Furthermore, the effects on water-use factors of improving thermal plant efficiency over time are not considered in many energy-water studies, which could lead to biases in regional water demand estimates for future scenarios.

Energy Modeling for Alternative Low-Carbon Scenarios

Energy modeling tools have been employed widely to forecast regional electricity generation and the generation mix under alternative low-carbon technology, climate, regulation, and policy scenarios. The current major tools used for energy-water assessments include the US EIA's National Energy Modeling System (NEMS), the National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS), the Joint Global Change Research Institute's Global Change Assessment Model (GCAM), and the Energy Technology Systems Analysis Program's MARKet ALlocation (MARKAL) model, briefly described as follows:

- *NEMS* is a regional, energy-economy modeling system of the US with a projection horizon of approximately 25 years into the future. It is used to project the complex interactions of the US energy system and its response to a range of alternative energy policies and different assumptions [15].
- *ReEDS* is a long-term capacity-expansion and dispatch model for the deployment of electric power generation technologies and transmission infrastructure throughout the contiguous US in 2-year increments to the year 2050 [2•, 16•]. The model can be applied to evaluate numerous key issues related to renewable energy, such as regional quality of renewable resources, seasonal and diurnal load, and generation profiles [2•, 16•].
- *GCAM* is an integrated assessment model designed for long-term analysis of energy, agriculture and land use, and climate, and offers projections of future energy supply and demand and water use for the electric power sector [17, 18]. GCAM can be used to evaluate climate change mitigation policies, including carbon taxes and trading, regulations and accelerated deployment of energy technology, as well as emission targets from various sources with a simulation period from 1990 to 2095.
- *MARKAL* is a data-driven, energy systems/economic optimization model that determines the least cost set of technologies over time to meet the specified demands under various user-defined constraints, including resource supplies, energy conversion technologies, and end-use demands and associated technologies [19]. EPA has developed a nine-region MARKAL model that can be applied to explore future energy scenarios [19].

It is difficult to make predictions about the future. The projections made by these tools should be considered to be statements of what might happen for the given methods, assumptions, and inputs. Thus, the model validation for either business-as-usual (BAU) or alternative low-carbon energy scenarios is widely missing or barely discussed in literature. Projections of energy future are basically presented in deterministic form rather than probabilistic form.

Water Impacts of Low-Carbon Electricity Generation

A variety of regulatory and policy strategies have been proposed or evaluated to help promote the use of low-carbon energy resources and technologies. The enactment of the US EPA's proposed CO₂ emission standards would produce substantial impacts on the electric power sector. The implementation of partial CCS to comply with the proposed standards will increase plant-level water use by approximately 20–50 % in coal-fired plants, varying with power plant and CCS designs [20•]. In contrast, new NGCC plants are able to meet the emission standards without any need for carbon capture. As a result, the levelized cost of electricity (LCOE) of a new baseload NGCC plant is 20 % less than that of a coal-fired plant, but is highly dependent on the gas price; water use of the NGCC plant is approximately 70 % less than that of the regulated coal-fired plant [20•]. In the electric power sector, the proposed emission standards may also facilitate the shift from coal to natural gas as a bridge to a lower-carbon energy future, resulting in less water use.

A variety of low-carbon fuels and technologies for electricity generation can produce different impacts on regional water resources. Regional water demand is also highly affected by the share of cooling technologies in the generation fleet. As summarized in Table 2, we review and discuss recent studies that investigate various combinations of technological pathways and policy strategies towards a low-carbon energy future for the period from 2030 to 2055, and evaluate their national and/or regional water impacts.

- *CCS retrofit and carbon price* Chandel et al. evaluated four low-carbon scenarios that explore different combinations of carbon price and CCS retrofit [13•]. Among these, the low-price scenarios start with a carbon price of \$15/tonne, whereas the high-price scenarios start with a carbon price of \$25/tonne. Nuclear power would increase by 34–49 % for the low-price scenarios and 95–98 % for the high-price scenarios. Higher carbon prices than \$50/tonne of CO₂ would drive the deployment of CCS to reduce CO₂ emissions from coal plants and increase freshwater consumption. The low-carbon policies would decrease freshwater withdrawals by 2–14 % compared with those of the BAU scenario without climate policies. Freshwater

consumption of all the scenarios would increase by 24–42 % from 2010 to 2030, mainly because of the shift from once-through to closed-loop cooling systems. If wind and PV plants are installed to replace conventional coal plants, water withdrawals and consumption would decrease by 18–23 % and 14–21 %, respectively.

Chandel et al. further illustrated that the water impacts of low-carbon electricity generation would vary by location [13•]. By 2030, the low-carbon climate policies would lead to remarkable reductions in water withdrawals from 5 to 33 % in the ECAR, MAIN, NY, and NRCC/NE regions (defined by the North American Electric Reliability Corporation), but increases in water withdrawals by 10 % and 13–44 % in the FRCC/FL and RM regions, respectively. Most pronounced increases in water consumption are projected to take place in the South and East, including Florida, New England, New York, Texas, and the Mid-Atlantic, which result from the collective effects of multiple factors: electricity generation increase, generation mix change, and CCS retrofit for coal plants.

- *Improved fossil fuel and renewable energy technologies* Tidwell et al. estimated future water demands for electricity generation based on the EIA's energy projections for multiple alternative cases, including the Reference Case, Low Fossil Technology Cost Case, and Low Renewable Technology Cost Case, and further evaluated water availability based on the water supply data collected at the six-digit hydrologic unit code level [21•]. The major difference between the alternative cases is the mix profile characterized by fuel and technology types. Their assessment of water availability indicates that, for the Reference case, 19 % of new electric power generation between 2007 and 2035 is likely to be sited in basins with limited surface water or groundwater availability. In contrast, 17 % of new thermoelectric power generation projected in the Low Fossil Technology Cost scenario is likely to be sited in regions with limited water availability, whereas that of the Low Renewable Technology Cost scenario is 9.5 %; the retirement of once-through cooling systems and the deployment of wet closed-loop cooling systems will collectively decrease water withdrawals but increase water consumption, and significant portions of the Great Plains, Southwest, West, and Florida are identified to be regions with limited water availability for future development.
- *Carbon budget with or without low-carbon technology preference* Macknick et al. and Clemmer et al. evaluated the national and regional water-use impacts of low-carbon energy production under the constraints of an economy-wide carbon budget (170-Gt CO₂eq) and generation technology preference illustrated in Table 2 [2•, 16•]. In the BAU scenario, natural gas is expected to become the

Table 2 Water impacts of alternative low-carbon electricity generation pathways

Study, year	Energy modeling tool	Time horizon	Geographic modeling resolution	Low-carbon electric power generation scenarios	National or regional water impacts
Chandel et al. [13•], 2011	Modified NEMS with an added module for CCS	2030	North American Reliability Corporation regions	<ul style="list-style-type: none"> • Low-carbon allowance price, no CCS retrofits allowed • Low-carbon allowance price, CCS retrofits allowed • High-carbon allowance price, no CCS retrofits allowed • High-carbon allowance price, CCS retrofits allowed 	<ul style="list-style-type: none"> • Freshwater withdrawals of low-carbon scenarios would decrease by 2–14 % compared with those of the business-as-usual scenario • Freshwater consumption of low-carbon scenarios would increase by 24–42 % between 2010 and 2030 • The addition of CCS to coal plants under the constraint of carbon prices more than \$50/ton of CO₂ would increase freshwater water consumption • The water impacts of low-carbon policies vary by location
Tidwell et al. [21•], 2011	EIA's AEO2011	2035	Hydrologic unit code	<ul style="list-style-type: none"> • Low fossil technology cost case • Low renewable technology cost case 	<ul style="list-style-type: none"> • 17 % of new thermoelectric power generation projected in the low fossil technology cost case is likely to be sited at regions with limited water availability. In contrast, that is 9.5 % for the low renewable technology cost case • The identified regions with limited water availability are significant portions of the Florida, Great Plains, Southwest, and West.
Macknick et al. [2•], 2012	ReEDS	2050	Hydrologic unit code	<ul style="list-style-type: none"> • Carbon budget, no technology targets • Carbon budget with technology preference on coal-CCS and nuclear • Carbon budget with technology preference on efficiency improvement and renewable energy 	<ul style="list-style-type: none"> • The phase-out of conventional coal plants and the increased share of NGCC plants would decrease the national water withdrawals • High penetration of renewable energy in the future electric power sector would significantly decrease national water withdrawals by up to 97 % • The national water consumption for power generation under the carbon constraints may decrease by 55–85 %, highly dependent on the share of renewable energy. However, the low-carbon scenario heavily dependent on coal-CCS and nuclear plants is expected to have a higher level of national water consumption in 2050 than in 2010 • Regional trends in water consumption change with generation pathways. Substantial deployment of nuclear facilities and coal plants with CCS will increase consumptive water use in the Mid-Atlantic, Great Lakes, Central, Southeastern, and Southwestern regions of the country. Some renewable energy technologies such as CSP solar power and geothermal energy systems can lead to high water consumption in arid Western states, which depends on the grid share
Clemmer et al. [16•], 2013	ReEDS	2050	Hydrologic unit code	<ul style="list-style-type: none"> • Carbon budget, no technology preference • Carbon budget with technology preference on coal-CCS and nuclear • Carbon budget with technology preference on efficiency improvement and renewable energy 	<ul style="list-style-type: none"> • Among several low-carbon scenarios, the heavy dependence on CCS and nuclear technologies for low-carbon electricity generation will increase national water consumption by 21.7 % than the 2010 level • Aggressive penetration of renewable energy plus ambitious reductions in energy demand via efficiency improvement would significantly reduce national water use by 85 % in 2050 compared with the 2010 level.
Webster et al. [23•], 2013	Generation Expansion Model	2050	Electric Reliability Council of Texas	<ul style="list-style-type: none"> • CO₂ emission constraints • Water withdrawal constraints 	<ul style="list-style-type: none"> • To achieve the 75 % emission reduction, most of the coal capacity is to be replaced by nuclear capacity and, in turn, would increase regional water withdrawals by 64 % • Constraining CO₂ emissions and water withdrawals would result in a very different generation mix, which would nearly double the NGCC capacity,

Table 2 (continued)

Study, year	Energy modeling tool	Time horizon	Geographic modeling resolution	Low-carbon electric power generation scenarios	National or regional water impacts
Cameron et al. [24•], 2014	MARKAL	2055	EPA's defined nine regions	• Three levels of reductions in energy system-wide CO ₂ emissions	<p>decrease the nuclear capacity by 40 %, and require more dry or hybrid cooling in comparison with the base-case.</p> <ul style="list-style-type: none"> • By 2055, CO₂ emission constraints would reduce the national water withdrawals by 31–46 % in comparison with that of the base-case in the electric power sector • By 2055, the national water consumption for the 50 % emission reduction scenario would increase by 42 % compared with that of the base-case, mainly because of the increased use of recirculating cooling, nuclear power plant, and NGCC-CCS

NEMS National Energy Modeling System, *CCS* carbon capture and storage, *EIA* Energy Information Administration, *AEO2011* Annual Energy Outlook 2011, *ReEDS* Regional Energy Deployment System, *MARKAL* MARKet Allocation, *EPA* Environmental Protection Agency, *CO₂* carbon dioxide, *NGCC* natural gas combined cycle, *CSP* concentrating solar power

major resource for future electricity generation. Conventional coal plants will be largely phased out by 2030 under the carbon constraints; wind and solar power is expected to have the largest growth and dominate future national generation, whereas natural gas will play a significant intermediary role.

The national water withdrawals of the BAU scenario will decrease by 26.6 % in 2030 and by 80.7 % in 2050 compared with those of 2010. High penetration of renewable energy would further significantly decrease national water withdrawals by 97 %. These national trends are mainly determined by the retirement of once-through cooling systems and the deployment of closed-loop cooling for new power plants, although coal-CCS plants and nuclear power plants use more water than other generation technologies. Under the carbon constraints, the phase-out of conventional coal plants and the increased share of NGCC plants make further contributions to the reductions in national water withdrawals. The high penetration of renewable energy will accelerate the water reduction pace. In spite of significant national water withdrawal reductions, some Western regions may experience increases in freshwater withdrawals because of increased energy demand plus the retirement of once-through coastal facilities. Parts of Texas and Arizona would have substantial increases in water withdrawals because more coal plants with CCS and nuclear plants would be installed in these regions.

Relative differences in water withdrawal and consumption factors for various power generation and cooling technologies lead to the difference in varying trends for national water consumption versus withdrawals [2•]. In the BAU case, the national water consumption would increase slightly by 0.6 % in 2030 and then decrease by 34.2 % in 2050 compared with

the 2010 level. The national water consumption may decrease by 55–85 % under the carbon constraints, highly dependent on the share of renewable energy in the future fleet. However, the low-carbon scenario heavily dependent on the deployment of coal-CCS and nuclear plants from 2030 to 2050 is expected to increase national water consumption by 21.7 % compared with the 2010 level. Aggressive penetration of renewable energy plus ambitious reductions in energy demand would significantly reduce national water use by 85 % in 2050 compared with the 2010 level. Arent et al. also found, at the penetration rate of 80 % for renewable energy, the water use for the electric power sector could be cut by approximately 50 % in 2050 relative to 2006 [22]. The regional trends in water consumption change with low-carbon technology roadmaps.

- *CO₂ emission and water withdrawal constraints in the electric sector* Webster et al. explored the tradeoffs under the constraints of CO₂ emissions and water withdrawals in planning regional electricity generation [23•]. They evaluated different scenarios: a base-case without CO₂ emission and water withdrawal limits; 75 % reduction in carbon emissions relative to the base case; 75 % reduction in carbon emissions and 50 % reduction in water withdrawals relative to the base-case. For the assumed fuel prices (\$12.6/MBtu for natural gas and \$3.5/MBtu for coal), most of the coal capacity is to be replaced by nuclear capacity in order to achieve the 75 % reduction in CO₂ emissions, which would increase the regional water withdrawals by 64 %, mainly due to additional water use for nuclear generation. Constraining both CO₂ emissions and water withdrawals would result in a very different generation mix. Compared with the base-case, the resulting

NGCC capacity would nearly double and would require dry cooling systems, and nuclear capacity would decrease by 40 % and would require hybrid cooling. For the scenario with both CO₂ emission and water-use limits, only 5 % of the total capacity will come from wind generation. The results show that the water-use constraint could also impact the generation mix and the choice of cooling technology.

- *Different levels of reductions in energy-system-wide CO₂ emissions* Cameron et al. evaluated the effects of reducing the energy-system-wide CO₂ emissions by 10 %, 25 %, and 50 % on water use for the US electric power sector [24]. For the 10 % and 25 % reduction scenarios, the electric power sector account for nearly all of the system-wide reductions. Conventional coal plants will be retired gradually. New electricity generation will be supplied by NGCC plants and wind power. In the 50 % reduction scenario, the electric power sector would contribute 75 % of the total system-wide reduction in CO₂ emissions. Nuclear power, NGCC-CCS plants, and renewable power (mainly wind) will be three major technologies dominating the future grid of the 50 % reduction scenario. CO₂ emission mitigation strategies change with regions. For the 50 % reduction scenario, eastern regions rely heavily on NGCC-CCS and nuclear power, whereas central and western regions rely mainly on wind and solar power plants.

By 2055, the constraint of CO₂ emissions would reduce the electric power sector's water withdrawals by 31–46 % in comparison with that of the base-case in 2055, depending on the level of CO₂ emission mitigation. However, the trends of water consumption for different mitigation scenarios appear complex. Stringent CO₂ emission reductions would increase the penetration of CCS and, in turn, regional water consumption for the electric power sector. By 2055, national water consumption for the 50 % reduction scenario would increase by 42 % compared with that of the base-case in 2055, mainly because of the increased use of closed-loop cooling, nuclear power plants, and NGCC-CCS plants.

Some caveats accompany the existing energy-water assessments. The production of shale gas as a potential major source of US natural gas supply can consume plenty of freshwater from 6,700 to 33,000 m³ per well over its lifecycle, excluding final gas utilization [25]. Water is also needed in the production of chemicals and materials used for CO₂ capture. However, existing studies have not carefully addressed the water impacts on a lifecycle basis; existing low-carbon studies do not broaden their outlook for new-generation CCS technologies [26, 27]; the implementation of CCS may start with partial CO₂ capture in response to the EPA's proposed CO₂ emission regulations. In addition, flexibly operating CO₂ capture at partial load in response to volatile electricity prices

could help maintain grid reliability and meet peak demand [28]. However, many studies look into the full CO₂ capture (90 %) via CCS for fossil-fuel-fired power plants rather than partial carbon capture; the feasibility of highly aggressive penetration (50–80 % of the fleet) of renewable energy in the future generation fleet needs further technical and economic assessments. Grid-scale energy storage holds the potential to facilitate high penetration of intermittent renewable energy resources into the electric power grid, manage peak demand, and support grid stability [29]. Although pumped-storage hydroelectricity is the major form of current energy storage for electric power systems [30], battery systems would offer a number of opportunities for grid-scale energy storage, given that lower costs can potentially be obtained [31]. However, there are a number of technical, economic, and regulatory challenges for grid-scale storage applications; without region-specific assessments on resource availability and costs, the recommendation of aggressively employing renewable energy and dry cooling to lower regional water use might misguide stakeholders. Climate change is likely to alter future patterns of regional water availability. However, existing studies mainly focus on the water demand side and barely examine the water demand/supply balance under the varying climate condition; along with water availability vulnerable to climate change, regional energy-water conflicts may vary with regions and seasons over time. However, existing assessments are conducted largely on an annual basis and lack estimates of high temporal resolution; uncertainty in estimating regional water use is ignored widely in existing studies.

Adaptive Approaches to Reinforce Resilience for Low-Carbon Electricity Generation

Advancing electricity-generation system designs would be helpful to reduce the water use for low-carbon electricity generation. At the plant level, plant efficiency improvements and the use of high-quality coal can remarkably reduce plant-level water use for new coal-fired plants, subject to the EPA's proposed emission performance standards [20].

Water availability for thermoelectric power generation could be vulnerable to future climate change [32]. Along with social and economic development, the electric power sector may have a conflict for water use with other sectors. Thus, advanced cooling systems and alternative water resources should be considered in support of low-carbon electricity generation [33], especially when water availability is of concern, including the following.

- *Shift from wet cooling to advanced dry or hybrid cooling technologies* A new study shows that employing hybrid cooling systems for new coal-fired power plants, subject to the EPA's proposed CO₂ emission standards, would

reduce plant water withdrawals and consumption by 54 % and 58 %, respectively, in comparison with the plants using wet cooling towers [20].

- *Water recovery and reuse from power-plant flue gases.* A technological assessment shows that 40 % of water vapor from flue gases could be recovered using advanced membrane condensers for reuse within the plant, which could lead to an increase of over 5 % in efficiency [34].
- *Reuse of produced water from CCS storage sites or oil and gas fields* A large amount of produced water can be extracted from the CO₂ storage sites and reused as makeup water for power plants after appropriate treatment [35].
- *Use of treated municipal wastewater or brackish water* An analysis on the feasibility of using reclaimed water for thermoelectric power plants indicates that sufficient treated wastewater is available within 25 miles of 92 power plants selected in a case study of Texas, representing 61 % of capacity and 50 % of generation in the state [36]. Treated municipal wastewater could be a suitable source of cooling water for thermoelectric power plants to offset some of the freshwater requirements [36]. The major technical challenges for power-plant use are biofouling, inorganic scaling, and corrosion [37].

When assessing the feasibility of alternative water sources, multiple key factors should be taken into account: water quality, water quantity, and source location to determine the water treatment cost, supply capability, and transport and infrastructure costs.

Conclusions

Recent research indicates that low-carbon electricity generation along with a switch from once-through cooling to wet recirculating cooling in the future would significantly decrease national water withdrawals but may increase national water consumption, especially if CCS and nuclear power are heavily employed in the electric power sector. High penetration of renewable energy into the future generation fleet will markedly lower national water use. Different from national trends, the regional water impacts of low-carbon electricity generation appear complex and vary by location, dependent on the region-specific low-carbon roadmap and the cooling technologies employed. Advanced dry or hybrid cooling systems and alternative water resources can be adopted to support low-carbon energy production for regions where consumptive water use will increase substantially or water supplies will become inadequate.

A changing climate would put significant pressure on the electric power industry's water management, especially in regions facing a water crisis or water scarcity. The availability of water and renewable resources can impact the deployment

of low-carbon energy technologies and cooling technologies in operating power generation systems. Thus, an integrated assessment framework that incorporates all the climate, energy, and water components, and examines both the water demand and supply sides, is needed to improve the understanding of the interactions among low-carbon energy production, climate change mitigation, and water-resource planning for a sustainable low-carbon future. Uncertainties in water-use factors and energy projections also need to be incorporated in the framework to offer risk-based assessments for decision making. When a large amount of water is used for the production of low-carbon fuels and materials, the scope of the assessments should be expanded from plant and regional levels to a lifecycle chain. Furthermore, new low-carbon regulatory and policy constraints such as the US EPA's proposed standards and plans for limiting CO₂ emissions from the electric power sector need to be considered in the energy-water assessments.

Compliance with Ethics Guidelines

Conflict of Interest Haibo Zhai and Edward S. Rubin declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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Papers of particular interest, published recently, have been highlighted as:

- Of importance
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