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Consumptive Water Use from Electricity Generation in the Southwest under Alternative Climate, Technology, and Policy Futures

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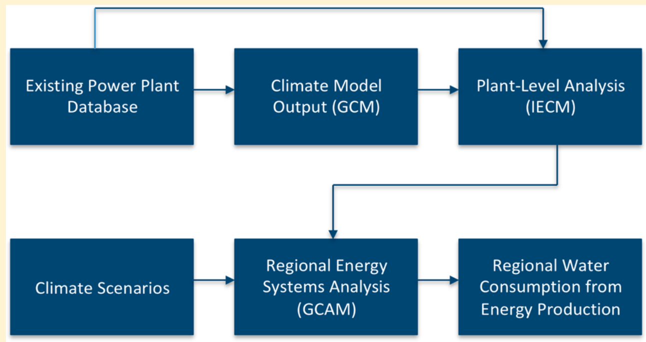
Supporting Information

ABSTRACT: This research assesses climate, technological, and policy impacts on consumptive water use from electricity generation in the Southwest over a planning horizon of nearly a century. We employed an integrated modeling framework taking into account feedbacks between climate change, air temperature and humidity, and consequent power plant water requirements. These direct impacts of climate change on water consumption by 2095 differ with technology improvements, cooling systems, and policy constraints, ranging from a 3−7% increase over scenarios that do not incorporate ambient air impacts. Upon additional factors being changed that alter electricity generation, water consumption increases by up to 8% over the reference scenario by 2095. With high penetration of wet recirculating cooling, consumptive water required for low-carbon electricity generation via fossil fuels will likely exacerbate regional water pressure as droughts become more common and population increases. Adaptation strategies to lower water use include the use of advanced cooling technologies and greater dependence on solar and wind. Water consumption may be reduced by 50% in 2095 from the reference, requiring an increase in dry cooling shares to 35−40%. Alternatively, the same reduction could be achieved through photovoltaic and wind power generation constituting 60% of the grid, consistent with an increase of over 250% in technology learning rates.



■ INTRODUCTION AND OBJECTIVES

Water is integral to power generation. In 2005, roughly 90% of electricity in the United States was produced by thermoelectric power plants, which accounted for 44% of national freshwater withdrawals and 6% of consumptive use.[1,2] Consumptive water use for power generation has been increasing due to capacity expansion and a shift from once-through to wet recirculating cooling systems.[3] In the future, changes in power generation technologies for low-carbon energy may increase water consumption intensity, including such efforts that may favor nuclear power and power generation technologies with carbon capture and storage (CCS).[4] For example, Chandel et al. evaluated the water impacts of climate policies and found a 24−42% increase in national water consumption by 2030 under different climate mitigation scenarios.[5] Similarly, Cameron et al. found changes in water consumption within a range from −4 to +42% by 2055, depending on emission reduction targets.[6] Macknick et al. demonstrated that 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.[7] In addition to these short- or medium-term projections, a recent study applied a U.S.-specific version of the Global Change Assessment Model (GCAM-USA) to project state-level water use over the century under alternative energy demand and policy scenarios and found that low-carbon policies promoting CCS installation and nuclear generation have impacts on water consumption higher than those of renewable-focused strategies.[3] While water withdrawals in the GCAM-USA scenarios were estimated to decrease by 91%, water consumption would increase over the next century by 40−80%. However, these studies did not incorporate direct impacts of climate change on power plant water use, which are potentially significant due to the influence of ambient air temperature and humidity on cooling water requirements.[8]

To limit carbon dioxide (CO_2) emissions, the U.S. Environmental Protection Agency (EPA) proposed emission performance standards for new fossil fuel-fired power plants in 2013 and finalized the proposal in 2015.[9] The implementation of CCS to comply with the proposed emission standards of 1100 lb/MWh would increase plant water use by roughly 20−50% at coal-fired power plants.[10] The EPA's Clean Power Plan proposes to reduce nationwide carbon pollution from existing

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power plants by 32% in 2030. This is to be achieved through the use of various mitigation measures such as increased utilization of natural gas and renewable energy for electricity generation.[11] In addition, the EPA also issued regulations on cooling intake structures under Section 316(b) of the Clean Water Act (CWA), promoting a switch from once-through cooling to wet cooling systems for both new and existing plants.[12] This shift will potentially double national water consumption from power generation by 2030.[2]

While different regions will face different issues, this study focuses on the Southwest, where population is projected to continue to rise, and water scarcity is an increasing concern. Water demand will soon exceed supply, and as the climate warms, water supply will likely shrink.[13] For example, the yield of the already overallocated Colorado River could drop by 10–20% by midcentury from climate change alone.[13−15] Many southwestern states are using groundwater to compensate for shortfalls in available surface water. However, total annual availability from this source is dropping.[12] In addition, all sectors are projected to increase water use as average temperatures rise, further depleting sources that are already stressed.[15] This study aims to deepen the understanding of the long-term water demands of the power sector in this region.

This study projects consumptive water use for electricity generation in the southwestern United States over a planning horizon of nearly one century and to examine how changes in climate, technological, and policy dimensions shaping energy systems would influence regional water consumption. It does not, however, look at water scarcity or how water availability will impact decisions in the power sector. It does not examine how climate change impacts on water temperature and water availability will impact generation capacity or decisions in the power sector, topics that have received attention in the literature.[16,17] The states considered include Arizona (AZ), New Mexico (NM), Utah (UT), Nevada (NV), Oklahoma (OK), and Texas (TX). We explore the implications for the electric power industry's technology choices and water management in the face of future policy constraints and varying regional conditions. Considering that long-term projections necessarily involve considerable uncertainty in the results, we examine multiple scenarios to gain a better understanding of how water consumption may potentially change under a range of different key factors and future outcomes.

■ ASSESSMENT METHODS AND TOOLS

Representative concentration pathways (RCP) from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) are used to drive three widely used general circulation models (GCMs) and project regional climate scenarios through 2095. To test the hypothesis that climate-related changes in ambient air temperature and humidity will have an effect on consumptive water use for electricity generation over the century, region-specific climate projections from the GCMs are used as inputs for a power plant model to estimate water consumption intensities of cooling system and power generation technologies under different climate scenarios. These plant-level water consumption intensities are used to calculate climate correction factors that account for the impacts of climate change on regional water use. Driven by RCP scenarios, we use GCAM-USA updated with recent water use and cost information to model regional energy systems and then estimate regional water consumption under different climate scenarios. 2005 was chosen as the base year, while 2050 and 2090 were selected as benchmark years for future scenarios.

Climate Pathways. Two RCP scenarios from IPCC AR5 that describe possible radiative forcing values in the year 2100 were employed. RCP 8.5 is a high emissions pathway with increasing greenhouse gas emissions throughout the 21st century. RCP 4.5 is a scenario with strategies or technologies deployed to stabilize radiative forcing.[18,19] Global carbon emitted per year by the end of the century under RCP 8.5 is almost six times that of RCP 4.5. Subsequently, the corresponding global surface temperature change leads to twice the warming compared to that in RCP 4.5.[20]

Ambient air temperature and relative humidity are the variables that affect evaporative losses in wet towers.[21,22] Given that once-through cooling will rarely be used in the future, we do not consider effects on the intake cooling water temperature. Region-specific estimates of these variables were determined based on the climate outputs from GCMs. Enough GCM ensemble runs were used to mitigate internal variability within each model.[23] Further information on the GCMs is available in the Supporting Information Section S-1. For each RCP scenario, average near surface air temperature and relative humidity specific to locations of representative power plants in the Southwest were from each ensemble run of the three GCMs.

Integrated Environmental Control Model for Power Plant Assessments. The Integrated Environmental Control Model (IECM) is a model developed by Carnegie Mellon University to perform systematic estimates of the performance, resource use, emissions, and costs for pulverized coal (PC), integrated gasification combined cycle (IGCC), and natural gas combined cycle (NGCC) power plants with and without CCS.[24] IECM also includes a set of major cooling technologies, including once-through cooling, wet towers, and air-cooled condensers for dry cooling. The water models in the IECM were developed based upon the mass and energy balances to estimate water use, energy penalties, and costs of cooling systems.[21,22] Additional information on IECM is provided in the Supporting Information. IECM was applied to model representative power plants in each state in terms of major plant designs and attributes and then to estimate water consumption intensities (m^3/MWh) for wet cooling systems under different climate conditions. The resulting values were used to derive the correction factors that quantify the water use impacts of climate change. These representative power plants were generated using the Union of Concern Scientists' Energy-Water Database and the EPA's National Electric Energy Data System (NEEDS) to characterize existing southwest fossil fuel-fired plants in terms of plant location, size, efficiency, capacity factor, and cooling type, and fuel type.[25,26]

For both PC and NGCC plants, a representative power plant was created for each state in terms of the estimates on average for these major plant attributes. Temperature and humidity inputs were based on current power plant locations. Temperature and humidity inputs for both current and future cases are state averages based on the general circulation model results of current plant locations.

Future energy systems will include low-carbon and advanced generation technologies. Thus, climate-related correction factors were also determined for PC plants with CCS, IGCC plants, IGCC plants with CCS, and NGCC plants with CCS. Because there are currently no plants with CCS or IGCC plants

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Table 1. Alternative Climate, Technology, and Policy Scenarios

technology or policy scenario	climate scenario	scenario code	scenario feature description
reference scenario	8.5, 4.5	RCP 8.5 ref RCP 4.5 ref	default settings in GCAM except for the changes noted
		alternative scenarios	
high natural gas prices	4.5	RCP 4.5-NG 50 or 100	increase in natural gas prices by 50% or 100% throughout the century relative to the default values under the RCP 4.5
CO_2 emissions performance standards	4.5	RCP 4.5-EPS 20 or 40	compliance with both the finalized and proposed U.S. EPA's CO_2 emission performance standards for new coal-fired power plants
renewable energy	4.5	RCP 4.5-RE	high penetration of PV and wind power in the electric power sector
dry cooling	4.5	RCP 4.5-DC	high penetration of dry cooling shares in thermoelectric power plants

Table 2. Average Changes in State-Level Parameters by 2095 Relative to 2005[a]

			absolute changes in ambient air conditions under RCP 8.5		absolute changes in ambient air conditions under RCP 4.5	
state	annual population growth (%)	annual GDP MER growth (%)	temperature (°C)	relative humidity (%)	temperature (°C)	relative humidity (%)
AZ	5.86	19.21	5.94	−2.62	3.12	−2.05
NM	−0.28[b]	1.32	5.85	−5.95	2.98	−3.63
NV	4.50	15.25	6.30	−6.41	3.31	−3.03
OK	0.21	2.74	5.84	−2.64	3.08	−1.54
TX	2.32	8.89	4.95	−0.83	2.71	−1.61
UT	2.36	9.02	5.03	−3.77	2.65	−2.73

[a]Data in this table is from output of GCMs as well as GCAM-USA model input. [b]Following U.S. census projections until 2030, New Mexico is projected to have an increasing population until mid century, after which it decreases, leading to an overall negative average growth. Dominant states are Texas and Arizona, with the highest projected population growth in the region.

in the region, the default designs within IECM were used for these plants. When CO_2 emission standards are considered for new PC plants, amine-based CCS is employed for partial CO_2 capture to comply with the standards.[10] As some states still utilize cooling ponds that are not an option available within IECM, it was assumed that the effects of ambient air conditions on cooling ponds' water use intensities are similar to those of wet cooling towers. Thus, water consumption intensities were estimated as a function of power plant designs, climate conditions, and low-carbon regulations.

Global Change Assessment Model for Regional Assessments. GCAM is an integrated assessment model developed by the Pacific Northwest National Laboratory to project global changes in energy, agriculture, emissions, and climate over the next century.[27,28] GCAM is a well-established integrated assessment model that has been widely used for various applications, such as evaluating climate impacts from increased natural gas usage, mitigation impacts on land use and energy systems, and comparative mitigation impacts on water stress in the United States.[29−31] This study employs a modified version of the model: GCAM-USA, a U.S., state-specific model nested within the global model.[3] This model includes coal (PC, IGCC), natural gas (steam turbine (NGST) and NGCC), nuclear, photovoltaic (PV) and concentrated solar power (CSP)), wind, hydro-, bio- (conventional and bio-IGCC), and oil-based energy generation systems. For each type of fossil fuel-fired generation system, there are three technology options available in GCAM-USA: conventional technology, an advanced technology, and that same advanced technology with CCS (e.g., PC, coal-fired IGCC and IGCC plants with CCS). In this analysis, we added PC with CCS as another option to the model. CCS technologies are only incorporated into RCP 4.5, whereas they are not included in the RCP 8.5 scenario because that assumes no climate policies. CCS is not employed until 2020, competing directly with the same type of generation systems without CCS. While the RCP 8.5 trajectory has no mitigation policies in place, the RCP 4.5 trajectory is sufficiently aggressive to drive large changes to the generation mix in the electric power sector.[3] This scenario enables analysis of impacts from large-scale shifts in the electric power sector. GCAM uses a carbon tax initiated in 2020 increasing at 5% per year until the stabilization target of 4.5 W/m^2 radiative forcing is reached.[3] All sectors in the model, including the power sector, are influenced by the equilibrium effects of the carbon price. Interstate trading of electricity is included in the model.

In GCAM-USA, regional water consumption is estimated as the product of plant-level water consumption intensities and regional power generation by each modeled power plant type. The effects of climate warming on the overall plant efficiency are not taken into account because they are just 0.12−0.45% for each 1 °C of climate warming for fossil fuel-fired power plants.[32] For each fuel and technology, water use is estimated for each five-year period for each state. The baseline water consumption intensities in GCAM are from a review study by Macknick et al.[33] Because these estimates are not provided for a range of ambient air conditions, average water consumption intensities were adjusted by a climate correction factor for each generation technology under each RCP. The correction factor is estimated as the ratio of plant-level consumption intensities from the IECM simulations based on base year and future climate conditions. The climate correction factor was calculated for 2050 and 2090, after which five-year interpolations were calculated starting with the base year of 2005. When a scenario with no climate change is considered, the same water intensity factors as those used in the base year are adopted for the future periods (see the Supporting Information, Table S3 for more details). Electricity demand within GCAM can take ambient air impacts into account using degree days, though this is not included in this study. Midcentury energy generation results from GCAM-USA for the states under analysis are similar to those of the National Energy Modeling System. In addition, the projected short-term demand increase is comparable to those

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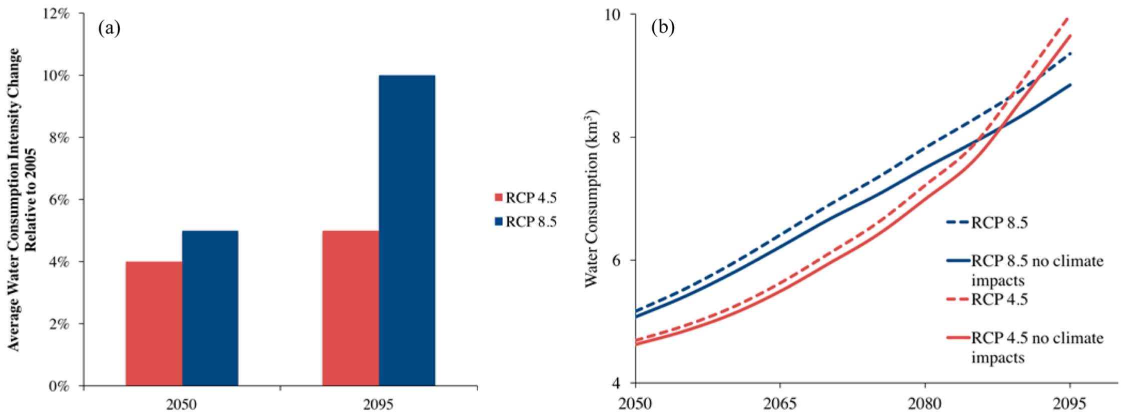

Figure 1. Impacts of changes in ambient air conditions: (a) changes in regional water consumption intensity of thermoelectric plants relative to 2005 in the Southwest and (b) total projected regional water consumption from energy generation over time from 2050 to 2095 under RCP 4.5 and 8.5 with and without direct ambient impacts from climate change.

made by EPA and NREL.[3] Further information is in Section S-3 of the Supporting Information.

Alternative Future Scenarios. In addition to the climate scenarios specified by two RCPs, the inherent uncertainty in long-term projections necessitates sensitivity to other potential important changes in technology and policy that would significantly affect the electric power sector. Table 1 describes these alternative scenarios analyzed.

■ RESULTS AND ANALYSES

Regional Features. Electricity demand in GCAM-USA is driven by the activities of end-use consumption sectors, whose activity levels respond to population and GDP and whose fuel substitution capacities are exogenous and sector-specific.[28] Electricity generation values in each state are calculated endogenously.[3] These sociodemographic projections are based on the U.S. census as well as growth functions made by the builders of GCAM-USA.[34] The growth of these variables is summarized in Table 2 by state through 2095. Emissions in the study region under RCP 8.5 reach 237 million tonnes of carbon (MtC) in 2095, growing by 99% from 2005, while regional emissions under RCP 4.5 reach 41 MtC across, a decrease of 65% from 2005.

The future climate scenarios corresponding to RCP 8.5 and 4.5 are characterized in terms of ambient near surface air temperature and relative humidity.[22] Table 2 summarizes the multimodel projected average changes in the two parameters by the end of this century relative to 1990 under each RCP scenario. The temperature increases are estimated to be 5−6 and 2−3 °C for RCP 8.5 and 4.5, respectively (see the Supporting Information Section S-1 for more information). Relative humidity is estimated to drop by 4% on average for RCP 8.5 and 2% for RCP 4.5. The stabilization of radiative forcing via mitigation strategies or technologies under RCP 4.5 would generally result in smaller air temperature and humidity changes.

Plant-Level Water Consumption. Region-specific near surface air temperature and relative humidity from GCMs are used as inputs for IECM to estimate water consumption intensities of fossil fuel-fired power plants and their relative changes over time. As nuclear, concentrated solar power (CSP) plants, and natural gas steam turbine (NGST) use the same type of wet recirculating cooling systems, the relative changes derived from fossil fuel-fired power plants are used to account for climate impacts on their water use intensities. Figure 1a depicts average percent changes in water consumption intensities over time under both climate scenarios. For plants using wet recirculating cooling, there is an 8−10% increase in water consumption intensity by the end of the century under RCP 8.5 and a 4−5% increase under RCP 4.5. This is expected, as RCP 4.5 is a stabilization scenario resulting in less temperature change after 2050. More specific results are available in the Supporting Information, Table S2. As described earlier, water consumption intensities in GCAM are adjusted by the climate correction factors derived from these IECM modeling results.

Reference Scenarios. The reference scenarios are based on current cost and technological and socioeconomic values and projections, which is representative of only potential outcomes under both RCP 8.5 and 4.5.

Electricity Generation. The generation profile of a future grid is dependent on the capital and operating and maintenance costs of power generation technologies. The baseline year costs used in GCAM are updated with the National Energy Technology Laboratory's baseline report for PC and IGCC plants and the U.S. Energy Information Administration (EIA)'s recent power plant cost estimates for other technology types.[35,36] Future cost changes over time are inherited from the GCAM assumptions with minor changes to adjust for input cost changes.

Regional electric power generation over time was estimated under RCP 8.5 and 4.5. Under RCP 4.5, the carbon price is projected to be about \$100/tC (2012) by 2050: a comparable value based on the social cost of carbon analysis conducted by the U.S. Government[37] (see the Supporting Information, Section S-3 for further expansion). The price then rapidly increases in the latter half of the century to more than \$700/tC by 2095 due to the radiative forcing constraint to motivate shifts to low-carbon technologies. While climate mitigation policies led to high electricity prices, they also led to slightly higher demand (approximately 2.2% in the reference scenario) due to electricity replacing direct combustion of fossil fuels in the building, transportation, and industrial sectors.[7] The phenomena that the substitution effect can cause electricity demand to increase in emissions mitigation scenarios also has been demonstrated with other models, such as the Research Triangle Institute's Applied Dynamic Analysis of the Global

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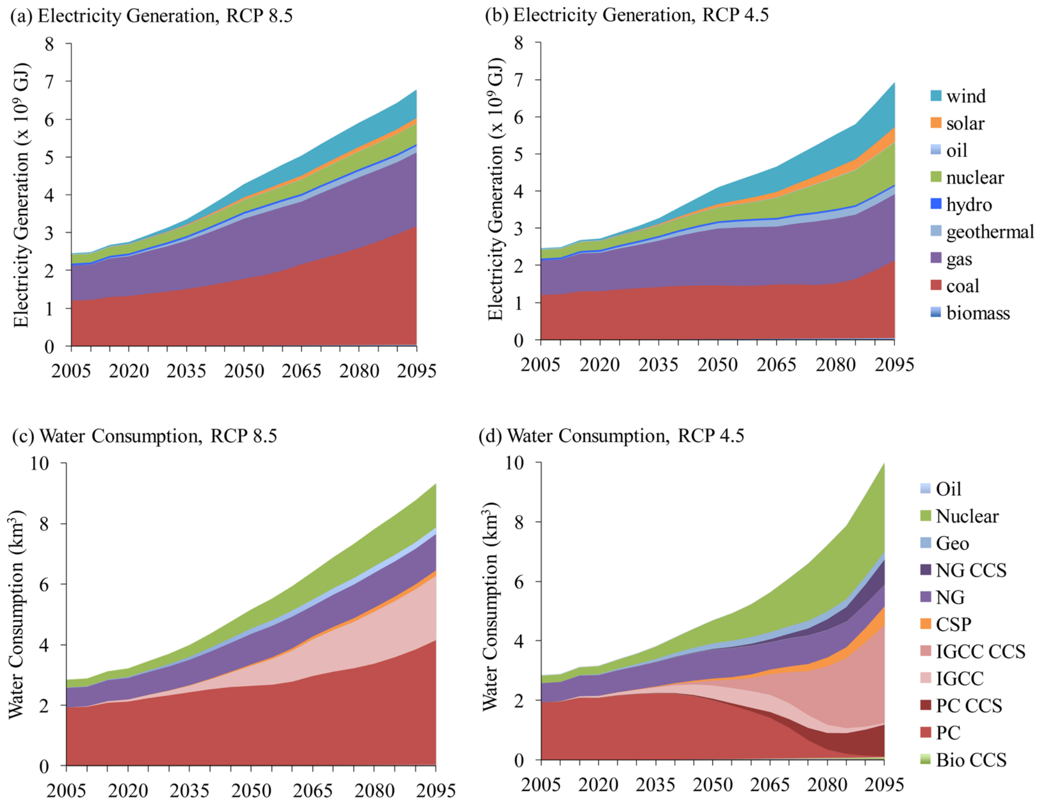

Figure 2. Projected profiles of the distribution of electricity generation and water consumption over the next century in the Southwest. In comparing GCAM's electricity generation to recent projections from the EPA in accordance with the Clean Power Plan, the total regional generation for 2050 is very similar. However, the generation mix projections differ, likely due to differing model formulations and assumptions about the future characteristics of power generation technologies. Additional detail is provided in the Supporting Information. (a) Electricity generation under the RCP 8.5 ref. (b) Electricity generation under the RCP 4.5 ref. (c) Water consumption under the RCP 8.5 ref. (d) Water consumption under the RCP 4.5 ref.

Economy model and MIT's Integrated Global System Model.[38,39]

As shown in Figure 2, the projected regional energy generation increases by approximately 177% from 2005 to 2095 under RCP 8.5 and by 184% under RCP 4.5. In 2095, nuclear and renewables account for 25% of regional power generation under RCP 8.5 and 44% under RCP 4.5, which indicates that the electric sector shifts to these low carbon technologies under climate policies. Compared to that under RCP 8.5, total fossil fuel-based electricity generation under RCP 4.5 is 6% lower in 2050 and 20% lower in 2095. PC, IGCC, and NGCC plants are almost exclusively installed with CCS under RCP 4.5. Coal-based generation encompasses IGCC plants, which are not part of the 2005 mix but account for about 50 and 72% of total coal generation in 2095 under RCP 8.5 and 4.5, respectively.

Water Consumption. Regional water consumption is significantly affected by energy demands, electricity generation technology shares, cooling technology shares, and ambient air conditions. Future cooling systems installed at thermoelectric power plants in each state are estimated as described below. In the base year, almost all coal and NGCC plants in AZ, NM, NV, OK, and UT use wet cooling towers or ponds, whereas 15−20% of coal and natural gas power plants use once-through cooling in TX. Nuclear, CSP, and geothermal plants in the study region also exclusively use wet recirculating cooling. Among NGCC plants, 90% of plants use wet recirculating cooling with 10% using dry cooling. It was assumed that future cooling shares up to 2095 for each electricity generation technology are equal to the average of new investment in 2000−2008 for relevant GCAM-USA grid regions; in the study region, the shares are as follows: 83% for wet towers, 2% for cooling ponds, 15% for dry cooling, and 0% for once-through cooling. Under the regulation of CWA Section 316(b), existing once-through cooling will be phased out, and wet recirculating or dry cooling systems will be installed in all new thermoelectric power plants. The performance of wet cooling systems is assumed not to change over time because it is a mature technology.

For each reference scenario, water consumption from power generation over the century was projected for both cases with and without incorporating the effects of climate change on ambient air conditions. Under RCP 8.5 ref without incorporating climate change impacts, absolute consumptive use in the Southwest would increase by 210% from 2005 to 2095 and reach approximately 8.8 km^3. With ambient air impacts incorporated, water consumption rises by about 7% in 2095 to 9.4 km^3, as shown in Figure 1b. While not a large percent change, this absolute difference is equivalent to almost 20% of the baseline (2005) water consumption from electricity generation in the Southwest. Under RCP 4.5 ref without incorporating ambient climactic impacts, absolute consumptive use is approximately 9.6 km^3, a 250% increase from 2005. With ambient air impacts incorporated, water consumption rises to 10 km^3. Under this scenario, these changes lead to a lower increase of almost 4% in water consumption, as illustrated in

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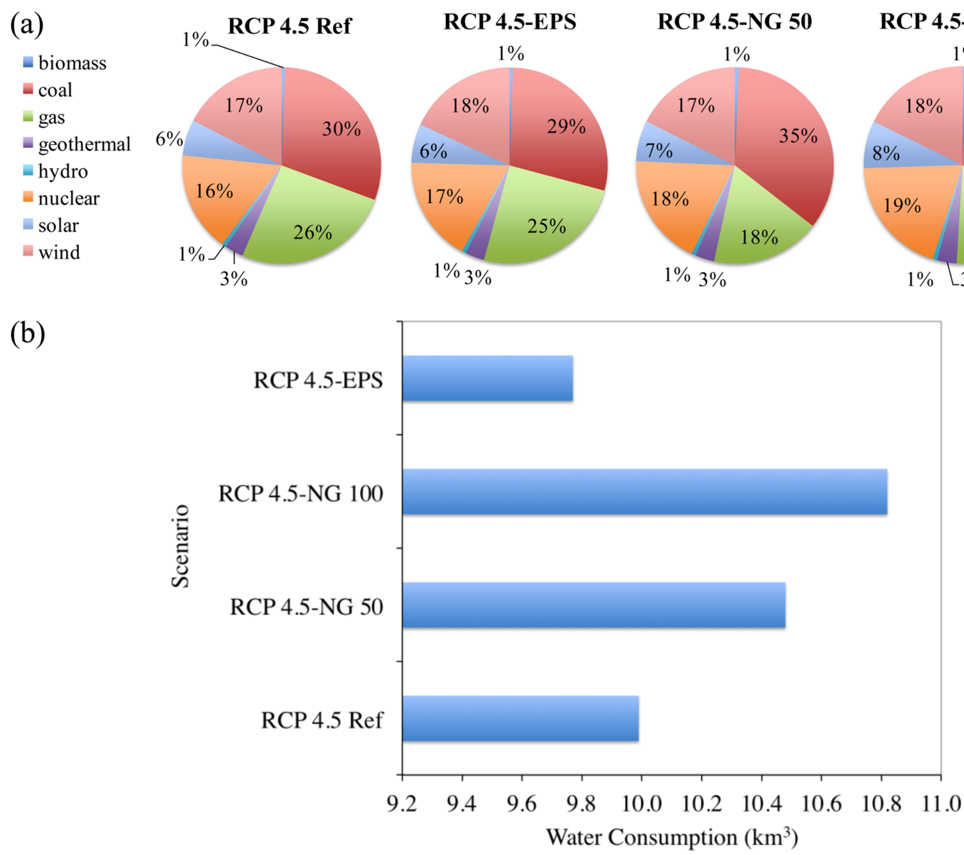

Figure 3. Projected generation profile and water consumption under alternative policy and gas market futures. (a) Electricity generation profile by scenario. (b) Comparative absolute increase in water consumption by scenario.

Figure 1b, which is almost 14% of the baseline value. These results imply that the growth in energy demand driven by population and GDP increases. This factor and the wide deployment of wet cooling towers are the major factors elevating future water consumption for electricity generation.

Figures 2c and d show water consumption by generation technology over the century under RCP 4.5 ref and RCP 8.5 ref, respectively. When the two reference scenarios are compared, there is 6% higher water consumption in 2095 under RCP 4.5 ref. The difference in water consumption is due to the higher total energy generation under RCP 4.5 ref as well as the different grid generation mix. In this scenario, fossil fuel generation almost entirely utilizes CCS, and nuclear power significantly rises.

Alternative Future Scenarios. RCP 4.5 simulates a future grid that facilitates the use of low-carbon technologies. The future grid mix also will be highly affected by natural gas price, solar and wind power costs, carbon policies, and potential shifts from the current projections on population and GDP growth. Thus, alternative scenarios given in Table 1 were evaluated to demonstrate the potential effects on water use and explore adaptation strategies for low-carbon electricity generation under RCP 4.5. These alternative scenarios were chosen based on the parameters that would have potentially high impact on the generation mix and, in turn, the water consumption projection.

Sociodemographic Changes. To account for possible lower population and wealth growth in the region, a more conservative projection was assessed for both RCP 4.5 and 8.5 based on 1990 U.S. census state projections. This led to absolute population and GDP values of approximately 25% less than the reference, a percentage chosen as compared to our current population trends based on the 2000 state-level census projections. When incorporating slower population and GDP growth, energy generation drops accordingly. The resulting water consumption would drop approximately 20% under RCP 4.5 and 22% under RCP 8.5 by 2095 in comparison with the reference cases.

High Natural Gas Prices. In RCP 4.5 ref, the assumed natural gas prices are relatively low, reaching \$6.7/MMBtu (2012) by the end of the century. In contrast, the EIA's AEO projects that gas prices will be approximately \$7.0/MMBtu by 2035, roughly 50% higher than GCAM-USA's reference case in that same year.[40] Thus, alternative gas price scenarios were simulated to examine the effects of higher gas prices on electric power grid and water consumption. The first alternative scenario (RCP 4.5-NG 50) closely follows the EIA/AEO projections and has gas prices 50% higher than those of RCP 4.5 ref throughout the century, ending with a natural gas price of \$10/MMBtu. The second alternative scenario (RCP 4.5-NG100) was assumed to have gas prices 100% higher than those of RCP 4.5 ref, resulting in a price of \$13/MMBtu in 2095.

In the RCP 4.5-NG50 scenario, there is a remarkable shift in the electricity generation profile, while overall generation remains the same as the reference. Figure 3a shows that while there is an 8% drop in electricity generation from natural gas as compared to that of the reference, electricity generation increases by 5% from coal, 2% from nuclear, and 1% from solar and wind. The shift moves toward coal and nuclear plants,

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which have water consumption intensities 50−100% higher than those of NGCC plants. Thus, overall water consumption increases by approximately 5% over the reference scenario seen in Figure 3b. In the RCP 4.5-NG100 scenario, the shift in the generation profile follows the trend of RCP 4.5-NG50. However, the changes in the generation profile are not linear: there is a smaller shift in the grid mix between the 50% price increase scenario and the 100% increase scenario. Electricity generation from natural gas in the RCP 4.5-NG100 scenario decreases by approximately 13% compared to that in the reference scenario. The resulting shift in the grid mix would elevate the overall water consumption by 8%.

Carbon Dioxide Emission Performance Standards. CCS can be employed to comply with the U.S. EPA's CO_2 emission performance standards for new PC plants. Compliance with the proposed emission limit of 1100 lb CO_2/MWh requires roughly 40% CO_2 capture at PC plants.[10] However, the finalized standard of 1400 lb CO_2/MWh-gross requires approximately 20% carbon capture. Over the century, to significantly reduce CO_2 emissions for stabilizing climate change, more stringent emission limits may be needed. To assess both the regulation proposal and finalized rules, we evaluated additional scenarios: RCP 4.5-EPS40−CCS is employed for 40% CO_2 capture at new PC plants to meet the emission limit before 2050, and 90% CO_2 capture is considered after 2050. RCP 4.5-EPS20−CCS is employed for 20% CO_2 capture at new PC plants to meet the emission limit before 2050, but 90% CO_2 capture is considered after 2050. Because PC plants with CCS for partial CO_2 capture have a higher plant efficiency but less water use and costs than plants with CCS for 90% CO_2 capture, a set of performance and cost adjustment factors were derived from the plant-level simulations in IECM and then applied to GCAM-USA.

The modeling results of the RCP 4.5-EPS40 and EPS20 scenarios show that the overall generation profile remains relatively similar to that of the reference scenario, as illustrated in Figure 3b. However, within the coal fleet, there is a higher penetration in electricity generation from IGCC plants with CCS for 90% CO_2 capture, which increases from 72% in the reference scenario to 88% in 2095. This shift is driven by the need to meet the radiative forcing target. Because IGCC plants have water consumption intensities lower than those of PC plants for both cases with and without CCS, this shift leads to a small drop (about 3%) in the overall water consumption in 2095 as compared to that of the reference.[33]

High Renewable Energy Penetration. PV and wind are key options to decarbonize the electric power sector and significantly reduce water consumption.[33] Driven by technology advances and low-carbon policies, more renewables will likely be integrated into the future grid. Projecting the cost trajectories of electricity generation technologies is important to the understanding of the evolution of energy systems and the implications of policy measures.[41] Thus, alternative scenarios of renewable energy (RCP 4.5-RE) were examined to quantify the relation of water consumption reduction with PV and wind technology learning.

GCAM-USA contains inherent learning curves to project technology cost trajectories. Technology learning used in GCAM-USA is a time-based rather than capacity-based learning function. Average learning rates of capital cost for PV and wind power are 0.5%/year and 0.25%/year in the reference scenario, respectively. While lower than learning rates in other major modeling systems, the ratio of learning rates of PV versus wind power is similar, such as the National Energy Modeling System (NEMS) that has learning rates of 3.1 and 1.6% per year, respectively.[42] It is this ratio that determines what proportion of each technology will be built in any given year. As shown in the Supporting Information, Table S3, the results for midcentury electricity generation by technology yielded from NEMS for the 2015 AEO are very similar to those of GCAM-USA. The specific learning rate functions used in GCAM-USA are given in the Supporting Information, Table S7. To evaluate the impacts of technology learning, GCAM-USA was updated with a range of higher learning rates for PV and wind power and then run to project the future generation grid mix. Figure 4 shows regional

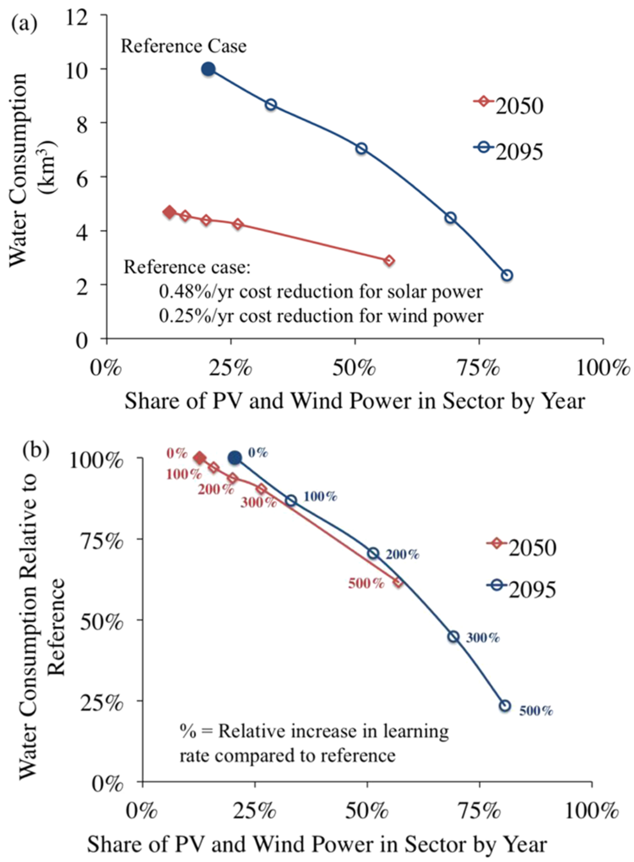

Figure 4. Water consumption in 2050 and 2095 as a function of the total share of PV and wind power in the electric power sector under the RCP 4.5-RE. (a) Absolute water consumption. (b) Relative water consumption.

water consumption in 2050 and 2095 as a function of the total share of PV and wind generation. To reduce water consumption by 50% in 2095, PV and wind generation must account for 60% of the generation grid. To reach this generation share, the learning rates of PV and wind power systems are 260% higher than those of the RCP 4.5 ref scenario, which lowers their capital costs by 0.92 and 0.63% per year, respectively. When learning rates reach 500% higher than those of the reference scenario, PV and wind generation account for 82% of total fleet generation. As a result, regional water consumption drops to 2.35 km^3 in 2095, which is 23% of the reference case.

High Dry Cooling Penetration. A shift from wet to dry cooling in thermoelectric power plants can reduce water consumption significantly and secure low-carbon energy

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production. Thus, alternative scenarios (RCP 4.5-DC) for dry cooling in thermoelectric plants are examined to quantify the relation of water consumption reduction with dry cooling penetration. When amine-based CCS is needed, a dry/wet hybrid system is employed for PC and NGCC power plants, as cooling water is needed for the carbon capture process.[10,22] IGCC plants use different CCS systems; thus, a hybrid system was not employed.

Figure 5 shows regional water consumption for electricity generation in 2050 and 2095 as a function of the dry cooling share on both absolute and relative bases. The regional water consumption falls significantly with the dry cooling share over a range from 13% (RCP 4.5 ref) to 25% but appears to be a relatively flat reduction trend beyond the 25% cooling share, mainly due to the increased generation from low-carbon renewable resources without water use over time. It would be hard to eliminate regional water consumption because amine-based CCS systems still need water for cooling. If the dry cooling share was increased to 90%, the regional water consumption would decrease by approximately 50% by 2050. If that ambitious penetration target was achieved, the regional water consumption would fall by approximately 65% in 2095. A 35−40% dry cooling share would lead to a 50% decrease in the regional water consumption in 2095.

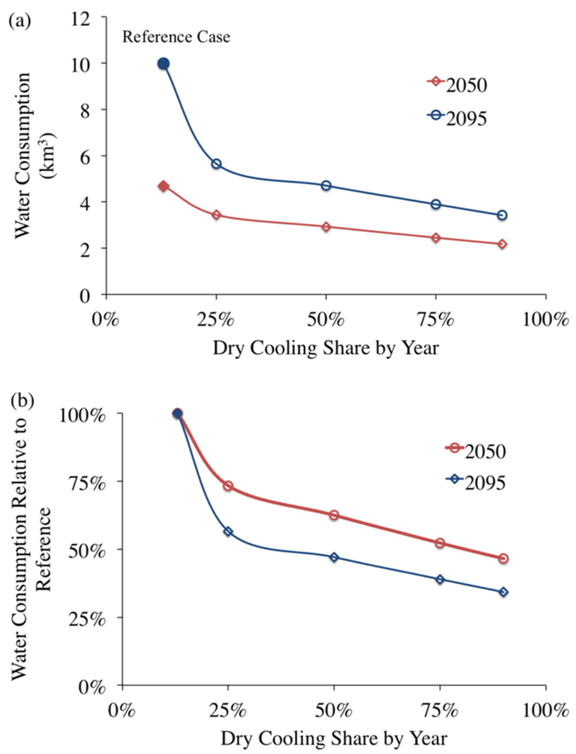

Figure 5. Water consumption in 2050 and 2095 as a function of dry cooling share in the electric power sector under the RCP 4.5 pathway. Because there are no entries to specify parasitic loads and costs of cooling systems in GCAM-USA, the effects of dry cooling systems on the demand and cost of electricity generation are not considered in the GCAM modeling, though the application of dry cooling to a PC power plant may lead to a 1−2% reduction in overall plant efficiency and $3−6 MWh increases in the cost of electricity generation compared to that in a similar plant with wet cooling.[21] This scenario assumes that wet/dry hybrid cooling is used for PC and NGCC with amine-based CCS, whereas dry cooling is used for all IGCC plants. (a) Absolute water consumption. (b) Relative water consumption.

DISCUSSION

The Southwest will have high growth expected in upcoming decades despite historical and present-day water shortages. Projections for increased water consumption by the power sector fall in the range of 200−250% for the Southwest in 2095, far more than the national projections for the same sector (55−110%). Regional population and GDP growth are the major driving forces for energy demand growth and, in turn, regional water consumption for electricity generation. In both reference scenarios (RCP 8.5 and 4.5), future energy will be highly dependent on thermoelectric generation throughout the century. If these trends take place, the existing stressed water supply will struggle to maintain the growing water demand for electricity generation.[14] Note, however, that these scenarios do not consider water scarcity or feedback between water availability and technology choice in the power sector. While water limitations are becoming a more prevalent concern,[43] they have historically not been a limiting factor for power plant construction. This is evident as the Southwest already accounts for a disproportionate share of U.S. water consumption in the power sector, as seen in our modeling results, and could continue to do so in the foreseeable future. While uncertainty in the long term projections should be a significant consideration in interpreting the results, this study is meant to illustrate the potentially growing demand of water consumption in the region, even as they are already starting to face constraints.

Direct changes in ambient air temperature and humidity from climate change alone have a relatively modest impact on regional water consumption for energy production. Among the scenarios analyzed, the reference scenario under RCP 8.5 will face the relatively largest water impacts from such changes. However, it is important to note that the increases in water consumption incurred from climate change along with the growing energy demand by the end of the century are equivalent to 20−25% of current water consumption in the Southwest, which may sizably exacerbate regional water pressure in the future. In addition, it is important to note that considering water availability limitations would likely increase the importance of any climate-driven changes in the water demands of power plants, further increasing the stresses on the remainder of the system.[44] These changes in water demand and availability will increase competition between sectors and change the allocation frameworks that currently exist.

Climate mitigation policies would facilitate deployment of low-carbon generation systems in the future fleet. Although the deployment of CCS would significantly increase water use, the shift from fossil fuels to renewables for low-carbon electricity generation could offset the added water use. High natural gas prices would shift electricity generation to technologies with larger consumption intensities, namely coal and nuclear power, and in turn would increase water consumption. Implementation of CO_2 emission performance standards under RCP 4.5 would have little extra effect on regional water consumption by the end of the century, as the radiative forcing target does not change, but electricity generation shifts slightly toward IGCC and NGCC plants.

From a regional perspective, electricity generation is not a large proportion of regional water consumption. However, significant increases in consumptive water use over the century would affect the allocation of water to different sectors. Our

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GCAM modeling results show that the amount of water consumed by the regional electric power sector from 2005 to 2095 relative to national consumption increases from 15 to 25%, which might be an unacceptable increase given the already present water constraints in the Southwest.[14] Growing investment in renewables and dry cooling can significantly decrease water consumption by the end of the century. These decreases, however, would necessitate that long-term supporting policies are in place.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01389.

> Additional text, tables, and figures regarding climate analysis, additional information on models, and assumptions (PDF)

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Notes

The authors declare no competing financial interest.

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