Modeling Climate-Water Impacts on Electricity Sector Capacity Expansion

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MODELING CLIMATE-WATER IMPACTS ON ELECTRICITY SECTOR CAPACITY EXPANSION

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ABSTRACT

Climate change has the potential to exacerbate water availability concerns for thermal power plant cooling, which is responsible for 41% of U.S. water withdrawals. This analysis describes an initial link between climate, water, and electricity systems using the National Renewable Energy Laboratory (NREL) Regional Energy Deployment System (ReEDS) electricity system capacity expansion model. Average surface water projections from Coupled Model Intercomparison Project 3 (CMIP3) data are applied to surface water rights available to new generating capacity in ReEDS, and electric sector growth is compared with and without climate-influenced water rights. The mean climate projection has only a small impact on national or regional capacity growth and water use because most regions have sufficient unappropriated or previously retired water rights to offset climate impacts. Climate impacts are notable in southwestern states, which experience reduced water rights purchases and a greater share of rights acquired from wastewater and other higher-cost water resources. The electric sector climate impacts demonstrated herein establish a methodology to be later exercised with more extreme climate scenarios and a more rigorous representation of legal and physical water availability.

KEYWORDS: Energy-water nexus, Climate change, Electricity, Thermal cooling

CLIMATE VULNERABILITIES OF POWER PLANT THERMAL COOLING

Thermal power plants require water for operations. Water use includes both “withdrawal” and “consumption,” where withdrawal is the amount of water removed from the water source for use (but then returned to the source, often at a higher temperature), whereas consumption is the amount of water that is evaporated, transpired, incorporated into products, or otherwise removed from the immediate water environment [1]. Water withdrawals for thermal power plant cooling account for 41% of total U.S. water withdrawals, making electric sector withdrawals the largest of any sector [1]. The electric sector consumes a smaller portion (~3%), but this consumption can have important regional implications in areas of water stress [2]. Thermal power plants account for 80% of U.S. electricity, meaning any short- or long-term disturbance in water resources can impact the reliability of electricity supply [3]. Already, this vulnerability has caused power plant shutdowns or output reductions on several occasions, primarily during heat waves and drought [4–6].

Climate change has the potential to exacerbate power plant water availability problems by altering spatial and temporal distributions of freshwater resources and their thermodynamic properties, most importantly temperature [7]. Temperature is especially important because higher cooling water inlet temperature leads to less efficient cooling and potentially higher outlet temperatures, which are limited by Environmental Protection Agency (EPA) regulation. Climate-related water availability changes will vary throughout the United States, with water supply expected to increase in some regions and decrease in others [8]. Less water available for thermal cooling could produce operational difficulties or instigate legal disputes over water rights. The expectation of lower water availability could impact decisions on what types of power plants to install, where to install new capacity, and regulatory decisions on water rights availability to proposed power plants. Thermal power plant lifetimes vary greatly, but they are generally expected to be 30–60 years; new power plant construction decisions can therefore have lasting impacts on and can be affected by water resource changes [9]. Water planning decisions often are made on different temporal and spatial horizons. This work could lead to insights that would assist in coordinating energy and water management decisions.

MODELING THE CLIMATE-ENERGY-WATER NEXUS IN ELECTRICITY SYSTEMS

Integrated models with a wide range of spatial and temporal resolution are required to analyze the nexus of climate, water, and electricity systems. Hydrological cycle impacts are often connected to climate modeling and analysis, but few climate studies integrate hydrologic phenomena with electric sector models. Several analyses have examined the energy-water nexus in the electric sector, but most use decoupled electricity and water models, where water impacts are examined as post-processing calculations of electric sector model results [10–13]. These studies do not include climate and water impacts within electricity sector models that can actively respond to changes in water resources.

The National Renewable Energy Laboratory (NREL) Regional Energy Deployment System (ReEDS) model has recently been updated to endogenously represent thermal power plant cooling water demands and constraints on water rights available to new generating capacity [14]. Note that the term "water rights" in this paper refers to a modeling construct that represents combined legal and physical water availability. Although this construct is intended to resemble the prior appropriation water rights regime used for surface and groundwater throughout much of the western United States, we use the term more generally in order to characterize water resources from all regions and many sources within a "rights" framework to represent the cost of gaining access to that water resource. That is, the ReEDS model represents the relationship between the long-term expected water demand and water availability through a water rights framework, regardless of the relevant legal regime in a region. This first-of-its-kind capability allows water availability to directly impact both the siting and type of generating capacity that is built.

This paper describes a further evolution of the model that integrates an initial representation of climate impacts on water availability and examines scenarios for some possible impacts on electricity system capacity expansion.

This paper describes initial insights into how climate driven changes in average surface water availability can be integrated into the model. The procedure and assumptions outlined below are a first step in a larger project that will elicit sensitivities of the power sector to risks associated with water availability scenarios. The results will demonstrate how future vulnerabilities can be reduced by considering projected changes in water resources when planning electricity system capacity expansion.

SCOPE

This work describes and exercises an initial linking of Coupled Model Intercomparison Project 3 (CMIP3) climate projections and the ReEDS model. The ultimate goal of this endeavor is to determine how consideration of long-term changes in water availability may affect current decisions about power plant siting. Key characteristics of the ReEDS model, focusing on the cooling water supply and demand representation, are discussed, followed by a description of how CMIP3 data are utilized to represent climate-water impacts on electricity system planning. ReEDS simulations are performed with and without climate impacts and for a more restrictive case with climate impacts and without certain water resource types available. National and regional electricity and water results are then examined. Scenarios are intended to demonstrate the new capability and motivate continued analysis under additional climate, water, and energy conditions. We make no assertions about the likelihood of any scenario beyond the assumptions embedded in input climate, water, and electricity data.

METHODOLOGY

The Regional Energy Deployment System (ReEDS) Model with Cooling Water Availability Constraints

Model Formulation: ReEDS is an electric sector capacity expansion model for the contiguous United States that estimates cost-minimized construction and operation of generation and transmission assets from 2010–2050 [15]. The model is a linear program that optimizes capacity expansion in two-year time steps with limited foresight using exogenous electricity demand projections. Within each time step, ReEDS performs a simplified electricity dispatch that meets electricity demand and reserve requirements in 17 time slices, four for each season and one "superpeak" representing the 40 highest demand hours in a year. Spatially, the contiguous United States is resolved into 134 supply-demand balancing areas connected by an aggregated transmission system of ~300 lines, and wind and solar resources are characterized in 356 resource regions.

All major generating technologies are represented in the model, including nuclear, coal, natural gas combined cycle (GasCC), natural gas combustion turbine (GasCT), hydro, wind, solar, geothermal, biopower, and storage. Technology types are differentiated by costs and operating characteristics, and renewable resources have region-specific quantities and costs that comprise regional supply curves. Variable renewable resources such as wind and solar are further described by statistically calculated capacity value at peak for supplying planning reserves, induced operating reserve requirements, and curtailments. Existing fossil and nuclear capacity is retired based on proposed and lifetime-based retirements from Ventyx, and renewable technologies with lifetimes within the study period are assumed to be automatically rebuilt when their expected project lifespans are reached [16].

Thermal power generating technologies (nuclear, coal, GasCC, CSP-concentrating solar power) are distinguished by the following cooling technology types: once-through, cooling pond, recirculating tower, and dry (air cooling). Geothermal technologies are currently assumed to use dry cooling, but later model versions will allow alternative cooling technologies. Each power-cooling technology combination has a specific capital and operating cost, water withdrawal and consumption rate, and heat rate.

Water withdrawal rates determine the quantity of water rights that must be purchased when new capacity is installed. Water rights must be purchased in the balancing area where capacity is built, and each balancing area has a water rights supply curve with quantity and cost of the following water rights types: unappropriated fresh surface water, appropriated fresh surface water, shallow groundwater, wastewater, and brackish groundwater.

The water rights supply curve was developed at Sandia National Laboratories (SNL) by Tidwell et al. [17]. Though the legal definition of water rights applies only in certain western states, "water rights" is used throughout this analysis as a functional definition, where a quantity of available rights represents the amount of water available for use by new generating capacity, and a rights cost represents the capital investment required to access the water. This interpretation translates water availability data based on physical metrics into a "right" that new generating capacity must pay to access. Water rights data indicate the maximum withdrawal rate allowed during the annual average low flow condition, so ReEDS requires new capacity to purchase sufficient rights to operate at maximum output during this condition. In addition, when thermal power capacity retires, its water rights are made available at a cost assumed slightly below that of appropriated water rights in that region. Retired rights in eastern states have negligible cost.

There is a key distinction between the water rights availability constraint used for this analysis and a physical water availability constraint. The data developed by Tidwell et al. are based on gaining access to water resources and the capital investment required for that access, so the constraint implemented within ReEDS only influences generating capacity investment decisions, not operational decisions. Once capacity is built, there is no further constraint on the physical availability of water. Existing data have not yet been transformed to physical water availability data necessary to inform such a constraint, and doing so is the subject of ongoing work.

Key Model Input Data: Technology cost and performance projections are primarily derived from the Energy Information Administration Annual Energy Outlook 2013 Reference Scenario [3]. Table 1 lists 2010 capital costs for several technologies. Only slight cost changes are projected for all of these technologies except solar, which has declining costs to $1,580/kW in 2020, where it remains thereafter based on achieving 62.5% of SunShot Vision goals [18][1]. Capital costs dominate investment decisions for low operation and maintenance (OM) cost technologies such as nuclear and renewables, with fuel costs playing an important role for fossil-based technologies.

Table 1: Capital cost projections for select technologies in $/kW for the initial ReEDS solve year, 2010[2].

Technology	2010 capital cost ($/kW)
Coal	2,940
GasCC	970
GasCT	830
Nuclear	4,800
Solar photovoltaic	4,210
Onshore wind	1,770

Fossil fuel costs depend on heat rate and fuel price projections. Based on Energy Information Administration (EIA) Annual Energy Outlook 2013 (AEO2013) projections, coal- and gas-based heat rates decline from 2010 to 2025 and are constant thereafter at 8.74, 6.57, and 10.65 million British thermal units per megawatt hour (MMBTU/MWh) for coal, GasCC, and GasCT, respectively [3]. Coal and uranium prices are exogenously defined from AEO2013, with coal prices varying by North American Reliability Corporation (NERC) region (Table 2) [3]. Natural gas prices are defined endogenously within ReEDS using regional price multipliers and a linear national natural gas supply curve with a constant slope regressed from natural gas price-quantity pairs in EIA AEO2012 scenarios and y-intercepts regressed from the AEO2013 reference scenario [19,3]. For reference, uranium prices, coal prices, and energy-weighted average natural gas prices for the baseline scenario (described below) appear in Table 2.

Table 2: Fuel prices in $/MMBTU to power producers.

Fuel	2010	2030	2050
Uranium	0.79	1.05	1.2
Coal	1.43–3.49	2.33–3.97	2.71–4.08
Natural gas[3]	5.40	5.63	9.58

Cost and performance variation across cooling technologies for a given thermal power plant type are defined by multipliers on capital cost, OM cost, and heat rate that are normalized by recirculating cooling (i.e. all multipliers are 1 for recirculating cooling). Several of these are shown in Table 3 [20]. Pond cooling systems are highly variable so are assigned characteristics of open-loop cooling. Water withdrawal and

[1] Sensitivity analysis on technology cost and performance is outside the scope of this paper, but analysis leading up to the results herein suggests that the climate-water impacts discussed below are relatively insensitive to solar technology cost projections.

[2] All monetary quantities are 2012 U.S. dollars.

[3] Natural gas prices are calculated endogenously within the model. These values are derived from the baseline scenario.

consumption rates for select technologies are shown in Table 4 [20]. Once-through systems withdraw 1 to 2 orders of magnitude more water than recirculating cooling, though recirculating cooling consumes substantially more water through evaporation. Water withdrawal and consumption rates for dry cooling are negligible. Generally, systems that withdraw less water are more costly and less efficient.

Table 3: Cooling technology cost and performance multipliers for select technologies.

Power technology	Multiplier on capital cost/OM cost/heat rate Once-through	Dry cooled
Nuclear	0.981/0.989/0.973	1.045/1.051/1.050
Coal	0.981/0.989/0.985	1.045/1.051/1.050
GasCC	0.978/0.996/0.980	1.102/1.021/1.050

Table 4: Water withdrawal and consumption rates in gallons (gal) per MWh.

Power technology	Water withdrawal/consumption rate Once-through	Recirculating
Nuclear	44,350/269	1,101/672
Coal	27,088/113	587/479
GasCC	11,380/100	255/208

Water rights availability and cost data were developed in a long-term effort by SNL researchers [17]. Availability of each rights class is based on region-specific water law, physical availability metrics, and assumed technical and economic barriers. Though appropriation doctrine applies only to western states, unappropriated surface water and groundwater availability are estimated for eastern states using streamflow data, environmental flow considerations, recharge rates, and groundwater pumping data. Costs of unappropriated water rights are negligible because they consist solely of transaction costs to request the rights. Appropriated rights costs are based on known transactions in the region. Fresh and brackish groundwater rights costs include drilling, pumping, and transportation costs. Wastewater rights costs include water leasing, conveyance, and treatment costs. Figure 1 provides a sense of national water rights availability and cost. Available rights are primarily unappropriated surface water in regions outside the southwest, groundwater in the eastern half of the country, and groundwater between the Pacific Northwest and Rocky Mountains. Wastewater and brackish groundwater resources are substantially more expensive but are well-distributed across the country. Appropriated water is defined only for the western half of the country and has intermediate costs and relatively low availability in western states except California, where there is no available appropriated water. One model limitation is the omission of saltwater resources for coastal regions; the SNL work does not include salt water resources, and no other salt water resource assessment exists, so water rights estimates for coastal regions are likely lower than actual.

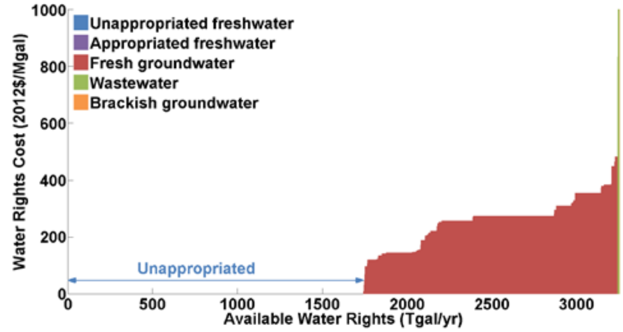

Figure 1: Most available water rights are unappropriated fresh surface water and fresh groundwater.

Adapting CMIP3 Climate Data for Water Availability Projections in ReEDS

We estimate future water supplies based on the central predictions of a large number of general circulation models represented in the CMIP3 project, as published by Milly et al. [8]. These projections come from an ensemble of 12 general circulation models that were selected for performance in modeling observed changes in twentieth century water flows between the period of 1900–1970 and that of 1971–1998. We focus on the spatially explicit central estimates for changes in average annual runoff between a baseline climate for 1900–1970 and the climate projected for 2041–2060 using the A1B SRES scenario developed by the Intergovernmental Panel on Climate Change [8]. In previous research [21], we spatially interpolated these data from a grid (approximately two degrees longitude by two degrees latitude scale) onto the 8-digit Hydrologic Unit Code (HUC) scale by matching the nearest grid centers to each watershed, then we propagated these changes through a flow routing network that connects the inflow and outflow among watersheds, subject to a full water balance. This central prediction will provide a reference from which future analysis will consider a broader range of climate scenarios.

For preliminary analysis of the effect of including projected climate impacts in ReEDS, the projected percentage change in surface water supply is assumed to approximate the percent change in unappropriated and appropriated water rights available to the power sector. This assumption does not reflect possible changes to groundwater availability, so overall water impacts could be greater than what is modeled. This preliminary method may overestimate future unappropriated water availability, because in regions following the prior appropriation water rights regime (i.e., certain western states), current state policies would allocate the entire change in available water volume to unappropriated rights; legally appropriated rights are fulfilled in entirety in order of decreasing priority in these regions. Figure 2 shows 2050 percent change in surface water available for each ReEDS balancing area, clearly demonstrating that the western half of the United States is expected to experience substantially more water stress than the eastern half of the country, where some areas are projected to have increased surface water. The southwest, in particular, has the greatest reduction in water availability.

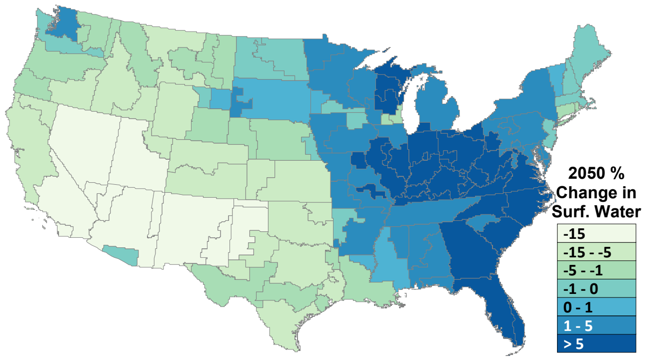

Figure 2: Reductions in 2050 surface water availability are greatest for water resources in the southwestern states.

The water availability constraints in ReEDS require water rights purchases for new builds but have no impact on subsequent operation. Thus, to reflect a change in investment planning due to expected climate change, climate change scenarios modify available surface water rights by the 2050 percent changes in 2016and beyond, the all years the model considers after the present day. In addition, water rights retired with power capacity retirements are presumed to be surface water, so the quantity of rights returned is the original quantity multiplied by the expected 2050 percent change.

Climate and Water Availability Scenarios

The primary purpose of this article is to provide an initial comparison of electric sector growth and operation with and without climate impacts on water rights availability to demonstrate and test key assumptions in including future hydrology with climate change impacts in the ReEDS model. This paper provides a proof of concept and an initial test of assumptions. We recognize that average changes in future water supplies may not be greater than the observed or future variability in the climate system. Subsequent research will evaluate the sensitivities of siting to the tails of the probability distribution function for streamflows, a more practical mechanism for identifying risks and vulnerabilities.

A baseline (Base) scenario uses original water rights data, while the climate change (CC) scenario uses CMIP3-adjusted surface water rights availability for the IPCC A1B SRES Scenario. In addition, to examine a more restricted case, the climate change with limited water (CC-LW) scenario applies CMIP3 modifications to surface water and removes appropriated surface water and fresh groundwater from the stock of available rights. These exclusions are plausible because appropriated surface and groundwater resources are primarily rights currently owned by agriculture, which could be politically or legally unavailable to the power sector. Unappropriated surface water, wastewater, and brackish groundwater resources are available in all scenarios.

Other cooling technology restrictions are common to all scenarios. Cooling ponds are not included as an option for new builds because systems are highly site-specific, so cost and performance parameters are too uncertain to be a defensible technology option in the model. In addition, due to industry trends and pending EPA regulations, once-through cooling systems are unavailable to new capacity.

Table 5: ReEDS scenarios toggle climate change impacts and available water classes.

Scenario	Climate Impacts	Available Water Classes
Base	None	All
CC	CMIP3	All
CC-LW	CMIP3	No appropriated water or groundwater

RESULTS & DISCUSSION

ReEDS produces results for capacity expansion, electricity dispatch, and reserve provision in each of the two-year time steps from 2010 to 2050 along with myriad outputs to describe electricity system behavior. To remain focused on climate-water impacts on the electricity sector, this discussion emphasizes capacity expansion results and water-related output associated with capacity growth.

Water Rights Purchases

Before discussing capacity growth directly, examining water rights purchases over time highlights differences between scenarios and helps explain the accompanying results. Figure 3 plots cumulative water rights purchases over time in the contiguous United States for the baseline scenario without climate effects. Most new rights in early years are unappropriated fresh surface water, with retired rights playing a substantial role after 2035 and only a small fraction of the total coming from other water rights classes. The large jump in rights purchases to 2014 occurs due to actual construction of once-through cooled facilities, which is only allowed in the model for known facilities. In addition, comparing the scale to that on Figure 1, there are orders of magnitude more water rights available than are required for electric sector growth, notably among unappropriated resources. Thus, the percent changes in water rights imposed by climate change effects, ranging from -20.2% to 9.8% in each balancing region (see Figure 2), are not expected to substantially impact the electricity system where unappropriated rights are prevalent. Only in regions lacking unappropriated water, where climate effects are imposed on appropriated and retired surface water rights, would the modifications to water rights be expected to alter electric sector development.

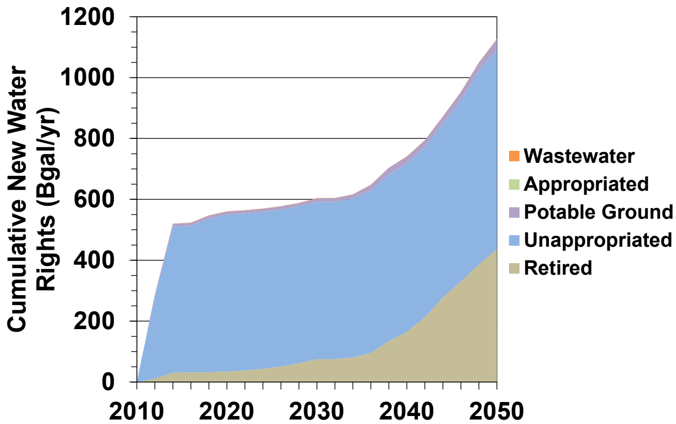

Figure 3: Nationally, most new water rights are acquired from unappropriated resources and retired rights.

States where the modeled impacts on water rights are important include California, Nevada, Arizona, and New Mexico, which have no unappropriated water, and Texas, where unappropriated water is limited or unavailable in the southern and western portions of the state. Figure 4 plots cumulative rights purchased over time in these states, subsequently referred to as the southwest, for the baseline scenario along with the 2050 total for all scenarios. Unappropriated rights make up a notable fraction of the total, but these are all in Texas. Groundwater resources are an important source of electric sector water in the southwest, representing nearly a quarter of all new water rights, split primarily between Texas, New Mexico, and Nevada. Retired rights are most often used for new capacity, but 97% of retired rights are purchased in Texas and California. Outside of Texas and California, groundwater dominates, with lesser contributions from retired rights and wastewater.

Southwest water rights purchases in 2050 are approximately 0.5% lower in the climate change scenario, and more than 6% lower in the limited water climate change scenario. Most of the change manifests in fewer unappropriated water rights. When groundwater and appropriated water rights are eliminated (CC-LW), wastewater and retired rights are primarily used instead, and rights purchases are substantially lower. Though utilizing wastewater is more expensive than obtaining new freshwater sources, substituting wastewater for freshwater is favored to using less water-intensive (and more expensive) technologies.

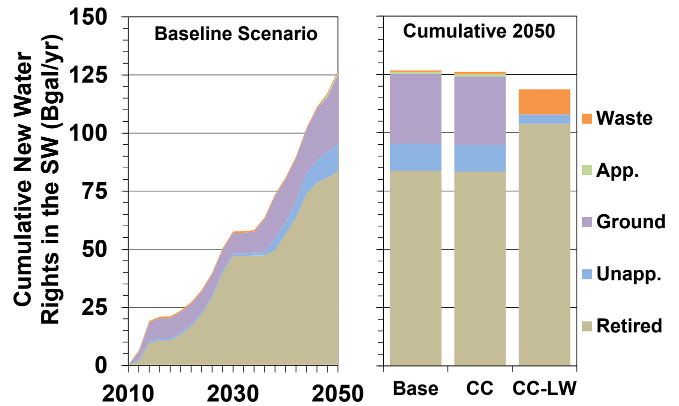

Figure 4: In the southwest (CA, NV, AZ, NM, TX), retired and high-cost rights are more prevalent, with less rights purchased when planning for climate change.

National and Regional Capacity Expansion

Water rights purchases suggest that planning for average climate projections might have little effect on national capacity expansion, so this section begins with a national-scale discussion before transitioning to regional capacity growth.

Figure 5 plots capacity over time by technology type, with cooling technology denoted as O (once-through), P (cooling pond), R (recirculating), and D (dry). The "other" category includes oil- and gas-based steam turbines (OGS), biopower, geothermal power, and landfill gas-based generation. Reductions in nuclear, coal, and OGS capacity reflect assumed retirements in the ReEDS model [16]. Capacity growth is dominated by GasCT, GasCC, Solar, and Wind. This transition reflects projected costs as well as the need for capacity in early years and energy in later years, as GasCT is used only sparingly for electricity, primarily during peak demand hours. GasCC with recirculating cooling is the primary thermal technology experiencing capacity growth when nuclear and coal-based capacity, much of which uses once-through cooling, retires.

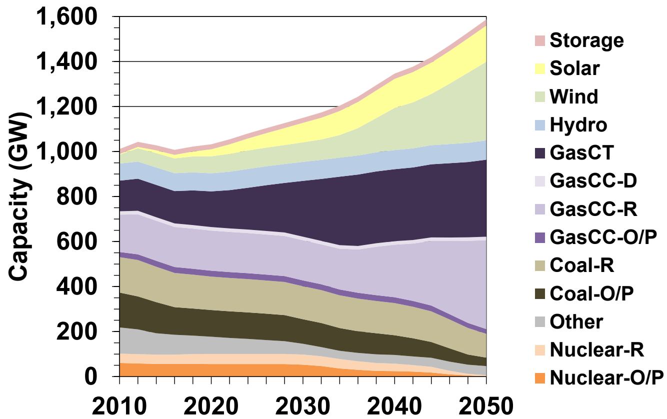

Figure 5: Most capacity growth is combined-cycle natural gas with recirculating cooling and natural gas combustion turbines[4].

To compare capacity expansion across scenarios, Figure 6 shows the capacity mix in 2010 and in 2030 and 2050 for all scenarios. For a given year, differences across scenarios are negligible. At a national level, water rights are abundant enough for the central prediction of surface water availability to have a minimal impact on overall electric sector development in the contiguous United States.

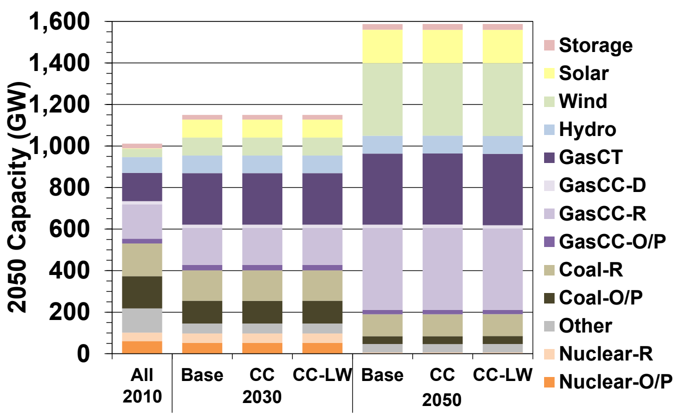

Figure 6: Nationally, capacity expansion is very similar across scenarios.

GasCC is the only thermal power technology built at a large scale, so regional impacts on electric sector development are made evident by mapping GasCC capacity across ReEDS balancing areas. Figure 7 maps the net 2010–2050 growth in GasCC capacity for each balancing area in the baseline scenario. Thermal capacity growth is concentrated in the eastern half of the country. Given limited baseline thermal power growth in water-stressed regions, the regional distribution of net GasCC growth is nearly identical for climate change scenarios. For a given balancing region, GasCC capacity in 2050 differs across scenarios by less than 1 GW, which is generally small compared to total generating capacity in a region. Though expected water availability falls in climate change scenarios, there remains sufficient water rights at low enough cost such that even water-stressed regions experience little change in capacity expansion. New GasCC capacity might resort to wastewater under modeled climate change scenarios, but the costs of these alternative water resources are still very small compared to total capital costs; hence, they are not large enough to drive major changes in capacity expansion decisions.

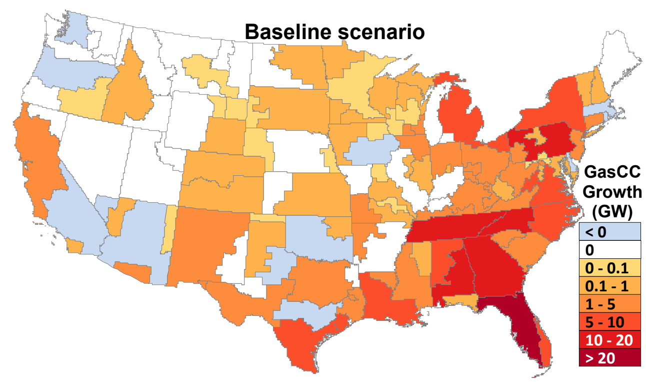

Figure 7: Growth in thermal capacity (GasCC) is concentrated in high-demand, high-water regions in the eastern United States, and the regional distribution is almost identical across scenarios.

Water Withdrawal and Consumption Patterns

Physical water withdrawal and consumption is calculated from electrical output of thermal power plant types. Figure 8 plots water withdrawals over time throughout the contiguous United States for the baseline scenario. Once-through cooled coal-based and nuclear capacity account for most withdrawals. As these plant types are retired and replaced primarily by GasCC with recirculating cooling, withdrawals fall considerably because the replacement technology (primarily driven by cooling system choice) has withdrawal rates two orders of magnitude smaller. The general electricity market trend toward less withdrawal-intensive technology reduces the overall influence of climate change modifications to expected water rights availability, so national withdrawals over time are almost identical for the CC and CC-LW scenarios.

[4] In applicable figure legends, cooling technologies are denoted by: O = once-through, P = cooling pond, R = recirculating, and D = dry.

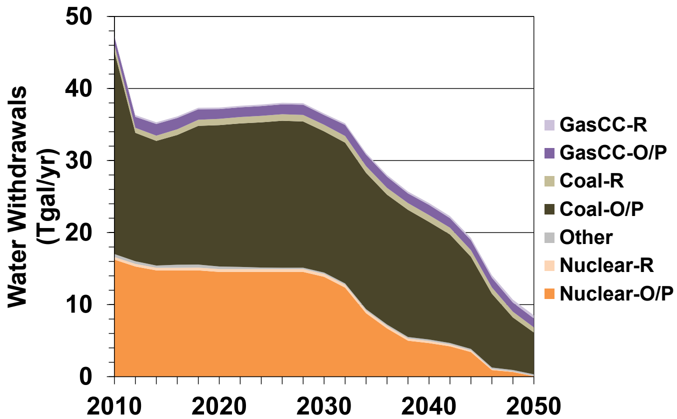

Figure 8: Water withdrawals fall over time as retired once-through cooled systems are replaced by GasCC with recirculating cooling.

National water consumption over time for the baseline scenario is shown in Figure 9. Consumption rates are higher with recirculating cooling than with once-through or pond cooling, so water is consumed primarily by coal-based, nuclear, and GasCC capacity with recirculating cooling. Overall consumption is relatively stable over time because GasCC-R has a slightly lower water consumption rate than the once-through cooled nuclear and coal-fired capacity it replaces. Again, there are negligible differences in national consumption between the baseline and climate change scenarios.

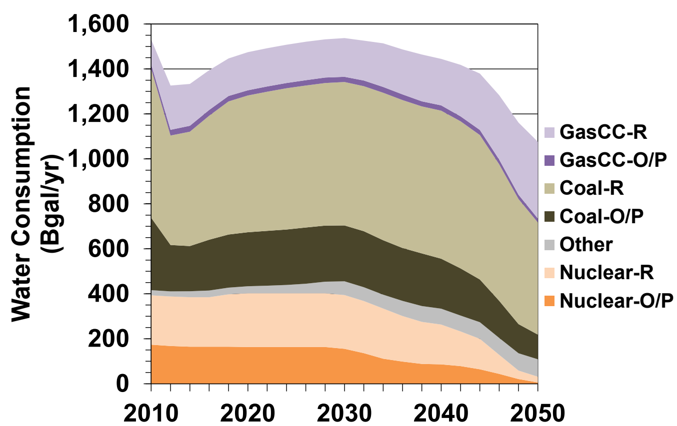

Figure 9: Water consumption remains relatively steady as GasCC with recirculating cooling replaces consumption needs of retired capacity.

Regional differences in water withdrawals are evident in Figure 10, which maps 2050 water withdrawals for each ReEDS balancing area in the baseline scenario. Most water withdrawals are attributed to existing but unretired nuclear and coal-fired capacity in the eastern half of the country, where water resources are more prevalent. Low water withdrawals correlate with regions of water scarcity, but many of these regions also have relatively low electricity demand. Reflecting the minimal changes in regional capacity growth, regional water withdrawals do not vary significantly between the baseline and climate change scenarios.

Regional water consumption is also similar across scenarios. Though increased consumption owing to the shift from once-through cooling systems to GasCC with recirculating cooling could create physical water supply problems in high-risk regions, physical water constraints are not available in the model. Scenarios are differentiated by the availability of water rights at the time of capacity investment, and demands for water rights are based on withdrawal rates.

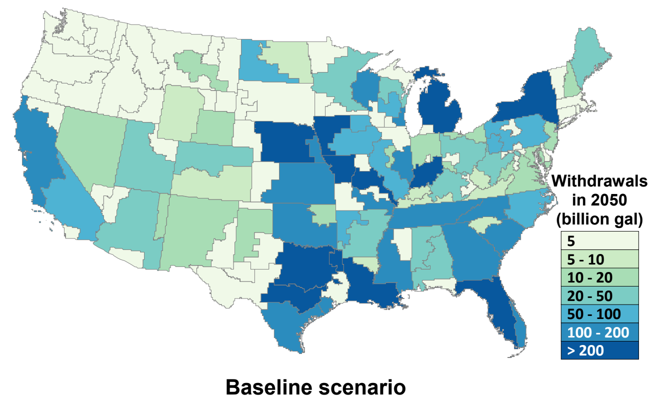

Figure 10: 2050 water withdrawals are greater in regions with more abundant water resources and high demand, and the regional distribution is almost identical across scenarios.

CONCLUSIONS

We have integrated projected changes in water resource availability resulting from climate change into the ReEDS capacity expansion model. This was accomplished through adjusting available water rights based on average regional climate impacts on surface water. This new capability allows the ReEDS model to assess changes in electric sector planning from expected climate impacts on cooling water supplies.

The central prediction of surface water resources from CMIP3 climate modeling data applied to available surface water rights has a negligible impact on aggregate national electric sector growth and operation. This result is not surprising as systems are generally stressed during extreme climatic events, not the average. In addition, assumptions made to simplify this preliminary analysis tend to underestimate changes in water availability, particularly in the western states. Capacity growth and water withdrawals and consumption change negligibly with average climate change projections, even if appropriated surface water and shallow groundwater resources are unavailable. Abundant unappropriated surface water rights overshadow the comparably small changes in surface water resources. In regions where unappropriated water is scarce or unavailable, water rights retired from coal- and nuclear-based capacity utilizing once-through cooling technologies are often sufficient to meet the demand for new water rights from combined cycle natural gas with recirculating cooling.

Expected climate change and water availability restrictions also have little effect on regional electric sector growth and water use patterns. Average climate impacts are notable only for select southwestern states (CA, NV, AZ, NM, and TX) with limited to no unappropriated water. Without unappropriated water, retired rights are an attractive source of cooling water rights for new capacity, and wastewater and brackish groundwater are utilized if necessary. Results indicate that the model generally chooses more expensive water rights over building less water-intensive power or cooling technologies (e.g. dry cooling) or building elsewhere and incurring transmission costs. Though wastewater and brackish groundwater are far more expensive than traditional cooling water sources, these costs are minimal relative to the total cost of new generating capacity.

Reliance on retired rights in water-stressed regions emphasizes the importance of assuming such rights would be immediately available to new power plants. If not, the southwest United States could be substantially more dependent on wastewater or brackish groundwater resources in the future.

The scenarios examined in this analysis demonstrate relatively minor impacts to electric sector growth and water use when considering only a mean water availability projection that does not reflect annual variability. The analysis herein represents an important stepping stone to more rigorous integration of climate impacts on thermal cooling water availability in the ReEDS model. This would enable consideration of more extreme water restrictions, for example drought conditions with climate change, in future analysis.

FUTURE WORK

Future analysis could take several directions. Under the existing water rights framework model, additional scenario analysis could examine more extreme climate scenarios with larger changes to regional water availability. An evolution from the water rights formulation would add physical water availability constraints where power output within a region is constrained by the quantity of water available in that region in the time period being considered. Physical constraints would allow inclusion of seasonal water availability variations. At the same time, future work would benefit from representing spatial variation in the legal water right regimes across the country, as this has important implications for how changes in physical water availability affect current and potential water users. To enable such analysis, methodology must be developed to translate CMIP data into physical quantities of water available to the power sector. A combination of rights-based and physical water availability constraints could then be examined for a wide range of potential future climate and electricity market scenarios.

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