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Impact of climate change on water availability and its propagation through the Western U.S. power grid

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HIGHLIGHTS

- Changes in water availability conditions in one region triggers a response in others.
- Northwest and Northern California water availability dictate regional power flows.
- The generation in the Desert Southwest alleviates water stress in other regions.
- Regional power flow directions are maintained under climate change conditions.
- Regional dependencies representation is critical to evaluate climate change impact.

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ABSTRACT

Climate change is expected to affect the availability of water for electricity generation, yet the propagation of climate impacts across a large and diverse power grid remains unexplored. In this study, we evaluate how projected changes in water availability affect electricity generation at hydroelectric and thermal power plants and how the coincident impacts propagate locally and throughout the interconnected power grid of western United States. We also evaluate whether the prospect of climate-driven change could affect regional power dependencies. Hydrologic simulations derived from three Global Circulation Models (CCSM4, INMCM4, and GFDL-CM3), two radiative scenarios (RCP4.5 and RCP8.5) and the VIC hydrology model are used to force a large-scale, distributed water management model (MOSART-WM), which translates water availability into power generation constraints at hydropower plants and water-dependent thermoelectric plants. Power system dynamics are evaluated using the production cost model PLEXOS. We find that the interregional connections across the contemporary Western U.S. electricity infrastructure play an essential role in managing variations in regional generation due to hydrological variability. Projected WECC-scale changes in mean annual precipitation ranging from −3.8% to +17% are moderated to −6% to +4% in mean annual production cost changes. Climate change impacts on water availability in the Northwest drive future changes in other regions' generation and in regional power flows. Northwest total generation influences interannual variability in other regions' net generation, explaining about 40%, 50%, and 35% of the variability in Southwest, Rockies, and Southern California regions respectively. The propagation of Northwest climate change impact throughout the grid is exacerbated by the occurrence of dry years in Northern California. Generation from the Desert Southwest emerges as a critical resource to compensate for variations in water availability, and generation, in these regions. Though the regional power flow directions seem insensitive to long-term variations in water availability, our analysis highlights the need to consider other compounding regional factors, such as changes in Southern California's net load and changes in regional fuel prices.

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1. Introduction

Electricity supply in the United States relies heavily on natural flows of fresh water to fill reservoirs, drive hydroelectric turbines, and cool thermoelectric plants, including coal, gas, and nuclear plants. More than 90% of U.S. generating capacity depends on water [1]. Thermoelectric plants—which account for 40% of the nation's water withdrawals [2]—supply most of nation's electrical power, while hydroelectric plants make up the bulk of generation in certain states (e.g., about two-thirds of generation in Washington State) and contribute about 6% of U.S. electricity generation overall [1]. With climate change projected to affect the spatial and temporal distribution of water resources [3], a number of studies have established how changes in water availability could affect the electricity sector. Focusing on the impact on electricity supply, studies have evaluated the impacts of changing climate on regional hydropower [4–9], and even globally [10]. Other studies have focused on impacts to thermoelectric resources [11–14]. Few have evaluated both hydropower and existing thermoelectric plants [4,15–19]. And fewer used a power grid model, limited to regional applications, and assuming status quo on other's regions operations [5,20–23].

Power grid operations consist of diverse generators (hydropower, thermoelectric, wind, solar, combustion turbine, batteries) and transmission line infrastructure managed to meet electricity demand with security constraints for reliability purposes. Operational and planning responsibilities are comanaged within subregions of the power grid. These may be individual countries, or in the case of the United States, groups of states or large spatial units referred to as reserve regions. Because reserve regions are interconnected through the transmission system, a drought in one region that affects the ability of generators to produce energy does not necessarily imply there will be a lack of electricity in that region. Generators in other regions can supply more electricity to compensate [24]. To our knowledge, the science community has yet to evaluate the impact of future water availability on both hydropower and thermoelectric plants, coincidently, while also simulating the coordination of those resources by grid operations, and across regions also impacted by climate change.

The objective of this analysis is to evaluate how climate change impacts on water availability influence not only the regional electricity supply, but also the indirect, secondary effects on extra-regional total generation propagated through the contemporary power grid. We also evaluate whether climate change could affect regional power dependencies. The study is conducted on the Western U.S. power grid, which is sensitive to climatic changes through its dependence on water-dependent thermoelectric plants and hydropower dams [4,19,24,25]. We follow a top-down climate impact assessment framework, wherein an ensemble of future climate and associated hydrologic simulations is used to estimate hydropower and thermoelectric plant generation capabilities, which then constrain simulations of the power grid dispatch conducted using a production cost model (Table 1). The model represents the generation and transmission operations within the 2010 Western U.S. power grid. We evaluate the grid-scale changes in operations and extend the analytics with regional power flows exploring the interregional dependencies. The novelty of this work lies in its use of power system models to represent complex regional and inter-regional dynamics associated with a network of technologies across the power grid. We produce an ensemble of 100 yearlong hourly power system operations to support new analytics of power system operations under climate change. Findings are expected to guide further research in energy-water long-term planning by identifying the scales at which climate change impacts on water availability should be considered to provide appropriate guidance for investments to maintain system reliability under future conditions.

2. Domain, models and analytical approach

We leverage previous climate change impact assessment studies linking climate, hydrology and river routing water management models. We extend those previous experiments with a bulk electricity operations model (Table 1).

2.1. Domain

The Western U.S. power grid is managed by the Western Electricity Coordinating Council, which is herein referred to as the WECC. The WECC extends from the Pacific Ocean to the Rocky Mountains. It spans more than 4.7 million square kilometers and encompasses territory across 14 states, 2 Canadian provinces, and northern Baja, Mexico (Fig. 1). The WECC envelopes the hydrologic regions of the Columbia, Sacramento, San Joaquin, and Colorado Rivers, the Great Basin hydrologic region, as well as the headwaters of the Missouri, Arkansas-Red, and Rio Grande Rivers and the Gulf hydrologic regions (Fig. 1 upper panel). Inter-basin water transfers are present between and within Southern Colorado and California hydrologic regions. Fig. 1 (lower panel) also presents the Western United States as energy reserve regions as defined in Table 55 of the WECC 2024 Common Case [45]. The electricity demand within each of those regions must be met according to security constraints and typically using within-region generators before relying on interregional transfers. Overall, about a quarter of WECC generation comes from hydropower and just over 40% comes from thermoelectric plants [1].

Reliability studies and transmission planning for the WECC are needed at the grid scale, while socioeconomic decision-making and governance is conducted at a sub-regional scale [7,22,47]. We therefore perform our analysis at both the WECC scale and for the six reserve regions, rather than hydrologic regions or states.

2.2. Climate and hydrology datasets for historical and projected future conditions

2.2.1. Climate datasets

We leverage historical and future climate projections from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) [26]. The ensemble of climate projections available under CMIP5 includes a combination of general circulation models (GCMs) and representative concentration pathways (RCPs) which may be interpreted as plausible emission scenarios and boundary conditions to the GCMs. Though the entire ensemble of GCMs and RCPs does not reflect the full climate change uncertainty, it is common practice to adopt a representative subset to evaluate the sensitivity of potential changes. Because of computational requirements from the production cost model, we limit the analysis to six climate change conditions based on three GCMs (CCSM4, INMCM4 and GFDM-CM3) and two RCPs (RCP4.5 and RCP8.5). While the downscaled data sets [31] are available for 1950 until 2004 for the historical period and for 2005 to 2095 for the future period, we define the historical period as 1981–2010 and the future period as 2036–2065 to represent the 2050 s. Table 2 shows the range of future 2050 s climate projections aggregated over the Western United States relative to our historical period. Projections agree on a warming trend, ranging from 0.8 °C to 2.3 °C under mitigation scenario RCP4.5 and from 1.5 °C to 2.8 °C under RCP8.5, a scenario of comparatively high greenhouse gas emissions. Precipitation projections tend to be less consistent across atmospheric models, ranging from 1% to +11% under RCP4.5 and from −3% to +17% under RCP8.5 (Table 2). The selected GCMs represent large variability in the projections of climate and water availability under both scenarios and especially the widest range of possible precipitation changes as further demonstrated in Supplemental Material S1.

Table 1
Overall workflow presenting the top down approach and specifying the datasets, associated references and model versions for each stage (row).

	Datasets	Reference for datasets	Models' version used to derive the datasets
Climate simulations	**[Step 1]** Six monthly 1915–2095 spatially distributed climate datasets (3 climate models × 2 emission scenarios)	CMIP5, [26]	Representative Concentration Pathways [27] GFDL-CM3 [28] INMCM4 [29] CCSM4 [30]
	[Step 2] Bias corrected temperature and precipitation datasets, daily time scale and 1/8th degree spatial resolution	[31]	BCSD approach [32–34]
Hydrology simulations	**[Step 3]** Hydrologic simulations, daily time scale, 1/8th degree spatial resolution	[35,36]	VIC hydrology model, version 4.1.2 [37]
	[Step 4] Six 1955–2095 regulated river flows, daily time scale, 1/8th degree spatial resolution)	[9]	River routing and water management model [38–40]
Electricity operations simulations	**[Step 5]** Six 1981–2095 monthly potential hydropower generation and summer months thermoelectric plant capacity for the Western U.S. power plant database	**This manuscript** [41]	Approach developed in [25,42]
	[Step 6] Six 1981–2095 hourly simulations of Western U.S. grid operations	**This manuscript** [43]	PLEXOS production cost model [44] WECC 2024 Common Case [45] adjusted to represent 2010 infrastructure, 2010 load and 2005 water conditions as described in [42]

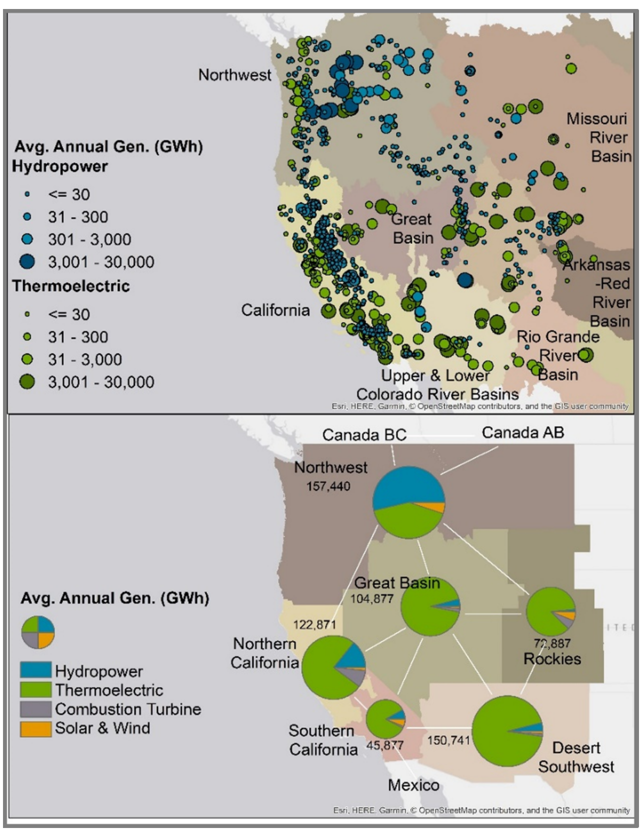

Fig. 1. Western U.S. annual generation for individual hydropower and thermoelectric plants by hydrologic regions as represented by the integrated hydrologic modeling (upper panel), and annual generation mix by reserve regions (lower panel). Source: power plants and generation [46] and reserve region [45].

2.2.2. Hydrology datasets

We leverage historical and future spatially distributed runoff and subsurface flow for each climate projection. These data have been derived in previous work [35,36] using the Variable Infiltration Capacity Model [37]. We force a large-scale river routing water management model (MOSART-WM) [39,40,48] with these runoff time series to generate daily river flow time series. The river routing water resources management represents the effect of river regulation from large dams (GRaND database [49] and multisectoral water withdrawals (see Supplemental material S2.1 for more details). Sectoral water demands are maintained at the 2010 level to ensure changes in water availability are due to climate change effects on hydrology only. The outcome is a spatially distributed daily regulated river flow data set for the 1955–2095 period for each GCM and RCP combination [50]. Projections in flows are then processed at individual power plant locations. Note that each GCM provides a historical period that we use in our analysis as a reference to evaluate the change between the historical and future periods. Each GCM is bias corrected, and the historical distributions' water availability at power plants are very close to those in the data sets derived using observed gridded climate.

Table 2
Summary statistics for WECC climate and electricity generation constraints projections for 3 GCMs under 2 RCPs. See supplemental material S1, S2 and Table S1 for an evaluation across 10 GCMs.

	CCSM4	GFDL-CM3	INMCM4
RCP 4.5			
Diff. ann. T (°C)	1.4	2.3	0.8
Diff. ann. P (%)	1	11	3
Flows at hydropower plant locations (%)	−3.8	5.7	−4.5
Flows at thermoelectric plant locations (%)	−5.8	5.7	−0.7
RCP 8.5			
Diff. ann. T (°C)	1.9	2.8	1.5
Diff. ann. P (%)	3	17	−3
Flows at hydropower plant locations (%)	−6.7	13.9	−11.8
Flows at thermoelectric plant locations (%)	1.3	2.7	−4.6

In Table 2, the potential impact of climate change induced changes in water availability on flows at thermal and hydropower plants are inferred from average deviation in flow relative to the historical period. These are aggregated to the WECC-region by taking the average deviation and weighting according to average generation at each plant. Overall, impacts on water availability at hydropower plants range from −4.5% to +5.7% under RCP4.5 and −11.8% to +13.9% under RCP8.5, and at thermoelectric plants from −5.8% to +5.7% under RCP4.5 and −4.6% to +2.7% under RCP8.5. Those numbers are within the range of previous analyses [4]. See Supplemental material S2.1 for an evaluation with 10 GCMs. Note that those relative changes in water availability at isolated hydropower and thermoelectric plants in response to temperature and precipitation changes are not necessarily coincident, which is why an electricity production cost model is required to understand the differences between potential and actual impact of climate change on grid operations. The Water Scarcity Grid

Impact Factor (WSGIF, [25] combines coincident relative changes in water availability at hydropower and thermoelectric plants. We use WSGIF here to characterize system-scale water availability conditions, allowing us to map hydrological change to the power grid dynamics as simulated by the production cost model. In particular here, the WSGIF is used to select water availability conditions (10th, 50th and 90th percentile for dry, median and wet conditions) and evaluate the corresponding power system dynamics. A supplemental analysis of the impact of climate change on the WSGIF distribution over the WECC under multiple GCMs and RCPs is provided in Supplemental Material S2.2. The WSGIF is useful to select water year conditions associated with specific grid response outcomes when one cannot run 270 years of simulations as performed in this analysis.

2.3. Electricity datasets for historical and future environmental conditions.

2.3.1. Fresh surface water-dependent generation constraints

We represent 1540 hydropower plants and 1539 thermoelectric plants over the WECC domain. For this study, we adopt the commercial power system model PLEXOS licensed by Energy Exemplar [44] with a set up that uses plant-level, monthly resolution estimates of available hydropower for power plants that have some flexibility to dispatch based on energy markets. This comprises about 75% of the annual hydropower generation; the other 25% of hydropower generation comes from plants with fixed hourly dispatch profiles. Representing monthly water-constrained generation at each power plant is non-trivial, as hydropower operations depend on reservoir characteristics, other water user needs, and changes in electricity demand and market structure. Conveniently, annual regulated flow is closely correlated with annual hydropower generation [25,51] over the Western United States. The monthly hydropower potential generation reported in the PLEXOS reference database represents water and market conditions for 2005. As in previous studies, annual plant-level regulated flow deviations with respect to reference year 2005 provide the annual projection of hydropower while the plant-level 2005 monthly pattern is conserved [25] (see Supplemental Material S3 for details about the hydropower computation).

While we recognize that the conserved seasonality is a source of uncertainty in this climate change analysis, regional and seasonal load and fuel prices are also conserved in this experiment. The combination of changes in water availability seasonality compounded with changes in load and fuel prices seasonality on monthly hydropower appears in very few studies [52] and warrants further investigation. Our analysis assesses the impact of climate change on annual hydropower availability. While we also present seasonal results, we limit our main conclusions at the annual scale until further research can reconciliate the dependencies between supply, load, and market dynamics at the seasonal scale. A similar approach is adopted for derating of thermoelectric plants that use fresh surface water. One difference is that we adjust generating capacities rather than actual potential generation, implying that the adjusting factor cannot exceed 1 and that the plants' monthly generation is not limited. We also adjust only summer capacities (e.g., July, August, and September), as we assume plants are operating without derating (i.e., full capacity) under average water conditions the rest of the year. The six 1950-2095 monthly generation constraints datasets for 3 GCMs and 2 RCPs drive PLEXOS to calculate the least-cost solution to balance generation and load across the entire interconnection, within the constraints of the transmission system.

2.3.2. Hourly power system operations

The PLEXOS Integrated Energy Model [44] minimizes system production cost subject to power system constraints and input data sets. We use an adaptation of the WECC Transmission Expansion Planning Policy Committee (TEPPC) 2024 common case [45], which represents a 2010 grid infrastructure of the Western interconnection in the United States, including 1540 hydropower plants and 1539 thermoelectric plants with respective total capacities of 58 and 152 GW, 2010 wind resources, and 2005 hydrological conditions [42] (Fig. S4). There is a small amount of solar generation (<1 GW) in the 2010 infrastructure, which has increased significantly since then and will be addressed in the discussion section. Hydropower generation incurs zero fuel cost in PLEXOS, leading to a simulation that maximizes generation from hydropower as well as other renewable technologies, like wind and solar. More costly resources, in particular thermoelectric plants, are used to complement the generation and reserve needs that impact the system-scale production cost [20]. The electricity demand is maintained to the 2010 level and is always fully met. We simulate annual generator commitment and dispatch with 365 (daily) optimization steps that are solved at hourly resolution for the entire interconnection.

Data for monthly maximum capacity of thermal generators, monthly maximum energy for hydropower generators, and hourly fixed generation of other hydropower generators are derived using the large-scale river routing model (described above) and then input into the PLEXOS model. Database properties include generator fuel; ramp rates; heat rate; maximum capacity and minimum up and down times; transmission line limits and locational data connecting all transmission lines; and balancing area boundaries set up by what lines, nodes, and generators belong to which area, including balancing area level load. The transmission system is simplified for this study by aggregating transmission in each of the 407 counties and using a transport algorithm for power flow (Fig. S4). Line limits between counties are (softly) enforced by imposing a penalty for line flow violations.

2.4. Analytical approach

The outcome of the entire modeling experiment (Table 1) is six data sets (three GCMs under two RCPs) of monthly generation constraints at fresh surface water-dependent power plants for the 1955–2095 period and six associated data sets of hourly power operations over the WECC for the 1981–2095 period. To analyze the impact of climate change, we use the 1981–2010 time-slice to represent historical conditions and the 2035–2064 time-slice to represent 2050 conditions. Power operations are evaluated at the WECC scale and energy regions, at the annual time scale (and seasonal timescale in supplemental material S7) using three performance metrics: net generation, production cost, and cross-regional power flows.

At the system scale, the generation always meets the electricity demand throughout all our simulations. To understand if and how grid connectivity moderates the propagation of climate-driven impacts, we evaluate the impact of climate-driven change in water availability on the WECC-scale electricity production cost.

At the regional scale, we focus on generation and power flows metrics. Our other science questions focus on the ability of regionally connected generation assets to influence regional generation responses to other regions' changes in water availability. We structure the analytics with the questions below:

- How are regional generations sensitive to changes in water availability in their own region?
- Are there connections between regional responses?
- What, if any, are the regions whose climate-driven generation changes explain other regions' generation response?
- Are regional power flow directions sensitive to climate-driven changes in water availability?

The results section presents the main findings associated with those system- and regional-scale questions.

Table 3
System-scale changes in operations as simulated by the production cost model.

	CCSM4	GFDL-CM3	INMCM4
RCP 4.5			
Diff. Hydropower Generation (%)	−3.8	4.8	1.2
Diff. Production Cost (%)	2.1	−2.9	0.5
Range of Inter-Annual Production Cost Variability (%)	−12;14	−16;14	−17;17
RCP 8.5			
Diff. Hydropower Generation (%)	−3.6	10.4	−7.6
Diff. Production Cost (%)	1.9	−5.9	4.4
Range of Inter-Annual Production Cost Variability (%)	−14:14	−18;16	−15;12

3. Results

3.1. Grid connectivity moderates the propagation of climate-driven impacts on WECC-scale electricity production costs.

Our selected climate change conditions for 2050 ranged from 0.8 °C to 2.8 °C increases in annual air temperature and from −3.8% to +17% changes in annual precipitation, and −11.8% to +13.9% changes in annual flow availability at hydropower plants over the Western United States from the historical period, across GCMs and RCPs. With the hydropower and thermoelectric generation constraints integrated with the power grid operations, we find the overall range of change in system-scale hydropower generation to be −8 to +10% and the change in average annual cost of producing electricity maintained at between −6% to +4% (Table 3). Mean changes in production cost estimated by GFDL-CM3 RCP 8.5 (decrease) and INMCM4 RCP 8.5 (increase) are significant at the 95% confidence level. These long-term changes in annual production cost, albeit significant, must be put in perspective with historical interannual (shorter term) variability. Over the 30-year historical period, the simulated interannual variability in annual production cost ranges from −14% to +17% around the historical mean (Table 3, Fig. S5). This overall variability is maintained in the six future projections studied (−18% to +16%).

Fig. 2 relates the changes in Western U.S. precipitation with system-scale changes in hydropower generation (dashed line) and system-scale reduction in production cost (solid line). With the slope of production cost response being smaller than the hydropower generation response, we find that the interconnected grid mutes climate change impacts on generation at individual plants. In the following sections, we evaluate how these effects play out at the scale of energy regions.

3.2. Power system dynamics influence regional generation responses to other regions' changes in water availability

Fig. 3 shows the relationship between annual hydropower generation in the Northwest and Northern California (for all GCMs and periods) and net electricity generation (regional generation minus regional load) over all energy regions. Though it is related to total regional generation, the net electricity generation has implications for importing/exporting status and regional interdependencies. The California regions' loads tend to exceed their generation. These regions therefore import electricity on an annual basis apart from a few exporting years for Northern California. The other regions export electricity in all years.

Because of the significant hydropower contribution in the regional generation mix, the Northwest and Northern California are the only two of six reserve regions for which the net regional generation is sensitive to the in-region changes in water availability. For both the Northwest and Northern California, water availability and associated hydropower generation explain over 90% of the inter-annual variations in local net generation. The positive relationship between net generation and local water availability indicates that the Northwest exports more in a wet Northwest year and that Northern California imports less on a wet Northern California year. This dynamic is the result of fuel price differences between regions, potential transmission constraints, and reserve guidelines that motivate an increase in generation in Northern California associated with increasing local hydropower, reducing imported electricity rather than maintaining the imports, and reducing the overall Northern California non-water-dependent generation [42]. Despite large interannual climatic variability over Northern California and the climate change impact on the Northwest, each region maintains its overall historical annual importer/exporter status (Fig. 3).

Fig. 3 also introduces the regional interdependencies addressed next. The reservoir storage capacity over the Southwest seems to stabilize the local response to dry conditions, and net generation is not sensitive to local changes in water availability. We can observe however that the Southwest net generation (exporter) is negatively correlated with Northwest and Northern California water availability conditions (correlation coefficients of −0.82 and −0.75 respectively).

Therefore, the regional analysis demonstrates how complex power grid dynamics need to be considered in regional climate change impact assessment and long-term planning. This is particularly important for regions where the local generation (and net generation) is not linearly related to local water availability, as well as for regions that typically import.

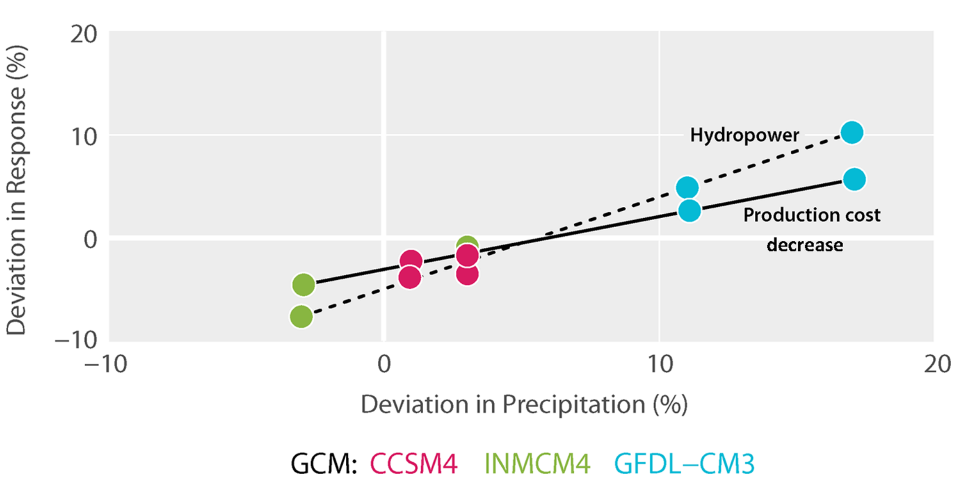

Fig. 2. The muting of the precipitation signal over the power system is shown by plotting the change in hydropower generation (dashed line) to the decrease in production cost (solid line). Note that zero change in WECC total precipitation does not equal zero change in WECC hydropower because of spatial diversity of the precipitation.

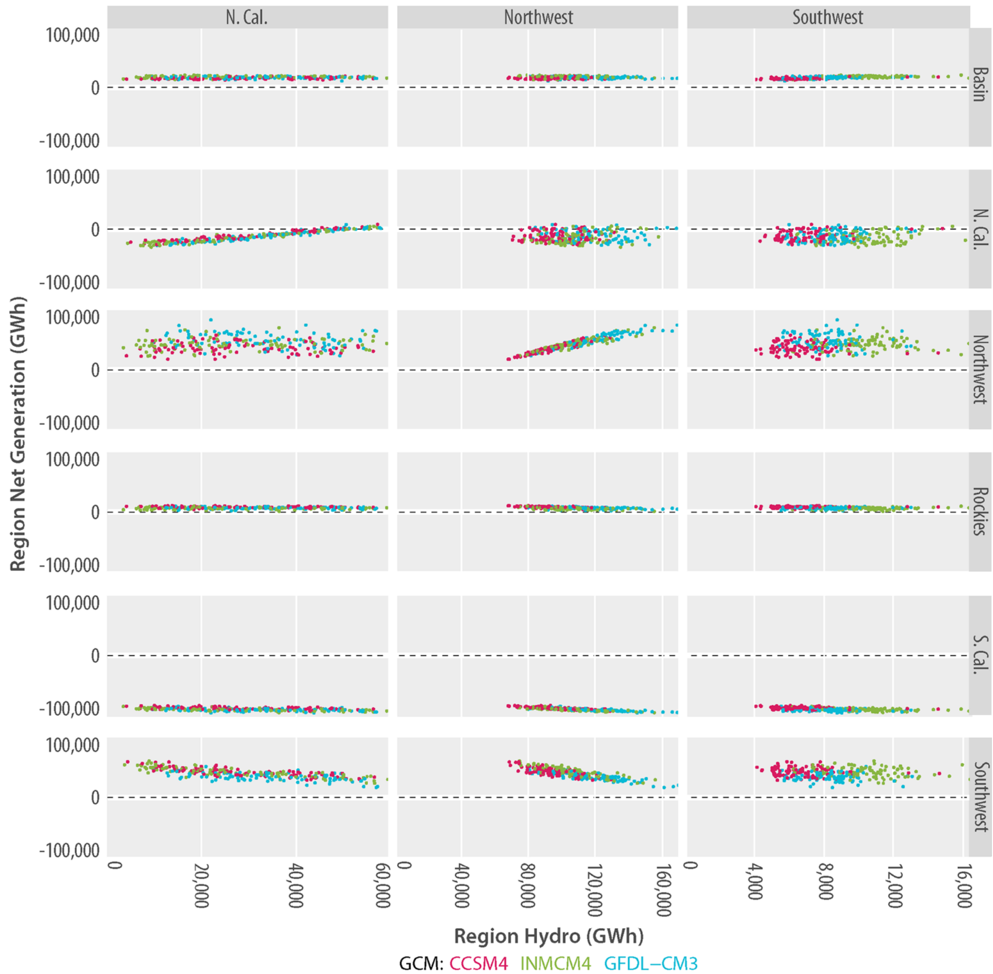

Fig. 3. Impact of local and other's regions hydropower generation on local electricity generation. All historical and future GCM year simulations are considered as the relationship is not changing.

3.3. Northwest generation explains most of the variance in other regions' generation changes.

With only the Northwest and Northern California net generation being responsive to hydrology within their respective regions, we posit that changes in water availability propagate through the grid (Fig. 3), starting from those regions. The impact of climate change on water availability is significant only in the Northwest, and therefore we further posit that climate change impact on water availability would propagate from the Northwest. We perform a covariance analysis (Fig. 4, and Fig. S6) of each region's local net generation and all other regions' local net generation to identify the import/export interdependencies. The analysis shows that increased generation in the Northwest in any year coincides with reduced generation in the Southwest, Rockies, and Southern California. Northwest generation explains approximately 40%, 50%, and 35% of the variability in generation in these regions, respectively (these coefficients of determination vary marginally depending on RCP and period of analysis). Though other variance indices are very high, as we discuss next, those relationships are the indirect results of variations over both the Northwest and Northern California on an interannual basis, and changes that are due to future water availability over the Northwest.

3.4. Desert Southwest generation responds to generation changes in the Northwest.

Net generation in the Desert Southwest is unresponsive to changes in local hydropower. The Desert Southwest is an exporting region; it generates more electricity when generation is constrained elsewhere. Desert Southwest generation is negatively correlated to the generation in the Northwest, with net generation in the Southwest explaining approximately 40% of variability in net generation in the Northwest (Figs. 3 and 4). This inverse relationship is similar for Northern California, where 33% of variability in net generation is explained by net generation in the Southwest.

Regional dependencies studies typically look at import-export relationships [53]. In contrast, we have exposed export-export dynamics. Exports from the Desert Southwest depend on exports from the Northwest, which in turn depend on climate conditions in the Northwest. Generation from the Desert Southwest is not only responsive to changes in generation over the Northwest and Northern California; it also compensates for the variability in generation over the Northwest, as demonstrated by the magnitude of the variations shown in Fig. 3. This implies that while the regional changes in generation are mostly driven by changes in water availability in the Northwest, the stability of the grid relies on the Desert Southwest region's flexibility in exporting under the current power grid infrastructure.

3.5. Maintained regional interdependencies under future water availability

We compare power flow patterns between regions for all 270 simulated historical and future water years, 3 GCMs, and 2 RCPs. Each year is associated with water conditions as measured by the water scarcity grid impact factor (combined hydropower and thermoelectric

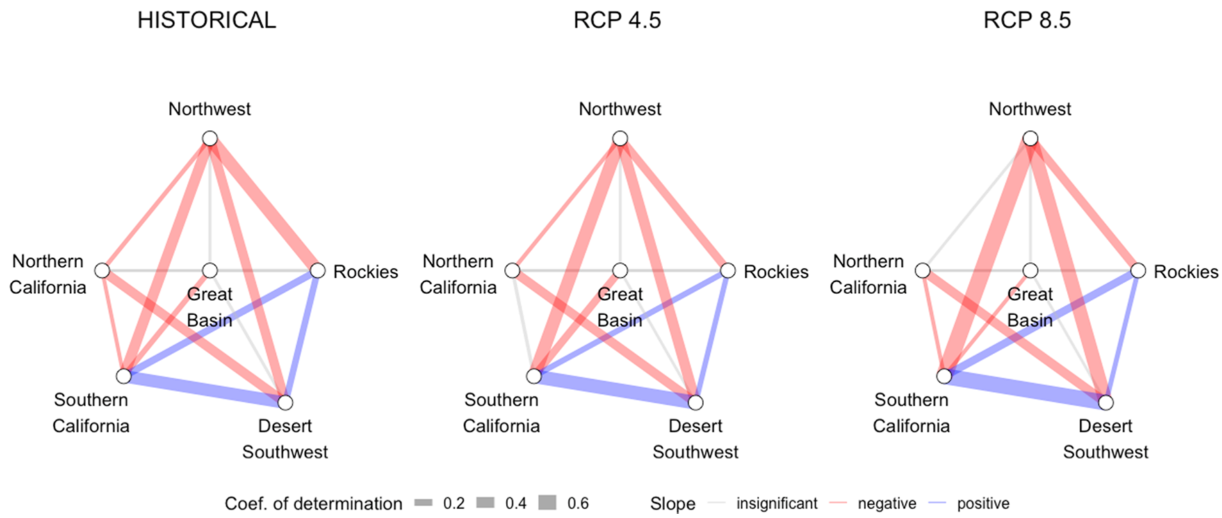

Fig. 4. Variance analysis of regional net generation under historical and future conditions, all GCMs and RCPs combined. Positive slope indicates positive correlation in net generation (and vice versa). Coefficients of determination less than 0.2 are greyed out.

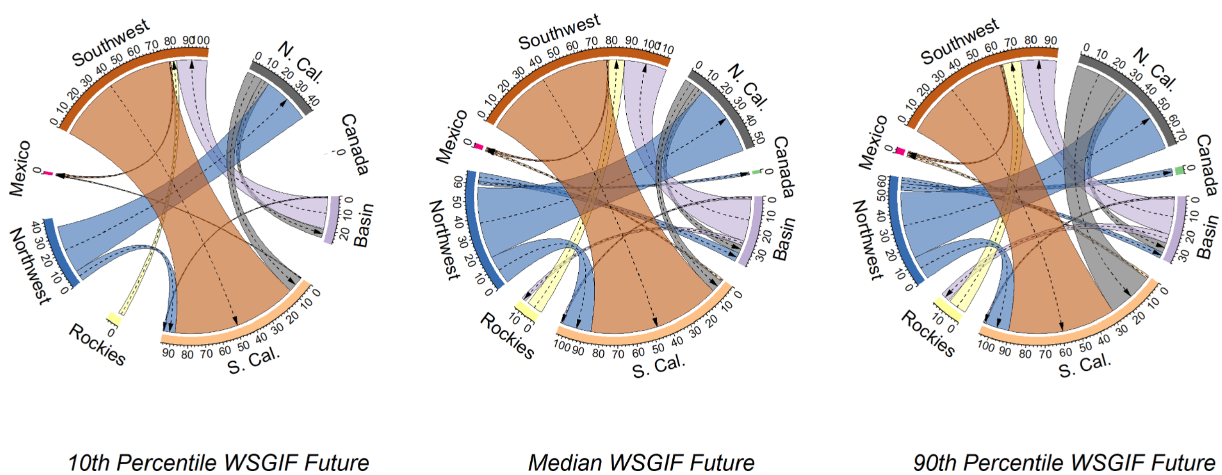

Fig. 5. Regional power flows during a dry (10th percentile WSGIF), normal (median), and wet (90th percentile) year. The WSGIF represent coincident water availability conditions at hydropower and thermoelectric plants.

generation constraints, WSGIF, see supplemental material S2.2 and methods). Fig. 5 shows the net interchange between region pairs for an example of wet, median, and dry years while the description of dependencies that follows is based on all 270 simulated years. Whether stressed by large interannual variability or future water availability, we find that the import/export status of the energy regions under current infrastructure and load is largely maintained. Power flows from the Northwest into Northern California increase with dry to normal conditions (increasing WSGIF) and tend to level off beyond 40 TWh around median WSGIF. Power flows from the Northwest to Southern California also reach 20 TWh, with increasing WSGIF before leveling off at median WSGIF value. The flows from Northern California to Southern California increase continuously with increasing WSGIF. The largest interchange is from the Desert Southwest to Southern California and this decreases from nearly 80 to 50 TWh as we move from dry to normal to wet conditions.

Southern California is hidden from our analytics so far because it is a major importer (Figs. 3 and 5), with the Desert Southwest as the largest source (Fig. 5). With the energy demand held constant in our analysis, variations in the exports to Southern California are driven by regional water availability in the Northwest and Northern California, and the response of the Southwest to those regions' water availability (Fig. 4). Given these import-export dynamics, the potential major changes in the generation portfolio in Southern California with the addition of distributed solar generation should be compounded with evolving water availability in other regions when evaluating the WECC grid resilience. This analysis exposes the importance of representing regional diversity in water availability and indicates how other drivers of power grid operations (e.g., regional fuel prices and technology innovation) might influence the regional responses of power operations to changes in water availability.

4. Discussion

4.1. Research implication: complex regional interdependencies to be considered for long-term planning

Regional electricity importer/exporter interdependency between the Northwest and California associated with their local variations in water availability had been previously established with modeling studies [24,51] and more recently with data-driven analytics of virtual water flows [53]. The work presented here explores more-complex regional interdependencies where pairs of importers/exporters (Northwest to Southern California and the Desert Southwest to California) are intertwined with exporter/exporter pairs (Northwest-Desert Southwest). As shown in Figs. 3–5, water availability in the Northwest drives the regional net generation and therefore the exports toward Southern California. When the regional net generation is lower in the Northwest, the Desert Southwest mitigates the generation loss in the Northwest by increasing its net generation and exporting more to Southern California. Any changes in water availability in the Northwest therefore propagate to the importer (i.e., Southern California) and alternate exporter (i.e., the Desert Southwest).

Our research highlights the need to identify interconnected importers and exporters, as well as their sensitivities to local and extra-regional water availability conditions. Such an approach allows for improved representation of regional long-term planning autonomy with realistic boundary conditions. Even if one region is not sensitive to changes in local water availability, the import/export boundary conditions likely are. Climate may thus amplify grid-scale changes and boundary conditions rather than, or in addition to, driving changes in local water-energy dynamics.

4.2. Limitations of the analysis

Although this study highlights the importance of grid-scale modeling for evaluation of climate change impacts on a generation, there are several potential improvements that may be addressed in future work.

We purposely kept the water demand level, the electricity demand level, and the electricity infrastructure to 2010. The assumption of fixed 2010-level for water demand is reasonable [54] and the implications over the Western United States is somewhat limited because many basins are fully allocated [55]. There remain large uncertainty in projected changes in water demands and how those changes could affect water availability [56–58]. Maintaining the electricity demand level allowed the analytics to focus on water availability driven changes in regional responses and dependencies. Future work would benefit from considering changes in electricity demand and associated changes in electricity infrastructure. While a number of studies have provided projections of electricity demand associated with increased temperature and population [59–61], there is no existing hourly nodal electricity demand datasets coincident with the climate and hydrology datasets at the scale of the entire Western U.S. Those electricity demand datasets are an area of ongoing research [62–65]. The fixed electricity infrastructure assumption will need to be addressed in future work. Technology innovations and (e.g., electricity storage devices and smart appliances to mitigate peaks in electricity demand, and distributed electricity generation from roof solar panels) and regulatory policies (e.g., regulations regarding market structure and integration of renewables) lead to uncertainty in future infrastructure growth that requires a substantial extension to the analytics in this study. However, the findings provide guidance on how regionally diverse water availability conditions should be considered when evaluating future electricity infrastructure and electricity demand.

In regard to generation constraints, we did not include effects from either air or water temperature on thermoelectric plant generating capacity. These effects have limited implications over the Western United States in comparison to water availability, but they should be considered in other grids and perhaps in future work [4,11,66,67]. Water availability in most hydrologic regions in the Western United States is snowmelt-driven; therefore, a seasonal look into the existing analysis is needed. While the fixed seasonality in generation is an uncertainty in this analysis, monthly hydropower generation patterns are driven not only by water availability but also by regulatory constraints and power grid operational needs to meet evolving electricity demand, which were also held constant and therefore consistent. A seasonal analysis is performed (see supplemental material S7) demonstrating that key power flows between the Northwest, Northern California, the Desert Southwest, and Southern California are conserved at a seasonal scale as well. Future research focusing on seasonal power flows would need to address the connection between regional generation and water availability, market prices, and loads.

Pumped storage hydropower (PSH) contributes only 2.5% of power generation in the WECC, but is much more dominant in the generating portfolios of other power girds, such as in Brazil and the European Alps. These grids would benefit from more detailed simulation of PSH dispatch. In these power grids, the impact of future water availability cannot be isolated from uncertainty in future market conditions using the same approach to modeling conventional hydropower, as done in this study. Ongoing research demonstrates the complexity in evaluating the impact of climate change on PSH amid environmental constraints and uncertainty in market conditions [68,69] and how PSH could reduce dependence on conventional hydropower and decouple the grid from natural water variability [70].

5. Conclusions

This study explores the impact of future water availability (2050 s) as driven by climate change onto the existing Western U.S. interconnection (WECC) and regional operations, and in particular on regional interdependencies. It includes six 1985–2095 hourly electricity operations simulations derived from three bias-corrected and downscaled climate projections from global atmospheric models CCSM4, INMCM4 and GFDL-CM3 and two radiative scenarios RCP4.5 and RCP8.5 which represent large variability in future climate under both scenarios with changes in temperature ranging from 0.8 °C to 2.8 °C and changes in precipitation from −3.8% to +17%. Historical and future spatially distributed hydrologic simulations [36] inform a large-scale spatially distributed river routing water management model MOSART-WM [40] that translates water availability into power generation constraints at hydropower plants and water-dependent thermoelectric plants across the Western United States. Historical and future time series of monthly hydropower generation and thermoelectric plant capacity deratings for the six studies are input into the production cost model PLEXOS [44] – a high spatial resolution hourly-resolution economic dispatch to represent WECC power system operations. Resulting PLEXOS-simulated regional and WECC-scale generation portfolio, production cost and interregional power transfers are used to evaluate the impact of climate change on power system operations and regional interdependencies.

Our simulation results suggest:

i) Grid operations over the Western United States benefit largely from diversity in generation technology and spatial location; under climate change conditions, WECC-scale initial stress of −3.8% to +17% changes in mean precipitation is moderated to −6% to +4% in mean annual production cost changes, even though the absolute changes in cost are substantial.
ii) Inter-annual changes in net electricity generation in Northern California and the Northwest are directly related to the local changes in water availability, which explains over 90% of the variability in both regions. The Northwest is an exporting region, and the net-generation response over the region could be inferred without the production cost model. However, the generation response in mostly importing Northern California to local changes in water availability highly reflects cross-regional power system dynamics.
iii) Northwest total generation determines the interannual variability in other regions' net generation, explaining about 40%, 50%, and 35% of the variability in generation in Southwest, Rockies, and Southern California regions respectively. Northern California variability in generation also explains about 30% of the generation in Desert Southwest.
iv) Climate-induced changes in water availability and total generation are significant only in the Northwest. While the direction of future water availability change is not definitive at the WECC scale, climate change impacts on the Northwest propagate throughout the Western U.S. power grid by driving future regional changes in other regions' generation and regional interdependencies. This pattern is

amplified by large interannual variability in Northern California's water availability and generation.

v) The Desert Southwest serves as the primary generation response region to adapt to changes in water availability in the Northwest and Northern California, in our simulations.

vi) Regional importer/exporter relationships, and specifically power flow directions, are largely maintained under both interannual and climate-change-only variations in water availability.

Many previous water-energy studies have examined the impacts of climate change on region-specific resource adequacy. Building on this foundation, our study uses a grid-scale approach and a production cost model to explore an unprecedented range of projected grid-scale water availability conditions and focus on regional impacts as well as complex interregional interactions, such as importer-exporter pairs but also exporter-exporter pairs dynamics. Our results highlight important practical implications for long-term capacity and transmission planning studies as well as resource adequacy studies. Given the importer-exporter and exporter-exporter pairs dynamics exposed in this work, regional planning authorities ought to take the precaution of including in their models the effects of climate change on grid operations beyond their immediate locales. A key example is the interdependent net generation in the Northwest and Desert Southwest linked to water availability in the Northwest and electricity demand in Southern California. At the grid-scale, power system models may be used to better understand how climate change impacts propagate into regional power system dynamics. This would enable a more comprehensive approach to regional long term planning, with more accurate boundary conditions, complex regional power dependencies, and consideration of the amplifying effects of climate change on factors driving future grid expansion needs.

Data availability

Monthly generation constraints [41] and aggregated power system operations [43] datasets under historical and future conditions derived in this study are available at https://nam03.safelinks.protection.outlook.com/?url=https%3A%2F%2Fgithub.com%2FIMMM-SFA%2Fvoisin-etal_2020_apen&data=02%7C01%7CC.Corrections%40elsevier.com%7Cda4375995df14aca787108d82771504c%7C9274ee3f94254109a27f9fb15c10675d%7C0%7C0%7C637302714922606959&sdata=E9OzddVag6ewcOtUO%2B1oB%2FefnVJ%2FnQFdC22R80clDxs%3D&reserved=0.

CRediT authorship contribution statement

Nathalie Voisin: Conceptualization, Formal analysis, Funding Acquisition, Methodology, Supervision, Visualization, Writing - original draft. **Ana Dyreson:** Formal analysis, Methodology, Software, Visualization, Writing - original draft. **Tao Fu:** Software, Visualization. **Matt O'Connell:** Methodology, Software, Writing - review & editing. **Sean W.D. Turner:** Formal analysis, Software, Visualization, Writing - review & editing. **Tian Zhou:** Formal analysis, Software. **Jordan Macknick:** Conceptualization, Funding acquisition, Methodology, Writing - review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.115467.

References

[1] EIA. Net generation by state by type of producer by energy source 1990–2018; 2019.
[2] Maupin MA, Kenny JF, Hutson SS, Lovelace JK, Barber NL, Linsey KS. Estimated use of water in the United States in 2010; 2014. p. 64, Reston, VA.
[3] Field CB, Barros VR, Mach KJ, Mastrandrea MD, van Aalst M, Adger WN, et al. Climate Change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. contribution of working Group II to the fifth assessment report of the intergovernmental panel on climate change. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, editors; 2014. p. 35–94.
[4] Bartos MD, Chester MV. Impacts of climate change on electric power supply in the Western United States. Nat Clim Change 2015;5:748.
[5] Forrest K, Tarroja B, Chiang F, AghaKouchak A, Samuelsen S. Assessing climate change impacts on California hydropower generation and ancillary services provision. Clim Change 2018;151(3):395–412.
[6] Kao S-C, Sale MJ, Ashfaq M, Uria Martinez R, Kaiser DP, Wei Y, et al. Projecting changes in annual hydropower generation using regional runoff data: an assessment of the United States federal hydropower plants. Energy 2015;80:239–50.
[7] Parkinson SC, Djilali N. Robust response to hydro-climatic change in electricity generation planning. Clim Change 2015;130(4):475–89.
[8] Schaefli B, Hingray B, Musy A. Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties. Hydrol Earth Syst Sc 2007;11(3):1191–205.
[9] Zhou T, Voisin N, Fu T. Non-stationary hydropower generation projections constrained by environmental and electricity grid operations over the western United States. Environ Res Lett 2018;13(7):074035.
[10] Turner SWD, Ng JY, Galelli S. Examining global electricity supply vulnerability to climate change using a high-fidelity hydropower dam model. Sci Total Environ 2017;590–591:663–75.
[11] Liu L, Hejazi M, Li H, Forman B, Zhang X. Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations. Nat Energy 2017;2:17109.
[12] Miara A, Vörösmarty CJ, Macknick JE, Tidwell VC, Fekete B, Corsi F, et al. Thermal pollution impacts on rivers and power supply in the Mississippi River watershed. Environ Res Lett 2018;13(3):034033.
[13] Tarroja B, Chiang F, AghaKouchak A, Samuelsen S. Assessing future water resource constraints on thermally based renewable energy resources in California. Appl Energy 2018;226:49–60.
[14] van Vliet MTH, Yearsley JR, Ludwig F, Vögele S, Lettenmaier DP, Kabat P. Vulnerability of US and European electricity supply to climate change. Nat Clim Change 2012;2(9):676–81.
[15] Behrens P, van Vliet MTH, Nanninga T, Walsh B, Rodrigues JFD. Climate change and the vulnerability of electricity generation to water stress in the European Union. Nat Energy 2017;2(8):17114.
[16] Hejazi MI, Voisin N, Liu L, Bramer LM, Fortin DC, Hathaway JE, et al. 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating. Proc Natl Acad Sci 2015;112(34):10635.
[17] Klein DR, Olonscheck M, Walther C, Kropp JP. Susceptibility of the European electricity sector to climate change. Energy 2013;59:183–93.
[18] Steinberg DC, Mignone BK, Macknick J, Sun Y, Eurek K, Badger A, et al. Decomposing supply-side and demand-side impacts of climate change on the US electricity system through 2050. Clim Change 2020;158(2):125–39.
[19] van Vliet MTH, Wiberg D, Leduc S, Riahi K. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nat Clim Change 2016;6:375.
[20] Bain DM, Acker TL. Hydropower impacts on electrical system production costs in the Southwest United States. Energies 2018;11(2):368.
[21] NWPCC. Seventh Northwest conservation and electric power plan. Portland, OR: Northwest Power and Conservation Council; 2016.
[22] Tarroja B, Forrest K, Chiang F, AghaKouchak A, Samuelsen S. Implications of hydropower variability from climate change for a future, highly-renewable electric grid in California. Appl Energy 2019;237:353–66.
[23] Turner SWD, Voisin N, Fazio J, Hua D, Jourabchi M. Compound climate events transform electrical power shortfall risk in the Pacific Northwest. Nat Commun 2019;10(1):8.

[24] Voisin N, Kintner-Meyer M, Wu D, Skaggs R, Fu T, Zhou T, et al. Opportunities for joint water-energy management: sensitivity of the 2010 Western U.S. electricity grid operations to climate oscillations. Bull Am Meteorol Soc 2018;99(2):299–312.
[25] Voisin N, Kintner-Meyer M, Skaggs R, Nguyen T, Wu D, Dirks J, et al. Vulnerability of the US western electric grid to hydro-climatological conditions: How bad can it get? Energy 2016;115:1–12.
[26] Taylor KE, Stouffer RJ, Meehl GA. An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 2012;93(4):485–98.
[27] van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. The representative concentration pathways: an overview. Clim Change 2011;109(1):5.
[28] Donner LJ, Wyman BL, Hemler RS, Horowitz LW, Ming Y, Zhao M, et al. The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL global coupled model CM3. J Clim 2011;24(13):3484–519.
[29] Volodin EM, Diansky NA, Gusev AV. Simulation and prediction of climate changes in the 19th to 21st centuries with the Institute of Numerical Mathematics, Russian Academy of Sciences, model of the Earth's climate system. Izv Atmos Oceanic Phys 2013;49(4):347–66.
[30] Gent PR, Danabasoglu G, Donner LJ, Holland MM, Hunke EC, Jayne SR, et al. The community climate system model version 4. J Clim 2011;24(19):4973–91.
[31] Reclamation 2013 Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information, and Summary of User Needs p. 47pp, prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado; 2013.
[32] Salathe Jr EP, Mote PW, Wiley MW. Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States pacific northwest. Int J Climatol 2007;27(12):1611–21.
[33] Wood AW, Leung LR, Sridhar V, Lettenmaier DP. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim Change 2004;62(1):189–216.
[34] Wood AW, Maurer EP, Kumar A, Lettenmaier DP. Long-range experimental hydrologic forecasting for the eastern United States. J Geophys Res: Atmos 2002;107(D20). ACL 6-1-ACL 6–15.
[35] Reclamation 2014 Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Hydrology Projections, Comparison with preceding Information, and Summary of User Needs p. 110 pp, prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado; 2014.
[36] Wood, A.W.N.M. 2014 CMIP5 1/8th degree daily weather and VIC hydrology datasets for CONUS; 2014. p. 32, NCAR.
[37] Liang X, Lettenmaier DP, Wood EF, Burges SJ. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J Geophys Res: Atmos 1994;99(D7):14415–28.
[38] Li H, Wigmosta MS, Wu H, Huang M, Ke Y, Coleman AM, et al. A physically based runoff routing model for land surface and earth system models. J Hydrometeorol 2013;14(3):808–28.
[39] Voisin N, Hejazi MI, Leung LR, Liu L, Huang MY, Li HY, et al. Effects of spatially distributed sectoral water management on the redistribution of water resources in an integrated water model. Water Resour Res 2017;53(5):4253–70.
[40] Voisin N, Li H, Ward D, Huang M, Wigmosta M, Leung LR. On an improved subregional water resources management representation for integration into earth system models. Hydrol Earth Syst Sci 2013;17(9):3605–22.
[41] Voisin N, Dyreson A, Fu T, O'Connell M, Turner SW, Zhou T, Macknick J. PLEXOS Inputs for Voisin et al. 2020 [Data set]; 2020. [accessed 2 July 2020].
[42] O'Connell M, Voisin N, Macknick J, Fu T. Sensitivity of Western U.S. power system dynamics to droughts compounded with fuel price variability. Appl Energy 2019;247:745–54.
[43] Voisin N, Dyreson A, Fu T, O'Connell M, Turner SW, Zhou T, Macknick J. Results for Voisin et al. 2020 [Data set]; 2020. [accessed 2 July 2020].
[44] Energy-Exemplar. PLEXOS integrated energy model; 2018.
[45] WECC 2014 TEPPC 2024 common case, Western Electricity Coordinating Council - Transmission Expansion Planning and Policy Committee (TEPPC) Study Program, Salt Lake City, UT; 2004.
[46] Platts. 2009 Platts Power Plants. S&P Global Platts (ed), Westminster, CO; 2009. http://www.gisdata.platts.com/.
[47] Dai J, Wu S, Han G, Weinberg J, Xie X, Wu X, et al. Water-energy nexus: a review of methods and tools for macro-assessment. Appl Energy 2018;210:393–408.
[48] Voisin N, Liu L, Hejazi M, Tesfa T, Li H, Huang M, et al. One-way coupling of an integrated assessment model and a water resources model: evaluation and implications of future changes over the US Midwest. Hydrol Earth Syst Sc 2013;17(11):4555–75.
[49] Lehner B, Liermann CR, Revenga C, Vörösmarty C, Fekete B, Crouzet P, et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Front Ecol Environ 2011;9(9):494–502.
[50] Zhou T, Voisin N, Leng G, Huang M, Kraucunas I. Sensitivity of regulated flow regimes to climate change in the Western United States. J Hydrometeorol 2018;19(3):499–515.
[51] Voisin N, Hamlet AF, Graham LP, Pierce DW, Barnett TP, Lettenmaier DP. The role of climate forecasts in Western U.S. power planning. J Appl Meteorol Climatol 2006;45(5):653–73.
[52] Madani K, Guegan M, Uvo CB. Climate change impacts on high-elevation hydroelectricity in California. J Hydrol 2014;510:153–63.
[53] Chini CM, Djehdian LA, Lubega WN, Stillwell AS. Virtual water transfers of the US electric grid. Nat Energy 2018;3(12):1115–23.
[54] Dieter CA, Maupin MA, Caldwell RR, Harris MA, Ivahnenko TI, Lovelace JK, et al. Estimated use of water in the United States in 2015;2018. p. 76, Reston, VA.
[55] Tidwell VC, Bailey M, Zemlick KM, Moreland BD. Water supply as a constraint on transmission expansion planning in the Western interconnection. Environ Res Lett 2016;11(12).
[56] Brown TC, Mahat V, Ramirez JA. Adaptation to future water shortages in the United States caused by population growth and climate change. Earth's Fut 2019;7(3):219–34.
[57] Huang Z, Hejazi M, Li X, Tang Q, Vernon C, Leng G, et al. Reconstruction of global gridded monthly sectoral water withdrawals for 1971–2010 and analysis of their spatiotemporal patterns. Hydrol Earth Syst Sci 2018;22(4):2117–33.
[58] Scott MJ, Daly DS, Hejazi MI, Kyle GP, Liu L, McJeon HC, et al. Sensitivity of future U.S. Water shortages to socioeconomic and climate drivers: a case study in Georgia using an integrated human-earth system modeling framework. Clim Change 2016;136(2):233–46.
[59] Auffhammer M, Baylis P, Hausman CH. Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. Proc Natl Acad Sci; 2017: 201613193.
[60] Dirks JA, Gorrissen WJ, Hathaway JH, Skorski DC, Scott MJ, Pulsipher TC, et al. Impacts of climate change on energy consumption and peak demand in buildings: a detailed regional approach. Energy 2015;79:20–32.
[61] van Ruijven BJ, De Cian E, Sue Wing I. Amplification of future energy demand growth due to climate change. Nat Commun 2019;10(1):2762.
[62] Craig MT, Losada Carreño I, Rossol M, Hodge B-M, Brancucci C. Effects on power system operations of potential changes in wind and solar generation potential under climate change. Environ Res Lett 2019;14(3):034014.
[63] Ralston Fonseca F, Jaramillo P, Bergés M, Severnini E. Seasonal effects of climate change on intra-day electricity demand patterns. Clim Change 2019;154(3):435–51.
[64] Tarroja B, Chiang F, AghaKouchak A, Samuelsen S, Raghavan SV, Wei M, et al. Translating climate change and heating system electrification impacts on building energy use to future greenhouse gas emissions and electric grid capacity requirements in California. Appl Energy 2018;225:522–34.
[65] Taylor ZT, Xie Y, Burleyson CD, Voisin N, Kraucunas I. A multi-scale calibration approach for process-oriented aggregated building energy demand models. Energy Build 2019;191:82–94.
[66] Ke X, Wu D, Rice J, Kintner-Meyer M, Lu N. Quantifying impacts of heat waves on power grid operation. Appl Energy 2016;183:504–12.
[67] Klimenko VV, Fedotova EV, Tereshin AG. Vulnerability of the Russian power industry to the climate change. Energy 2018;142:1010–22.
[68] Gaudard L. Pumped-storage project: A short to long term investment analysis including climate change. Renew Sust Energ Rev 2015;49:91–9.
[69] Gurung AB, Borsdorf A, Füreder L, Kienast F, Matt P, Scheidegger C, et al. Rethinking pumped storage hydropower in the European alps. Mt Res Dev 2016;36(2):222–32.
[70] Hunt JD, Byers E, Riahi K, Langan S. Comparison between seasonal pumped-storage and conventional reservoir dams from the water, energy and land nexus perspective. Energ Convers Manage 2018;166:385–401.