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Multi-scale impacts of climate change on hydropower for long-term water-energy planning in the contiguous United States

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Abstract

Climate change impacts on watersheds can potentially exacerbate water scarcity issues where water serves multiple purposes including hydropower. The long-term management of water and energy resources is still mostly approached in a siloed manner at different basins or watersheds, failing to consider the potential impacts that may concurrently affect many regions at once. There is a need for a large-scale hydropower modeling framework that can examine climate impacts across adjoining river basins and balancing authorities (BAs) and provide a periodic assessment at regional to national scales. Expanding from our prior assessment only for the United States (US) federal hydropower plants, we enhance and extend two regional hydropower models to cover over 85% of the total hydropower nameplate capacity and present the first contiguous US-wide assessment of future hydropower production under Coupled Model Intercomparison Project phase 6's high-end Shared Socioeconomic Pathway 5-8.5 emission scenario using an uncertainty-aware multi-model ensemble approach. We present regional hydropower projections, using both BA regions and US Hydrologic Subregions (HUC4s), to consistently inform the energy and water communities for two future periods—the near-term (2020–2039) and the mid-term (2040–2059) relative to a historical baseline period (1980–2019). We find that the median projected changes in annual hydropower generation are typically positive—approximately 5% in the near-term, and 10% in the mid-term. However, since the risk of regional droughts is also projected to increase, future planning cannot overly rely on the ensemble median, as the potential of severe hydropower reductions could be overlooked. The assessment offers an ensemble of future hydropower generation projections, providing regional utilities and power system operators with consistent data to develop drought scenarios, design long duration storage and evaluate energy infrastructure reliability under intensified inter-annual and seasonal variability.

1. Introduction

In the United States (US) hydropower is an important source of stored and dispatchable renewable electricity. The development of historical hydropower datasets at the scale of bulk power grids that account for the impact of water management and hydrologic variability has advanced power systems studies by unlocking the ability to explore regional dependencies between water availability and hydropower production during drought events (Voisin *et al* 2018) and by quantifying the seasonal capabilities and limitations of using hydropower to support the integration of non-dispatchable renewables (Dyreson *et al* 2022).

Periodic assessments of climate change impacts on projected future hydropower generation across

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the contiguous US (CONUS) are needed to support long-term energy planning (Craig *et al* 2018). Driven by the SECURE Water Act (SWA, Public Law 111–11) Section 9505, the US Department of Energy has conducted three rounds of assessments examining the impacts of climate change on US federal hydropower using the most current Coupled Model Intercomparison Project (CMIP) projections at that time. These assessments examined 132 federal hydropower facilities, which represent ∼46% of US nameplate capacity (42.5 GW) (Sale *et al* 2012; Kao *et al* 2016, 2022a). However, the assessments did not examine the broader set of non-federal hydropower plants, which are in general smaller and have less storage and flexibility to cope with the increasing hydrologic variability projected in the future climate.

With respect to the previous few assessments with a substantial facility-scale representation at the CONUS scale (Boehlert *et al* 2016), energy market scale (Tarroja *et al* 2016), and selected bulk power grid scale (Voisin *et al* 2020), this assessment specifically focuses on evaluations at both water and energy scales to inform the water and power planning communities consistently across CONUS. A review of studies examining the impact of climate change on hydropower is presented in Wasti *et al* (2022) including how changes in natural quantities—glacial melt, snowmelt, precipitation, and drought—are impacting hydropower generation regionally across the globe. In addition, there have been limited studies that examine these climate impacts considering water and energy infrastructure that can greatly impact water available for hydropower generation in both quantity and timing, considering infrastructure operations are important when developing hydropower generation projections at decision-relevant scales. In this context, several unique datasets that enhance facility characteristics and geolocate hydropower facilities on the river network can be used to promote multi-sector modeling consistency. The advance of hydropower data and models support the simulation of hydropower generation across a much larger number of facilities more reliably and efficiently. This enhanced assessment provides a fuller representation of the future impacts and capabilities of hydropower across electrical interconnections that can inform planning and operational decisions for water management and power system operators.

The energy and water communities require consistent projections of hydropower production at decision-relevant scales to support their long-term planning. Therefore, we develop in this study a set of climate change-informed future hydropower projections using the latest downscaled Coupled Models Intercomparison Project phase 6 (CMIP6) climate model outputs, which offers opportunities to improve joint planning efforts across water and electricity systems. Additionally, we leverage a multi-model approach that can better characterize modeling uncertainty to inform decision making. To develop this spatially consistent hydropower assessment across the CONUS, we build upon the federal-only hydropower modeling in the Third SWA Section 9505 Assessment (9505V3; Kao *et al* 2022a) by significantly expanding the extent of the assessment to cover 1544 federal and non-federal hydropower facilities with a total nameplate capacity of 86.4 GW, representing over 85% of the total hydropower capacity across the country. This was achieved by enhancing the hydropower models and developing validated novel datasets to accurately simulate this expanded set of facilities. With this expanded modeling capability, we can finally examine the concurrent climate change impacts on the overall US hydropower generation. Further, this assessment quantifies projected hydropower production at multiple spatial scales, including balancing authority (BA) and watershed. BAs in the US are regional grid entities responsible for balancing electricity generation and electricity demand within their footprint, and electricity exchange with other BAs.

We also evaluate the impacts of severe droughts at the scale of the Western and Eastern bulk power grids to support the water and electricity managers in selecting and evaluating common scenarios in their long-term planning efforts. When examining an entire interconnection containing multiple BAs, hydropower projections are valuable to understanding how regional changes in future hydropower availability could impact grid reliability, considering the existing generation mix and a decarbonized grid (Hill *et al* 2021). On the other hand, hydropower projections at the watershed scale are informative to water managers' decisions in examining how generation is impacted by climate change, particularly in watersheds with water scarcity issues. These two scales can jointly capture the multiple and often competing uses of water within a watershed and provide an ability to assess how these interactions impact hydropower production in the projected future climate conditions.

2. Methodology

The development of hydropower generation projections relies upon an existing modeling framework that starts with global climate model (GCM) projections, downscales them to finer spatial scales, simulates hydrologic processes using hydrologic models, simulates water management and withdrawals, and then simulates hydropower generation. At each step of this modeling chain, multiple approaches were used to account for uncertainties in model selection and parameterization and ultimately produce a 96-member ensemble of hydropower generation projections encompassing all permutations of model

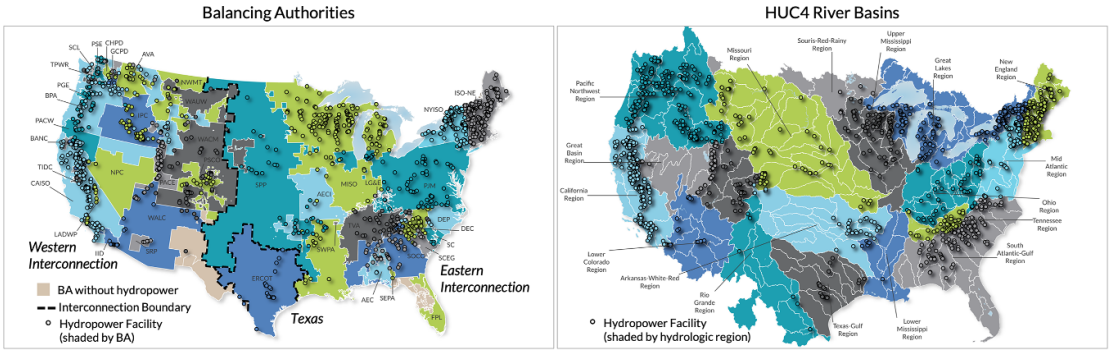


Figure 1. Hydropower facilities included in this study by BA (left panel) and HUC4 Subregions (right panel). The left panel shows the approximate boundaries of each BA and the approximate boundary between the three grid interconnections in the CONUS (excluding Canada and Mexico). The right panel shows US HUC2 Hydrologic Regions (shaded areas) and HUC4 Subregions (white outlines) for CONUS (including contributing areas in Canada and Mexico). Sources: Homeland Infrastructure Foundation-Level Data for BA boundaries, USGS Watershed Boundary Dataset for HUC2 and HUC4 boundaries, and EHA revised in this study for hydropower facility locations.

combinations from each stage in the modeling chain (Kao *et al* 2022a). In particular, for this study, our new efforts are to expand the coverage of hydropower plants to 1544 that cover 86.4 GW over 85% of the total US hydropower capacity, which has been one of the largest climate change-informed US hydropower modeling exercise to date to our best knowledge.

The hydropower generation projections produced were processed and evaluated at two spatial scales: BAs and HUC4 Subregions (Broman *et al* 2024a, 2024b) to examine how generation may change from a perspective aligned with energy planning, and a perspective aligned with water management. The generation projections were evaluated by examining how mean generation at the annual and seasonal timescales differ from the historical baseline period. The mean generation for each ensemble member was first computed for the historical baseline period and each future period. Percent change was then computed by comparing mean future generation with mean historical generation and this provided an ensemble of mean generation change at annual and seasonal scales: winter (December to February, DJF), spring (March to May, MAM), summer (June to August, JJA), and fall (September to November, SON). From these ensembles, the median, 5th, and 95th percentile values were identified to capture the range of uncertainty in future change.

The spatial variability of change is important, particularly in energy planning contexts where understanding not only the range of change but how changes are distributed across an interconnection within individual years as they are likely heterogeneous and not every location will experience increases or decreases at the same time. To illustrate how these datasets can be used, we identified the lowest three generation years in each future period for the Eastern and Western Interconnections, and we computed changes in generation relative to the historical median generation in each of the years. The hydropower drought years at the interconnection scale were selected using the hydropower component of the water-scarcity grid impact factor (WSGIF; Voisin *et al* 2016); this component is calculated by dividing the annual total generation for each year by the mean annual historical generation across all BAs within each interconnection. Since no widespread drought looks alike spatially and temporally, the three lowest years provide insight into potential 'worst-case' generation scenarios looking across interconnections which can be useful in grid planning and evaluating grid reliability studies informed by climate change (Cohen *et al* 2022, Dyreson *et al* 2022).

2.1. Hydropower fleet across CONUS

The 2021 Existing Hydropower Asset (EHA, Johnson *et al* 2021) dataset, along with monthly hydropower generation data compiled from the EIA Form-923 dataset (EIA 2022), RectifHyd (Turner *et al* 2022), and federal hydropower generation data from 9505V3, were used to identify 1544 facilities with an approximate total nameplate capacity of 86.4 GW. Facilities without reported generation during the 2001–2019 period were not included in the assessment; they represent a very small percentage of the overall CONUS nameplate capacity. Facilities' geolocations were used to associate them with HUC4 Subregions and EHA to associate them with BAs as shown in figure 1.

2.2. Climate projections

Six GCMs from CMIP6 (Eyring *et al* 2016) selected by Ashfaq *et al* (2022) were used to examine hydropower production under projected future climate conditions. These projections are under the high-end Shared Socioeconomic Pathway 5 (SSP5; O'Neill *et al* 2017) and Representative Concentration Pathway 8.5 (Van Vuuren *et al* 2011) SSP5-8.5 emission scenario, which reflects rapid 'fossil-fueled' development

along with high greenhouse gas concentrations by the end of the 21st century. It represents the 'worse case' scenario in terms of warming and was selected based on the collaborative discussion among federal hydropower stakeholders during the 9505V3 assessment. Climate projections were downscaled (Rastogi *et al* 2022) using two approaches: statistically using the Double Bias Correction Constructed Analogues method (Werner and Cannon 2016), and dynamically using Regional Climate Model version 4 (Giorgi *et al* 2012), with respect to two reference meteorological forcing datasets, Daymet (Thornton *et al* 2021) and Livneh (Livneh *et al* 2015) for statistical training and bias-correction. The outcome is an ensemble of 24 climate projections at a daily timestep and 4 km spatial resolution across the CONUS (Rastogi *et al* 2022).

2.3. Hydrologic simulation

Two hydrologic models were used to develop projections of runoff: the Variable Infiltration Capacity model version 5 (VIC; Liang *et al* 1994, 1996, Nijssen *et al* 1997, Hamman *et al* 2018) and the Precipitation Runoff Modeling System version 5.1.0 (PRMS; Leavesley *et al* 1983, Markstrom *et al* 2015). VIC and PRMS were calibrated independently for each forcing dataset, Livneh, and Daymet, using the US Geological Survey (USGS) WaterWatch monthly runoff dataset (Brakebill *et al* 2011). For details on hydrologic model calibrations, refer to Oubeidillah *et al* (2014), Naz *et al* (2016) and Kao *et al* (2022a). The outcome from these calibrated hydrologic models was an ensemble of 48 runoff projections at the daily timestep and a 4 km spatial resolution across the CONUS (Kao *et al* 2022b).

2.4. Hydropower modeling

The hydropower modeling leverages two models that were implemented in the Third SWA Section 9505 Assessment (9505V3; Kao *et al* 2022a) and were iteratively enhanced with feedback from federal and industry hydropower stakeholders. The first model, Watershed Runoff-Energy Storage (WRES; Kao *et al* 2016), is statistically based and simulates monthly hydropower generation at the watershed scale using precipitation, naturalized runoff, and observed generation as inputs. WRES simulates hydropower generation and runoff using multivariate regression relating precipitation and simulated runoff to observed hydropower generation considering several months of potential lag times. Watershed mass balance checks are then performed along with checks on simulated hydropower generation to ensure that water storage within a watershed and hydropower generation does not exceed known storage and generation capacity limits. Overall, WRES provides lumped estimates of generation at the watershed scale and is an effective model for simulating hydropower generation that leverages historical relationships between precipitation, runoff, and generation. Specifically for this study, WRES was modified to run at each or groups of neighboring HUC4 Subregions with hydropower presence. For cascade systems that include several connected HUC4s, the regulated runoff from the upstream HUC4 is inputted into the downstream HUC4 to account for the overall runoff regulation. The performance of the modified WRES is shown in the supplementary information (SI).

The second approach for simulating hydropower generation uses an approach that attempts to first develop streamflow estimates that include the influence of reservoir operations and water withdrawals and then explicitly simulate hydropower generation at individual hydropower facilities using facility characteristics. Runoff simulated by each of the hydrology models is passed into *mosartwmpy* (Thurber *et al* 2021), a Python representation of the gridded water management and river routing MOSART-WM model (Voisin *et al* 2013) enhanced in this study with hybrid generic and data-driven reservoir operations (Turner *et al* 2022) and reservoir and demand databases. These enhancements and database development were informed by stakeholder engagement. It simulates regulated streamflow at 1/8th degree across CONUS including reservoir operations that use policy developed from historical data (Turner *et al* 2021, 2022) and water withdrawals. In this study water demands are kept at the 2010 level. Hydropower generation was simulated using *wmpy-power* (Zhou *et al* 2018, 2023), a process-based hydropower model. The CONUS *mosartwmpy* model developed for this study, the databases developed in this study, and *wmpy*-power are available in public repositories (see data section). Hydropower generation is simulated using time series of inflow and reservoir storage, and facility characteristics including nameplate capacity, average head, and reservoir storage capacity (where applicable). Model parameters are calibrated using monthly observed hydropower generation. Inflow and storage (where needed) time series were obtained from *mosartwmpy* simulations by identifying the representative 1/8th degree grid cell using the mapped actual spatial location for the source of water for each hydropower facility. Using EHA as a starting place, three distinct datasets were developed: one containing the geographic location of the hydropower facility, one containing the geographic location of the source of water for each hydropower facility, and a crosswalk relating the source of water to the 1/8th degree representation used by the water management and river routing model. The source of water in particular is a novel dataset, that in addition to supporting the modeling performed in this study, provides the ability for others to more thoroughly examine impacts to hydropower generation at broad scales as it contains the source of water information for facilities across CONUS. This is particularly notable as many facilities

receive water through diversion structures and conveyance from locations distant to the actual generators, and in some cases from an adjoining watershed through transbasin diversions.

WRES simulated generation natively for HUC4 Subregions, and for the conversion to BA, a linear scaling factor that weights generation by the nameplate capacity fraction of each BA within each HUC4 Subregion was used to reaggregate the HUC4-based estimates into each BA. Individual facility projections from *wmpy-power* were aggregated to each spatial scale, and facilities not simulated by *wmpy-power* but included in WRES were captured by scaling up the *wmpy-power* generation by the difference in historical observed mean annual generation. The outcome is a 96-member ensemble of SSP5-8.5 monthly hydropower projection for near and mid-term at both HUC4 Subregion and BA scales.

3. Results

Hydropower model performance for WRES and *wmpy-power* was evaluated; monthly simulations over the 2001–2019 validation period had reasonable median NSE values of 0.7 and 0.5 respectively, and median correlation coefficients of 0.86 and 0.81. Additional skill scores can be found in supplementary material.

3.1. Annual hydropower projections

The ensemble of hydropower generation projections can be used to examine projected hydropower changes at different decision-relevant scales, including by BA for energy and power-systems-focused applications, and by watersheds for water-focused applications.

Figure 2 shows the projected change in mean annual potential hydropower production by BA in two future periods—the near-term (2020–2039) and the mid-term (2040–2059) relative to a historical baseline period (1980–2019). There are modest increases in median mean annual hydropower generation—approximately 5% near-term, and 10% in the mid-term—across BAs, with increases in almost all. The exception to this is that in the near term, three BAs in the southwest—Imperial Irrigation District, the Los Angeles Department of Water & Power, and the Salt River Project—show modest decreases in generation, ranging from 3% to 6%. As uncertainty exists in projected future change, the 5th and 95th percentiles of mean annual generation change are also shown. At the low end, the 5th percentile difference is approximately −5% in the near-term and −4% in the mid-term, and at the high end, the 95th percentile difference is approximately 21% in the near-term and 28% in the mid-term when looking across all BAs. While median changes (figure 2, middle column) are fairly uniform across the CONUS, there are regional differences when looking at the spread (figure 2 left and right columns). The range of projected changes in the northeast (−3% to 20% near-term; 3% to 23% mid-term), Pacific Northwest (PNW) (−3% to 17% near-term; −6% to 27% mid-term), mid-Atlantic (−3% to 20% near-term; 0% to 27% mid-term) and Midwest (−1% to 22% near-term; −1% to 29% mid-term) is relatively narrower than in the southwest and California (−27% to 36% near-term; −24% to 55% mid-term), and the southeast (−11% to 31% near-term; −4% to 41% mid-term).

The percent change in mean annual projected hydropower output by HUC4 Subregions (figure 3) follows the same pattern as the projected change in mean annual hydropower production shown in BAs (figure 2). There are modest increases in median mean annual hydropower generation (figure 3 middle column)—approximately 6% in the near-term, and 10% in the mid-term. Median mean annual generation decreases in four HUC4 Subregions in the near term—the Rio Grande Headwaters and Rio Grande-Elephant Butte showing a 3% decrease, and Southern California Coastal and Southern Mojave-Salton Sea showing a 9% decrease. In the mid-term, median mean annual generation decreases only in the Rio Grande Headwaters and Rio Grande-Elephant Butte HUC4 Subregion group by 4%, with the spread (figure 3, left and right columns) ranging from a 22% decrease to a 17% increase. As expected, projected changes by HUC4 Subregions are similar to those seen by BA. Therefore, the seasonal assessment is presented only for BAs thereafter while assessments at the HUC4 Subregions are in supplementary material. While being similar, the availability of those monthly datasets at both scales (Broman *et al* 2024a, 2024b) promotes consistent and accessible long-term water-energy planning.

3.2. Seasonal hydropower projections

Water and energy management are based on the ability to meet water and energy demands, which also have strong seasonal patterns. For example, seasons with potential grid stress arise from decreases in hydropower generation and increases in electricity demand (Turner *et al* 2019). The seasonal assessment for the near term is shown in figure 4, with the corresponding figure for the mid-term available in the supplemental material. Within the winter season, the median mean seasonal percent change across the CONUS shows a 12% increase in the near term and an 18% increase in the mid-term. In contrast, the 5th percentile mean seasonal generation change shows a wet-dry trend in the northern states in comparison to the southern states, as shown by the increases in generation in the north and decreases in generation in the south. The winter season 95th percentile mean seasonal generation change increases across all BAs, with

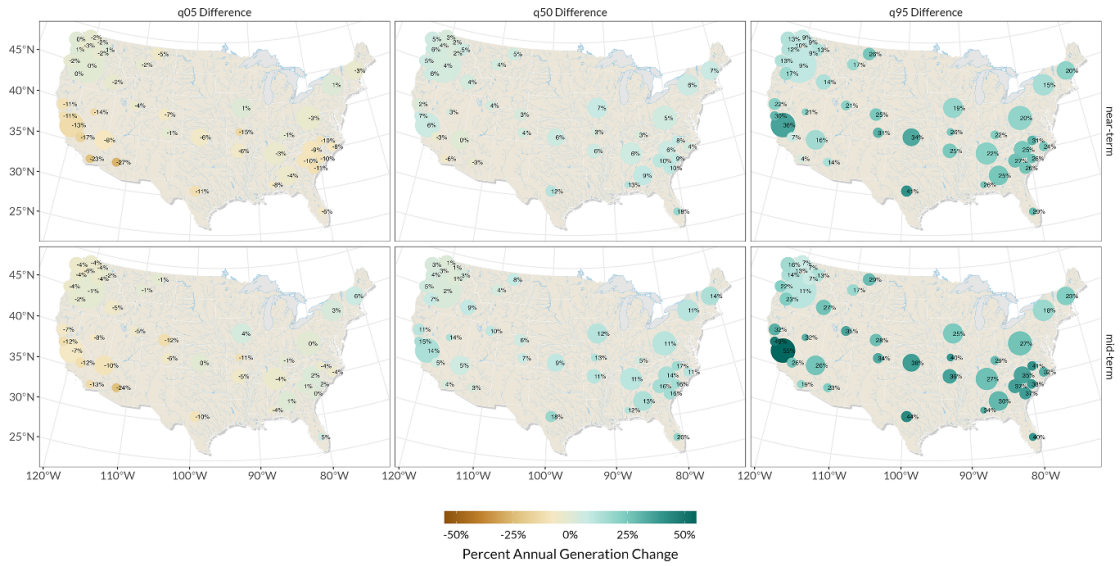


Figure 2. Percent change in mean annual hydropower production for BAs in CONUS. Percent changes are shown for the near-term (2020–2039; top row) and mid-term (2040–2060; bottom row) and for the 5th percentile (q05; left column), median (q50; middle column), and 95th percentile (q95; right column). BAs without hydropower are not shown. Circle size indicates the relative size of hydropower nameplate capacity.

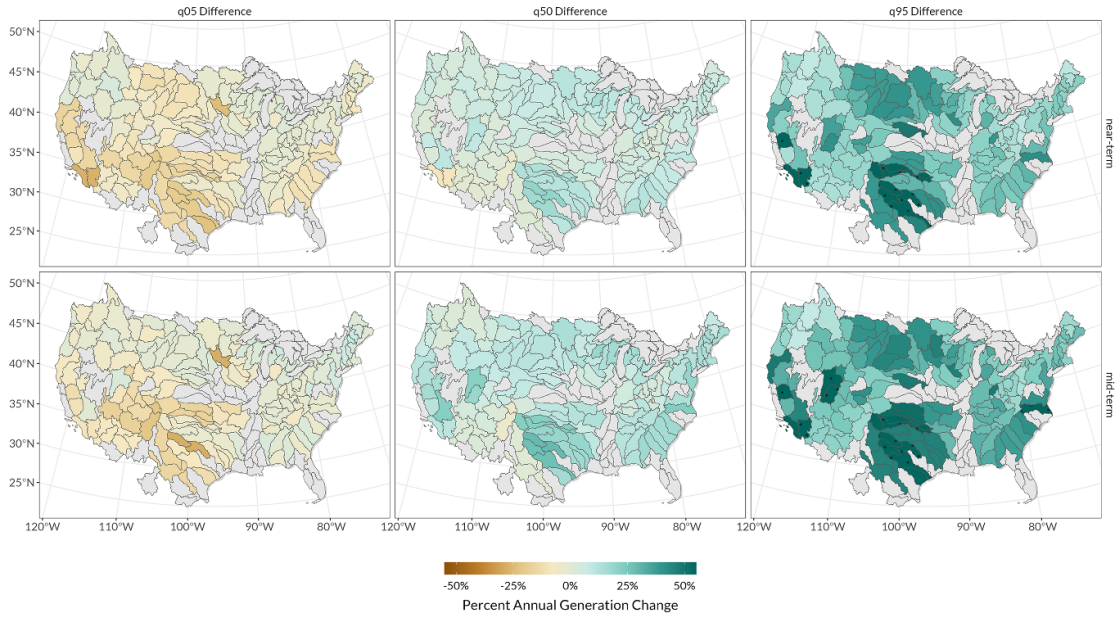


Figure 3. Percent change in mean annual hydropower production for HUC4 Subregions in CONUS. Percent changes are shown for the near-term (2020–2039; top row) and mid-term (2040–2060; bottom row) and for the 5th percentile (q05; left column), 50th percentile (q50; middle column), and 95th percentile (q95; right column). Stippling indicates a greater than 55% increase.

the smallest changes in the southwest (7%–14% in the near term and 17%–23% in the mid-term), and the largest change in California (50%–60% in the near-term and 70%–90% in the mid-term). These findings highlight much greater uncertainty in winter generation in California, the Southwest, and the Southeast relative to the PNW and the Northeast.

Changes in spring season generation are smaller in comparison to the other seasons. There is a 7% increase in median projected generation in the near term and a 14% increase in the mid-term. It exhibits a similar but more modest wet-dry trend as the winter season in the 5th percentile mean seasonal generation changes with increases in generation in the PNW and generally decreases in generation across the remainder of CONUS.

The summer season generation change at the median is split east and west, with the western US showing a projected decrease in generation by approximately 1%–5% and the eastern US showing a

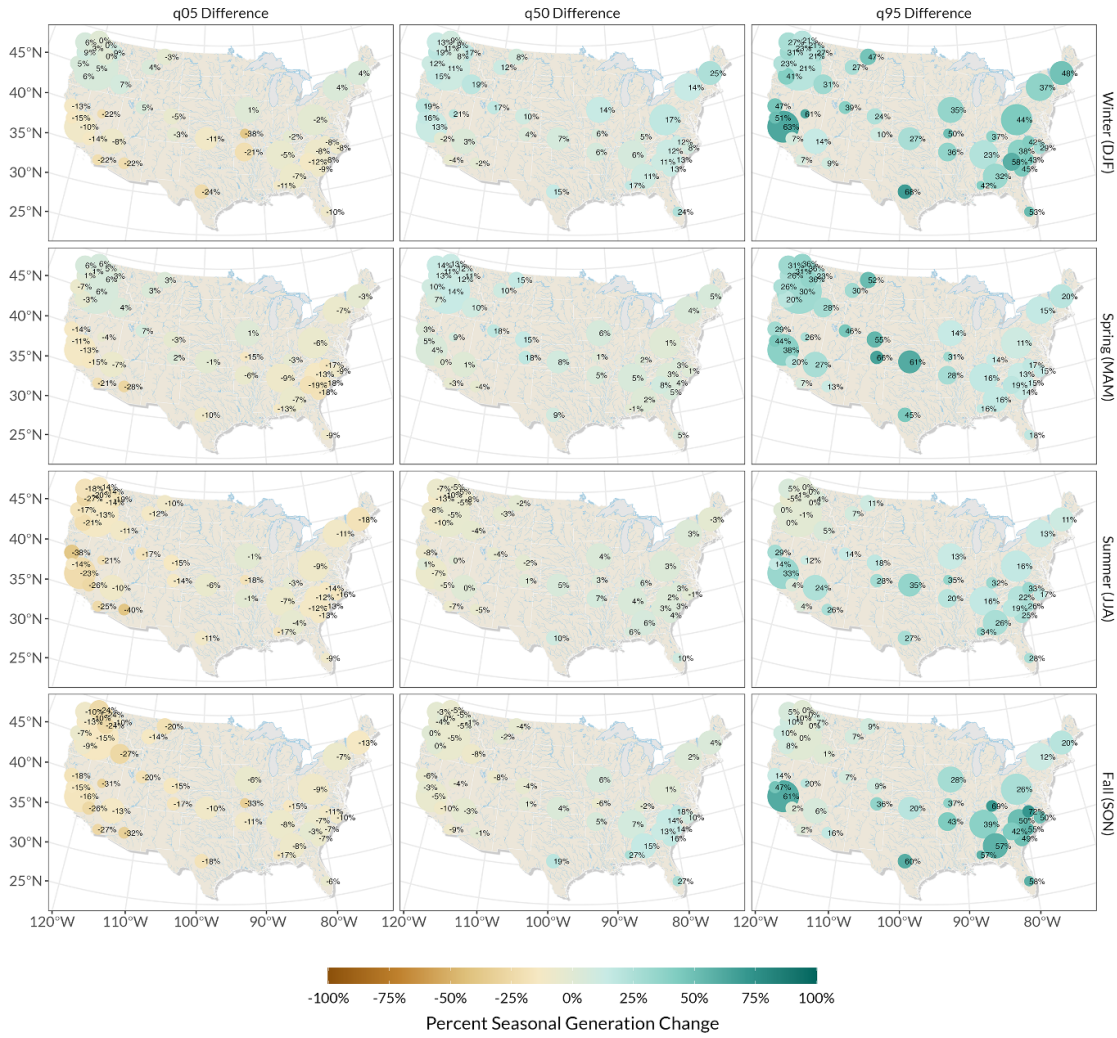


Figure 4. Percent change in seasonal mean hydropower production for BAs in CONUS. Percent changes are shown for the near-term (2020–2039) for the winter (DJF; top row), spring (MAM; second row), summer (JAS; third row), and fall (SON, bottom row), and for the 5th percentile (q05; left column), 50th percentile (q50; middle column), and 95th percentile (q95; right column). Circle size indicates the relative size of hydropower nameplate capacity for that region.

projected increase by approximately 1%–5% increase. Like the winter season, there is much greater uncertainty in generation change in California and the southwest, which shows a large range in generation change when looking at the 5th and 95th percentiles.

Changes in fall season generation are strongly positive in the Southeast with increases of approximately 5%–20% at the median, positive but much smaller in the Northeast and Midwest, and negative across the western US, with decreases of approximately 1%8%. Of note, there is much greater uncertainty in generation change in the southeast and California, which show moderate decreases in generation at the 5th percentile, −5%–15%, but potential for large increases at the 95th percentile, 50%–70%.

The annual and seasonal scale projections help characterize overall hydropower expectations and droughts. Hydropower-river services provide important support for flood control, navigation, recreation, environmental conservation, and water supply—a long list of services that need to be managed under evolving water availability conditions. At the watershed scale, hydropower is often evaluated for its local revenues amidst tradeoff discussions with river services that are rarely monetized. Conversely, the provided datasets at the BA scale provide important local drought characteristics at a scale appropriate for integrating wind and solar through storage sizing and operational design. Except for hybrid system considerations, river services are fully considered in those efforts. Therefore those consistent datasets can help with local consistent drought designs to enhance water-energy tradeoff planning.

3.3. Drought scenarios to inform regional coordination

While consistent local datasets are important, major river and power grid services are also managed at larger scales (HUC2 and bulk power grid scales).

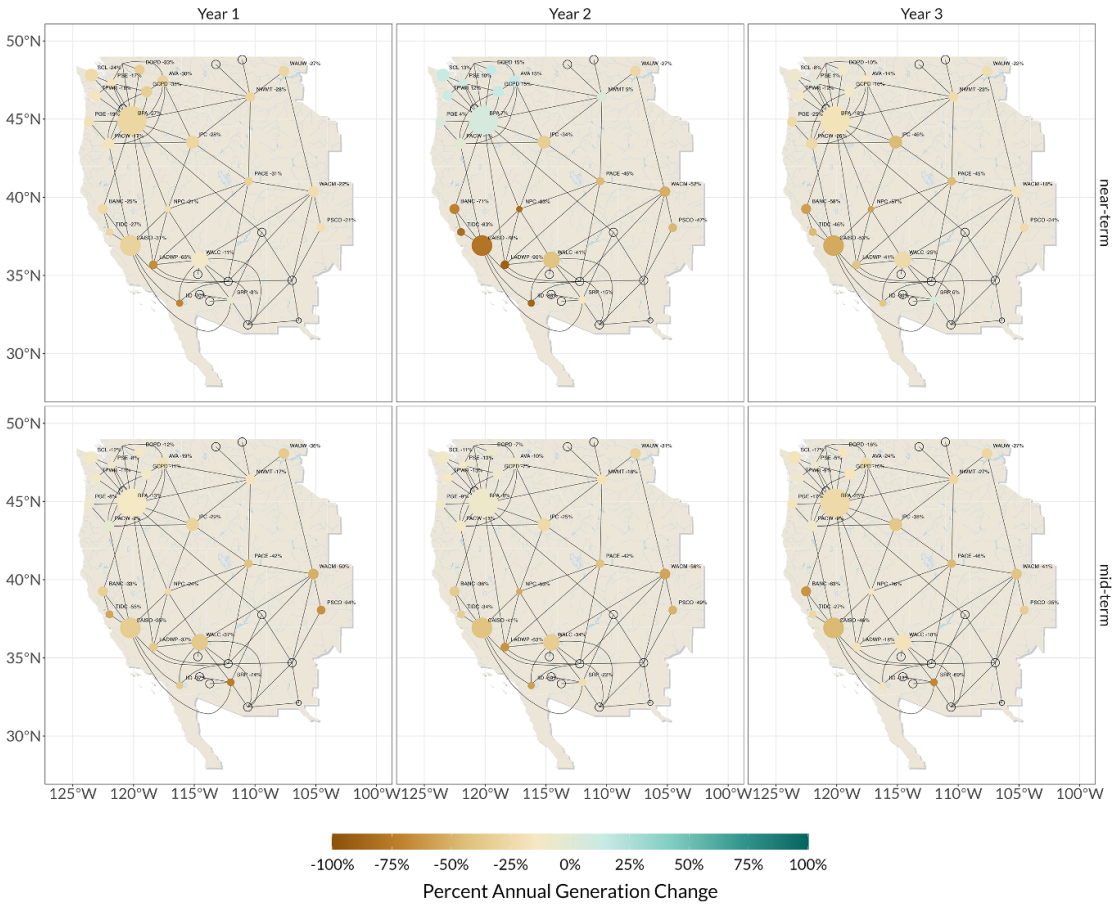


Figure 5. Percent change in hydropower production for BAs in the Western Interconnection, shown for the 1st to 3rd ranked lowest hydropower years as defined by WSGIF for the near-term (2020–2039; top row) and mid-term (2040–2060; bottom row). The shaded circle size indicates the relative size of hydropower nameplate capacity, and open circles show BAs without hydropower. Lines show the connections between BAs. Year 1 represents the lowest overall hydropower availability of the super ensemble for that time period.

Coincident hydropower datasets across a whole interconnect provide realistic expectations of regional imports and exports and specifically expose regional coordination needs to address the impact of low hydropower generation on bulk power grid operations (Voisin *et al* 2020). Therefore, the historical and future hydropower datasets can be further processed for the Western and Eastern interconnect to develop a library of droughts to be considered in reliability studies. To characterize those drought events, we leverage the WSGIF (Voisin *et al* 2016). While the factor typically reflects the impact of water availability on both hydropower and thermo-electric plants, we develop it for hydropower only in this exercise (as in Cohen *et al* 2022). Each calendar year is therefore ranked according to their WSGIF and independently across interconnect, for the historical, near, and mid-term periods. For illustration purposes, figures 5 and 6 show the three worse drought years—as defined by their WSGIF- for the near and mid-term periods, and for the Western and Eastern Interconnects respectively. The drought severity is represented by the BA-scale changes in annual generation from their historical long-term means.

For droughts in the Western Interconnection, overall generation is lower than the long-term mean between 10% to 24% in the near-term, and 7% to 19% in the mid-term across the entire interconnection. In the lowest identified year in the near term, decreases are seen across all BAs—an average decrease of 27%—with the lowest decreases seen in California (30%–70%). The spatial pattern differs in the second lowest year with large decreases in generation in California (40%–58%), little change in the PNW, and more modest decreases in generation across the remaining BAs. Spatial patterns in the third lowest year are more like the lowest year, with decreases in generation across almost all BAs, but with more pronounced decreases in California and smaller decreases in the PNW.

For droughts in the Eastern Interconnection, generation is lower than the long-term mean between 0% and 3% in the near term and between 13% and 18% in the mid-term across the entire interconnection. In

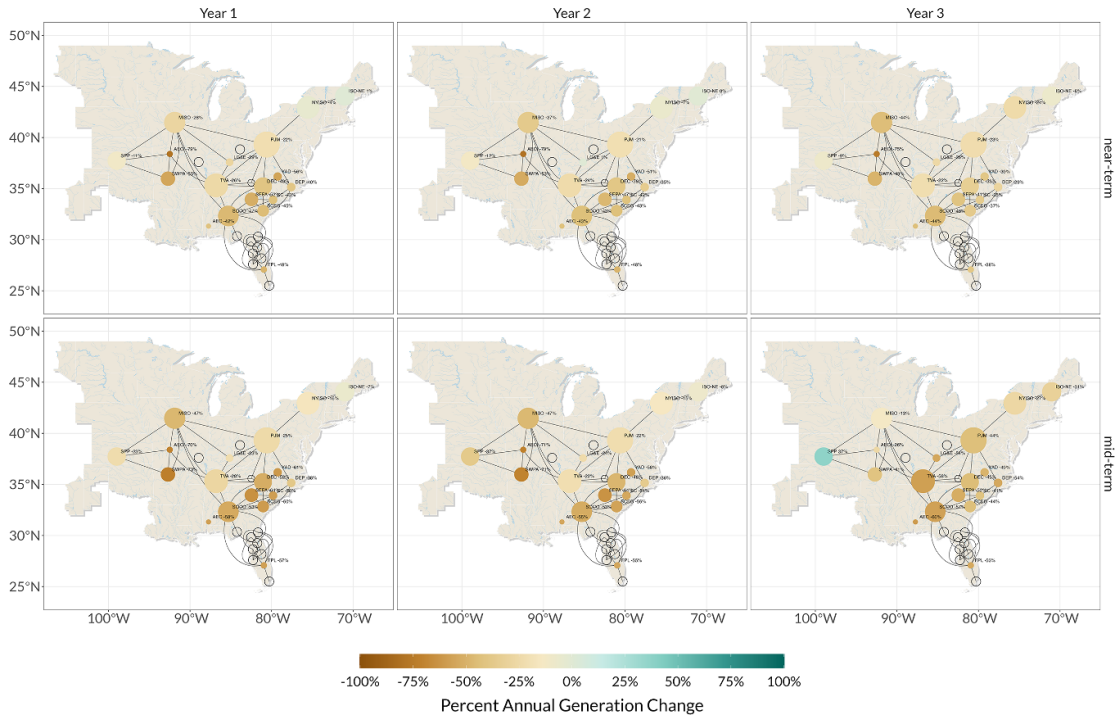


Figure 6. Percent change in hydropower production for balancing authorities in the Eastern Interconnection. Percent changes are shown for the 1st to 3rd ranked lowest years as defined by WSGIF for the near-term (2020–2039; top row) and mid-term (2040–2060; bottom row). The shaded circle size indicates the relative size of hydropower nameplate capacity, and open circles show BAs without hydropower. Lines show the connections between BAs. Year 1 represents the lowest overall hydropower availability of the super ensemble for that time period.

the lowest identified year in the near term, decreases are seen across all BAs except for the Southwest Power Pool, with the largest decreases seen in the southeast. In each of the three lowest years, the largest generation decreases are seen in the southeast and for the Southwestern Power Administration, with smaller, but still significant decreases in the mid-Atlantic and Midwest (MISO, PJM) and much smaller decreases in the Northeast (NYISO, ISO-NE).

Consistent hydropower projection datasets that extend across entire interconnections, like the one developed through this study, can be leveraged to develop 'stress test' scenarios that can be used by energy planners to quantify how hydropower variability would impact the grid, e.g. beyond the BA or utility-scale assessments, in support of reliability studies and associated transmission and storage design research.

4. Discussion

Understanding projected hydropower generation, informed by climate change, helps navigate the sometimes-conflicting relationship between river and power grid services that are at the forefront of both water management and power system planning efforts. The computational effort to develop such hydropower datasets is substantial, leading to irregular updates and availability. This assessment leveraged the SWA assessment that underwent a thorough evaluation of each modeling stage with public comment and provided multiple decades and horizons of projections at the spatial scale supporting collaboration with federal partners and hydropower stakeholders. It offers the prospect of consistent and more regular updates as new climate scenarios and modeling tools emerge.

We recognize that energy planners and water managers would benefit from hydropower projections at the facility scale, which are available in this assessment (for the subset made by *mosartwmpy*). However, the projections are not appropriate for facility-scale investment and adaptation decisions due to the limitations of the current modeling chain, including calibration and validation of hydrology simulations for individual reservoirs, reservoir operations fidelity, withdrawals, and return flows. The study also does not include interbasin transfer or water demand projections informed by climate change at this time, nor changes in environmental regulation (USACE *et al* 2020).

The hydropower projections developed in this assessment characterize potential future generations given projected climate change impacts, with the understanding that in the future, hydropower may be used for capacity and reserve services. We emphasize that this assessment refers to the potential monthly generation only, with some implicit representation

of operational capacity. Ancillary services and short-term operations are not represented. Over 1500 hydropower facilities are represented in this assessment. The fidelity of the modeling (daily, 1/8th degree, data-driven water release decisions) is appropriate for regional and monthly analytics, however, not for processes such as forebay and afterbay elevations, unit loading strategies, and ramping constraints. Those hydraulic considerations at the power plant are typically needed to support the evaluation of operational capacity and sustained capacity operations for a couple of hours or days, and therefore resilience studies.

We also note that the hydropower datasets developed in this study are close to the format required by production cost models used in the US (Oikonomou *et al* 2022) but differ from long-term hydropower scheduling toolchains used in countries with a higher share of hydropower such as Brazil and Norway (Helseth *et al* 2023). In the US long-term water and energy planning require consistent datasets of hydropower generation that account for water management and hydropower scheduling. However, given the dispersed nature of decision-makers, who interact but often work to achieve their own objectives within the system, there is limited utility in comparing these results to countries where decision-making is centralized.

5. Conclusion

This study provides the first CONUS-wide assessment of climate impacts on hydropower potential production using CMIP6 climate projections, with the overarching objective of supporting water-energy coordination across federal water and energy agencies. The assessment leverages the latest hydroclimate modeling efforts and provides projections at both the watershed and BA scales for the historical, near-, and mid-term periods. The analytics demonstrates the use of the super-ensemble for designing local and regional normal conditions and extreme events and offers publicly available projections to support further assessment. The multi-scale assessment supports local water-energy discussions on the impact of climate change on local resources, as well as the development of regional scenarios to highlight the regional dependencies on both the water and grid services.

Under expected future warming, mean annual hydropower generation is projected to increase in the near-term and mid-term future periods across almost all BAs. This is consistent with the average annual runoff trends found in the 9505V3 assessment of projected federal hydropower (Kao *et al* 2022b). The spread in percent changes points out regional differences with a narrow range of potential change in the northeast, PNW, mid-Atlantic, and Midwest as compared to a larger potential change in the southwest, California, and the Southeast in the near- (15 years out) and mid- (30 years out) terms. Examining these changes seasonally refines the relevance to seasonal resource adequacy and potentially needs to address water and electricity demands for joint management purposes as needed. There are decreases in generation in the summer and fall across the western US and corresponding increases in generation across the eastern US for the same seasons. For the Western Interconnection loss of snowpack storage and earlier melt shift water availability to the late winter and spring along with generation and away from summer and fall. For the Eastern Interconnection, increased precipitation increases generation, particularly in the southeast during the fall; however, there is a large amount of uncertainty in seasonal generation, exemplified by a large range in the projections for California and the southwest in all seasons. This is likely arising from a combination of uncertainty around changing snowpack and uncertainty around the timing and frequency of precipitation events, including winter atmospheric rivers in California and the North American Monsoon in the southwest (Swain *et al* 2018, Hernandez and Chen 2022). Similar but slightly narrower uncertainty exists in the fall and winter season generation in the Southeast.

Projected changes in generation are the result of the compounding effect of hydrologic changes driven by climate change, the physical characteristics of each hydropower facility, and the operational constraints and objectives of each facility. This assessment examined how hydrologic change would impact generation assuming that facility physical characteristics and operational constraints and objectives remained fixed, and with no changes to the hydropower fleet—through construction of new facilities or decommissioning of existing facilities. Further examination of our projections, coupled with an assessment of the underlying drivers of hydrologic change, quantification of the interaction between hydrologic change with other controls on hydropower generation, and comprehensive uncertainty quantification would offer additional insight into the results presented in this assessment.

Future work includes further development of the datasets to represent hydropower flexibility accounting for current environmental regulation and water use and with the ability to modify regulation and water use to reflect anticipated future conditions. To evaluate the contribution of hydropower to the reliability of future power grids, power system modeling is needed and requires the development of coincident wind, solar, and electricity demand projections that pair with the hydropower projections presented in this study.

Data availability statements

The hydropower generation projection datasets developed in this study are openly available at the BA scale https://zenodo.org/records/10525253, and at the HUC4 scale https://zenodo.org/records/10535565 with all the modeling inputs and outputs available at following URL/DOI: https://github.com/9505-PNNL/broman-etal_2024_erl.

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