Current Sustainable/Renewable Energy Reports
https://doi.org/10.1007/s40518-024-00237-6

COMMENT

Hydroclimate Risks to the Western US Electric Grid under a Warming Climate

Adrienne Marshall[1] · Surabhi Upadhyay[1]

Accepted: 18 June 2024

Abstract

Purpose of Review Changing hydroclimate creates risks to the western U.S. electric grid, particularly when hydropower generation changes, but tools to characterize these risks are relatively new. Here, we ask: how is hydropower changing in a warming climate, and what are the consequences of hydroclimate change for the grid?

Current Findings Climate projections of future hydropower generation are somewhat uncertain due to precipitation change uncertainties, but production is consistently expected to shift from summer towards winter, out of phase with changes in load. Interactions between hydrologic drought and hot temperatures are particularly problematic, yielding increased prices and greenhouse gas emissions, with uncertain shortfall risks.

Summary Future work should continue stress-testing new tools, evaluate hydroclimate risks under a wider range of emissions scenarios, evaluate potential energy-hydroclimate feedbacks (including those with complex causal pathways), and consider the impacts of potential changes in non-energy water uses and reservoir operator adaptations.

Keywords Hydroclimate · Climate Change · Electric grid · Western U.S · Hydropower

Introduction

Climate change is altering water availability in ways that will have critical but as-yet poorly understood consequences for electricity production, particularly in the context of a decarbonizing grid [1]. In the western U.S., temperatures have warmed and are expected to continue to do so under all emissions scenarios [2, 3]. The magnitude and sign of precipitation change is much more uncertain, though climate models generally indicate increasing precipitation in the northern part of the region, and decreasing precipitation further south [2, 3]. In the western U.S., more than half of streamflow originates as snow [4]. In this temperate region, snow is sensitive to warming, regardless of the direction of precipitation change: warming temperatures result in more precipitation falling as rain, rather than snow, though this effect is largest in relatively warm areas [5–7]. Smaller snow accumulations melt more easily in the winter months [8, 9] and melt earlier in the year [10]. These changes yield earlier snowmelt runoff timing [11–16], with uncertain net changes in total runoff influenced by a complex suite of hydrologic processes that sometimes have contrasting impacts [17–21]. Projected future hydroclimatic changes include both multi-year snow droughts [10], declines in the largest snow years [22], and dramatic swings between wet and dry years [23].

These shifts in runoff timing and uncertain changes in total runoff can have significant impacts on the electric grid, and the risks will likely differ among the current electricity generation portfolio and multiple potential decarbonization pathways. In particular, hydropower facilities in the western U.S. are often managed primarily for water uses beside hydropower, with hydropower a lower priority or ancillary benefit [24] (Fig. 1) that nonetheless provides essential power and ancillary services – including energy storage and load balancing – for the grid [25, 26]. Conflicts commonly exist between using water stored in a reservoir for meeting water demand for high-priority water users, managing flood control storage, and producing hydropower [27, 28]. Particularly during the snowmelt runoff season, water managers must decide whether to store water until later in the season when it is most needed for water supply and potentially more valuable for hydropower, or release water to maintain

✉ Adrienne Marshall
adriennemarshall@mines.edu

1 Hydrologic Science and Engineering Program, Colorado School of Mines, Golden, CO 80401, USA

Published online: 09 July 2024

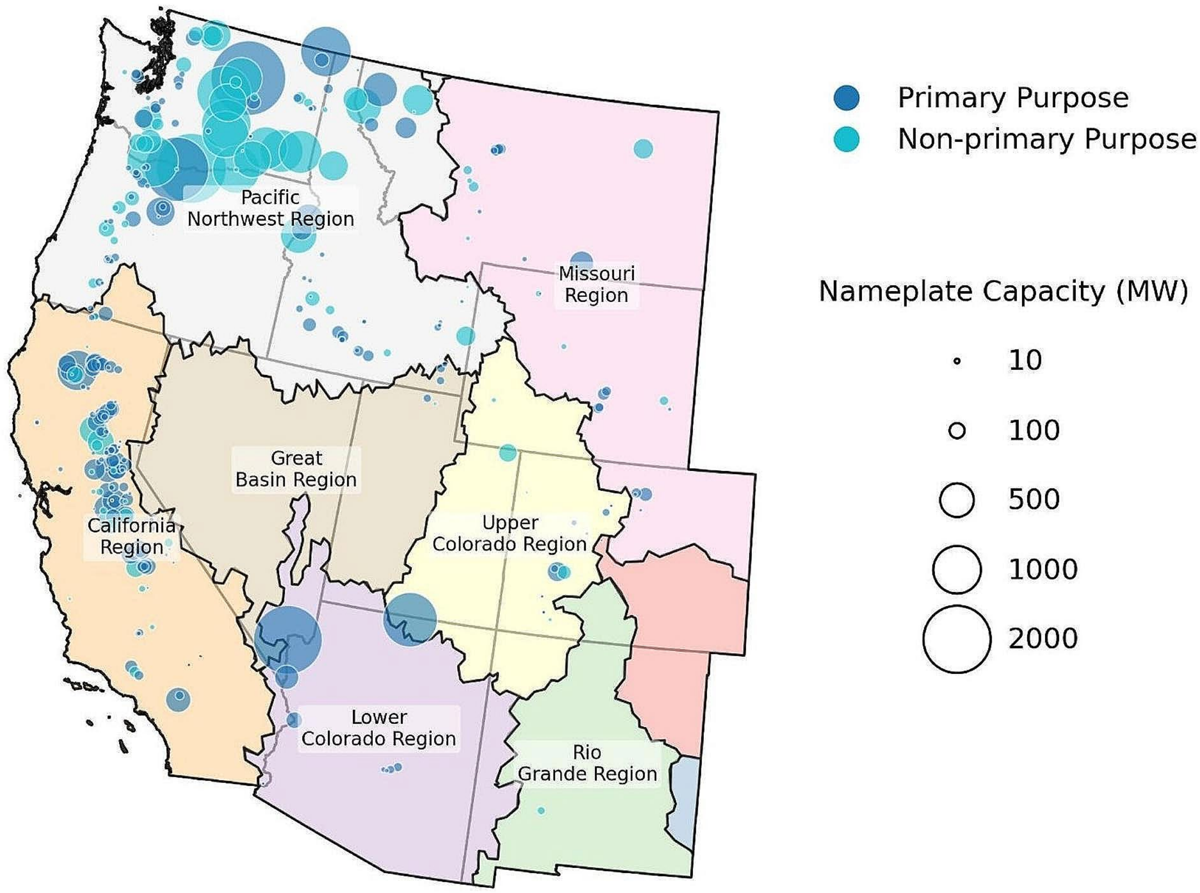

Fig. 1 Hydropower production facilities in the western U.S., with color denoting whether hydropower is denoted as a primary or non-primary purpose according to the National Inventory of Dams [24]

flood storage capacity in the reservoir [29, 30] - which, if not maintained, could have catastrophic consequences. Water managers are also often required to respond to water demands by those who have water rights senior to those of a hydropower facility in a prior appropriations context [31], which can result in reservoir operations that are not optimized for hydropower production. Water withdrawn and consumed for other electric generation purposes [32, 33] is subject to similar constraints.

Here, we review recent literature aimed at understanding the consequences of hydroclimate change for the western U.S. electric grid, particularly in light of dual nonstationarities, in which both the electric and water systems are changing [1]. We evaluate literature that describes challenges and solutions related to hydropower data and modeling; observed and projected changes in hydropower production; consequences of hydropower change for the electric grid; and hydroclimate risks to the grid that extend beyond hydropower. Finally, we highlight some open questions that we believe are important areas for future research.

We focus here on the western U.S., which is a geographically diverse region with overallocated water resources [34] and a hydropower-reliant grid. The operations of the bulk electric grid in the region are physically interconnected throughout the entire Western Interconnection. Hourly and daily grid operations are overseen by regional balancing authorities and utilities, which collectively ensure real-time balancing of electricity demand with adequate supply, including exchanges of electricity among regions. In 2021, 16.2% of total electricity generation and 53% of renewable generation came from hydropower in the western U.S [35]. Hydropower exists throughout the region, with the largest capacity in the Pacific Northwest, considerable high-elevation hydropower generators along California's Sierra Nevada, and a few major hydropower facilities along the lower Colorado River (Fig. 1).

Challenges and Solutions for Understanding Hydropower

Hydropower data

What data is available to help us understand hydropower facilities and their operations? A suite of databases provide time-invariant information about hydropower facilities and the bodies of water associated with them. In addition to U.S. Energy Information Administration (EIA) data common to all electricity generators [36], the National Inventory of Dams (NID) is produced by the Army Corps of Engineers with a primary focus on dam safety [24]. The Global Reservoirs and Dams (GRanD) dataset describes global reservoirs with an emphasis on linking hydrology with reservoir capacity [37]. A common challenge is the lack of explicit linkages among different datasets; the Hydropower Infrastructure - LAkes, Reservoirs, and RIvers (HILARRI) dataset links NID and GRanD data [38], while Grubert [39] links EIA and NID data via identification of corresponding identification numbers. Two recent papers use satellite remote sensing data to estimate storage-area-depth relationships for global reservoirs [40, 41].

Additional datasets describe the operation of the hydropower system. The EIA-923 product provides monthly generation from individual hydropower generators (and other energy facilities) across CONUS dating back to 2001 (EIA, 2024). However, these values are imputed, rather than directly observed, for about half of the total nameplate capacity of hydropower generators, and observed values overrepresent large, rather than small, generators [42]. This imputation typically generates excessively smooth seasonal patterns of estimated hydropower production. The Rectif-Hyd database therefore re-estimates monthly generation based on reservoir releases and downstream flow records [42]. Hourly records for individual hydropower facilities are not available from the EIA (although the EIA-930 product produces these at a regional scale beginning in 2019 [43]); hourly releases from 160 U.S. hydropower facilities were published by Marshall & Grubert [44] and provide estimates of the observed flexibility of the hydropower system in terms of ramp rates, daily reversal frequency, high and low flows, and seasonality. At the daily temporal scale, the ResOpsUS dataset provides reservoir inflows, outflows, and storage for reservoirs across CONUS [45].

Modeling Challenges and Solutions

Hydroclimate risks to the grid due to changes in hydropower operations are challenging to adequately represent in energy system models, and their absence can result in overestimation of available hydropower generation [46]; including more specific weekly, rather than monthly, hydropower operations increases simulated wind and solar curtailment [47]. In general, modeling hydropower impacts on the grid requires climatological inputs, hydrologic models, and hydropower operations models to be integrated with capacity expansion and/or production cost models, depending on the research objective [48]. Up to 50% of the estimated seasonal variability in hydropower generation can be attributed to the choice of hydropower model, particularly in regions with substantial reservoir storage [49]. While models of hydropower operations exist, they are typically developed for basin-scale operations with well-known operating rules and can be challenging to adapt to the grid scale; challenges and advances in this area were recently reviewed by Turner and Voisin [48] and Rheinheimer et al. [50]. Turner et al. [51] recently introduced approaches to model hydropower at the grid scale by introducing a seasonally-varying, linear piecewise data-driven scheme that improved model performance in 75–95% of dams relative to existing generic reservoir release models. A later addition that incorporated forecast horizons yielded a set of forecast and release policies for 1,930 major U.S. reservoirs [52]. A complementary approach has been demonstrated with the CAPOW model, which combines a stochastic weather generator with hydropower simulations using models from reservoir operators when possible and statistical relationships based on observed flows otherwise, and with a unit commitment and economic dispatch model across California and the Pacific Northwest [53].

Observed and Projected Hydroclimate Impacts on Hydropower Production

Observed Impacts

Western U.S. hydropower production has historically been somewhat resilient to variability and change in hydroclimate, with the western hydropower fleet sustaining 80% or more of its average annual generation even during the most severe droughts of the 20th century [54] and throughout the early 21st century (Fig. 2). This resilience is largely attributable to the spatially interconnected nature of the electric grid, with the impact of droughts in individual regions often mitigated by power production in other regions [54]. Hydropower generation is nonetheless sensitive to hydroclimate variability, and a primary determinant of interannual variability in electricity generation, with water availability explaining 90% of the variability in net electricity generation in Northern California and the Pacific Northwest [55]. Generation in the Pacific Northwest is highly impactful to generation in other regions within the Western Interconnection because of its role as a power exporter [55]. The

Fig. 2 (**a**) Annual net generation by hydropower facilities in 11 western states. (**b**) Net generation for the same facilities as a percent of annual average for each state, with black dashed line showing the western U.S. total

seasonal timing of hydropower generation is also responsive to interannual climate variability, with lower fractions of precipitation falling as snow advancing hydropower generation timing, though this effect is somewhat mitigated by reservoir storage [56].

Projected Impacts

Integrated hydrologic, water management, and grid operations modeling indicates that climate-induced changes in total generation are most significant in the Northwest, but these changes propagate to the rest of the Western Interconnection because of the importance of Northwest generation for regional power flows [55]. Several studies have shown that the projected direction of change in total annual hydropower production depends in large part on the sign of precipitation change, which varies among GCMs. For example, integrated modeling with three climate models and two emissions scenarios (RCP4.5 and RCP8.5) used as forcing to a hydrologic and water management model for the western U.S. indicated that climate model-derived uncertainty in precipitation changes could cascade to uncertainty in the sign of change in water availability and hydropower production [57]. Another study using dynamically downscaled hydroclimate variables, the VIC model (as in [57]), and hydropower generation based on both statistical and process-based approaches found that in the long term, all regions in the western U.S. had projected increases in hydropower production in future climate scenarios, following near-term decreases in the Northwest [49]. Another agreed that western U.S. changes in hydropower production are projected to range from negative to positive (+5% to -20% from 2020 to 2050) but found consistent decreases in summer hydropower production [58]. Indeed, despite uncertainty in the direction of change of total annual hydropower production, modeling exercises that include uncertainty from climate model, downscaling method, hydrologic model, and hydropower model indicate that higher average annual generation could nonetheless yield decreasing generation in summer and fall, paired with increasing generation in winter and spring [49, 59].

Potential for Hydropower Thresholds

In addition to declines in hydropower production when streamflow declines, there are also potential threshold impacts of drought. Notably, there is a risk of increasing frequency of reservoirs falling below the elevations at which they can produce power ("minimum power pool"). For example, an anomalous minimum power pool event occurred in 2021, when California's Oroville Dam (645 MW) shut down energy production for five months [60]. In 2022, Glen Canyon Dam's (1312 MW) proximity to minimum power pool conditions motivated unprecedented reductions in reservoir releases to salvage hydropower infrastructure and energy production [61]. Potential future changes in minimum power pool occurrence are not currently well characterized. Similarly, changes in the energy generated per unit of water released due to changing reservoir elevations (and associated changes in hydraulic head) are not well captured even in the most sophisticated integrated modeling studies [57] and are primarily missing from current literature on hydroclimate risks to the grid. As part of a complex water allocation system, hydropower operations were often designed to repay debts incurred to build multipurpose dams and associated water management infrastructure [62, 63], though hydropower revenues no longer subsidize other water users as much as they once did [64]. Dramatic changes to hydropower generation could also therefore have financial consequences for reservoir operators that are generally not well characterized in the scientific literature or incorporated into models of the decarbonizing electric grid.

Consequences of Hydroclimate Change for the Electric Grid

Droughts and combined hot/dry conditions generally increase electricity prices and greenhouse gas and criteria air pollutant emissions from the grid [65, 66, 67] and have led to outages [68]; hot, dry anomalies also increase air pollutant emissions from power plants in ways that exacerbate racial disparities in air quality [69]. Indeed, estimates of costs based on electricity generation alone understate the impacts of drought on the western U.S. electricity system; monetized costs of associated mortality risk and greenhouse gas emissions costs are 1.2 to 2.5 times higher than direct economic costs [67]. In the western U.S., drought is one of the biggest climatic impacts on electricity prices in both observed [70] and future conditions [71], though natural gas price volatility can compound or mitigate the effects of drought on electricity prices [70]. In the 2012–2016 drought in California, electricity prices increased in hot/dry conditions, with natural gas prices being the major driver of the increased prices [72]. System-wide operation cost has a non-linear response to water availability, with impacts that are typically larger in sub-regions than at the system scale [70]. Projected changes in precipitation are moderated in terms of their impact on mean annual production cost, with smaller changes in grid production costs than precipitation [55].

The potential for drought to reduce reliability (i.e., result in blackouts) remains somewhat uncertain but previous efforts suggest that this outcome is most likely when drought co-occurs with heat waves that increase electricity use [71]. In the Pacific Northwest, drought is the main driver of simulated supply shortfalls, while heat waves are the most important contributor in California [71]. Coupled capacity expansion and production cost models indicate that drought resulting in blackouts is unlikely in climate scenarios extending to 2038, but the authors note that modeling assumptions, including perfect coordination of unit-commitment and dispatch; day-ahead foresight; and simplified transmission representation, could affect these results [57]. In these scenarios, droughts typically result in increased natural gas usage to compensate for lost hydropower; droughts also increase solar photovoltaic (PV) and wind generation due to reduced curtailment in variable generation technologies [57]. Climate change in the Pacific Northwest is anticipated to shift shortfall risk from winter towards summer, with higher probability of shortfall but shorter duration events than in historical conditions [73]. These impacts create risks for hydropower suppliers, although these risks can be mitigated or exacerbated by tariff structures [74] and decarbonization incentive policies [1].

Multiple studies show that spatial variability of hydroclimate changes and interactions among multiple types of hydroclimate change are critical to understanding how changing hydroclimate affects the electricity system. Changing water availability for the grid can trigger responses in interconnected regions, generally affecting the magnitude but not the direction of regional power flows [55]. For example, drought in the Pacific Northwest reduces power deliveries from the Northwest to California (although does not substantially alter California electricity prices or reliability), while heat waves in California can pull power from the Pacific Northwest, even when power is scarce in the Pacific Northwest [75]. In the Pacific Northwest, changes in hydropower availability in conjunction with increased summer loads can increase summer shortfall risk in ways that are not apparent using simulations of hydropower or load change alone [73]; the same is true across the western U.S [58].

Hydrologic change could interact with changes in other renewable availability in important ways: compound energy droughts that include wind and solar reductions are most severe when these energy droughts are combined with high load events [76]. Advancing runoff timing as snowmelt runoff occurs earlier in the year could increase seasonal-scale complementarity of hydropower and solar generation [56], but could decrease the hourly-scale complementarity needed to offset energy droughts. Simulations of the western grid with a stochastic weather generator indicate that hot/dry extremes drive high greenhouse gas emissions and electricity prices, but that different components of the hydroclimate system affect electricity prices on different timescales: for instance, differences in solar irradiance and generation are important to hourly price extremes but not annual; the opposite is true for hydropower generation [65].

Hydroclimate Impacts to the Grid: Beyond Hydropower

We have focused primarily on potential changes in hydropower because these are widely recognized as one of the most important ways that hydroclimate variability impacts the western electric grid, particularly in conjunction with heat-induced changes in load. However, hydroclimate risks to the grid are not limited to changing hydropower and its interactions with other forms of energy drought. Freshwater consumption and withdrawal varies substantially among energy generation technologies [32, 33], and fossil capacity retirements could yield substantial water savings [77]. In California, freshwater consumption varies by over an order of magnitude among decarbonization scenarios compliant with California targets, and the lowest-cost decarbonization scenarios tend to deploy large amounts of higher capacity factor generation resources that also have higher water footprints, such as geothermal plants and battery storage systems (rather than high quantities of variable renewable capacity) [78]. Alternatively, optimizing renewable energy electric grid scenarios to minimize water consumption, rather than cost, results in substantially different generation portfolios modeled in California, with less utility-scale and more distributed solar, more wind and hydrogen energy storage, and less battery storage (because of the favorable longer duration storage of hydrogen) in the low-water case [79]. In addition to changing water quantity and timing, projected increases in water temperature are expected to increase the proportion of aquatic species exposed to risks associated with warmer water temperatures downstream of both thermoelectric and hydropower plants [80].

Finally, some hydroclimate risks to the grid may also have more complex causal pathways that are only nascently apparent. For example, wildfire in the western U.S. is increasing in terms of area burned and intensity [81, 82], and new evidence indicates that wildfire smoke reduces solar power production [83, 84]; potential interactions among these solar power reductions and other hydroclimate risks have not been evaluated to our knowledge. Fires in California bankrupted Pacific Gas and Electric [85], and new pre-emptive de-energization policies could affect 1.6 million person-days per year in recent historical climate conditions, with an additional 70% increase in these impacts under future climate scenarios [86]. In another example, the Maui wildfires of 2023 - possibly ignited by downed power lines according to news reporting [87] - reinvigorated old debates about Hawai'an water law and the rights of Native Hawai'ans to water [88]; changes to water rights in Hawaii or elsewhere would interact with water availability for power production, likely in unpredictable ways. Feedbacks among hydroclimate change, decarbonization, water law and politics, and energy law and politics are difficult to quantify but could nonetheless substantially shape future hydroclimate risks to a decarbonizing grid.

Conclusions

In recent years, awareness of potential hydroclimate risks to a decarbonizing grid has rapidly expanded, and a suite of data products and modeling tools have facilitated quantitative inquiry into these risks. There is broad consensus in the literature that drought conditions - particularly when combined with warm temperatures - can increase greenhouse gas emissions, criteria air pollutants, and electricity prices, with some uncertainty around the potential for these events to result in power shortfalls. Projected changes in hydropower generation range from positive to negative, depending largely on uncertainty in precipitation changes, but with a seasonal shift from summer towards winter and spring that is out of phase with the projected changes in energy demand (decreases in winter and increases in summer). The burgeoning growth of literature on hydroclimate risks to the grid in recent years leaves several important areas yet to be addressed. In addition to the potential thresholds and energy-hydroclimate feedbacks that have been described in the text above, we suggest a few important additional areas where future work would be valuable:

Climate Scenarios Uncertainty in precipitation projections is emerging as a major limitation to predictability of total annual hydropower in future scenarios, but we have not yet adopted a clear framework for decision-making in light of that uncertainty. Moreover, many studies using future climate scenarios use mid- to high-emissions scenarios. While important for understanding the largest risks, these neglect the potential to understand "how much we can save" [89], non-linear or non-monotonic impacts of various warming trajectories [90], or mid-transition issues that might not be clearly addressed by analyses of pre-defined historical and future periods [91].

Reservoir operations and adaptation Current estimates of hydroclimate risks to the grid assume fixed operations, whether implemented in statistical or operational models. However, climate adaptations could alter these operational patterns: for example, forecast-informed reservoir operations (FIRO) are currently being explored and tested for select reservoirs in California, and could substantially alter operational patterns if successful [92, 93]. Hydropower operations could also potentially change in response to a decarbonizing grid, though the extent to which this is possible is uncertain [44, 94, 95].

Additional Water use Priorities and Equity Considerations Electricity generation ultimately accounts for a relatively small fraction of water use in the western U.S. Agricultural demand is much greater [96], so changes in agricultural water use could have complex interactions with hydroclimate risks to the grid [97]. Moreover, we identified one study in this review that explicitly considered equity and justice in hydroclimate risks to the grid [68], but more work is likely needed to fully understand inequitable impacts of hydroclimate grid risks and how to mitigate them.

Ultimately, a holistic understanding of hydroclimate risks to the western U.S. electric grid is essential to identifying and incentivizing decarbonization pathways that are most resilient to such risks. The substantial body of evidence identified in this review provides some guidelines in this regard, but additional future work will support policy development to incentivize climate-resilient decarbonization infrastructure.

Acknowledgements The development of this manuscript benefited from discussions with Eleanor Andrews, Adrianne Kroepsch, and Lucas North.

Author Contributions S.U. and A.M reviewed and synthesized literature. S.U. prepared Figs. 1 and 2 and A.M. prepared the main manuscript text. Both authors reviewed the manuscript.

Funding AM and SU were supported in part by NSF award #2241892. AM was also supported in part by Sloan Foundation award #2023–19665.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

1. Grubert E, Marshall AM. Water for energy: characterizing co-evolving energy and water systems under twin climate and energy system nonstationarities. WIREs Water. 2022;9(2):e1576.
2. IPCC. Climate Change 2021:. Cambridge University The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte P, Zhai VP, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR. T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou, editors].
3. U. S. Global Change Research Program. Fifth National Climate Assessment [Internet]. Fifth National Climate Assessment. U.S. Global Change Research Program, Washington, DC; 2023 [cited 2024 Mar 29] pp. 1–470. https://nca2023.globalchange.gov/chapter/4/
4. Li D, Wrzesien ML, Durand M, Adam J, Lettenmaier DP. How much runoff originates as snow in the western United States, and how will that change in the future? Geophys Res Lett. 2017;44(12):6163–72.
5. Barnett TP, Adam JC, Lettenmaier DP. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature. 2005;438(7066):303–9.
6. Gottlieb AR, Mankin JS. Evidence of human influence on Northern Hemisphere snow loss. Nature. 2024;625(7994):293–300.
7. Klos PZ, Chain-Guadarrama A, Link TE, Finegan B, Vierling LA, Chazdon R. Throughfall heterogeneity in tropical forested landscapes as a focal mechanism for deep percolation. J Hydrol. 2014;519:2180–8. Part B:.
8. Marshall AM, Link TE, Robinson AP, Abatzoglou JT. Higher Snowfall Intensity is Associated with reduced impacts of warming upon Winter Snow ablation. Geophys Res Lett. 2020;47(4):e2019GL086409.
9. Musselman KN, Addor N, Vano JA, Molotch NP. Winter melt trends portend widespread declines in snow water resources. Nat Clim Chang. 2021;11(5):418–24.
10. Marshall AM, Abatzoglou JT, Link TE, Tennant CJ. Projected changes in interannual variability of peak snowpack amount and timing in the Western United States. Geophys Res Lett. 2019;46(15):8882–92.
11. Dudley RW, Hodgkins GA, McHale MR, Kolian MJ, Renard B. Trends in snowmelt-related streamflow timing in the conterminous United States. J Hydrol. 2017;547:208–21.
12. Hidalgo HG, Das T, Dettinger MD, Cayan DR, Pierce DW, Barnett TP, et al. Detection and attribution of streamflow timing changes to Climate Change in the Western United States. J Clim. 2009;22(13):3838–55.
13. Maurer EP. Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. Clim Change. 2007;82(3–4):309–25.
14. Rauscher SA, Pal JS, Diffenbaugh NS, Benedetti MM. Future changes in snowmelt-driven runoff timing over the western US. Geophys Res Lett. 2008;35(16):L16703.
15. Regonda SK, Rajagopalan B, Clark M, Pitlick J. Seasonal cycle shifts in Hydroclimatology over the Western United States. J Clim. 2005;18(2):372–84.
16. Stewart IT, Cayan DR, Dettinger MD. Changes in Snowmelt Runoff timing in Western North America under a `Business as Usual' Climate Change scenario. Clim Change. 2004;62(1–3):217–32.
17. Ficklin DL, Abatzoglou JT, Robeson SM, Null SE, Knouft JH. Natural and managed watersheds show similar responses to recent climate change. PNAS. 2018;115(34):8553–7.
18. Gordon BL, Brooks PD, Krogh SA, Boisrame GFS, Carroll RWH, McNamara JP, et al. Why does snowmelt-driven streamflow response to warming vary? A data-driven review and predictive framework. Environ Res Lett. 2022;17(5):053004.
19. Hoerling MP, Eischeid JK, Diaz HF, Rajagopalan B, Kuhn E. Critical effects of Precipitation on Future Colorado River Flow. J Clim. 2024 Apr 19.
20. Milly PCD, Dunne KA, Vecchia AV. Global pattern of trends in streamflow and water availability in a changing climate. Nature. 2005;438(7066):347–50.
21. Milly PCD, Dunne KA. Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. Science. 2020;367(6483):1252–5.
22. Marshall AM, Abatzoglou JT, Rahimi S, Lettenmaier DP, Hall A. California's 2023 snow deluge: Contextualizing an extreme snow year against future climate change. Proceedings of the National Academy of Sciences. 2024;121(20):e2320600121.
23. Swain DL, Langenbrunner B, Neelin JD, Hall A. Increasing precipitation volatility in twenty-first-century California. Nat Clim Change. 2018;8(5):427–33.

24. NID. National Inventory of Dams Database [Internet]. U.S. Army Corps of Engineers; 2020. https://nid.sec.usace.army.mil/ords/f?p=105:1
25. Hansen C, Ghimire GR, Kao SC. Evaluation of Nominal Energy Storage at existing Hydropower reservoirs in the US. Water Resour Res. 2022;58(11):e2022WR032210.
26. Mongird K, Viswanathan V, Balducci P, Alam J, Fotedar V, Koritarov V, et al. An Evaluation of Energy Storage Cost and performance characteristics. Energies. 2020;13(13):3307.
27. Qin Y. Global competing water uses for food and energy. Environ Res Lett. 2021;16(6):064091.
28. Zeng R, Cai X, Ringler C, Zhu T. Hydropower versus irrigation—an analysis of global patterns. Environ Res Lett. 2017;12(3):034006.
29. Gleick PH, Chalecki EL. The impacts of climatic changes for Water resources of the Colorado and Sacramento-San Joaquin River Basins1. JAWRA J Am Water Resour Association. 1999;35(6):1429–41.
30. Sturm M, Goldstein MA, Parr C. Water and life from snow: a trillion dollar science question. Water Resour Res. 2017;53(5):3534–44.
31. Smith SM. The relative economic merits of alternative water right systems. J Environ Econ Manag. 2021;105:102389.
32. Grubert E, Sanders KT. Water Use in the United States Energy System: A National Assessment and unit process inventory of Water Consumption and withdrawals. Environ Sci Technol. 2018;52(11):6695–703.
33. Peer RAM, Grubert E, Sanders KT. A regional assessment of the water embedded in the US electricity system. Environ Res Lett. 2019;14(8):084014.
34. Fleck J, Udall B. Managing Colorado River risk. Science. 2021;372(6545):885–885.
35. Energy Information EIA. Administration. 2022. Form EIA-923 detailed data with previous form data (EIA-906/920). https://www.eia.gov/electricity/data/eia923/
36. Energy Information EIA. Administration. 2020. Form EIA-860 detailed data with previous form data (EIA-860A/860B). https://www.eia.gov/electricity/data/eia860/
37. 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.
38. Hansen C. Hydropower Infrastructure - LAkes, Reservoirs, and RIvers (HILARRI). Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States); 2021. https://www.osti.gov/servlets/purl/1781642/
39. Grubert E. Conventional hydroelectricity and the future of energy: linking national inventory of dams and energy information administration data to facilitate analysis of hydroelectricity. Electricity J. 2020;33(1):106692.
40. Hao Z, Chen F, Jia X, Cai X, Yang C, Du Y, et al. Water Resour Res. 2024;60(1):e2023WR035781. GRDL: A New Global Reservoir Area-Storage-Depth Data Set Derived Through Deep Learning-Based Bathymetry Reconstruction.
41. Yigzaw W, Li HY, Demissie Y, Hejazi MI, Leung LR, Voisin N, et al. Water Resour Res. 2018;54(12):10372–86. A New Global Storage-Area-Depth Data Set for Modeling Reservoirs in Land Surface and Earth System Models.
42. Turner SWD, Voisin N, Nelson K. Revised monthly energy generation estimates for 1,500 hydroelectric power plants in the United States. Sci Data. 2022;9(1):675.
43. EIA. U.S. Energy Information Administration (EIA) 930. 2021. https://www.eia.gov/opendata/qb.php
44. Marshall AM, Grubert E. Hydroelectricity modeling for Low-Carbon and No-Carbon grids: empirical operational parameters for optimization and dispatch models. Earth's Future. 2022;10(8):e2021EF002503.
45. Steyaert JC, Condon LE, Turner S, Voisin N. ResOpsUS, a dataset of historical reservoir operations in the contiguous United States. Sci Data. 2022;9(1):1–8.
46. Magee TM, Turner S, Clement MA, Oikonomou K, Zagona EA, Voisin N. Evaluating power grid model hydropower feasibility with a river operations model. Environ Res Lett. 2022;17(8):084035.
47. Stark G, Barrows C, Dalvi S, Guo N, Michelettey P, Trina E et al. Improving the Representation of Hydropower in Production Cost Models [Internet]. National Renewable Energy Laboratory (NREL), Golden, CO (United States); 2023 Aug [cited 2024 May 8]. Report No.: NREL/TP-5700-86377. https://www.osti.gov/biblio/1993943
48. Turner SWD, Voisin N. Simulation of hydropower at subcontinental to global scales: a state-of-the-art review. Environ Res Lett. 2022;17(2):023002.
49. Zhou T, Kao SC, Xu W, Gangrade S, Voisin N. Impacts of climate change on subannual hydropower generation: a multi-model assessment of the United States federal hydropower plant. Environ Res Lett. 2023;18(3):034009.
50. Rheinheimer DE, Tarroja B, Rallings AM, Willis AD, Viers JH. Hydropower representation in water and energy system models: a review of divergences and call for reconciliation. Environ Res: Infrastruct Sustain. 2023;3(1):012001.
51. Turner SWD, Doering K, Voisin N. Data-Driven Reservoir Simulation in a large-scale hydrological and Water Resource Model. Water Resour Res. 2020;56(10):e2020WR027902.
52. Turner SWD, Steyaert JC, Condon L, Voisin N. Water storage and release policies for all large reservoirs of conterminous United States. J Hydrol. 2021;603:126843.
53. Su Y, Kern JD, Denaro S, Hill J, Reed P, Sun Y, et al. An open source model for quantifying risks in bulk electric power systems from spatially and temporally correlated hydrometeorological processes. Environ Model Softw. 2020;126:104667.
54. Turner SWD, Voisin N, Nelson KD, Tidwell VC. Drought impacts on hydroelectric power generation in the Western United States. Pacific Northwest National Lab. (PNNL), Richland, WA (United States); 2022 Sep. Report No.: PNNL-33212. https://www.osti.gov/biblio/1887470
55. Voisin N, Dyreson A, Fu T, O'Connell M, Turner SWD, Zhou T, et al. Impact of climate change on water availability and its propagation through the Western U.S. power grid. Appl Energy. 2020;276:115467.
56. Marshall AM, Chen JM. Impacts of changing snowfall on seasonal complementarity of hydroelectric and solar power. Environ Res: Infrastruct Sustain. 2022;2(2):021001.
57. Cohen SM, Dyreson A, Turner S, Tidwell V, Voisin N, Miara A. A multi-model framework for assessing long- and short-term climate influences on the electric grid. Appl Energy. 2022;317:119193.
58. Yates D, Szinai JK, Jones AD. Modeling the Water systems of the Western US to support climate-resilient electricity System Planning. Earth's Future. 2024;12(1):e2022EF003220.
59. Kao SC, Ashfaq M, Rastogi D, Gangrade S, Uria Martinez R, Fernandez A et al. The Third Assessment of the Effects of Climate Change on Federal Hydropower. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States); 2022 Sep. Report No.: ORNL/TM-2021/2278. https://www.osti.gov/biblio/1887712
60. Hodge T. Short-Term Energy Outlook Supplement: Drought Effects on California Electricity Generation and Western Power Markets. 2022;14.
61. Bureau of Reclamation. 2022 Drought Response Operations Plan. 2022 p. 85.
62. Karambelkar S. Hydropower Operations in the Colorado River Basin: Institutional Analysis of Opportunities and Constraints. Hydropower Foundation; 2018 Sep. https://www.osti.gov/biblio/1638690

63. Poupeau F, O'Neill B, Cortinas Muñoz J, Coeurdray M, Benites-Gambirazo E. The field of Water Policy: power and scarcity in the American Southwest. Abingdon, Oxon: Routledge; 2020. p. 248.
64. Bauer CJ. The Long View of the Water/Energy Nexus: Hydropower's First Century in the U.S.A.Century in the U.S.A. Nat Resour J. 2020;60(2):173–206.
65. Su Y, Kern JD, Reed PM, Characklis GW. Compound hydrometeorological extremes across multiple timescales drive volatility in California electricity market prices and emissions. Appl Energy. 2020;276:115541.
66. 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.
67. Qiu M, Ratledge N, Azevedo IML, Diffenbaugh NS, Burke M. Drought impacts on the electricity system, emissions, and air quality in the western United States. Proc Natl Acad Sci. 2023;120(28):e2300395120.
68. Dyreson A, Devineni N, Turner SWD, De Silva MT, Miara A, Voisin N, et al. The role of Regional connections in planning for Future Power System Operations under Climate extremes. Earth's Future. 2022;10(6):e2021EF002554.
69. Zeighami A, Kern J, Yates AJ, Weber P, Bruno AA. U.S. West Coast droughts and heat waves exacerbate pollution inequality and can evade emission control policies. Nat Commun. 2023;14(1):1415.
70. O'Connell VN, Macknick. Fu. Sensitivity of Western U.S. power system dynamics to droughts compounded with fuel price variability. Appl Energy. 2019;247:745–54.
71. Wessel J, Kern JD, Voisin N, Oikonomou K, Haas J. Technology pathways could help drive the U.S. West Coast Grid's exposure to Hydrometeorological uncertainty. Earth's Future. 2022;10(1):e2021EF002187.
72. Kern JD, Su Y, Hill J. A retrospective study of the 2012–2016 California drought and its impacts on the power sector. Environ Res Lett. 2020;15(9):094008.
73. 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.
74. Denaro S, Cuppari RI, Kern JD, Su Y, Characklis GW. Assessing the Bonneville Power Administration's Financial vulnerability to hydrologic variability. J Water Resour Plan Manag. 2022;148(10):05022006.
75. Hill J, Kern J, Rupp DE, Voisin N, Characklis G. The effects of Climate Change on Interregional Electricity Market Dynamics on the U.S. West Coast. Earth's Future. 2021;9(12):e2021EF002400.
76. Bracken C, Voisin N, Burleyson CD, Campbell AM, Hou ZJ, Broman D. Standardized benchmark of historical compound wind and solar energy droughts across the Continental United States. Renewable Energy. 2024;220:119550.
77. Siddik MAB, Grubert E, Caldwell P, Marston LT. Retirement of US fossil fuel-fired power plants will increase water availability. J Hydrol. 2023;617:128984.
78. Tarroja B, Peer RAM, Sanders KT, Grubert E. How do non-carbon priorities affect zero-carbon electricity systems? A case study of freshwater consumption and cost for Senate Bill 100 compliance in California. Appl Energy. 2020;265:114824.
79. Tarroja B, Peer R, Grubert E. Assessing how non-carbon co-priorities affect zero-carbon electricity system development in California under current policies. J Clean Prod. 2023;403:136833.
80. Jager HI, Manning K, Nicole Welch J, Corsi F, Miara A, Yoon HS, et al. Indicators of thermal alteration in US waters reveal patterns of climate risk at the energy-water nexus. Ecol Ind. 2024;159:111755.
81. Williams AP, Livneh B, McKinnon KA, Hansen WD, Mankin JS, Cook BI et al. Growing impact of wildfire on western US water supply. Proceedings of the National Academy of Sciences. 2022;119(10):e2114069119.
82. Parks SA, Abatzoglou JT. Warmer and Drier Fire Seasons Contribute to increases in Area burned at high severity in Western US forests from 1985 to 2017. Geophys Res Lett. 2020;47(22):e2020GL089858.
83. Donaldson DL, Piper DM, Jayaweera D. Temporal solar photovoltaic generation capacity reduction from wildfire smoke. IEEE Access. 2021;9:79841–52.
84. Gilletly SD, Jackson ND, Staid A. Evaluating the impact of wildfire smoke on solar photovoltaic production. Appl Energy. 2023;348:121303.
85. Copeland C, Law S. Water-related risks and impacts on the U.S. energy system. Council on Foreign Relations; 2019. pp. 22–31. (Impact of Climate Risk on the Energy System: Examining the Financial, Security, and Technology Dimensions). https://www.jstor.com/stable/resrep21839.5.
86. Abatzoglou JT, Smith CM, Swain DL, Ptak T, Kolden CA. Population exposure to pre-emptive de-energization aimed at averting wildfires in Northern California. Environ Res Lett. 2020;15(9):094046.
87. Kormann C. Why Maui Burned. The New Yorker. 2023; https://www.newyorker.com/magazine/2023/11/06/maui-wildfire-response-recovery
88. Note. Kānāwai from Ahi: revitalizing the Hawai'i Water Code in the wake of the Maui wildfires. Harv Law Rev. 2024;137(7):1994–2015.
89. Marty C, Schlögl S, Bavay M, Lehning M. How much can we save? Impact of different emission scenarios on future snow cover in the Alps. Cryosphere. 2017;11(1):517–29.
90. Johansson DJA. The question of overshoot. Nat Clim Chang. 2021;11(12):1021–2.
91. Grubert E, Hastings-Simon S. Designing the mid-transition: a review of medium-term challenges for coordinated decarbonization in the United States. WIREs Clim Change. 2022;13(3):e768.
92. Jasperse J, Ralph FM, Anderson M, Brekke L, Malasavage N, Dettinger M et al. Lake Mendocino Forecast Informed Reservoir Operations: Final Viability Assessment. UC San Diego; 2020. https://escholarship.org/uc/item/3b63q04n
93. Ralph FM, James J, Leahigh J, Anderson M, Forbis J, Haynes A et al. Yuba-Feather Forecast Informed Reservoir Operations: Draft Preliminary Viability Assessment. UC San Diego; 2022. https://cw3e.ucsd.edu/FIRO_docs/Yuba-Feather_PVA.pdf
94. De Silva T, Jorgenson J, Macknick J, Keohan N, Miara A, Jager H, et al. Hydropower operation in future power grid with various renewable power integration. Renew Energy Focus. 2022;43:329–39.
95. Jager HI, De Silva T, Uria-Martinez R, Pracheil BM, Macknick J. Shifts in hydropower operation to balance wind and solar will modify effects on aquatic biota. Water Biology Secur. 2022;1(3):100060.
96. Mongird K, Rice JS, Oikonomou K, Homer J. Energy-water interdependencies across the three major United States electric grids: a multi-sectoral analysis. Utilities Policy. 2023;85:101673.
97. Szinai JK, Deshmukh R, Kammen DM, Jones AD. Evaluating cross-sectoral impacts of climate change and adaptations on the energy-water nexus: a framework and California case study. Environ Res Lett. 2020;15(12):124065.