Impacts of changing snowfall on seasonal complementarity of hydroelectric and solar power

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Abstract

Complementarity of variable renewable energy sources at multiple temporal scales is important in order to ensure reliability of a decarbonizing energy system. In this study, we investigate the hypothesis that a decrease in the fraction of precipitation falling as snow (SWE/P) would increase monthly complementarity of hydro and solar power generation in the western U.S. With a focus on 123 dams responsible for 93% of generation, we found that these resources are seasonally complementary at about half of dams, as indicated by the sign of correlation coefficients (ρ). As hypothesized, average SWE/P at individual dams was generally positively correlated with ρ, but the dependence of ρ on SWE/P was non-linear and SWE/P only explained a modest portion of the variance in complementarity. At each dam, the dependence of annual ρ on interannual variations in SWE/P between 2002–2020 was assessed; these relationships were positive at 72% of dams but not statistically significant at the level of individual dams. Finally, at the system scale ρ was significantly related to SWE/P, with a stronger relationship observed than the dependence of total hydropower generation on SWE/P. Notably, the system-scale relationship between ρ and SWE/P changed dramatically in the latter part of the temporal domain (2012–2020), with a much steeper slope and greater fraction of variance explained by SWE/P. These results illustrate the historical relationship between SWE/P, monthly complementarity of hydro and solar power, complexities of these relationships due to snow and watershed hydrology and reservoir management, and a change in the observed relationship between SWE/P and hydropower generation timing. To the extent that hydro and solar power generation complementarity is responsive to SWE/P, expected declines in SWE/P may indicate greater seasonal complementarity but reduced hydropower available for load-balancing when solar power generation is highest.

1. Introduction

As efforts to decarbonize electricity systems progress, the synchrony of variable generation electricity resources with firm generation capacity will become increasingly important to the reliability of electricity systems (Shaner et al 2018, Dimanchev et al 2021). At the same time, climate change may alter the seasonal availability of environmental resources used for electricity generation. Yet, the current electricity system is built and operated based on historical seasonal patterns of generation resources, and models of decarbonizing grids typically do not account for changing seasonality of individual or joint distributions of renewable resources (Oikonomous et al 2022). Understanding the historical dependence of variable generation technology synchrony on interannual climate variability can therefore be an important foundation for identifying how these resources might change in the future and how operations or capacity expansion should take these changes into account.

In particular, the impacts of climate change on the magnitude and timing of water availability are relatively large and well understood (Pachauri et al 2015). In the western U.S., a decreasing fraction of precipitation falling as snow has been well established in both observations (Feng and Hu 2007, Safeeq et al 2016, Mote
and models of future conditions (Klos et al 2014), with expectations for increasingly frequent low- or no-snow conditions (Siriila-Woodburn et al 2021). These changes are often denoted as the ratio of liquid snow water equivalent (SWE) to precipitation (SWE/P). Changing snow to precipitation ratios will likely alter the spatial locations of snow to rain transitions (Klos et al 2014) and advance snowmelt timing (Gergel et al 2017, Marshall et al 2019), and have already yielded earlier runoff timing, with this trend projected to continue (Stewart et al 2004, 2005). The impacts of changing inflow timing have already impacted reservoir operations in the Columbia River System, with increased hedging in the spring and greater outflows in the summer (Jones and Hammond 2020).

Projected changes in runoff and methodological treatment of the relationship between runoff and hydropower generation impact on the estimated sensitivity of hydropower production to climate change. Projected changes in total runoff in the western U.S. are somewhat uncertain and spatially variable due to uncertain projected changes in precipitation (Hamlet and Lettenmaier 1999, Wu et al 2012, Dai 2016). Purely empirical approaches to assessing the impacts of hydroclimate on hydropower generation have found that total runoff had a positive correlation with hydropower generation between 1989–2008, with limited explanatory effect of temperature and maximum explanatory effects from 5 years running averages of runoff, implying considerable interannual hysteresis in the Western U.S. system (Kao et al 2015). A study that used downscaled climate forcings as input to a hydrologic model to estimate hydropower generation as a linear function of simulated streamflow found limited impacts of climate change on hydropower generation in the Western Interconnection (WECC) for several emissions scenarios in 2040–2060, though there were some impacts in the Colorado River region (Bartos and Chester 2015). An approach that used a reservoir operations scheme globally found that hydropower utilization rates were reduced by 5.2% in drought years when droughts were defined as the three years with the maximum number of days on which streamflow was less than the 10th percentile in 1980–2010 (van Vliet and Sheffield 2016). When the same approach was applied with future climate scenarios, reductions in usable capacity were identified for 61%–74% of hydropower facilities in 2040–2069, depending on emissions scenario (van Vliet et al 2016).

Estimates of the impacts of climate change on hydropower have been particularly prevalent in high elevation reservoirs in California; the diversity of methods and findings in this region highlights the complexity of the topic. For instance, an electric dispatch model was integrated with a monthly surface water reservoir model; results for future climate scenarios indicated more inflow overall, but with greater spillage in high flow events (Tarroja et al 2016). The net effect was a 3.5% decrease in hydropower generation in RCP 4.5 and no change in RCP 8.5. These changes tend to increase the system-wide greenhouse gas emissions (Tarroja et al 2019, Carlino et al 2021). Another study using monthly hydrology and hourly energy pricing in a model that optimizes for hydropower generation found that projected changes in hydropower revenues depended on whether warming was accompanied with increasing or decreasing precipitation (Madani and Lund 2010). Yet another study using a reservoir model that minimized spillage with a temperature delta approach to simulate climate change projected decreases in generation throughout the region (Rheinheimer et al 2014). These study results remain somewhat difficult to compare quantitatively due to differences in spatial domain, treatment of climate inputs, and response variables.

Some of the above methodological approaches to assessing the impacts of climate change on hydropower account for changing runoff timing, either explicitly or implicitly, while others do not. In general, process-based models account for changing runoff timing while statistical approaches typically have not. Yet, changing streamflow timing has important implications for hydropower generation and energy system dynamics. Shifts in streamflow timing are partially mitigated by reservoir storage dynamics, which vary based on the rule curves of individual reservoirs. However, as streamflow timing shifts earlier, modeled future hydropower generation tends to decrease in the summer, when it is most needed to meet higher demands for air conditioning along the West Coast (Hill et al 2021). In sum, while the total magnitude of projected change in hydropower availability appears to depend strongly on methodological assumptions and uncertain total runoff changes, changes to the expected timing of inflows are relatively well understood and may also be important for grid operations, particularly in high renewable energy scenarios.

Understanding the joint distribution of timing of availability of climate-dependent energy resources is therefore important for accurately evaluating the sustainability and reliability of decarbonized grids. Climatically, changes to joint distributions of changing variables can be larger or more impactful than the changes in distributions of individual variables (Abatzoglou et al 2020). Complementarity of renewable resources has been a major focus of energy reliability literature, and can span space and/or time complementarity at temporal scales ranging from sub-hourly to monthly and spatial scales ranging from small states or countries to large regions (Jurasz et al 2020). Solar and hydropower generation have been identified as important and effectively complementary resources at the monthly scale in Brazil (Beluco et al 2013, de Jong et al 2013). Hydropower offers particularly interesting challenges and opportunities with respect to complementarity and space-time
variability of renewable energy sources due to its integration of atmospheric and Earth surface processes, capacity for controlled storage, and interactions with other water management objectives (Engeland et al 2017, Zeng et al 2017).

In the case of the joint distribution of solar and hydropower generation, the impacts of changing SWE/P on advancing runoff timing in conjunction with the seasonal stability of solar power generation imply a simple hypothesis as articulated by François et al (2014): that decreasing SWE/P ratios might increase the complementarity of solar and hydropower by decreasing their seasonal synchrony. This simple hypothesis may be complicated at scale, however, by the differing extents to which individual watersheds are snow-dominated, runoff generation processes, the impacts of reservoir storage on modifying timing of hydropower generation, and the linked nature of reservoirs in hydropower systems.

In this study, we evaluate the following research questions:

(a) How do the monthly correlations between solar and hydropower generation vary spatially?
(b) To what extent does the mean SWE/P ratio at individual dams govern the mean correlation coefficient at these dams?
(c) To what extent do SWE/P ratios govern the interannual relationship between solar power and hydropower generation at (a) individual dams throughout the WECC and (b) at the system scale?

For context, we also evaluate the extent to which SWE/P correlates with total annual hydropower generation in order to facilitate comparisons with prior literature focused on the impacts of climate change on total annual generation. Evaluations of the impacts of hydroclimate conditions on a response variables of interest, when motivated by questions about climate change, have often used spatial and/or temporal analog approaches (Luce et al 2014). In a spatial analog approach, variability in conditions across space are evaluated, while a temporal analog model evaluates variability in conditions across time, typically at multiple locations. Here, we use both approaches to complement each other.

These results provide a new empirical approach to understanding the impacts of changing hydroclimate on the energy system. While the impacts of changing total runoff on hydropower generation have been relatively extensively explored, changing snow and subsequently runoff timing are much more certain in their projected changes, yet their impacts on the energy system are less well understood. In mountainous regions in particular, where snowpack dynamics are often highly sensitive to climate change, studies of climate change impacts are often not well integrated with studies of climate change mitigation (Marshall et al 2020a); the results of the present study will also provide an example of integrating knowledge about climate change impacts and mitigation.

2. Methods

2.1. Energy generation data

Net monthly hydropower and solar generation data were obtained from the Energy Information Administration (EIA) 923 database for the years 2002–2020 (EIA 2020b). The locations of each hydropower generation facility were obtained from the EIA 860 dataset (EIA 2020a). We used data only from dams within the WECC. For analysis of individual facilities, we identified the 123 out of a total of 635 hydropower facilities in the WECC that contribute 90% of total annual hydropower generation in 2020. This subset, rather than all dams in the system, was selected because watershed delineation was required for these facilities in order to determine relevant climatological characteristics. For system-scale analysis, all hydroelectric power facilities in the WECC were retained.

For each month and year, solar generation across the WECC was summed. Solar generation was analyzed at the WECC scale in conjunction with hydropower generation data at the facility scale because individual hydropower facilities are subject to important spatially and interannually variable climatological influences, but the solar power that they complement or substitute is distributed across the Western grid. We note, however, that smaller spatial scales for grid distribution, such as balancing authorities, may also be relevant for comparable analyses. Here we focus on the relationship between solar and hydropower because both resources are distinctly seasonal, with a relationship that may be complementary or substitutive, depending on location and year. In a decarbonizing grid, the complementarity of hydropower with load and other variable generation renewables will also be important, but of those variables with which hydropower complementarity may be needed, solar has by far the most extreme seasonality in the WECC (figure 1).

2.2. Watershed delineation

Watersheds were delineated for each hydropower facility in order to determine the relevant contributing area. Due to the large number of facilities of interest, we developed a method to balance reproducibility and
Figure 1. Seasonality of hydroelectric, solar, and wind generation, and total load (assuming that monthly generation is equivalent to load), calculated as the fraction of annual generation by a given technology produced in each month. Lines show interannual averages, while shaded areas show the standard deviation for each month.

2.3. Climate data
Climate data were used to estimate the annual ratio of SWE to precipitation (P), or SWE/P. We used the daily 4 km resolution gridMET dataset for the contiguous United States (Abatzoglou 2013). Specifically, we obtained daily minimum temperature ($T_{\text{min}}$), maximum temperature ($T_{\text{max}}$), and precipitation (P) for the period of record. For each day and grid cell, we calculated the daily average temperature ($T_{\text{avg}}$) and estimated water equivalent of daily snowfall (SWE) as equal to precipitation on days when $T_{\text{avg}}$ was less than 1 °C, and zero when $T_{\text{avg}}$ was greater than 1 °C, choosing the precipitation phase threshold based on data presented in Jennings et al. (2018). Annual SWE/P was calculated over water years beginning and ending Oct 1. For each water year, the SWE/P ratio was then calculated as the sum of annual SWE divided by precipitation. Annual SWE/P was aggregated over the watershed draining to each hydropower facility using a mean weighted by total precipitation (figure 2). This ensures that grid cells with higher potential to contribute runoff to the hydropower facility receive heavier weights and avoids overweighting the SWE/P ratio in low-precipitation grid cells that do not have a large influence on the timing of water availability.

2.4. Analysis
At each hydropower facility, we calculated the Spearman correlation coefficient ($\rho$) between monthly solar and hydropower generation for each water year. In a spatial analog analysis, annual values of $\rho$ were averaged in order to identify a mean correlation coefficient ($\rho_{\text{mean}}$) for the dam; this approach avoids spurious conclusions due to potential trends over time in either total annual solar or hydropower generation. We evaluated the extent to which $\rho_{\text{mean}}$ at each dam was related to average annual SWE/P for a given dam using a generalized additive model (GAM) for which $\rho_{\text{mean}}$ was estimated as a function of mean SWE/P, using a cubic regression basis and the ‘mgcv’ package in the R programming language (Wood 2011, 2017, R Core Team 2021). In this
statistical analysis, each dam was an observation; the GAM was selected in order to allow for a non-linear and non-parametric relationship between the predictor and response variables.

In a temporal analog analysis, we also evaluated the interannual dependence of \( \rho \) on annual SWE/P ratios, using a linear regression and reporting the shape of the fit and estimate of the effect size (\( \beta \)) for each facility. Statistical significance of relationships between variables is often evaluated by identifying cases in which \( p \)-values are less than a given threshold, typically 0.05; however, when many such tests are conducted, a significant risk of false discovery emerges such that the majority of identified relationships may be statistical accidents (e.g., Wilks 2016). Spatial correlations in data may magnify this problem. An alternative approach is to use the false discovery rate (\( \alpha_{FDR} \)), rather than \( p \)-value, as a threshold for statistical significance, following Wilks (2016).

In this case, \( \alpha_{FDR} \) was set to 0.1; though note that this remains more stringent, with a lower chance of false discoveries, than a \( p \)-value threshold of 0.05. This procedure avoids the high false discovery rates associated with multiple statistical tests and is robust to spatial autocorrelation. It requires identifying a \( p \)-value associated with a pre-determined \( \alpha_{FDR} \) given the distribution of calculated \( p \)-values. For comparison with more commonly used measures, we also describe the apparent prevalence of statistically significant results using a standard \( p \)-value < 0.05.

Finally, we evaluated the system-wide dependence of the interannual correlation between total monthly hydropower generation at all facilities and solar power generation as a linear function of interannual SWE/P. SWE/P here was a precipitation-weighted average across all watersheds contributing to the hydropower facilities for which we had delineated watersheds. A limitation of this approach is that it excludes the SWE/P for dams that did not have delineated watersheds, predominantly in the southern Sierra Nevada where there are several small hydropower facilities. However, including all hydropower facilities was deemed valuable for this system-scale analysis, and delineating watersheds for all was impractical.

We evaluated the use of a generalized additive model for the system-scale analysis but found that it shrank to a linear model; we therefore report the results of a linear model. At the system scale, we also evaluated the dependence of interannual total hydropower generation on SWE/P for comparison. Based on a qualitative observation that the strength of the regression relationship appeared to change in the latter part of the temporal domain, we conducted regressions separately for 2002–2011 and 2012–2020 and reported the differences in regression statistics at the dam and system scale. Updating statistical methods after observing results should

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**Figure 2.** Average SWE/P ratio of contributing basins for each hydropower facility included in this analysis; size of points indicates mean generation. Background map illustrates SWE/P for each pixel.
3. Results

3.1. Correlations between hydro and solar power generation

Average monthly correlation coefficients between solar and hydropower generation were positive at 48% of dams, suggesting that at the monthly scale, these resources are synchronized (rather than complementary) at about half of the dams in this dataset (figure 3). Across all hydropower facilities included, the mean $\rho$ was $0.0 \pm 0.31$, reinforcing the considerable variation between dams and illustrating that on average, hydro and solar power generation are not systematically correlated.

Correlation coefficients reflecting the synchrony of hydro and solar power generation have distinct spatial patterns (figure 3(a)). Throughout California, the average monthly correlation between SWE/P and hydropower generation is predominantly high, except for a few reservoirs in Northern California with negative correlations. This illustrates that hydropower generation in California occurs almost uniformly relatively late in the summer when solar generation also tends to be high, even though some watersheds draining hydropower facilities are very strongly snow-dominated, while others are rain-dominated (figure 2). In contrast, hydropower facilities in the Columbia River system show decreasing correlation coefficients moving downstream along the length of the river system. Higher in the system, hydropower generation timing is closely correlated with solar power generation, while further downstream, these correlations are attenuated or negative. This could be due to the moderating influence of a linked system of reservoirs on streamflow in the lower parts of the basin, or due to the greater influence of rain, rather than snow, in the lower portions of the system. Notably, though, SWE/P ratios of the contributing areas remain relatively constant through most of the Columbia River system (figure 2), suggesting that these correlations are modified by infrastructure, more than physical geography.

3.2. Influence of SWE/P on $\rho$ spatially

Dams with higher average SWE/P tend to have greater correlations between hydro and solar power generation, but the explanatory power of this relationship is low and does not appear to hold at lower SWE/P values (figure 3(b)). A generalized additive model using average conditions at each dam as observations indicates that SWE/P is a statistically significant predictor of the average correlation coefficient ($p < 0.001$). The shape of the relationship indicates that at relatively low SWE/P values, SWE/P has only a minimal or even negative impact on $\rho$, but beginning around a SWE/P ratio of approximately 0.3, the two variables have a stronger positive relationship. However, the $R^2$ of this relationship is only 13.6%, indicating that many other factors attenuate or alter the relationship between the correlation coefficient and SWE/P.

3.3. Influence of interannual SWE/P on $\rho$

The interannual dependence of $\rho$ on annual SWE/P ratios varies across dams, but is positive at the majority (72%) of dams, indicating that at these dams, years with higher SWE/P also have a higher correlation between
hydro and solar power generation at most dams (figure 4(a)). Using a \( p \)-value threshold of 0.05, this relationship is statistically significant at only 3% of dams with a positive slope (\( \beta \)) and none of the dams with a negative \( \beta \). None of these relationships meet the statistical significance threshold when \( \alpha \text{FDR} \) is constrained to 0.1, illustrating that the interannual dependence of \( \rho \) on interannual SWE/P is not statistically significant at the scale of individual dams.

Some regional differences in the dependence of \( \rho \) on annual SWE/P are apparent: for instance, dams in the Pacific Northwest have relatively low \( \rho \) on average, suggesting higher seasonal complementarity of solar and hydropower, with relatively high \( \beta \) indicating higher interannual dependence on SWE/P ratios (figure 4(a)). Dams in California and the Northern Rockies tend to have relatively high average correlations but \( \beta \) values encompassing both positive and negative signs in both states, suggesting that hydropower generation occurs relatively late in the summer but that its dependence on SWE/P varies by dam in magnitude and direction. Mapped values of \( \beta \) reflect these patterns (figure 4(b)), and notably do not show the same gradual change in values along the Columbia River system in Washington that the values do (figure 3(a)).

3.4. System-scale dependence of \( \rho \) on SWE/P

System-scale results indicate that \( \rho \) is somewhat consistently correlated with SWE/P, again with relatively low explanatory power over the full temporal domain (figure 5(a); \( p < 0.05; \) adjusted \( R^2 = 21% \)). Qualitatively, the later years in the dataset appear to have a stronger relationship between SWE/P and \( \rho \). Indeed, when the regression is repeated for only the years 2012–2020, the \( R^2 \) increases to 62%, with \( p < 0.05; \) the slope coefficient more than doubles (from 2.1 to 4.8) relative to the full period of record. For comparison, total annual hydropower generation over the entire period of record shows a much smaller dependence on SWE/P, with \( p > 0.1 \) and \( R^2 \) = 0% (figure 5(b)).

To investigate the source of the unusually strong strength of regression between \( \rho \) and SWE/P in 2012–2020, we compared regression fit statistics for each dam when regressions were applied in 2002–2011 versus 2012–2020 (figure 6). Results vary somewhat by dam, but in most of the Columbia River System \( p \)-values consistently decreased, while \( \beta \) and \( R^2 \) increased. In this region, \( \rho \) became more dependent on SWE/P in the latter part of the years evaluated as measured by regression coefficient, \( R^2 \), and \( p \)-value. The change in regression slope in the large hydropower-producing dams in this region are therefore likely a large contributor to the observed system-wide change in \( \beta \).

4. Discussion

4.1. Dependence of historical \( \rho \) on SWE/P

At the monthly scale, hydropower and solar power generation have both positive and negative correlations at different dams, suggesting that synchrony between resources varies considerably by dam. This synchrony may be beneficial or detrimental to the reliability of the energy system, depending on the timescale of interest: at daily timescales, synchrony between these two major resources suggests that hydropower is available for
daily load-balancing when solar power is not available to meet net load requirements. In contrast, monthly complementarity may be problematic to the extent that hydropower generation is either less available or less needed in seasons in which solar generation is prevalent. Modelling studies incorporating hydrologic and grid processes suggest that this detrimental impact is more likely the case in the western U.S. (Hill et al. 2021).

Our results partially support the hypothesis posed by François et al. (2014), which suggested that higher SWE/P ratios would tend to decrease the monthly complementarity between solar and hydropower generation; in their initial case study in eight catchments in Italy, SWE/P had a very strong relationship with $\rho$. The findings of the present study agree in the direction of the effect, but SWE/P generally explains much less of the variability in $\rho$ in our study, with considerable variability between dams and years. Moreover, the relationship between interannual SWE/P and $\rho$ was essentially not statistically significant at any individual dams.

The complexity of the relationship between SWE/P and $\rho$ is generally to be expected in a large, hydroclimatically diverse region with considerable infrastructure. Three major factors moderate the influence of SWE/P on hydropower generation timing and therefore $\rho$: these are (1) natural watershed processes that moderate the influence of SWE/P on runoff timing, (2) storage in dams upstream of any particular facility, and (3) storage prior to hydropower generation in the target facility. Storage at the target dam or dams upstream is affected by a suite of factors that impact operations; these include releases that may be required to maintain flood storage capacity, maintain minimum environmental flows, or provide urban or agricultural water deliveries (e.g., Turner et al. 2021). The combination of inflows and storage could also result in seasonally bimodal patterns of hydropower generation, which could further complicate solar-hydropower correlations. $\rho$ was predominantly largest in California, where runoff is strongly snowmelt driven and many dams are at relatively high-elevation facilities with modest storage and at a given dam or upstream facilities (figure 2(a)). In the Pacific Northwest as well, $\rho$ was generally highest in the highest elevation and upstream watersheds of the Columbia River Basin. The decline in average $\rho$ from positive values to zero or negative values along the length of the Columbia River system is likely due to increases in total water volumes and transit times, and potentially more complex water use requirements. The impacts of interannual SWE/P variations on $\rho$ at individual dams had much less clear spatial patterns, though these relationships tended to be strongest in Oregon, Washington, and Montana (figure 3(a)).

4.2. Changes in relationship between $\rho$ and SWE/P
Climate change and the changing dynamics of a decarbonizing grid with high penetrations of variable renewable energy could alter any of the three major factors described above that influence $\rho$ and its dependence on interannual SWE/P. For instance, snow drought and snowpack decreases are well known to result in earlier runoff timing (Stewart et al. 2004, 2005) but the influence of snow drought on transit times in watersheds is
still an ongoing area of research (Segura 2021). The impacts of SWE/P on watershed hydrology are also moderated by factors such as changing snowfall intensity and melt timing (Lute and Abatzoglou 2014, Musselman et al 2017, Marshall et al 2020b). Moreover, low- to no-snow futures could arrive in the next few decades, and could create new nonlinearities in the relationships between SWE/P ratios and runoff timing (Livneh and Badger 2020, Siirila-Woodburn et al 2021). Changing climatology could also affect reservoir operations by creating multi-year snow droughts (Marshall et al 2019) or inter-annual climate sequences with ‘whiplash’ between exceptionally wet or dry years (Swain et al 2018). Climate change could also alter operating constraints and rules for multi-reservoir systems by altering the optimal parameters and relationships between different reservoirs (Nawaz et al 1999, Ahmadianfar and Zamani 2020), changing relicensing practices for hydropower dams (Madani 2011, Viers 2011), or altering cold pool storage requirements (Rheinheimer et al 2015). Both climate change and decarbonizing grid dynamics could change operational dynamics at any given reservoir: earlier runoff could result in more water released in the spring to maintain required flood storage capacity (Lee et al 2009); the additional spill associated with this could change relationships between inflowing hydrology and power generation by decreasing the fraction of total inflow that can effectively be stored for power generation. A decarbonizing grid and increasing summer demand in particular would change the timing of demand for hydropower generation to meet net load requirements in summer months (Hill et al 2021). Increases in forecast-informed reservoir operations (FIRO) as the quality of hydroclimate data improves could also fundamentally alter relationships between hydroclimate inputs, reservoir operations, and hydropower generation (Delaney et al 2020, Sumargo et al 2020). The specific impacts on hydropower generation could depend on the priority of hydropower generation relative to other water management objectives. Changing hydroclimate could also introduce new threshold events such as dead pool, in which reservoir elevations drop below those at which power can be generated. Such an event occurred at Lake Oroville in California in August of 2021.

Figure 6. Changes in (a) regression slope (β) in units of tenth of a change in correlation coefficient per fractional change in SWE/P, (a) p-value, and (c) R² of the linear regression between r and SWE/P from 2002–2011 to 2012–2020.
more such events, as well as other factors described above, could fundamentally alter historically observed relationships.

Our results indicate that the dependence of hydropower generation and its timing on at least certain aspects of hydroclimate (SWE/P) have changed considerably over the period of record, particularly in the Columbia River Basin, indicating important nonlinearities in this relationship. These changes could be ascribed to changes in the watershed hydrology processes that transport snow or precipitation from hillslopes to dams, as discussed above, or could be due to changes in operation. We posit that, given the very large shifts in this relationship, changes in operation are somewhat more likely. This result suggests significant challenges for methods of understanding hydropower generation dependence on climate that rely on statistical relationships (Kao et al 2015). Approaches that integrate process-based hydrologic or river management models with grid models may be able to represent these changing process relationships more adequately (van Vliet and Sheffield 2016, van Vliet et al 2016, Voisin et al 2016, 2020, Hill et al 2021) but more research is needed to identify the underlying causes of the increasing dependence of hydro and solar power complementarity and total hydropower generation on SWE/P.

4.3. Implications for grid operation and planning

To the extent that lower SWE/P is associated with greater monthly complementarity of solar and hydroelectric power generation, future decreases in SWE/P could have implications for grid operations and capacity planning. Low hydroelectric power generation is a major driver of high electricity prices, regardless of power sector scenario (Wessel et al 2022). The same study also found that shortfalls were most common when hydropower was unavailable during late summer heat events and that abundant hydropower in spring months tended to result in very low electricity prices. An exacerbation of this seasonality associated with declining SWE/P could imply a need for more low-carbon energy storage capacity at timescales ranging from sub-daily to seasonal; these could include battery storage or increased pumped storage hydropower (Pérez-Díaz et al 2015). At the operational time scale, declining SWE/P and earlier runoff paired with high loads later in the summer imply additional value for FIRM, which could allow operators to safely maintain more reservoir storage when forecasts indicate that new precipitation or runoff events are not likely so flood storage is not needed, or could further motivate modified or variable rule curves (Mateus and Tullos 2017).

4.4. Assumptions and limitations

This work contains several assumptions and limitations that are important for future consideration. First, the focus is on seasonal complementarity, rather than sub-daily; the temporal scale determines whether increases in complementarity are desirable or undesirable for electricity system reliability. We did not extrapolate the relationships identified here to hypothetical future SWE/P conditions because of the high potential for nonlinearities or changing conditions outside the historical observed range. Future work could include multi-variable evaluations of changing complementarity of hydro and solar power with wind generation or net load, compare complementarity of inflowing water to reservoirs with that of hydropower generation, and identify the reason for the observed increase in dependence of and total hydropower generation on SWE/P.

5. Conclusions

As hypothesized, SWE/P influences the synchrony of timing between hydropower and solar power generation in the western U.S., but the relationship is spatially variable and complicated by other factors, including snow and watershed hydrology, management of upstream reservoirs, and management of any given reservoir at which this relationship is evaluated. At the system scale and at many individual dams, this relationship has changed fundamentally over the 19 year period we analysed, suggesting considerable future potential for changing relationships between hydroclimate, time-varying hydropower capacity and generation, and the opportunities and challenges for hydropower in a decarbonizing energy system. Understanding these changing relationships is a critical area for further research into the relationships between geophysical constraints and sustainable infrastructure.

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Data availability statement

The data that support the findings of this study are openly available at https://doi.org/10.5281/zenodo.5806523.

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