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Shifts in hydropower operation to balance wind and solar will modify effects on aquatic biota☆

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ABSTRACT

To avoid negative consequences to freshwater biota from climate change, society must complete the transition from fossil to renewable electricity sources. However, temporal patterns in hydropower generation (and flow releases that affect aquatic biota) may change with increased wind and solar penetration. We used power cost modeling to characterize current and future within-day and seasonal patterns in hydropower generation across the Eastern Interconnection in a wet and a dry year. Compared to the baseline, future hydropower generation across the grid decreased during the day and increased before dawn and after dusk. At a project level, such a pattern would suggest 'double peaking' operation (up- and down-ramping before dawn and after dusk, with lower releases midday). Variation in generation was higher in wet years than dry years, foreshadowing possible flow constraints on hydropower flexibility. At the grid scale, projected ramping rates were higher in all seasons. A review of the ecological literature suggests that these changes would shift the timing of invertebrate drift and elevate the risk of nest scouring during up-ramping and the risk of stranding or dewatering during down ramping. Thermal conditions may be moderated by increased ramping. Strategies for adapting to future shifts in the renewable portfolio range from re-regulation in reservoir cascades to providing flow refuge (structures and vegetation) below individual projects. Coordinated basin-scale operation can distribute peaking operation to maintain grid support while restricting local ramping at critical ecological times. In addition, research to design hybrid renewable systems that add battery storage is needed to understand how we can mitigate future risks to aquatic communities while promoting the use of renewable energy. This study, which is among the first to examine ecological side-effects of the shift to renewable energy in freshwater ecosystems, lays out a path toward understanding and navigating changes to flow regimes under the energy transition.

1. Introduction

Understanding shifts in the relationship between biodiversity and our energy portfolio is an important scientific frontier that has thus far received little attention. In ecology, the concept of the 'ecological niche' is used to study competition among species for resources along multiple resource dimensions in time and space (Hutchinson, 1957). Thinking of hydropower as a 'species', we extend the ecological concept of the temporal niche (Hut et al., 2012; Ivar et al., 2017) because we expect to see mainly temporal shifts in hydropower generation in the US.

Hydropower has historically been a polarized topic. Environmental scientists that study negative impacts (Sharma et al., 2019) find themselves in conflict with hydropower development and energy interests. Yet, there are broad and important areas of agreement (Uncommon Uncommon Dialogue, 2020). Both sides recognize that if we continue on the current trajectory, climate warming will threaten aquatic biota through habitat loss (McManamay et al., 2021). Both acknowledge that avoiding further loss of biodiversity will require moving toward

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low-carbon sources of energy (Jager et al., 2021; Zhu et al.). Disagreements tend to be over the details of siting (spatial overlap) and operation (temporal overlap).

Hydropower can play a dual role in moving us toward a low-carbon energy future. Globally, two-thirds of new capacity is from solar and wind (Blakers et al., 2019, 2021) and both are trending upward. Hydropower can help to facilitate penetration of variable renewables by ramping up to support the grid when wind and solar are not available. Although natural gas has helped to integrate intermittent renewables, hydropower has flexibility similar to that provided by natural gas (Shan et al., 2020). In the United States, on average, each megawatt of hydropower performs more ramping work per year than each megawatt of natural gas (Uría-Martínez et al., 2018). Hydropower can displace natural gas in the electricity portfolio and provide a low-carbon source of electricity (Shan et al., 2020). However, it is unclear whether it can completely displace natural gas.

In this study, we explore how the temporal niches at the nexus of aquatic biodiversity and hydropower are changing and how those changes increase or decrease the niche partitioning between them. Our goal is to outline research paths to identify opportunities for coexistence between hydropower and aquatic biota during the transition to renewable energy. Specifically, we combine modeling of the electricity portfolio now and under future scenarios with a conceptual analysis to hypothesize how adding these variable renewables might impact aquatic biota given what we know. We hypothesize changes in temporal patterns for hydropower generation (and associated flow releases) at two scales. At the within-day scale, we expected to find increased nighttime generation and 'double peaking' (up- and down-ramping before dawn and after dusk) because solar generation is higher during mid-day and wind generation is higher at night (Shi et al., 2020). At the seasonal scale, we expected an increase in the ramping in winter for scenarios with high wind generation and in summer for scenarios with high solar generation. We review the implications for biota and outline potential future research to bridge the gap between grid-scale drivers and operational changes at individual plants. Finally, we review mitigation options to anticipate and avoid adverse ecological impacts.

2. Temporal niche partitioning between biota and hydropower value

One way to think about temporal trade-offs is to consider river flow as a resource that is shared by biota and hydropower generation. Each has different seasonal and diurnal preferences, which is to say that the value of river flow is higher for the two entities at different times. The question this paper seeks to address is whether future temporal patterns in flow releases for hydropower will be more compatible or less compatible with temporal patterns that favor aquatic biota.

2.1. Hydropower - past

Non-hydro electricity production has increased more than hydropower over the past few decades (Fig. 1). As a result, the hydropower share of total electricity production declined from 12% to 7% in the United States (and from 21% to 16% worldwide) between 1980 and 2019 (International Energy Agency, 2021; US Energy Information Administration (EIA), 2021a, b). Historically, the value of hydropower has historically been highest during hours of peak energy demand, that is, workdays between 9 a.m. and 5 p.m. Sub-daily fluctuations in flows regulated by hydropower plants were significantly higher than those in natural flow regimes (Haas et al., 2015).

2.2. Hydropower - future

Scenarios where the global energy sector reduces emissions in accordance with the goals of the Paris Agreement project great increases in the penetration of renewables in the electric sector. Projected increases are much higher for wind and solar than for hydropower making the role of hydropower as integrator of those other variable renewables increasingly salient. For example, the 2050 global installed capacities in the International Energy Agency's Net Zero Roadmap are 2,599 GW of hydropower, 8,265 GW of wind, and 14,458 GW of solar PV (starting from baselines of 1327 GW for hydropower and 737 GW for wind and solar in 2020) (International Energy Agency, 2021).

Shifts in the future electricity portfolio to accommodate greater wind and solar capacity will alter patterns of hydropower generation and associated turbine flows. Solar and wind energy are complementary to some extent, with a very strong pattern of high solar at midday and a weaker peak in wind energy at night (Shi et al., 2020). Increased solar penetration will lead to increased crepuscular 'double-peak' fluctuations, i.e., before dawn, after dusk. The so-called duck curve should compress load following into pre-dawn and post-dusk periods, while storing water in the middle of the day. This pattern will likely be strongest in summer when solar power is available at higher volumes. Increased wind energy will increase daytime fluctuations in flow, whereas increased solar

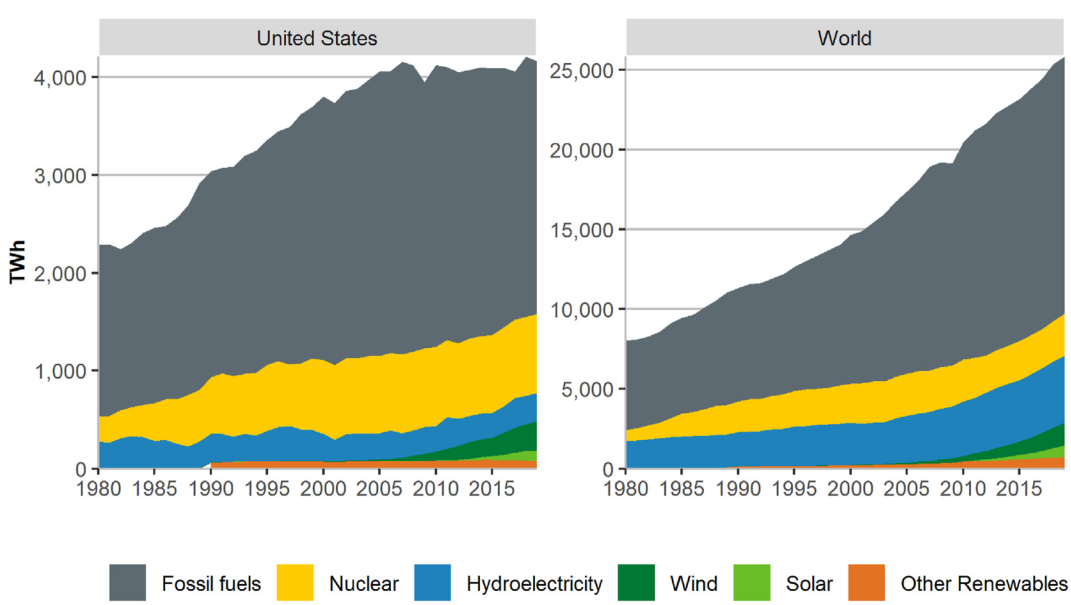

Fig. 1. Annual cumulative electricity generation for the US and the world. Data from the U.S. Energy Information Administration (http://eia.gov).

energy will increase nighttime fluctuations in flow. Thus, nighttime hydropower generation may increase when demand is not met by wind. Another important aspect of supporting increased wind is its within-day intermittency. Sub-daily fluctuations could be high enough to cause ecological impacts. A study of up to 15% future wind penetration in Chile projected that sub-daily fluctuations increased over time below some dams (Haas et al., 2015). However, the estimated future increase in flashiness (short-term variation in flow) in Chile was modest compared to that between natural flows and the pre-wind baseline (Haas et al., 2015).

3. Methods

To understand the implications of future shifts in hydropower generation under scenarios with different levels of renewable power, we simulated grid conditions in the Eastern Interconnection (Fig. 1) for a baseline year, 2024, and for a future year, 2036, with high penetration of wind and solar (De Silva et al., 2022). The capacity of variable renewable energy (wind and solar) was projected to be 20% in the baseline year and 46% in the future year (De Silva et al., 2022).

A range of future power grid scenarios were analyzed using a capacity expansion tool, Regional Energy Deployment System (ReEDS), that determines sizes and locations of new generators, retirement of old generators, and changes in interregional transmission capacity (Cohen et al., 2019). The ReEDS future scenarios for energy infrastructure are consistent with the Low Renewable Energy cost scenario (Cole et al., 2019). Two years were selected from a ReEDS scenario as input to a production cost model, PLEXOS (The Unified Energy Market Simulation Platform). Current conditions, represented by 2024, assumed 9% of wind penetration and 11% of solar penetration. To represent future year 2036, ReEDS assumed 18% wind penetration and 28% solar penetration. PLEXOS then optimized the power system's unit commitment and the dispatch of power plants at an hourly resolution. For each year, PLEXOS produced day-ahead dispatch decisions by minimizing the cost of meeting demand for both energy and other grid services (De Silva et al., 2022). Most hydropower plants were modeled as dispatchable plants with monthly energy limits. Parameters and assumptions for the Eastern Interconnection followed those of previous grid studies that quantified renewable contributions to regional power grids (Bloom et al., 2016; Brinkman et al., 2021; Novacheck et al., 2021).

To assess whether water availability limits the ability of hydropower to respond to intermittent generation by the variable renewables, we compared PLEXOS results for a dry (2012) and a wet (2013) year. Hydropower generation data for 2012 and 2013 was obtained from the US Energy Information Agency (EIA, 2021a). Short-term fluctuations in hydropower plant operating capacity occur in both up- and down-ward directions in response to changing power grid and water inflow conditions. The term ‘ramping mile’ refers to the sum of absolute values (changes in plant capacity) of 1-h ramps (up or down) over a given time horizon. We divided this ‘ramping mile’ value, calculated either over the week of maximum wind or solar generation, by installed hydropower capacity (MW). We report the ratio of the MW-normalized ramping for the future scenario to that of the baseline scenario for each week.

Once diurnal and seasonal patterns in hydropower generation were simulated, we examined the ecological implications of changes revealed by the PLEXOS scenarios by reviewing the ecological literature. We used the keywords ‘hydropeaking’, ‘thermopeaking’ and ‘load following’ and supplemented references identified with literature on ecological responses to seasonal and diurnal flows. Seasons were defined as spring (March–May), summer (June–August), fall (September–November), and winter (December–February). These inferences do not account for existing or future environmental mitigation restrictions on flow (Shi et al., 2020) that are not included in the energy models, as discussed in Section 7.

4. Results

PLEXOS simulations show a pronounced decrease in mid-day hydropower generation in the future scenarios (right in Fig. 3) when compared to the baseline (left in Fig. 3) accompanied by increased crepuscular generation in the morning (between 6 and 8 a.m.) and in the evening (between 5 and 8 p.m.) (Fig. 3). This illustrates a so-called ‘duck-curve’ pattern in hydropower generation with a dip during the middle of the day (duck's back), and higher before dawn (duck's tail), and after dusk (duck's head). The implications for individual projects are that daytime flows will be lower and that peak flows will be concentrated in shorter periods before dawn and after dusk. The peak is much higher in the evening than in the morning. This projected diurnal pattern is more pronounced in spring and summer than in fall and winter (Fig. 3). Hydropower generation during early morning and late evening was higher in the wet year than in the dry year for spring and fall seasons (Fig. 3). Increased generation during the wet (but not dry) year implies that hydropower was able to compensate for reduced wind and solar at the sub-daily scale when needed.

For each season, we compared current and future ramping rates (i.e., grid-scale fluctuations in hydropower generation) for the two hydrologic years during a week of highest solar and wind, respectively. For the high-wind week, we observed higher future ramping in spring (Fig. 4). In the dry year, future winter and summer ramping decreased for the high-wind weeks (Fig. 4). This is consistent with a pattern of high winter wind. The explanation for a summer decrease is less clear; perhaps generation was constrained by summer storage. We observed higher ramping rates in winter for the high-solar week (Fig. 4). Spring ramping, which can be ecologically important, was forecasted to increase under all future scenarios (Fig. 4). This increase was highest in the high-wind week and wet hydrologic year (Fig. 4). The smallest increase in spring ramping was for the high-solar week in the wet year (Fig. 4).

Hydrologic years produced different results in the weeks with the highest wind generation compared to the week with the highest solar generation. In the wet year (unconstrained by water availability), the increase in ramping was higher in the high-wind week than the high-solar week in all seasons except for winter. Fall ramping was higher in dry years than in wet years, whereas summer ramping was higher in wet years (Fig. 4). Results showed a decrease in ramping in the dry year for winter and summer for the week with highest wind generation (Fig. 4). This suggests that hydropower may have been unable to compensate for low wind and solar without adequate stored flows in seasons with high electricity demand.

The range of hourly hydropower generation provides a second measure of variability. Under future conditions with increased wind and solar, the range of hydropower generation projected by PLEXOS is wider in all seasons (Fig. 5). The widest ranges were projected to occur in spring and summer, and under wet conditions (Fig. 5).

Both measures of variability highlight the potential increase in the value of operational flexibility in hydropower generation to support penetration of wind and solar into the grid and the need to anticipate ecological consequences.

4.1. *Shifting future effects on aquatic biota*

The main changes in temporal patterns shown by our results are: (1) a shift in diurnal timing toward increased crepuscular and nighttime generation, especially in spring and summer (Fig. 2), (2) increased ramping/variability in hydropower generation in all seasons, especially spring (Fig. 4), and (3) larger increases under wet than under dry hydrologic conditions (Fig. 4).

Based on a review of the literature, we summarize our expectations of how these shifts in future hydropower operation might increase or decrease impacts on aquatic biota (Fig. 6). The ecological effects of flow fluctuations occur both above and below reservoirs and depend on a number of factors, including species, life stage, temperature, and more

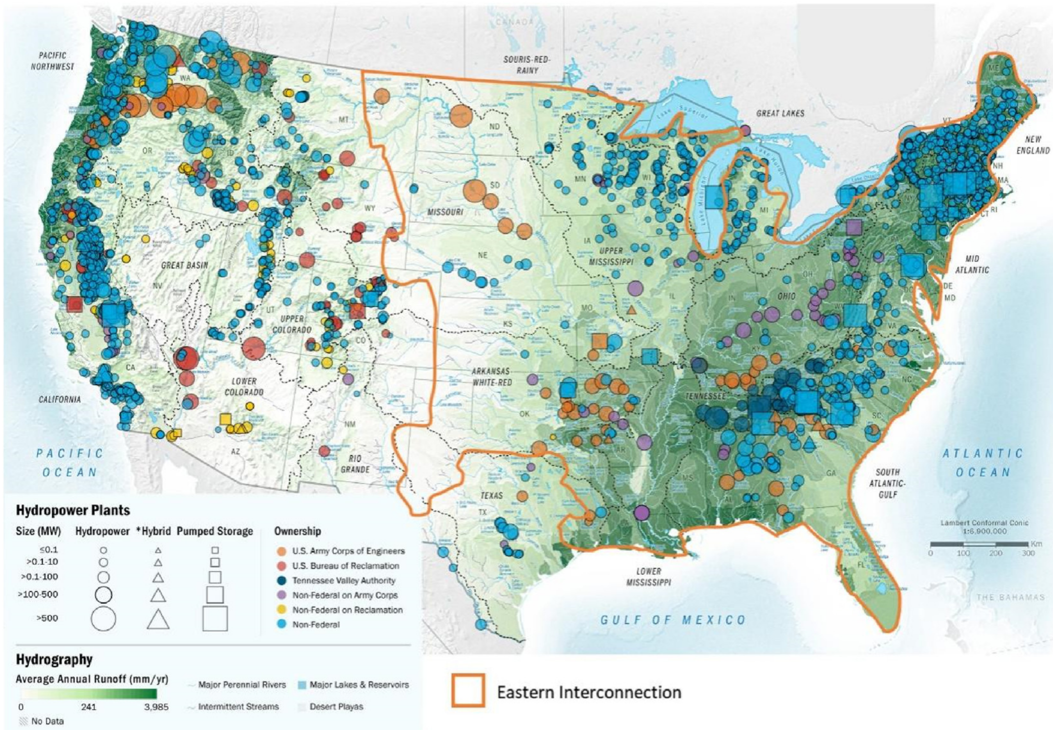

Fig. 2. Locations of hydropower facilities in the conterminous US shown in the context of US electricity grid interconnection regions including the Eastern Interconnection (North American Electric Reliability region outline for the Eastern Interconnection is from EIA). Hydropower facilities from the Existing Hydropower Assets Database (Johnson et al., 2021). Map credit: Nicole Samu.

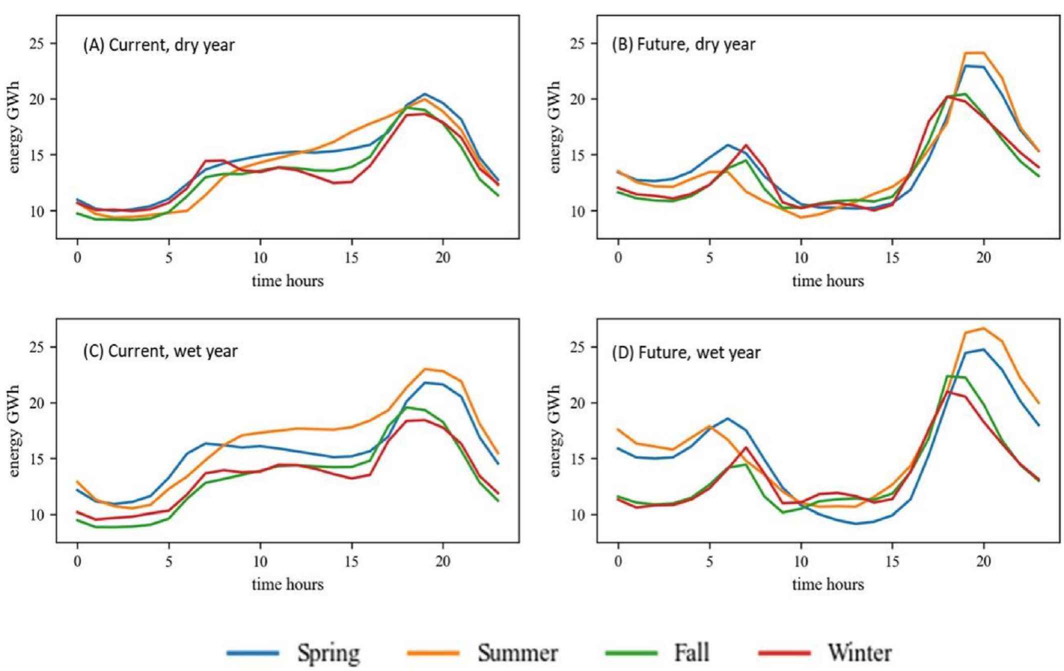

Fig. 3. Total daily hydropower fleet dispatches (i.e., output of power plants to meet electricity demand in GWh) to the Eastern Interconnection for each season (blue=spring, yellow=summer, green=fall, red=winter). Diurnal results on the left are for current grid conditions and those on the right are for future conditions. Curve shown in the top row are for a dry hydrologic year (2012); those on the bottom row are for a wet hydrologic year (2013).

(Cushman, 1985). The mechanistic risks associated with fast decreases in flow during down ramping include dewatering of nests and less-mobile taxa and stranding of older life stages. During increases in flow, early life stages may be exported downstream or fish nests may be scoured (Barton et al., 2021). Vulnerable periods tend to be in spring for species that breed in spring and winter for fall-spawning species.

4.1.1. Diurnal patterns: increased generation before dawn and after dusk

At the project level, the implication of the diurnal duck-curve pattern of generation is that double peaking, i.e., two periods of increase and

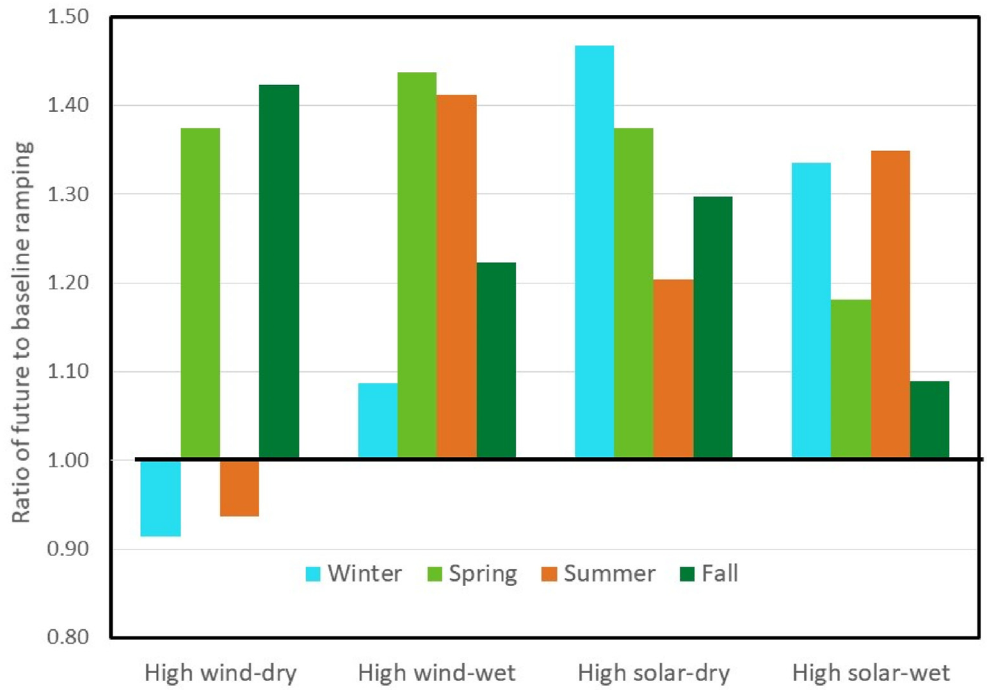

Fig. 4. PLEXOS results for a wet and a dry hydrologic year comparing hydropower ramping for the week with highest solar and the week with highest wind generation in each season for the Eastern Interconnection.

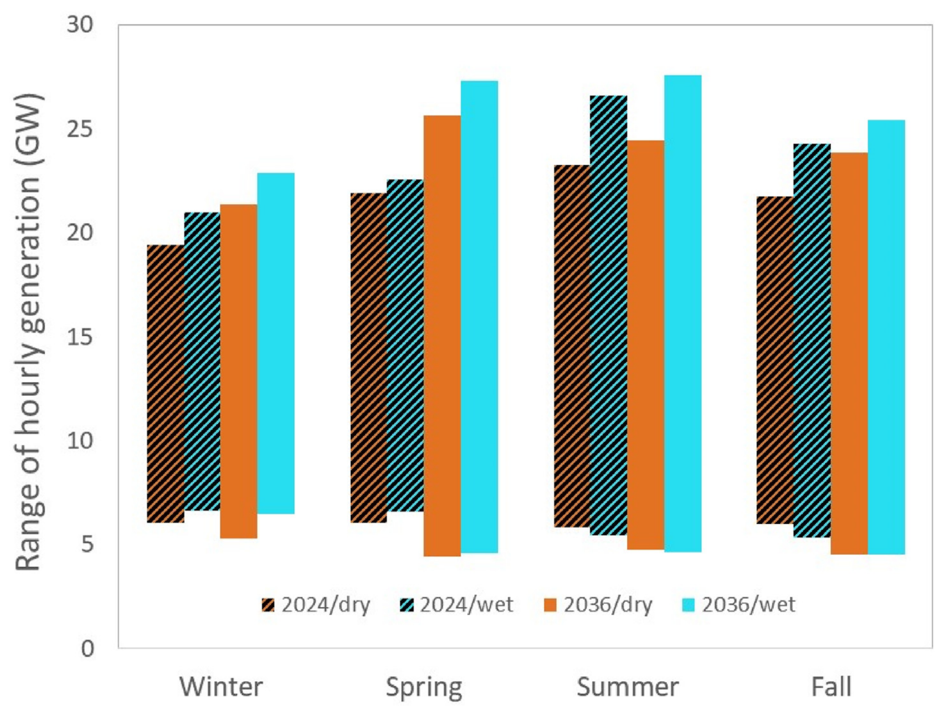

Fig. 5. Comparison of PLEXOS-simulated ranges in hydropower generation for current and future grid conditions for the Eastern Interconnection. We show results for a wet and dry hydrologic year, by season.

decrease in flow, will occur daily. Because solar power generation peaks during mid-day and because wind is also lower at night, we expected that increased solar and wind power would increase the demand for flow peaking early and late in the day. This would be especially true for solar during summer when days are longer. We observed this expected shift in PLEXOS results for hydropower generation, which would correspond with lower flows during the day and higher flows after dark and before sunrise (Fig. 2). For the Eastern Interconnection, results showed a larger shift in timing during spring and summer than in fall and winter (Fig. 3).

The shift in hydropower generation estimated by PLEXOS might restore historical drift patterns for invertebrates and early life stages of fishes (Fig. 6). Most benthic invertebrates exhibit nocturnal drifting patterns, likely to reduce exposure to predators (Elliott, 1969). The current situation of daytime up-ramping can increase rates of

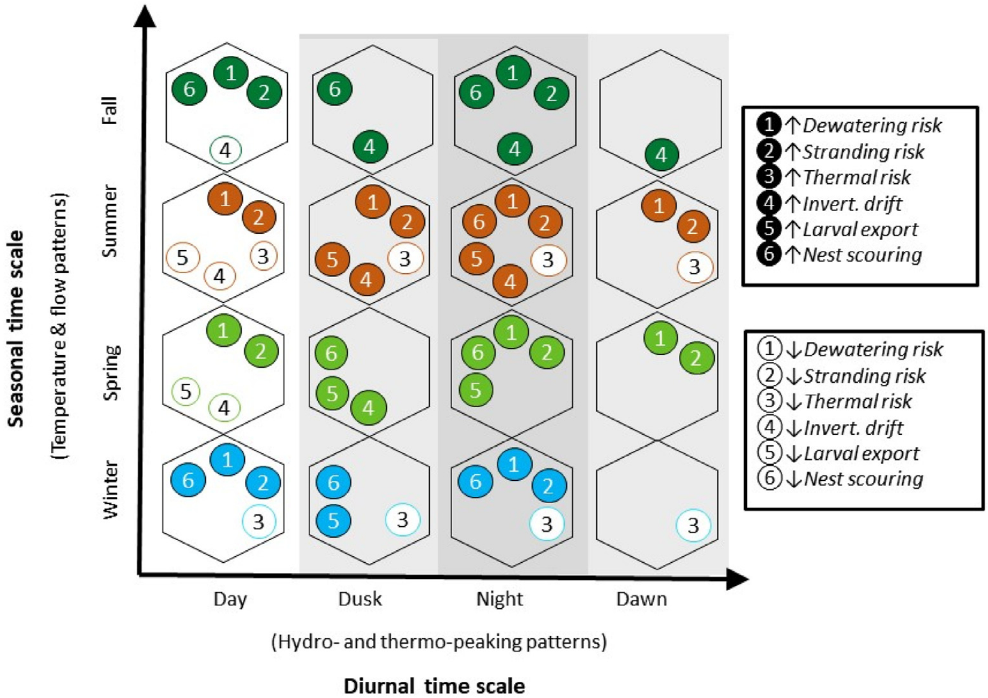

Fig. 6. Stommel diagram showing hypothesized changes in risks to biota associated with hydropower responses to a future renewable-penetrated grid at seasonal and diurnal time scales. Open circles show decreases and filled circles show increases in risk.

invertebrate prey drifting during the day and elevate feeding rates and growth of drift-feeding fishes (Rocaspana et al., 2016; Schulting et al., 2019). On the other hand, short-term increases in drifting aquatic prey can increase drift-feeding rates. A controlled experimental study of hydropeaking below Flaming Gorge Dam on the Green River compared drift rates with those at a control site below nearby Fontanelle Dam (Miller and Judson, 2014). Macro-invertebrate drift rates increased significantly during the rising limb of each peaking event, but then subsided after 2 h of high flows (Miller and Judson, 2014). As a result, drift-feeding salmonids may grow faster, and in some cases have been shown to have fuller stomachs below peaking dams (Abernethy et al., 2021; Kelly et al., 2017; Null et al., 2014a).

For larval fishes, juveniles with weak swimming ability, and smaller species, the risk of being swept downstream during up-ramping may also be a concern in regulated rivers. A wide-spread pattern among fishes is that higher abundances of drifting eggs and larvae are collected in samples taken at night (Lechner et al., 2016), presumably reflecting an adaptation to avoid visual predators. Up-ramping effects on drifting larval and juvenile fishes raise another concern in rivers fragmented by closely spaced dams. This can produce metapopulation scale impacts on upstream reaches when larval production is exported downstream with no way to return (Jager et al., 2007).

Many pelagic fishes are crepuscular feeders, feeding at dawn and dusk to avoid visual predators that tend to be active mid-day. Double peaking flow regimes may disrupt crepuscular feeding by forcing species to find refuge until flows are sufficiently stable. In particular, younger life stages of fishes and visual (e.g., pelagic) species are less capable of avoiding changes in flow and associated habitat when up-ramping occurs at night. Crepuscular ramping could potentially be tolerated by drift feeders provided velocities are moderate and do not prevent them from holding position in the water column. Although enhanced nocturnal drift might not benefit all ages and species of fishes in the short run, it would restore the timing of flow and drift-feeding closer to pre-dam conditions and could therefore potentially represent a long-term improvement.

The risk of stranding because of down-ramping may be higher at night. One study found fish stranding mortality to be ten-times higher at night than during the day for grayling (Auer et al., 2017). However, an experimental study found that stranding mortality was lower at night during winter because juvenile salmonids remained in interstitial gravel instead of the water column after dark (Bradford et al., 1995).

4.1.2. Seasonal patterns: increased fall and winter fluctuations

In the eastern US, solar generation is highest in spring and summer, whereas wind is highest in winter (fall-to-spring) (Lawson, 2019). Wind is weakly correlated with solar at the seasonal scale (EIA, 2021b). We expected that the largest increases in ramping rates in the future scenario would be observed in summer for the high-wind scenario to compensate for seasonal lack of wind. We found this to be true for the wet year, but the increase was higher in fall in the dry year (Fig. 3). We found that the largest increase in winter ramping rates occurred during the high-solar week, as expected if hydropower is replacing for solar. With one exception, variability in hydropower generation was lower in winter than in other seasons, whereas the greatest increases in ramping occurred during spring, as discussed in the next section.

Concerns about more-volatile flow regimes in winter are important for two reasons. First, ectotherms are unable to move quickly to avoid risks from ramping by seeking refuge when they are cold. Juveniles of cold-water species, such as salmonids, tend to be active at lower temperatures than warmwater species. This leads us to wonder whether a shift to double peaking with increased-magnitude fluctuations in winter would have different effects on cold- and warm-water fishes? Second, fishes and other species that spawn in fall have vulnerable early life stages present in winter. increased fluctuations can disrupt spawning in fall and cause dewatering or scouring of eggs in winter.

Fortunately, there are also factors that moderate the potential effects of hydropeaking in winter. Aquatic species in temperate climates have adaptations for avoiding the effects of variable flows during winter. In addition, thermopeaking has the effect of moderating extreme low temperatures in tailwaters (Zolezzi et al., 2011).

When temperatures are low, down ramping increases stranding rates for salmonids in tailwaters (Greimel et al., 2018), especially species that spawn in the fall. Stranding is also a risk for salmonids during migration through reservoirs. In winter, shallow depths in tailwaters at higher latitudes can damage nests as a result of freezing (Heggenes et al., 2018).

Many reservoirs provide flood control services, in addition to hydropower, and these are operated to drawdown reservoir levels in fall to accommodate high spring inflows. Winter drawdown has been shown to reduce the diversity of macro-invertebrates including mussels (Carmignani et al., 2021). Multivoltine invertebrate taxa that lay eggs in littoral areas are at higher risk from dewatering than other invertebrate taxa (Kennedy et al., 2016). Semivoltine taxa tend not to be found in the drawdown zone (Carmignani et al., 2021). Mussels depend on stable sediments and are most impacted by pulses of low temperature and frequent dewatering (Galbraith et al., 2010, 2020). One study showed that mussels attempted to escape dewatering by moving (Carmignani et al., 2021). Although mussels and many other invertebrates can burrow into sediments when dewatered, repeated impacts cause mortality. We do not know whether mussels are affected by the time of day when ramping occurs, and research to understand how species can withstand different frequencies of dewatering may be important. In addition, the cues that stimulate burrowing and time required to burrow when faced with ramping flows have not been determined (Allen and Vaughn, 2009). Risk may be lower for species that migrate to and aggregate in deep pools, lakes, or estuaries during winter, such as adult black bass (Langhurst and Schoenike, 1990) and sturgeons (Kessel et al., 2018). Vulnerability to short-term variability can be greater for earlier life stages that are present during fall and winter. For example, lower first-year survival of juvenile Paddlefish was linked to the number of upstream flow reversals in winter (Pracheil et al., 2009). For fall-spawning salmonids (e.g., Brown Trout), larvae emerging from gravel redds in spring are the most vulnerable life stage (Elliott, 2009; Hayes et al., 2019). Before this stage, eggs in nests (e.g., salmonid redds) can withstand short periods of dewatering if they are not exposed to extreme low air temperatures (Becker and Neitzel, 1985; Casas-Mulet et al., 2015). Conditions that reduce risk to eggs include high moisture retention in gravel, groundwater influence, and sufficient aeration (Becker and Neitzel, 1985; Casas-Mulet et al., 2015; Groves and Chandler, 2005). Once they attain a large-enough size, juvenile fishes might be able to seek shelter to avoid flow pulses, especially if the released water is sufficiently warm and the pulse is sufficiently gradual.

4.1.3. Seasonal patterns: increased spring and summer fluctuations

We observed the greatest simulated increases in ramping during spring (Fig. 4). Because early life stages have limited mobility, demographic risk is high during spawning and egg incubation, and larval rearing, which occur in spring and summer for many taxa in temperate climates. Our results showed increases in evening generation were highest in spring and summer (Fig. 2), which raises concerns for spring-nesting species with juveniles rearing in spring and summer. Hydropeaking can also have some positive effects during the hottest times (e.g., late afternoon in summer–fall) because tailwater temperatures are moderated by mixing-induced ‘thermopeaking’ (Maheu et al., 2016; Toffolon et al., 2010). Below, expected ecological responses are discussed for biota in tailwaters and reservoirs.

During low flows and down-ramping events, fish species adapted to shallow stream habitats are most at risk in tailwaters (Greimel et al., 2018). Older life stages and taxa are less vulnerable to disturbance by hydropeaking. For example, large, benthic fishes, such as sturgeon, are designed to withstand high flows by hugging the bottom. Sturgeons simply stop moving in response to fluctuating flows or flow increases (Geist et al., 2005). Stranding of older life stages has been relatively well studied for salmonid fishes (Auer et al., 2017; Bakken et al.). Although stranding of other fish taxa is less-well studied, some other large-bodied species of concern have been shown to experience mortality following fast reductions in flow that dewater nests (Fisk et al., 2013).

Seasonal timing can influence the severity of hydropeaking impacts in reservoirs as well as in tailwaters. One study estimated that spring mortality of salmonid fry (Chinook Salmon and Bull Trout) in reservoirs was highest in areas with low slopes (Bell et al., 2008). In reservoirs, fish species diversity is concentrated in the littoral zone (Van der Zanden et al., 2011). Littoral areas serve as good nursery habitat because they support insect prey and offer protection from predators. Ecosystem services (e.g., water purification) from mussels are also highest here. Note, however, that reservoirs that support recreational boating and fishing may be operated to reduce daytime fluctuations in summer (Petrich et al., 1989), and such plant-level restrictions would not be reflected in PLEXOS results.

During reproduction, nest-guarding species are relatively more affected by fluctuations, whereas species that release demersal eggs or spawn among macrophytes are less sensitive (de Lima et al., 2017). Quite a few invertebrate and fish species (e.g., Northern Pike, Common Carp) prefer to nest in inundated littoral vegetation increasing the risk of nest disruption under high-amplitude fluctuations. The effects of reservoir fluctuations are greater for nest-guarding species (e.g., centrarchids) during the nesting season(s) and at night when guarding parents are vulnerable to disturbance. Nest-guarding bass may also be disrupted by cold shocks during spring and summer (Ridgway, 1988). Adults may renest if disturbance occurs early enough in the season. In one modeling study of a reservoir, centrarchid nest survival was lowest when the amplitude was high and period (time between peaks) was low (Clark et al., 2008).

5. Climate change and timing

Warming temperatures will shift the timing of development and could reduce exposures to risk. In the upper lake of a pumped-storage reservoir, fluctuating water levels and low water temperatures combined to cause about 81% mortality of eggs and fry of bluegills, twice as high as that of faster-developing nests in the warmer lower reservoir (Bennett, 1975). In some cases, warming may increase populations by increasing the number of generations per year and the fitness of species with faster life histories, such as multivoltine aquatic insects (Musolin and Saulich, 2012) and repeat spawning fishes. On the other hand, species with specific breeding requirements and short breeding and rearing windows may be more vulnerable if those opportunities overlap with spring or fall periods that experience increased hydropeaking frequencies and magnitudes. Summer impacts of increased double peaking on crepuscular-feeding fishes may be exacerbated by thermal stress under future climate. However, increased reservoir mixing may reduce water temperatures compared to what they would be without peaking. The effects of lower mid-day flow releases could also elevate temperatures in tailwaters.

Precipitation is expected to increase across much of the eastern US, leading to increased flows (Naz et al., 2018). However, water demands (e.g., irrigation, cooling water) will likely also increase with temperature (Miara et al., 2017). The net change and timing of reservoir inflows will dictate how flexible hydropower generation will be in supplying the grid when wind and solar are not available.

6. Mitigation

The degree to which the environmental impacts of flows released for hydropower generation are being mitigated varies substantially across countries and facilities within the same country (Moreira et al., 2019; Schramm et al., 2016).

6.1. Spatial mitigation strategies at multiple scales

Spatial design of regulated river basins can add resilience to future shifts in hydropower-influenced flow regimes. This is true at multiple spatial scales, ranging from basin to cascade to channel. At the basin scale, coordinated operations can alleviate ecological risks, for example, through anticyclical generation by sequential power plants (Bruder et al., 2016). Wetter conditions under future climate may alleviate the pressures to peak hydropower plants. For example, in Chile, greater water availability in a wet year allowed peaking operations to be distributed among facilities on different rivers within a large basin and reduced the need for a single dam to fluctuate as much to meet water and electricity demands (Haas et al., 2015). This suggests that regulated river systems can be designed for resilience at the basin scale (Jager et al., 2015).

At the scale of reservoir cascades, one spatial strategy used to mitigate for hydropeaking is to place re-regulation reservoirs downstream of peaking projects. Based on physical habitat analysis, these basins improve habitat at high-flow conditions at a range of scales from large dams on mainstem rivers to weirs or low dams on low-order streams (Gore and Hamilton, 1996). For example, re-regulating dams are common below California's rim dams; these include Trail Bridge facilities below Carmen Power Plant, a peaking facility on the McKenzie River, Thermolito reservoir below Oroville Dam on the Feather River, and Englebright Dam on the Yuba River (Null et al., 2014). Toward the smaller end of the scale, stilling basins are most effective when sized to hold peak flows (Bruder et al., 2016).

A second design implication comes from the observation that larval export from hydropeaking has demographic consequences for upstream reaches only when dams are closely spaced (without upstream passage). One modeling study suggested that within-reach recruitment of White Sturgeon was higher in reaches long enough that larvae spawned in tailwaters of one dam would be able to drift and settle in free-flowing river, rather than drift into the next downstream reach (Jager et al., 2001). We hypothesize that fish metapopulations will be more resilient to increased nighttime hydropeaking in cascades designed with longer reaches between dams. At the channel or reservoir scale, spatial habitat features can also mitigate risks. In reservoirs, nests located in backwaters are better protected from fluctuating surface elevations than those in the main channel (Dagel and Miranda, 2012). Structure provided by submerged vegetation protects fishes from the effects of fluctuating flows (Baladron et al., 2021). This is especially important in shallow, slow, lotic habitats (Greimel et al., 2018). Germination and establishment of riparian vegetation, which serves as flow refuge, can depend critically on flow regime (Bejarano et al., 2020; Stella et al., 2010). For example, in temperate regions, spring snowmelt establishes the growth cycle for many riparian-adapted species. If hydropeaking destabilizes sediments by concentrating flows at dawn and dusk, vegetations will find it difficult to establish (Bejarano et al., 2018), especially those lacking rhizomes or other perennial root systems to withstand disturbance. On the other hand, increased sediment transport associated with concentrated crepuscular flows can help to reestablish natural sediment regimes (Wohl et al., 2015). Ultimately, these changes will have bottom-up effects on animals that depend on vegetation for food, structural refuge, and reproductive habitat.

6.2. *Temporal mitigation strategies*

Research on mitigation has focused on ramping rates to reduce ecological risks during key time periods (Hayes et al., 2019). For example, spring-spawning salmonids may be helped by qualitative shifts in hydropower operation and resulting flow regimes diagrammed in Fig. 7. A substantial body of literature has quantified hydropeaking effects on biota in different contexts. For example, one study found that juvenile stranding risk was lower when starting from a high flow than when starting from a low flow (Tuhtan et al., 2012). Yet, threshold magnitudes, rates of change, frequency, duration, and timing have not yet been systematically studied or consolidated from disparate studies (Moreira et al., 2019). This is a significant challenge, if we wish to move from general rules of thumb [e.g., minimize nighttime down-ramping (Auer et al., 2017)] to developing canonical operational thresholds that allow flexible operations at times that benefit (or do not harm) aquatic biota.

In the US, ramping rates are also required to slow the rate of changes in peaking flows. The Oak Ridge National Laboratory (ORNL) Environmental Mitigation Database found that 52 of 308 licenses issued by the Federal Energy Regulatory Commission from 1998 to 2013 included ramping restrictions (Bevelhimer et al., 2015a). Regulatory requirements limiting hydropeaking in North America and Europe were summarized by Moreira et al. (2019).

Alternative storage options are being explored that may reduce reliance on hydropeaking. Integrating hydropower with batteries can increase operational flexibility while mitigating the adverse effects of hydropeaking on aquatic species, improving fish passage outcomes, and moderating water quality (Bellgraph et al., 2021). Pumped storage hydropower and compressed-air energy storage are the two lowest-cost energy storage technologies for applications requiring storage durations greater than 4 h (Mongird et al., 2019). Both storage technologies are mature and not expected to experience further large cost reductions. In contrast, the cost of newer storage technologies, such as batteries, has declined rapidly in recent years and this trend is expected to continue, resulting in a progressively larger number of opportunities for cost-effective deployment. For specific projects, cost-effectiveness will depend how stringent operational constraints on the hydropower plant are and the percentage of variable renewables in the system (Anindito et al., 2019). In addition, reaping the benefits of operational flexibility may require co-locating batteries at the plant site. For example, hybrid hydropower-battery installations have been shown to increase revenue from peak energy sales or ancillary services and asset management optimization (Bellgraph et al., 2021).

7. Discussion

In this paper, we described temporal patterns in hydropower generation projected to change with increased wind and solar penetration in the Eastern US. These include a 'duck curve' diurnal pattern with double peaking that concentrates flow releases at dawn and dusk with lower midday flows. Seasonally, our power modeling suggests that we will see increased variability in generation and increased ramping in all seasons when unconstrained by hydrology.

Some caveats are important to mention. Research bridging the divide between large-scale grid modeling and local flows through future projections is challenging because local constraints, such as seasonal drawdown or restricted variation in pool elevations for summer recreation. These are not represented in PLEXOS. There are regional and even watershed specific idiosyncrasies that control how much dams will be able to help accommodate future grid dynamics. Similarly, ecological impacts are likely to vary widely, depending on a river's ecology and current status. Our results should therefore be viewed as a forecast of future economic pressures on flow releases; not what will happen at individual projects that follow the legal provisions of licenses issued by the US Federal Energy Regulatory Commission. Research approaches to scale between local environmental flow restrictions and grid-level constraints need to be developed. One approach used here was to infer water constraints by comparing weeks with the highest generation of wind and solar in a wet and dry year. Although this analysis could be improved by considering multiple years of each type and examining covariates, the analysis presented here is a first step that demonstrates how one might examine the implications of hydropower patterns associated with wind and solar.

We outlined spatial strategies for increasing resilience to shifts in the renewable portfolio at two scales and highlighted temporal mitigation strategies as well. These strategies will depend on understanding the timing of biological events in thermal units and dates so that appropriate responses can be timed. Because most research on hydropeaking effects has focused on salmonids, research to understand temporal flow niches of other taxa of fishes and invertebrates is needed, as well as those of the vegetation and other structural elements that support them.

To understand ecological effects of future shifts in the electricity portfolio, particular attention is needed to relate the diurnal and seasonal timing, frequency, and duration of hydropeaking flow regimes. At the hydropower project scale, we encourage the design of field experiments to better understand the effects of projected shifts in timing of variable flows to support wind and solar. This could involve comparing differently

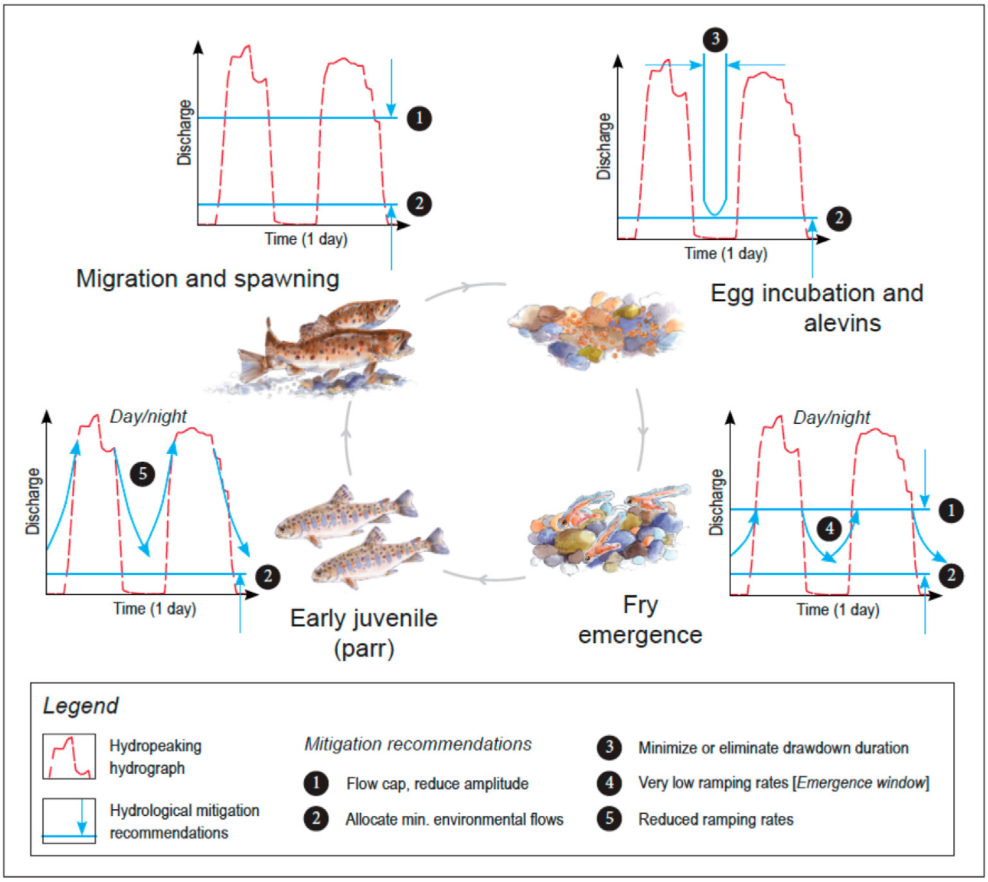

Fig. 7. Conceptual framework for the sensitive life stage approach to mitigate the adverse impacts of hydropeaking. The dashed red lines represent a schematic daily hydropeaking hydrograph (two peaks and a baseflow phase), whereas the solid blue lines depict recommendations for hydrological restrictions to aid the environmental enhancement of hydropeaking rivers. "Day/night" indicates that restrictions might differ. Source: (Hayes et al., 2019).

operated systems in the same basin or altered-flow experiments. Another approach is to examine statistical trends in peaking, following the methods of Déry et al. (2021), but including relevant covariates in the analysis.

Appropriate metrics will be needed that measure both environmental and energy performance in frequency space. Specifically, new metrics are needed to assess temporal compatibility between ecological and energy performance. Current metrics focus on the two aspects separately. Normalized metrics are useful to compare streams with different flows, but the number of choices is somewhat overwhelming (Olden and Poff, 2003). Three classes of metrics used to describe sub-daily variation include the flashiness index, daily range in flow, and the number of reversals (Bevelhimer et al., 2015b). Although these metrics capture short-term flow variability due to load following, they are not designed to capture timing relative to biological events. On the ecological side, habitat persistence has been identified as an important feature, especially for age-0 fishes (Freeman et al., 2001), but it does not measure energy performance. We recommend temporal cross-correlation between hydropower generation and ecological flow requirements to measure the degree of temporal synergy between these water uses.

As both climate and energy portfolios shift, new tools and perspectives will be needed to maintain performance along both dimensions. This can also be approached formally through multi-objective optimization and can involve stakeholders. A growing body of research has used optimization methods to expose the middle ground by simulating a range of solutions along a Pareto-optimal frontier (Almeida et al., 2019; Kuby et al., 2005; Null et al., 2014). Tradeoffs between the electricity market revenue and environmental outcome objectives can also be explored for mitigation options, such as hybrid hydropower-battery systems (Bellgraph et al., 2021). We envision an approach that determines how temporal niche overlap between environmental and energy can be reduced.

8. Conclusions

This study examined the ecological implications of future changes in the temporal patterns of hydropower generation associated with increased wind and solar penetration at multiple scales using a power model. Future daytime hydropower generation is projected to decrease, whereas increased generation will occur before dawn and after dusk. Projected ramping rates were higher in all seasons. The ecological literature suggests that these changes could result in higher crepuscular drift and scouring during up-ramping in the absence of flow refuge and in fish stranding or dewatering during down ramping. These potential effects may be restricted by hydropower license provisions. We recommend several strategies for adapting to future shifts in the renewable portfolio such as those projected here. Flow refuge can be provided through re-regulation in reservoir cascades, stilling basins, and structures and vegetation located below dams. Coordinated basin-scale operation can distribute peaking operation to maintain grid support while restricting local ramping at critical ecological times. Research to design hybrid renewable systems that add storage, for example by using battery support, is needed to understand how we can mitigate future risks while advancing the use of renewable energy from a variety of sources.

Author contributions - CRediT statement

HIJ was responsible for supervision and conceptualization, literature review, writing the original draft and revision, and producing figures. TDS ran PLEXOS simulations (methodology, formal analysis, and investigation), provided data for figures, contributed to discussions on manuscript conception, and reviewed the manuscript. RUM contributed to the manuscript and created a figure. BP authored, created a figure for, and reviewed the submitted manuscript. BP and JM provided funding for related HydroWIRES research.

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Declaration of competing interests

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