Adapting Hydropower Operations to Support Renewable Energy Transitions and Freshwater Sustainability in the Columbia River Basin

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Project Description

The Columbia River Basin (CRB), located in the Pacific Northwest (PNW), covers 258,000 square feet [1], running through seven states and one Canadian Province [1]. The basin is home to 19 hydroelectric dams between the US and Canada and the river provides about half the region's supply of electricity [2]. Most of this supply is provided to the Mid-Columbia (Mid-C) electricity market in the PNW, with some being exported to the California Independent System Operator (CAISO), servicing four zones in California: Pacific Gas & Electric (PG&E) Bay, PG&E Valley, Southern California-Edison (SCE), and San Diego Gas & Electric (SDG&E). As of 2018, CAISO manages the dispatch of approximately 1,080 power plants and other electricity generation resources across 26,000 miles of transmission lines within the state. This system provides power to over 30 million residents of California as well as a small portion of Nevada [3]. The Mid-C energy market includes most of the remaining PNW and CRB.

Hydropower will play an important role in meeting global carbon mitigation targets and eventually achieving net-zero carbon emissions. With the size and influence of hydropower in the Mid-C and CAISO energy markets, there is a large opportunity to utilize this resource for load balancing as renewable energy sources expand. Being able to optimize the system in place and improve it is crucial to this study and one potential improvement is the expansion of pumped storage systems. Pumped storage hydropower (PSH) is a type of hydroelectric energy storage using two water reservoirs at different elevations that can either use excess power, by pushing water up to the higher reservoir or generate power as water moves down through a turbine to the lower reservoir. PSH acts similarly to a giant battery and will help with optimization by providing a way to balance energy in the system [4]. Optimizing hydropower operations in the CRB system and adding the additional capacity of pumped storage is crucial in achieving a 95% renewable energy power grid in the Pacific Northwest by the year 2035.

However, when looking at the CRB hydropower operations, there are multiple stakeholders advocating for different objectives beyond load balancing. This research also investigates tradeoffs between these objectives based on different hydropower operations at several CRB dams. There are transboundary factors to consider such as the Columbia River Treaty and its pending renegotiation between the U.S. and Canada. The U.S. initially funded the construction of reservoirs in Canada for U.S. flood protection, but Canada may prefer to re-operate these reservoirs for hydropower production [5]. There are also cultural factors to consider as well as environmental factors. Local tribes have many cultural practices that were affected by the construction of the Columbia River Basin dams, including detrimental impacts on fish populations and migration patterns, flooding of sacred sites and burial grounds, and displacement from their homeland [6]. The optimization of operations should include minimizing environmental spill violations and temperature violations that take into account the fish that inhabit the rivers and the communities that rely on them. These factors are taken into consideration while focusing on one of the main objectives of this project: to minimize the costs of the dam operations as part of a more renewable grid so that the price of energy for the consumer is accessible while also generating a profit for the energy utility companies like Bonneville Power Administration (BPA), which operates the major CRB reservoirs.

Dworshak Dam is one of such major reservoirs, located on the North Fork Clearwater River (see Figure 1). It is a straight concrete gravity dam that has a structural height of 717 feet, a crest length of 3,287 feet, and is situated at an elevation of 1,613 Mean Sea Level (MSL). The dam is the highest straight-axis concrete dam in the Western Hemisphere. Only two other dams in the United States are taller (Oroville Dam in California and the Hoover Dam in Nevada) [7]. It was constructed in 1996 and became operational for flood damage reduction in 1972. It includes three power generating units, two 100,000-kW units and one 250,000-kW unit. It is the largest hydro-electric generator in the U.S. Army Corps of Engineers' (USACE) inventory. With a total rated capacity of 450-MW, over 1.35 billion kW hours of electricity were produced in the fiscal year 2017 [7].

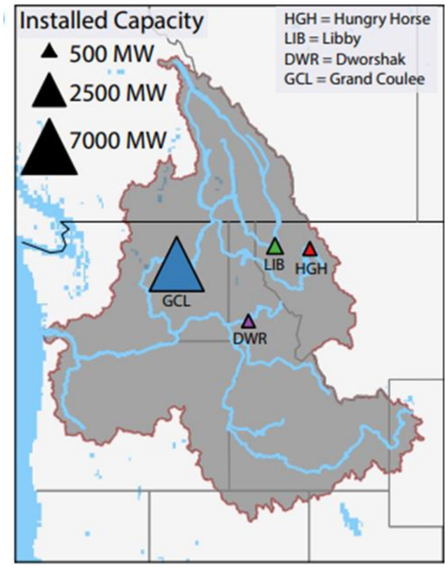


Figure 1: Map of four reservoirs and their capacities in the CRB, including Dworshak (DWR).

The DWR project includes the dam, DWR Reservoir lands, powerhouse, recreation facilities, wildlife migration, and the DWR National Fish Hatchery. The reservoir has a gross storage capacity of 3.5 million acre-feet, 2 million of which are used for local and regional flood control, as well as at-site and downstream power generation. See Table 1 for the water inflow data for DWR. The reservoir is at 1,600 MSL, about 54 miles long, and has a surface area of about 20,000 acres. It extends into the Bitterroot Mountains and provides substantial recreational and wildlife benefits. However, the filling of the reservoir resulted in the loss of about 15,000 acres of terrestrial habitat and converted the salmon and steelhead river habitats into a reservoir. The wildlife habitat loss most impacted the winter range for Rocky Mountain elk and white-tailed deer. To make up for the loss, 7,000 acres of mitigation lands were developed and are managed for winter range. Operational drawdowns and the construction of the DWR National Fish Hatchery help mitigate the fish losses. Drawdown in the reservoir occurs in early July to decrease temperatures on the Lower Snake River and support salmon/steelhead migrations. See Figure 2 for a diagram of current DWR reservoir water use allocations. The hatchery is operated by the U.S. Fish and Wildlife Service and the Nez Perce Tribe. It is a primary producer of Clearwater B-run steelhead, and after the reservoir was filled, kokanee salmon and smallmouth bass were stocked and became self-sustaining. The abundance of fish makes it a favored area for sport fisheries. [7].

Table 1: Water inflow patterns over time for DWR [7].

Minimum (of record) streamflow (cfs)		250
Standard project flood peaks (cfs)	Mean annual	5,727
	Winter	160,000
	Spring	120,000
	Probable maximum flood	411,000

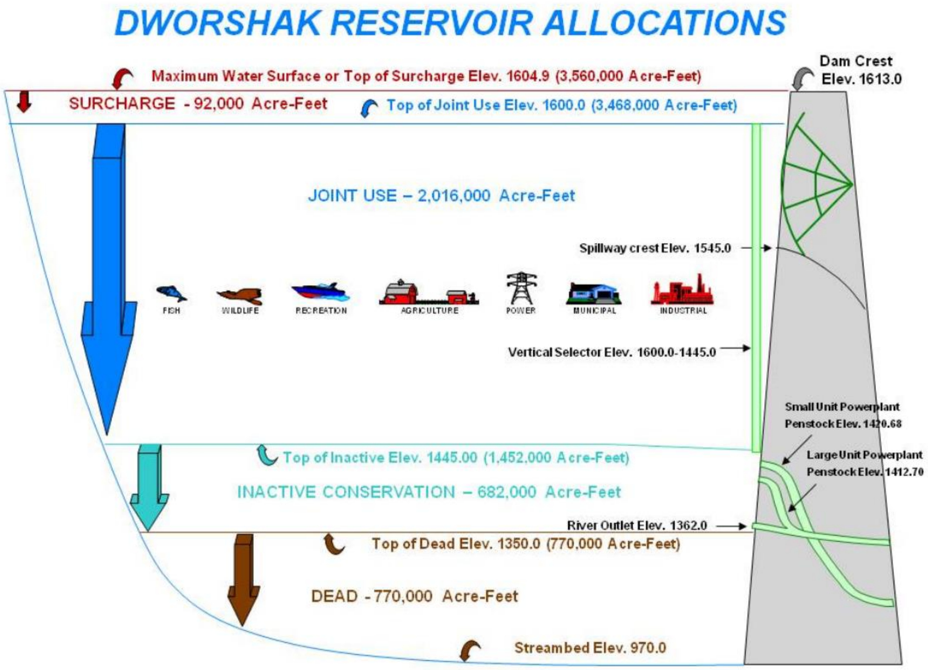


Figure 2: DWR Reservoir Allocations, based off pertinent storage and elevation data from USACE. Figure reproduced from Giovando and Dozier (2011) [8].

Operational Plan and Analysis

Model Description

To effectively re-model the design of alternative hydropower operations in the Columbia River Basin for a more renewable grid, we ran two loosely-coupled models: the California Power Systems model (CAPOW) and a reservoir systems model. Synthetic weather and energy scenarios were generated for three ten-year time step periods 20 years into the future: 2020-2029, 2025-2034 and 2030-2039. Figure 3 illustrates a schematic of the model coupling: after the weather and energy scenarios are generated, these inputs flow into the two major models (Power and reservoir). These models have additional components within them, such as the streamflow temperature model, the Vancouver water level model, and an electricity price model that emulates the power system model output. The functions and components of each of these models are detailed more extensively below. Following the schematic, this entire model generates a series of outputs, including reservoir operations that maximize hydropower output and BPA revenue, and minimize environmental spills violations, peak flood height, and moderate flood frequency (days in which the Vancouver water level exceeds 17 ft). These operations are optimized by a multi-objective evolutionary algorithm that finds different policies that trade-off performance on these objectives in different ways, which we investigate in the results.

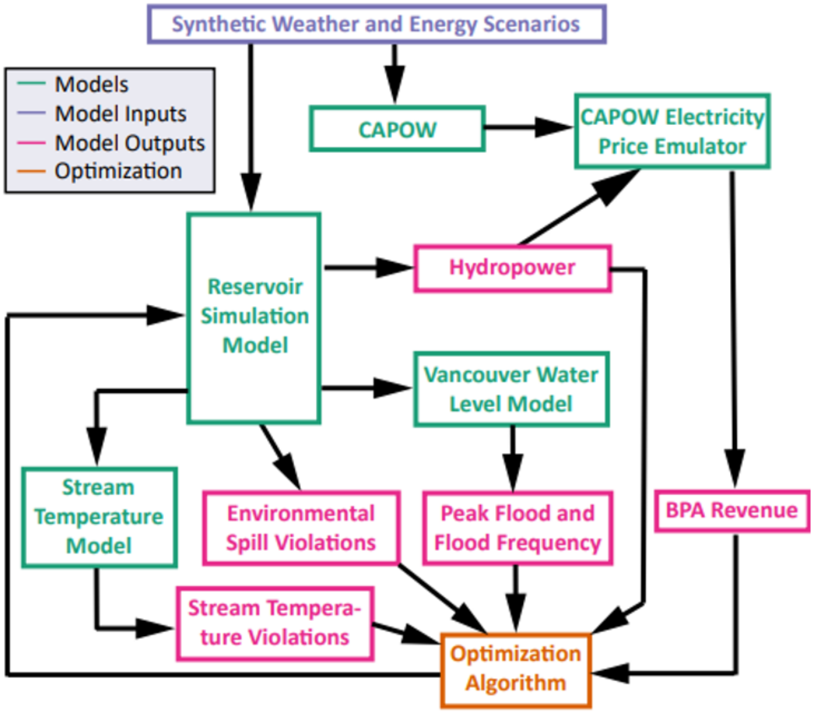


Figure 3. Columbia River Basin Model Flow Schematic

Power Systems Model

In order to simulate the operations of the U.S. West Coast bulk power system, we used the California and West Coast Power Systems (CAPOW) model, which was developed to explore the impacts of hydrometeorological uncertainty on the performance of this regional grid and is available on GitHub [9]. CAPOW utilizes a multi-zone unit commitment/economic dispatch (UC/ED) model, which inputs energy generation capacities and demands, and outputs energy prices associated with the least-cost dispatch of electric generators to meet demands in the California Independent System Operation (CAISO) and Mid-Columbia (Mid-C) wholesale energy markets. Relevant renewable energy inputs and demands for CAPOW are found by generating synthetic weather time series that closely reproduce observed statistical properties in air temperature, streamflow, wind speed, and solar irradiance values [9] while covering a wider range of plausible extremes.

Our team incorporated pumped storage as an energy source into this model. We generated an input file for the capacities of different renewable energy sources including pumped storage in California and the Pacific Northwest ranging from 2025 to 2035 using National Renewable Energy Lab’ s (NREL) Mid-Case Scenario with 95% Renewables by 2035. Building off of prior work by

Wessel et al. (2022) incorporating batteries into CAPOW [10], we modeled pumped storage in our UC/ED model as a battery with unique coefficients, hard-coded for pumped storage rate of charge, rate of discharge, and efficiency. Because NREL's scenarios assume capacity expansion and we assume the existing electricity grid in CAPOW, we scaled down the capacities of pumped storage and renewables from the NREL scenario so that they represented the same fraction of overall energy capacity in each market (CAISO and Mid-C).

Reservoir Systems Model

In order to understand how alternative reservoir operations~~,~~ influence socioeconomic and environmental performance metrics under changing climate and energy market conditions, we optimized reservoir operating policies at four reservoirs in the Columbia River Basin: Hungry Horse, Libby, Grand Coulee, and Dworshak. Operations were optimized using Evolutionary Multi-Objective Direct Policy Search [11]. This approach finds alternative parameterizations of operating rules using multi-objective optimization. We defined reservoir operations as radial basis functions describing how much water to release from each reservoir as a function of their storage, previous day's inflow, and a sinusoidal function of time with a period of one year. We then coupled a reservoir simulation model of the Columbia River Basin with the Borg multi-objective optimization algorithm [12] to find "non-dominated" operating rules across multiple system objectives, i.e., a set of alternative operations in which no policy outperforms another on all objectives, but trades off performance across them.

We defined six system objectives: (1) maximize hydropower production, (2) maximize hydropower revenue, (3) minimize maximum water level at Vancouver, WA, (4) minimize the percentage of days in which flood levels exceed 17 feet at Vancouver, WA, (5) minimize squared deviations from environmental spill guidelines, and (6) minimize squared deviations above desired water temperature maxima for fish at Lower Granite reservoir. Two of these objectives relate to maximizing generation and revenue from hydropower production, two to minimizing environmental spill and temperature deviations from desirable ranges for fish, and two to minimizing flooding frequency and severity. Revenue generation depends on energy prices, which are computed using a statistical emulator of CAPOW predicting prices in the CAISO and Mid-C markets as a function of generation from each energy source and demands. This emulator was built to a prior 1000-year run of CAPOW assuming historical reservoir operating rules. However, as we design alternative hydropower operations in the reservoir optimization model this changes prices predicted by the emulator, and consequently the revenue generated by BPA.

Flood levels were estimated through linear regression as a function of releases from Bonneville Dam (which vary as our upstream operations change), sinusoidal functions capturing the tidal cycle, and auto-correlated residuals. Desirable environmental spills from each reservoir were defined by discussions with Steven Barton from the U.S. Army Corps of Engineers (S. Barton, personal communication, September 20, 2022), while desirable stream temperatures (greater than 21.7°C) were taken from Richter and Kolmes, 2005 [13]. Stream temperatures at Lower Granite, through which salmon must migrate, were also predicted by a linear regression as a function of air temperature, wind speed, an annual sinusoid, and releases from Dworshak, which we optimize.

Social Implications of Reservoir Model

Aspects of our reservoir model were motivated by social concerns arising as a result of Dam construction. For example, local Native American tribes rely heavily on salmon and steelhead populations as their main food source. Changes in streamflow temperatures at dams along the Lower Snake River, such as Lower Granite below Dworshak, have drastic effects on fish populations. High temperatures can prove fatal to these species as they become more prone to diseases and the temperatures can affect growth during essential life stages. Our temperature objective ensures that the streamflow temperature at these days is not significantly raised due to the dam's hydropower operations, protecting the aquatic life.

Two of our main objectives, flood height and flood risk frequency, aim to protect the local environment and ecology from flooding. These objectives also are important for providing preventative safety measures to the nearby communities and neighborhoods. This is especially critical in highly populated cities near the Basin outlet, such as Vancouver WA and Portland OR just downstream. Modeling flood risks and making sure they are minimized is essential to prevent, but also notify the public in case of an emergency.

Future Climate and Energy Scenarios

After optimizing reservoir operations to 10 years of synthetic weather assuming historical statistics and current energy mixes, we simulated these policies over four climate change scenarios and the NREL Mid-Case scenario to inform the choice of a robust reservoir operations design that will perform well across these possible future scenarios. Different climate conditions should influence all six operating objectives through both increasing temperatures influencing stream temperature violations, and changing streamflow influencing hydropower production (and therefore revenue), environmental spills, and flooding. With respect to the NREL energy pathway, different energy mixes should influence energy prices, and therefore hydropower revenue. We expect some operations to generalize better across these possible futures, better balancing the system's needs in a more renewable grid experiencing changing climate conditions. Our analysis seeks to find such policies to make recommendations on how operations, particularly at Dworshak, should adapt.

Four general circulation model (GCM) projections were chosen to represent wet and dry futures, each with high and low warming. These were selected based on mean projected streamflow at Bonneville Dam, the most downstream reservoir in the Columbia River Basin and mean projected temperature across all NOAA weather station locations in CA and the PNW from 2019-2044 [14]. Projected streamflow and temperature across all CAPOW model sites in CA and PNW were then downloaded from the “Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections” archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ for these four GCMs [15]. "We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 2) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals."

Table 1: Climate models from CMIP5 used in this project.

Climate Scenario	**Corresponding GCM**
Wet High Warming	MIROC-ESM-CHEM RCP 8.5 r1i1p1
Wet Low Warming	GISS-E2-H-CC RCP 4.5 r1i1p1
Dry High Warming	HadGEM2-AO RCP 4.5 r1i1p1
Dry Low Warming	MRI-CGCM3 RCP 4.5 r1i1p1

We also simulated the optimized reservoir operations over three-time steps from the NREL Mid-Case Scenario with 95% Renewables by 2035: 2025, 2030 and 2035. We first ran CAPOW over these scenarios, each of which was represented by the same 10 years of synthetic weather as the historical scenario, but different energy mixes for each time step instead of the current energy mix. We then built six surrogate regression models of the prices in the CAISO and Mid-C electricity markets at each of these three-time steps as a function of electricity demands and production from wind, solar, and hydropower. The surrogates output the model parameters to utilize in the reservoir optimization model to predict energy prices, and subsequently hydropower revenue, under the alternative operations that were optimized to historical climate and energy mixes. Figure 4 shows how temperatures, wind speeds, and streamflow change across these scenarios for Dworshak and its closest weather station (Spokane, Washington). Figure 5 shows how different renewable energy sources' capacities change in future scenarios, while hydropower capacity stays roughly the same over time.

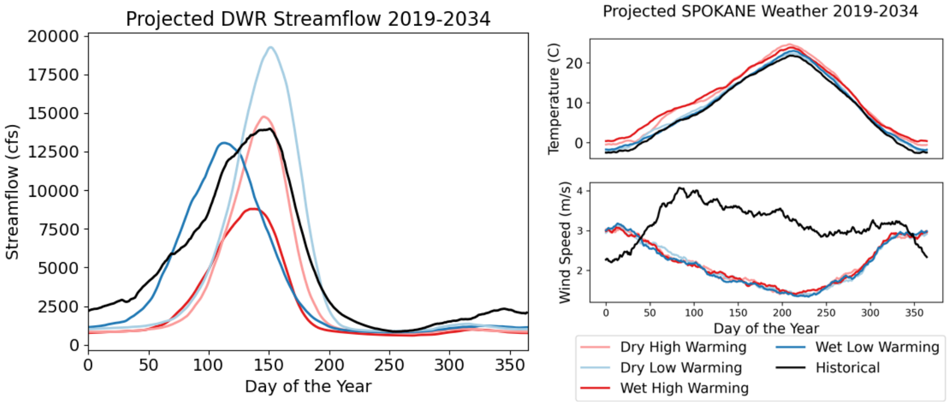


Figure 4. Projected Temperature, Windspeed, and Streamflow based on the 4 Climate Change Scenarios

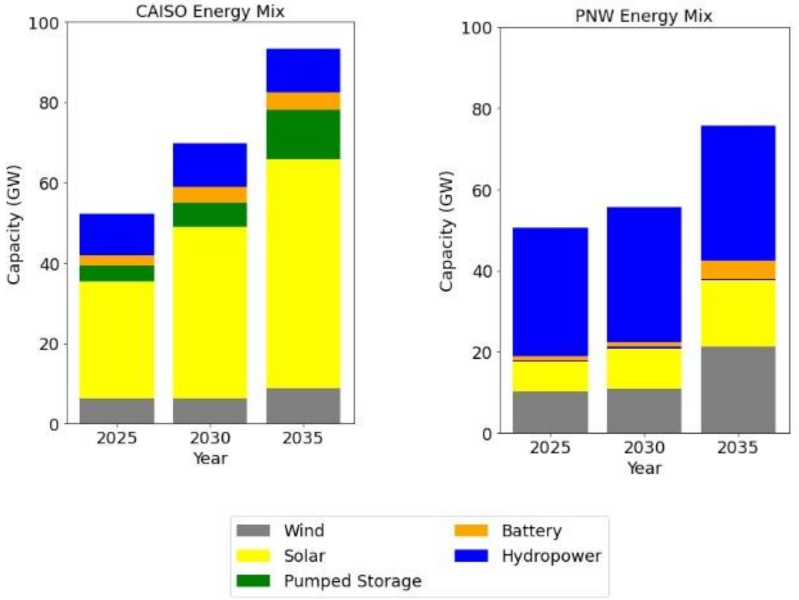


Figure 5. The distribution of energy sources by capacity (MW) in the CAISO and PNW regions over time for the 3 Energy Scenarios

Performance Tradeoffs under Different Scenarios and Chosen Optimal Policy

Our multi-objective optimization yielded 19 alternative reservoir operating policies whose performance we first evaluate across the three different energy scenarios. Figure 6a shows how the different energy mixes in these scenarios influence electricity prices optimized by CAPOW's unit-commitment, economic dispatch model. Mid-C and CAISO price correlations between energy demands in relevant regions (rows 1-6) and energy mix inputs (wind, hydropower, and solar) are indicated by heatmaps. Strong negative correlations between Mid-C prices and PNW hydropower, PNW wind, and BPA wind reveal positive externalities for the energy sector with increased renewables generation. The price correlation with PNW hydropower decreases over future timesteps, whereas the price correlation with PNW and BPA wind increase over future timesteps. We also see a moderate positive correlation between Mid-C prices and PNW demand. Similar effects are seen in California, with the exception that demands in the PG&E bay, PG&E valley, SDG&E, and SCE regions are instead positively correlated with CA prices.

Figure 6b shows the BPA revenue of the 19 optimized reservoir operating policies in each energy scenario. All policies see reduced BPA revenue into the future as electricity becomes cheaper from increased renewable generation. The selected optimal policy, shown in red, has average performance across the 2025, 2030, and 2035 BPA revenue objectives. This policy was selected because it favors environmental objectives (see Figure 7), but this comes at the expense of hydropower production which is BPA's main source of revenue.

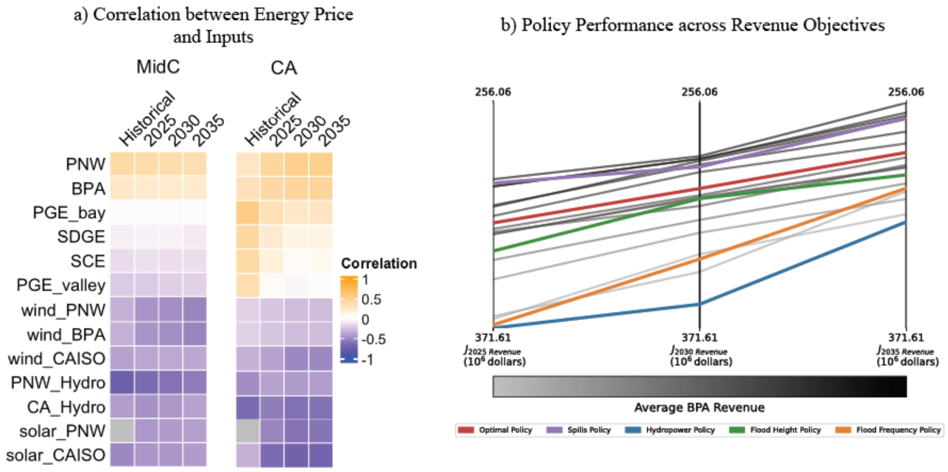


Figure 6. Correlation between energy prices and historical, 2025, 2030, and 2035 energy inputs in Mid-C and CA (a); 2025, 2030, and 2035 BPA revenue for 19 policies across 13 climate scenarios (b).

Figure 7, shows the tradeoffs across the 19 non-dominated operating policies under a) historical conditions, b) on average across the four climate scenarios and c) in the worst case across the climate scenarios, as well as d) one box-and-whisker plot showing the variability in performance across climate scenarios for our selected optimal policy (#10) and the policy that optimizes each individual objective over historical conditions (5 total policies). The parallel plots have the following objective functions: environmental spills, hydropower generation, peak flood height, and moderate flood frequency. The water temperature objective is not shown because no policy violated the water temperature threshold at Lower Granite in any climate scenario. BPA revenue is not shown because CAPOW was not run under these climate scenarios due to computational limitations, so we instead built surrogate price models for these scenarios.

Policy 10, shown in red, is the optimal selected policy as it has the least significant tradeoff between objectives. It performs near the median across policies on the historical hydropower and BPA revenue (Figure 6) objectives, while performing best or near-best on minimizing spills, flood height, and flood frequency regardless of the scenario. The principal aim of this research is to increase the environmental protection performance of the hydropower operations. There are some policies that perform better environmentally, but do not yield adequate revenue. The policies that perform the best for the revenue objective had a significantly higher tradeoff for the environmental objectives, so they were not considered over the more reasonable compromise option of Policy 10.

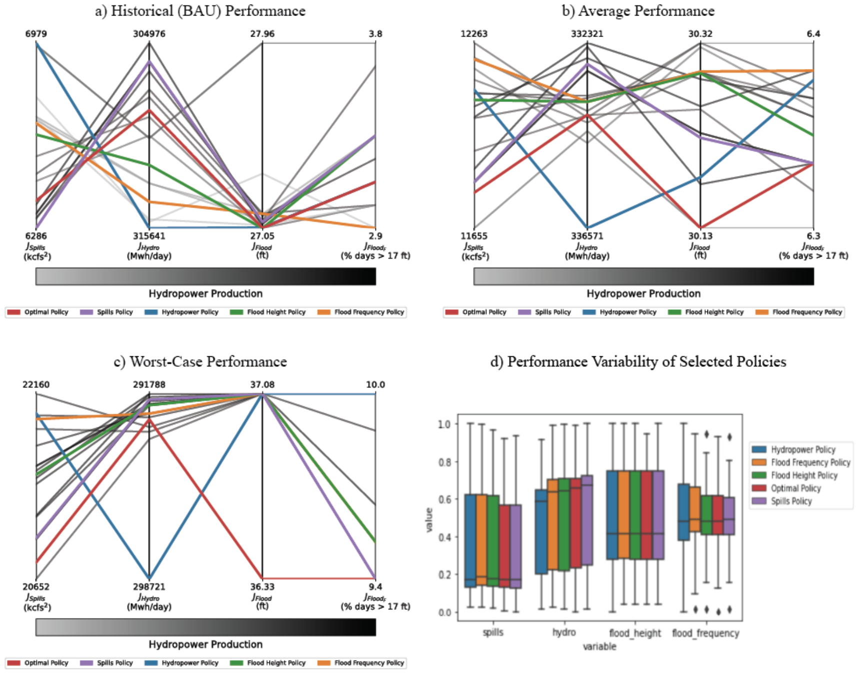
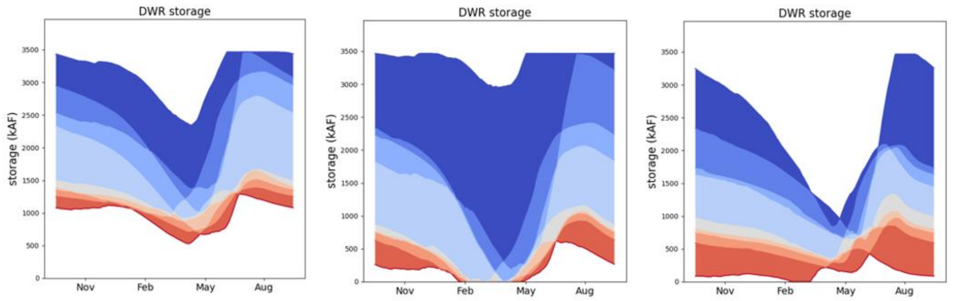


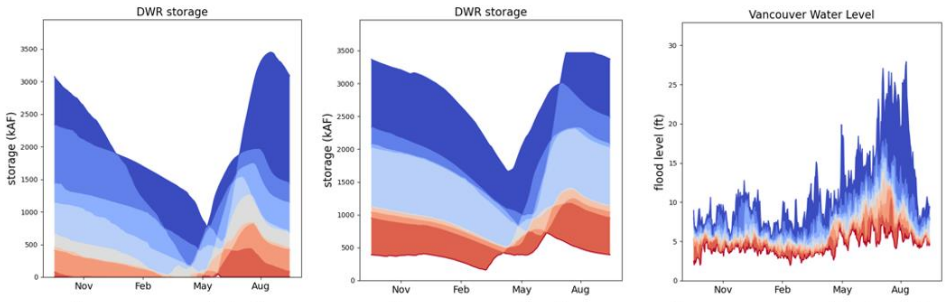
Figure 7. Four plots that summarize performance of the policies over varying climate cases and the variability of policy performance across environmental objectives. [Shown: Historical (BAU) Performance Parallel Plot (a), Average Performance Parallel Plot (b), Worst-Case Performance Parallel Plot (c), Performance Variability of Selected Policies Across Objectives for the Dworshak Dam(d)].

Comparing tradeoffs across climate scenarios, we see that while the historical climate is similar to the average climate across scenarios, performance on average results in very different tradeoffs (Fig 7b) than under historical conditions (Fig 7a). This suggests there is significant nonlinearity in performance across the climate scenarios. With the Average future climate case, we can see an increase in spills, flood frequency, and risk of large floods (greater than 17 ft) with the same policies, as compared to the historical case. The hydropower production minimum and maximum are also increased for the average climate case as compared to the historical case, but relative to historical performance, the hydropower production performance for our selected policy is comparable. In the worst-case climate scenario, there are extreme temperatures and stream flows, causing much higher flood heights, flood frequencies, and environmental spill violations. Additionally, there is lower hydropower production. Policy 10 was chosen over other comparable options because Policy 10 has significantly better performance for environmental objectives in these extreme climate scenarios for only marginally decreasing performance in the hydropower and revenue objectives. The justification for this policy aligns much more closely with the project's purpose of improving environmental protection of these hydropower power plant operations.

How Different Policies Operate Dworshak to Achieve these Performance Metrics



(a) DWR storage, Hydropower Policy (b) DWR storage, Flood Frequency Policy (c) DWR storage, Flood Height Policy



(d) DWR storage, Optimal Policy (e) DWR storage, Spills Policy (f) Vancouver Water Level, Optimal Policy

Figure 8. The Multipaneled DWR Storage Model for Selected Policies, including Vancouver Water Level under optimal Policy 10.

Figure 8 displays the distribution of reservoir storage over time for Dworshak when using Policy 10 vs. the policy that is optimal for each individual objective over the historical record, as well as the city of Vancouver's water level based on operations of Policy 10 over the 10 years in the historical record. Lines from red to blue show the different percentiles of storage/water level at each time step. Across policies, operations at Grand Coulee, the largest power-producing reservoir, kept storage at this reservoir full at all times to maximize hydropower revenue, using dams like Dworshak with smaller power capacity but large storage for flood protection. This figure shows how Policy 10 uses Dworshak for most of this flood protection compared to the other policies, as it keeps relatively low storages throughout the year, reaching the lowest storage compared to other operational policies. Under this policy, DWR begins filling up in late August to reduce peak flows downstream. The effectiveness of these operations can be seen by the persistence of the peak flood level at Vancouver as opposed to a sharper, higher peak. These figures can inform how operations at DWR should be adapted to balance these objectives in the future.

Stakeholder Engagement Plan

The goal of our Hydro4E team is to design adaptive hydropower operations to meet the *Energy* needs of a more sustainable grid reliant on renewable energy sources while *Equitably* balancing other *Economic* and *Ecological* objectives. Achieving this goal will require iterative engagement with stakeholders throughout the design process to ensure our multi-objective optimization of reservoir operations includes objectives that capture these 4 Es of Hydropower Systems (Figure 9). Below, we detail the role of these 4 E’s in the Columbia River Basin (CRB), and how we will engage with their respective stakeholders to appropriately represent their objectives in our design efforts.

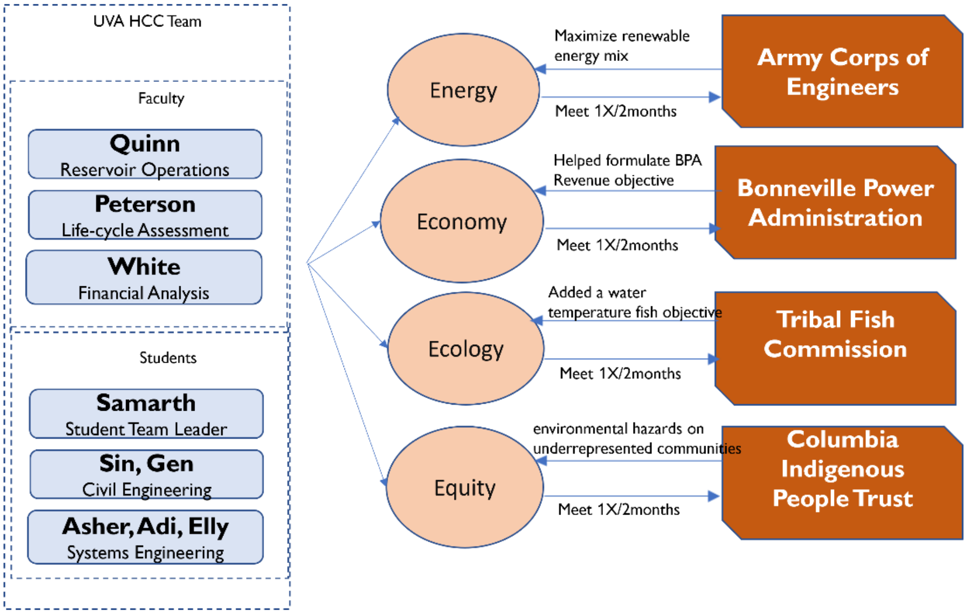


Figure 9: Iterative Stakeholder engagement plan where periodic meetings are held with the stakeholders to formulate multi-objective optimization objectives and constraints, across 4Es. (Figure added post mid-year reviewer comments)

Energy

Within the CRB, 31 federal dams primarily owned by the U.S. Army Corps of Engineers (USACE) provide 50-65% of the region's electric power. This plays a critical role in the sustainability of the West Coast Power System; consequently, maximizing hydropower is an important objective to include in our optimization. However, as the Pacific Northwest integrates additional wind power and the connected California Independent System Operation (CAISO) more solar power, hydropower operations will need to adapt to balance their intermittent supply.

We are working with the U.S. Army Corps of Engineers (USACE) in the Pacific Northwest and Pacific Gas & Electric in California to ensure we appropriately capture possible energy development scenarios to inform our modeling with the goal of maximizing the portion of energy demands met by renewables.

Steve Barton, a former BPA employee, informed us that USACE is always looking to adapt their operations to better balance trade-offs under changing climate and energy markets. This indicates that their goals are in alignment with ours, which is a good sign for market deployment. However, a big challenge to adoption will be in making the policies transparent, which is one of the goals we hope to fulfill with this optimization solution.

Economy

Hydropower operations have several economic implications. Two important economic impacts are on the revenue of the utility company and on preventing damages to downstream communities from flooding.

1) Utility Revenue

Economics of energy in the West are changing at an unprecedented rate due to decarbonization. While the massive deployment of cheap renewable energy sources across the West will have great environmental benefits, it has had a detrimental impact on the Bonneville Power Administration's (BPA's) revenue stream, which in time could threaten the viability of capital-intensive and debt-laden infrastructure projects in the CRB. Therefore, it's critical to ensure steady BPA revenue. Additionally, CRB reservoir operations can influence prices in the connected CAISO market, whose largest provider is Pacific Gas & Electric.

Our discussions with Steve Barton of BPA and Sue Nee Tan of PG&E have informed the economic revenue objective included in our multi-objective optimization.

2) Flood Protection

U.S. dams within the CRB also provide 55.3 million acre-feet of storage for flood protection. However, most U.S. flood protection comes from large storage dams in Canada whose operations are stipulated by the Columbia River Treaty, which expires in 2024. If Canada is no longer willing to accommodate U.S. flood protection needs, the U.S. will need to modify their reservoir operations to improve protection against flooding.

Flood protection objectives are governed by USACE operating guidelines that take all basin stakeholders into account, including residents and industries along the river. The locations of greatest economic interest are Vancouver, WA and Portland, OR near the Basin outlet, so we originally formulated our flood protection objective to minimize the maximum water level at this location. Iterative discussions with Steve Barton, Chief of the Columbia Basin Water Management Division the U.S. Army Corps of Engineers led us to add an additional flood objective related to the frequency of exceedances of a lower threshold that cause less significant, but non-negligible nuisance economic impacts.

Ecology

Another crucial CRB system objective is to maintain steady flows during fish migration, especially for salmon during the spring and fall. This objective is particularly important to Native populations, as salmon are one of the most important aspects of the cultures of the Indigenous peoples of the Columbia River Basin. Thus, protecting salmon both protects the environment and ensures equitable distribution of food resources and dignity to sacred tribal symbols.

We have been engaging with Alison Colotelo of the Pacific Northwest National Lab (PNNL) on how to capture flow requirements for fish in our optimization. She suggested we consult the Washington DART database and the USACE’s Fish Operations Plans to define spill targets. Steve Barton also suggested adding a water temperature objective to ensure reservoir releases provide more favorable cooler water downstream in the spring through fall. We will continue refining these objectives with them throughout the project.

Equity

Each of the above objectives is important to different stakeholders. Performing multi-objective optimization enables the discovery of alternative operations that favor these objectives in different ways. This can facilitate discussions among stakeholders to discover equitable compromise solutions that would likely be overlooked from strictly single-objective (often economic-only) optimizations.

The stakeholders influenced by BPA operations include utility companies like BPA and PG&E, as well as populations in the Basin that utilize the river water and its fish, or those who are potentially impacted by its flood flows. These include industries, farmers, and Indigenous populations. Strictly economic optimization would likely favor objectives for large utilities and industries like BPA. The Department of Energy (DOE) has put forth efforts to address the adverse impacts of environmental hazards on underrepresented communities. This includes working with communities with minority and low-income populations, as well as the American Indians who are disproportionately impacted. Those who have been historically excluded must have the same access to environmental decision-making and a working knowledge of the subject matter for their participation to be meaningful. DOE's environmental justice program aims to give stakeholders opportunities to participate in DOE decision-making to the greatest extent possible and to ensure they have the tools to strengthen their economies [16].

By also including objectives of more marginalized communities such as Indigenous populations and the environment, we hope to discover more equitable operations, and iterative deliberation with all stakeholder groups can help arrive at these alternatives.

Conclusion

We expect that climate change and our ability to mitigate it will cause great levels of uncertainty in terms of both the future energy mix and streamflow patterns. We need robust hydropower systems in order to adapt to such changing climate and energy grid needs. Based on our optimization model, the best policy for the Columbia River Basin hydropower system is Policy 10 which is illustrated and described in the results portion of this paper. This policy is designed to be effective in today’s and tomorrow's climate, through extreme weather and multiple energy mixes. As engineers, we are responsible to design and adapt systems to meet the needs of the growing population and the changing world, as well as the social needs of nearby communities. There are numerous social effects that result from dam construction and hydropower systems operations, and our design takes into account those effects. This case study's goal was to optimize the Columbia River Basin's hydropower system while focusing on the effects of our new design, specifically on the Dworshak Dam and its reservoir, to maximize the hydropower output and economic benefits while minimizing environmental and social effects. Our research and methodology could be mirrored by engineers globally, making hydropower and other renewable energy sources more efficient and reliable, and ultimately improving societies everywhere.

References

[1] American Rivers. (n.d.). Columbia River. Retrieved from https://www.americanrivers.org/river/columbia-river/
[2] Columbia River. (2019). American Rivers. Retrieved from https://www.americanrivers.org/river/columbia-river/.
[3] Western Electricity Coordinating Council. (2018). Technical Session book. Retrieved from https://www.wecc.org/Administrative/June%20Technical%20Session%20Book.pdf
[4] U.S. Department of Energy. (2021). Pumped Storage Hydropower. Energy.gov. Retrieved from https://www.energy.gov/eere/water/pumped-storage-hydropower
[5] Northwest Power and Conservation Council. (2021). Columbia River Treaty History. Retrieved from https://www.nwcouncil.org/reports/columbia-river-history/columbiarivertreaty/
[6] Northwest Power and Conservation Council. (n.d.). Grand Coulee Dam's Impacts on Fish and Wildlife. Columbia River History. Retrieved from https://www.nwcouncil.org/reports/columbia-river-history/grandcouleeimpactsonfish/
[7] US Amry Corps of Engineers. (n.d.). Dworshak Dam and Reservoir. Walla Walla District Website. Retrieved from https://www.nww.usace.army.mil/Locations/District-Locks-and-Dams/Dworshak-Dam-and-Reservoir/
[8] Giovando, J., & Dozier, D. (2011). Dworshak Dam-Storage Optimization: Improving power Generation with Historic and Climate Change Hydrology. *Hydrology Days*, 167-192. Retrieved from http://hydrologydays.colostate.edu/Papers_2011/Giovando_paper.pdf
[9] National Renewable Energy Laboratory. (n.d.). NSRDB Data Viewer. Retrieved from https://nsrdb.nrel.gov/data-viewer
[10] Wessel J., Kern, J., Voisin, N., Oikonomou, K., Jannik Haas, J. (2022). Technology Pathways Could Help Drive the U.S. West CoastGrid's Exposure to Hydrometeorological Uncertainty.
[11] Giuliani, M., Castelletti, A., Pianosi, F., Mason, E., & Reed, P. M. (2016). Curses, tradeoffs, and scalable management: Advancing evolutionary multiobjective direct policy search to improve water reservoir operations. *Journal of Water Resources Planning and Management*, *142*(2), 04015050.
[12] P.M. Reed, D. Hadka, J.D. Herman, J.R. Kasprzyk, J.B. Kollat. (2013) Evolutionary multiobjective optimization in water resources: The past, present, and future.
[13] Kolmes, K.A., & Richter, A. (2005). Maximum temperature limits for Chinook, Coho, and Chum Salmon, and Steelhead trout in the Pacific Northwest. Reviews in Fisheries Science, 13, 23-49. doi: 10.1080/10641260590885861
[14] National Centers for Environmental Information. (n.d.). Climate Data Online (CDO) - Access to NCDC climate data and information. Retrieved from https://www.ncdc.noaa.gov/cdo-web/
[15] U.S. Army Corps of Engineers. (n.d.). Columbia River Wildlife Mitigation. Northwestern Division. Retrieved from https://www.nwd.usace.army.mil/CRWM/
[16] Office of Legacy Management. (n.d.). What is Environmental Justice? Energy.gov. Retrieved from https://www.energy.gov/lm/what-environmental-justice