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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***Abstract*—There is unequivocal evidence that the Earth is warming at an unprecedented rate, and that the burning of fossil fuels is the principal cause. This situation is fostering a growing interest in shifting global energy production toward renewable energy sources such as solar, wind, and hydropower. Hydropower plays an important role in meeting global carbon mitigation targets and eventually achieving net-zero carbon emissions, especially within the Mid-Columbia (Mid-C) energy market in the Pacific Northwest (PNW), where hydropower currently comprises 50-65% of its generation. However, other renewable energy sources in the Mid-C market and connected California Independent System Operator (CAISO) power grid are expanding significantly, particularly solar power in California (CA). Thus, hydropower operations at plants within the connected Mid-C market may need to be re-operated to balance the more intermittent supply from renewables in CA so that energy supplies are in phase with demands. In this study, our goal is to re-design hydropower operations in the Columbia River Basin (CRB) of the PNW to achieve a 95% renewable energy power grid in CA and the PNW by the year 2035. This will require not only filling supply gaps from other renewable energy sources, but also balancing other conflicting objectives to be fulfilled by the dam operations, such as minimizing environmental spill violations, maximizing hydropower production, maximizing flood protection, and maximizing economic benefits. We use multi-objective optimization to design alternative operations at four CRB dams to balance these objectives over the historical record. We then simulate their operations over alternative possible future climate change and energy development scenarios to find a recommended set of operations that are robust to these uncertainties. The energy scenarios include the National Renewable Energy Lab's (NREL) Mid-Case Energy Scenario for the years 2025, 2030 and 2035, which achieve 95% Renewables by 2035, as well as a business as usual (BAU), or base case, scenario represented by the historical energy mix. The four climate scenarios are made from combinations of low or high warming and low or high streamflow for three overlapping time steps: 2020-2029, 2025-2034, and 2030-2039. Our optimization is able to find a robust compromise policy that balances the system's conflicting objectives well both now and in the future. We close by exploring how this policy coordinates operations across system reservoirs, which could inform reservoir operators in the CRB about how to adapt operations as the system changes in the future.**

I. INTRODUCTION

Human activities, principally through emissions of greenhouse gasses (GHGs), have unequivocally caused global warming, with global surface temperature reaching 1.1 °C above pre-industrial (1850–1900) levels in 2011–2020, precipitating widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere. Since then, GHG emissions have continued to increase, and global GHG emissions in 2030 implied by current climate action plans make it likely that warming will exceed 1.5 °C during the 21st century. With every increment of global warming expected to escalate risks, projected adverse impacts, and related losses and damages from climate change, deep and sustained emissions reductions through rapid and far-reaching transitions across all sectors and systems are necessary to secure a livable future for all [2]. The Paris Agreement, a legally binding international treaty on climate change adopted by 196 Parties in 2015, identifies limiting global warming to 1.5 °C above the pre-industrial average as a central goal [3]. All global modeled pathways that limit warming to 1.5 °C reach net-zero CO2 emissions in the early 2050s [2].

Decarbonization efforts should be especially prioritized within the energy sector which is responsible for approximately two-thirds of global CO2 emissions. Within the energy sector, burning fossil fuels like oil, coal, and natural gas generates 84.3% of global primary energy and is therefore the primary contributor to climate change; for comparison, nuclear energy accounts for 4.3% of global production, and only 11.4% of global energy demand is met by renewable sources like hydropower, wind, and solar [4]. Achieving net-zero emissions within the energy sector will require rapid investment in and adoption of renewable alternatives to fossil fuels to replace existing high-emissions infrastructure, especially as global energy demands are expected to nearly double by 2050 [5]. However, increased reliance on weather-dependent energy sources like wind and solar will make the energy supply more variable and out of phase with demand.

Due to its fast ramp rates which help balance supply and demand and its ability to store energy through pumped storage facilities, hydropower uniquely facilitates the necessary transition to renewable energy sources in pursuit of deep decarbonization of the energy sector. However, adapting hydropower operations for greater load balancing could come at the expense of sustaining environmental flows for wildlife and ensuring sufficient water supply and flood protection. Re-designing the operating policies of existing hydropower plants is therefore a crucial step in adapting hydropower systems to complement decarbonization of the energy sector while mitigating the impacts of floods, droughts, and regulated flows on freshwater sustainability. This study uses multi-objective optimization to design alternative reservoir operating rules that balance these conflicting objectives using the Columbia River Basin in the Pacific Northwest as a case study.

II. BACKGROUND

The Columbia River Basin (CRB), located in the Pacific Northwest (PNW), covers 258,000 square feet [6], running through seven states and one Canadian Province [6]. 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 [7]. 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 five zones in California. 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 [8]. 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 [9]. 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 [10]. 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 [11]. 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.

III. METHODS

A. 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 are generated for three ten-year time step periods 20 years into the future. Figure 1 shown below 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 energy storage price model, and climate change scenarios. The functions and components of each of these models are detailed more extensively in the following methods subsections B through D. Following the schematic, this entire model generates a series of outputs, including maximizing hydropower output and BPA revenue, and minimizing spills, peak flood height, and moderate flood frequency. These outputs are then optimized by an algorithm that finds different policies by analyzing trade-offs in performance across all objectives, which we investigate in the results.

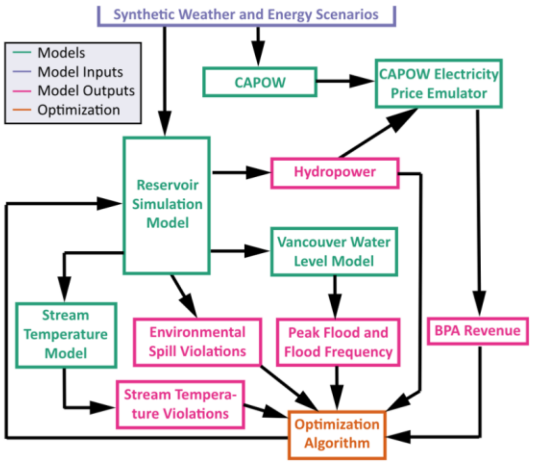

Figure 1. Columbia River Basin Model Flow Schematic

B. *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 [12]. 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 [12] 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 2022 to 2050 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 [13], 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).

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 [14]. 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 [15] 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 deviations from environmental spill guidelines, (6) minimize 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 1000-year run of CAPOW assuming historical reservoir operating rules. However, as hydropower operations in the reservoir optimization model vary, so too do the prices predicted by the emulator and the revenue generated by BPA. Flood levels are 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 [16]. 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.

D. *Future Climate and Energy Scenarios*

After optimizing reservoir operations to 10 years of synthetic weather assuming historical statistics, 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. Different energy mixes should influence energy prices, and therefore hydropower revenue.

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 [17]. Projected streamflow and temperature across all CAPOW model sites in CA and PNW were then downloaded from U.S. Army Corps of Engineers [18] for these four GCMs.

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 and 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 2 shows how temperatures, wind speeds, streamflow change across these scenarios for the Dalles Dam (TDA) just upstream of Bonneville and the closest weather station to Lower Granite (Spokane, Washington). Figure 3 shows how non-hydropower renewable capacity changes in future scenarios, while hydropower capacity stays the same.

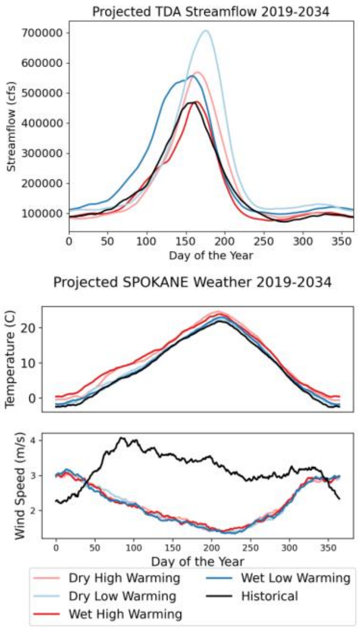

Figure 2. Projected Temperature, Windspeed, and Streamflow based on the 4 Climate Change Scenarios

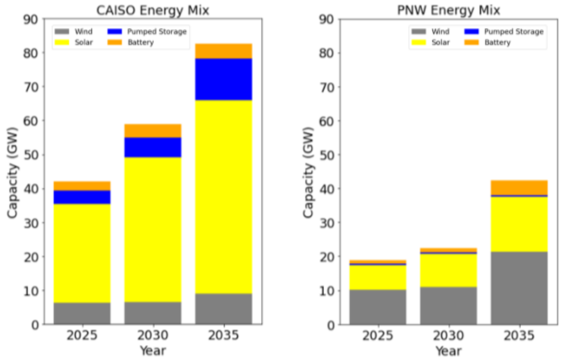

Figure 3. The distribution of energy sources by capacity (MW) in the CAISO and PNW regions over time for the 4 Climate Change Scenarios

IV. RESULTS AND DISCUSSION

A. 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 4a 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 PGE bay, PGE valley, SDGE, and SCE regions are instead positively correlated with CA prices.

Figure 4b 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 5), but this comes at the expense of hydropower production which is BPA's main source of revenue.

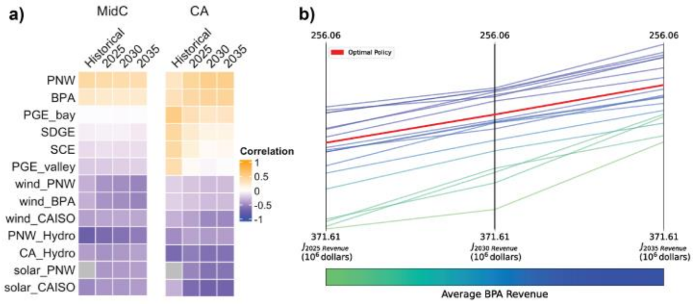

Figure 4. Correlation between energy prices and historical, 2025, 2030, and 2035 energy inputs in Mid-C and CA (a); 2025, 2030, and 2035 BPA revenue for 19 policies across 13 climate scenarios (b).

Figure 5, shows the tradeoffs across the 19 different operating policies under (a) historical (BAU) conditions, (b) on average across the three climate scenarios and (c) in the worst case across the climate scenarios, as well as (d) one box-and-whisker plot to show uncertainty for our chosen optimal policy across the four climate scenarios and three-time steps. The parallel plots have the following objective functions: environmental spills, hydropower generation, peak flood height, and moderate flood frequency. Policy 10, shown as the red line on each graph, is the optimal selected policy as it has the least significant tradeoff between objectives. It effectively maximizes hydropower output and BPA revenue, while minimizing spills, flood height, and flood risk. There are some policies that perform better environmentally, but do not yield adequate revenue. The principal aim of this research is to increase the environmental protection performance of the hydropower operations. 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.

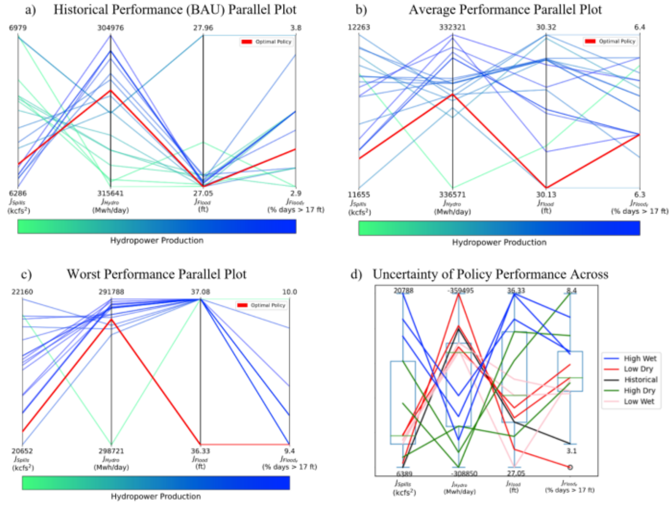

Figure 5. Parallel axis plots of historical scenario (a), average (b), and worst case (c) policy performance across five environmental objectives; measuring uncertainty of optimal policy across objectives (d).

The BAU climate case is a base case that models historical climate trends. While the BAU climate is similar to the average climate across scenarios, performance on average results in very different tradeoffs (Fig 5b) from BAU (Fig 5a). 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 BAU case. The hydropower production minimum and maximum are also increased for the average climate case as compared to the BAU 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 for only marginally decreasing performance in the revenue objective. The justification for this policy aligns much more closely with the project's purpose of improving environmental protection of these hydropower power plant operations.

B. Optimal Policy's Effect on Reservoirs

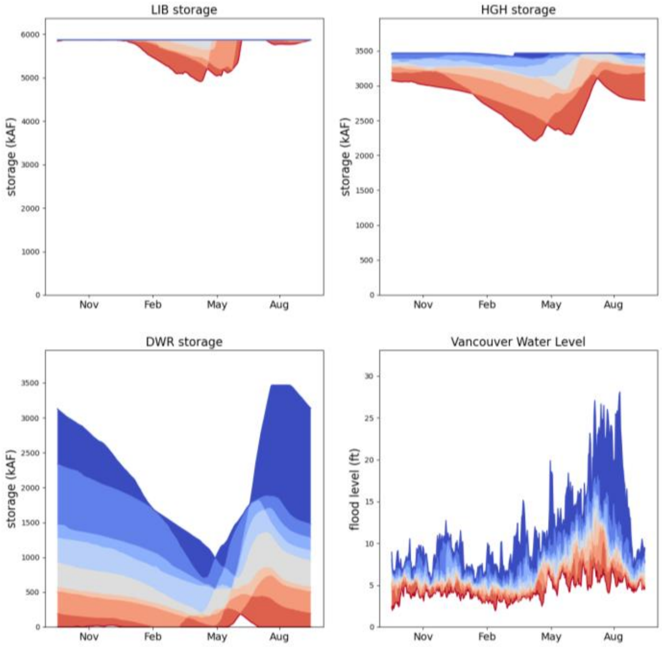

Figure 6. The Multipaneled Reservoir Storage Model

Figure 6 displays the distribution of reservoir storage over time for three different Columbia River Basin dams — Libby, Hungry Horse, and Dworshak — 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 at each time step across the 10 years. Operations at Grand Coulee are not shown because all policies chose to keep this reservoir full at all times to maximize hydropower revenue, using the dams with smaller power capacity but large storage for flood protection. This figure shows that Dworshak is used for most of this flood protection, as it keeps relatively low storages throughout the year until filling up in late August to reduce peak flows downstream. The effectiveness 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 these reservoirs should be adapted to balance these objectives in the future.

V. 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 streamflows. 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. In future work, developing a full factorial design describing the interaction between several climate and energy pathways would better represent future uncertainty and allow for the generation of more robust hydropower operating policies. Such an endeavor would require multiple CAPOW runs utilizing various combinations of climate and energy inputs across multiple future timesteps. In pursuit of facilitating the transition to global net-zero emissions, this analysis would ideally be conducted across timesteps through 2050 such that the generated policies continue to perform optimally amid increasing energy demands, decarbonization of the energy sector, and varying climate effects.

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