Hydropower Replacement and the Nexus of Food-Energy-Water Systems: Impacts on Climate Performance

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Abstract - **The nexus of food, energy, and water systems offers a meaningful lens to evaluate hydroelectric dam removal decisions. Maintaining adequate power supplies and flourishing fish populations hangs on the balance of managing the tradeoffs of water resource management. Aside from energy adequacy, substituting hydropower with other renewable energy sources impacts the overall energy dispatch behavior of the grid, including emissions of existing fossil fuels. This study extends earlier work in the literature to evaluate the adequacy impact to the power supply by removing four Lower Snake River dams in the Columbia River Basin in favor of supporting migratory salmon populations. The authors explore the climate performance, i.e., fossil fuel dispatch changes, of simulated renewable substitution portfolios to supplement performance metrics alongside adequacy and initial investment metrics. The study finds that including the climate metric greatly influences the favorability of some alternative portfolios that would otherwise be overlooked, with some portfolios improving climate mitigation efforts by reducing emissions over the baseline scenario. The contribution is in advancing a straightforward and supplementary climate performance method that can accompany any energy portfolio analysis.**

Keywords - **Food-energy-water nexus, dam removal, climate change, regional energy planning**

I. INTRODUCTION

Considering the nexus of food, energy, water and climate offers a valuable lens for the evaluation of dam removal or energy substitution decisions. On the one hand, hydroelectric dams provide power, in addition to other economic and transportation benefits. On the other hand, dams often have negative tradeoffs, such as jeopardizing migratory fish and adverse impacts on ecosystems [1]-[4]. For dam removal, this conflict is traditionally governed through regional water resource management decisions and is influenced by politics, economics, and cultural perspectives [5]-[9]. Aside from ecosystem considerations, climate change could also accelerate decisions on hydroelectric dam substitutions given that prolonged and severe droughts can lead to insufficient power generation due to lower water supply [10]. Applying a holistic food-energy-water approach can further shed light on these dynamics, especially when the climate perspective of greenhouse gas emissions is included.

Substituting hydroelectric dams with renewable resource portfolios requires a careful analysis of the economics and the adequacy impact to the power supply. Adequacy measures how well the power supply is sufficient to serve demand and is comprised of several interrelated performance metrics [11]-[13]. This is particularly important in renewable portfolios due to the intermittent nature of renewable energy generation technologies [14]-[18]. On financial aspects, decisionmakers must understand the investment opportunity alongside environmental performance to evaluate tradeoffs [19]-[23]. However, besides adequacy and financial metrics, it is also crucial to determine the overall greenhouse gas emissions (GHG) impact by evaluating the effects of such technological substitutions on existing fossil fuel megawatt hours (MWh) dispatch.

The impact of dams on migratory fish populations, the food component of the nexus consideration presented in this study, cannot be overlooked. In the Pacific Northwest, more than 40% of key river habitat for salmon and steelhead are permanently blocked due to dams, and fish passages to allow fish to migrate through do not fully mitigate the problem [24],[25]. This problem is not unique to the Pacific Northwest, and environmentalists cite dams as significant threats to marine ecosystems, especially as they inhibit migratory fish survival rates [26],[27]. The promising news for environmental advocates is that dam removal considerations are gaining traction as many dams in the U.S. are aging, becoming obsolete or uneconomical to maintain while also jeopardizing ecosystems [9],[26]. The calls for dam removals have resulted in a growing body of knowledge for incentivizing financial mechanisms for dam removal and trading schemes [28]-[30].

This study uses the Columbia River Basin (CRB) as a test case for evaluating the emission impact of substituting the four Lower Snake River (LSR) dams with renewable portfolios. The outcome of this study will provide the climate impact evaluations of the dam substitution portfolios that will increase the survivability of salmon and steelhead in the CRB as part of nexus considerations. Previous research has identified seven risk-comparable portfolios to substitute the effective capacity of 1,088 megawatt (MW) caused by the removal of the LSR dams [31]. The portfolios utilize a range of solar, wind, and battery storage capacity expansions, including three portfolios that included a small natural gas expansion due to probable investment in the technology. While the results focused on an adequacy analysis and initial capital expenditure of the portfolios, it is necessary to explore the climate perspectives of those portfolios to provide additional resolution on the technological substitutions. The portfolios under investigation to substitute the 1,088 MW effective capacity of the dams include in [31] include (1) wind-only, (2) solar-only, (3) 50% wind and 50% solar, (4) 250MW battery storage, wind, solar, and natural gas, (5) 500MW battery, wind, solar, and natural gas, (6)

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750MW battery, wind, solar, and natural gas, and (7) 1000MW battery, wind, and solar. Portfolios (4) and (5) are considered "low storage", and (6) and (7) "high storage" portfolios.

The CRB energy supply is comprised of over 50% hydropower, and along a mix of renewable sources such as wind and solar, there are still fossil-based generation sources from coal and natural gas [32]. When introducing new renewable sources, the dispatch behavior of the entire system changes according to the new energy generation characteristics. Thus, this paper evaluates how the fossil fuel dispatch changes under each risk-adequate substitution portfolio as a surrogate for climate performance through GHG impacts.

II. METHODOLOGY

The energy simulation for adequacy and dispatch was simulated using the GENeration Evaluation SYStem (GENESYS). GENESYS is the Monte Carlo power adequacy model used by the Northwest Power and Conservation Council (NPCC) [33]. The model simulates different power supply configurations in the CRB over a year, from October to September with April and August split to two segments due to the shift in seasons. The analysis presented in this study incorporates the projected climate change impacts utilized by NPCC to account for the added uncertainty due to climate change [34].

To simulate the portfolios, a baseline pre-removal scenario was created, followed by the removal of the four LSR dams. The removal scenario determined the 1,088 MW effective capacity gap [31]. Then, using iterations of GENESYS the seven substitution portfolios were generated via the associated system capacity contribution (ASCC), the measure of effective contribution of generation sources. The range of energy technology mixes was determined to provide a broad representation of alternatives. The actual megawatt capacity of each resource per portfolio is the result of the ASCC iterations until reaching the 5% loss of load probability (LOLP) when portfolios are considered risk-comparable and their key adequacy metrics can be compared.

To evaluate the fossil fuel dispatch (dispatch, for short), each portfolio's dispatch was compared to the pre-dam removal dispatch. The resulting performance of each portfolio is the percent change in dispatch, with a positive value indicating an increase in emissions and a negative value, a decrease. Three steps are required to evaluate the climate performance, an approximation of 95% of the fossil fuel MWh dispatch of each portfolio. First, the monthly hourly dispatch of coal and natural gas are averaged from the GENESYS climate scenarios, then multiplied by each months' number of hours. Second, the monthly percent difference for each portfolio from the baseline scenario, i.e., pre-dam removal fossil fuel dispatch, is calculated and called monthly climate performance. Lastly, the annual dispatch change captures the annual percent reduction/increase. Refer to (1), (2), and (3), with subscripts *i* as index for portfolio, and *t* as index for time (month).

$$Dispatch_{ij} = (Coal_{it} + Gas_{it}) * Hours_t \tag{1}$$

$$Monthly\ Climate\ Performance_{ij} = \frac{Dispatch_{it} - Baseline_t}{Baseline_t} \tag{2}$$

$$Annual\ Climate\ Performance_i = 1 - \frac{\sum_t Dispatch_{it}}{\sum_t Baseline_t} \tag{3}$$

The input data for the initial portfolio generation in GENESYS includes the planed decommissioning of some coal plants in the CRB, advocated removal of the four LSR dams, and expert judgment for the technology mix combined with ASCC iterations. The output of GENESYS, the fossil fuel dispatch, becomes the input data for the climate evaluation.

This methodology enables the evaluation of the seven portfolios' climate performance to supplement the adequacy and initial financial metrics to aid decisionmakers in comparing and determining the optimal tradeoff decision.

III. RESULTS

Figure 1 shows how the seven portfolios demonstrate a wide range of climate impact with the wind-only portfolio standing out as the best option for climate performance. Unlike the other portfolios, it is the only option that reduces the fossil fuel dispatch relative to the pre-dam removal scenario year-round, and by large percentage points: 10%-35% in the winter months, 10%-20% in summer, and 10%-30% in the spring. On the opposite end of the climate performance spectrum are the high storage portfolios, with increases in fossil fuel dispatch year-round, 10%-20% in late winter and early summer months. All scenarios show a dip from March till April as hydropower tends to operate at highest capacity around this time in the basin given the snowmelt.

This dip is responsible for the solar-only, wind and solar, and low battery storage scenarios to experience a localized reduction in fossil fuel emissions around April, expect for the high storage portfolios. From observing Figure 1, the runner up performance from a climate perspective is the wind and solar portfolio, demonstrating a slight reduction of fossil fuels for 7 months (OCT, NOV, APL, JUN, JUL, AUG, SEP) and a minor increase the remaining months. The monthly change in fossil dispatch helps decision makers understand the behavior of the system under each portfolio over time. However, to determine a comparable climate performance metric, the annual change in fossil fuel dispatch is more appropriate and can be observed in Figure 2.

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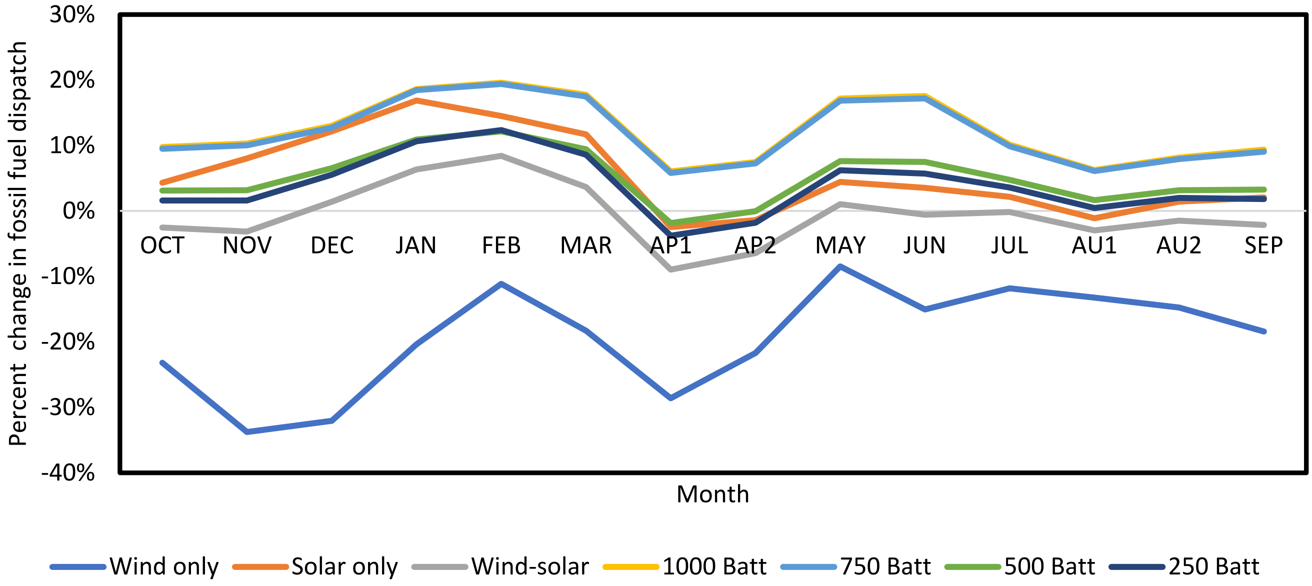

Fig. 1. Monthly difference in fossil fuel dispatch from baseline

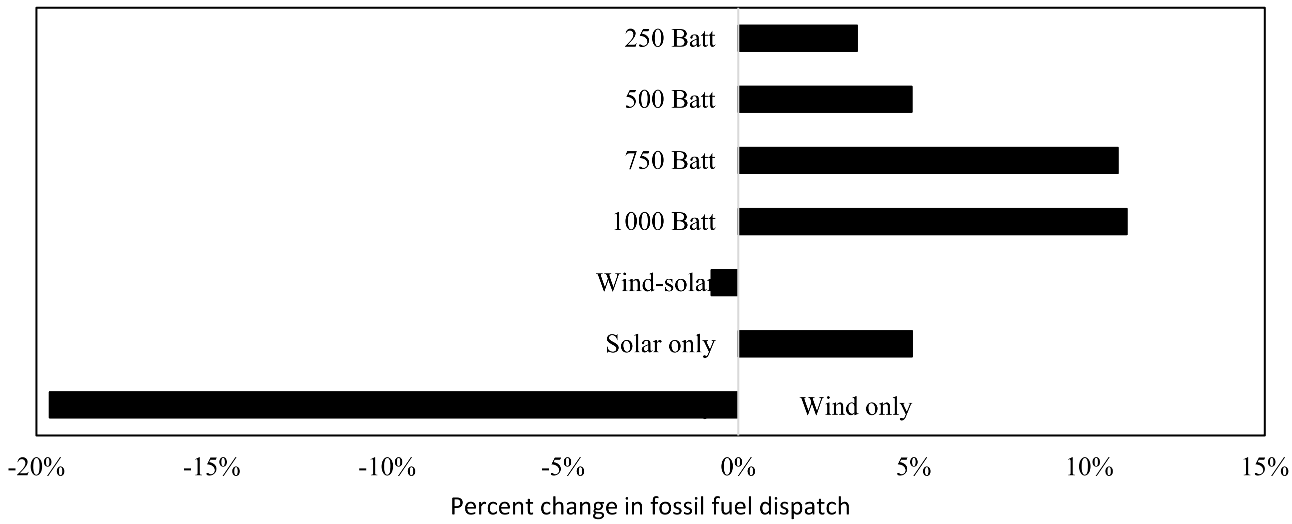

Fig. 2. Annual change in fossil fuel dispatch from baseline

The wind only portfolio offers almost a 20% reduction of annual fossil fuel dispatch, with the runner up wind-solar portfolio offering a reduction just shy of 1%, an expected outcome given the almost equal split of reducing/increasing months. The two high storage portfolios offer the worst climate performance, both increasing the fossil fuel dispatch by around 11% from the baseline. Lastly, the 250MW battery portfolio performs slightly better than the comparable 500MW battery and solar only portfolios.

IV. DISCUSSION

These results help energy decision makers see the seasonal impact of emissions for each portfolio, adding a valuable performance metric for consideration. The wind-only portfolio substantially reduced fossil fuel dispatch and, therefore, emissions from the baseline scenario. In other words, it is the best alternative to improve climate change mitigation efforts. However, the downside of this option is that it has the costliest capital expenditure and fixed operating costs [16], further emphasizing the importance of additional metric considerations. On the opposite spectrum, the high battery storage scenarios offer the cheapest capital expenditure and fixed operating costs, yet they have the worst performing climate metric and increase overall annual fossil fuel dispatch by ~11% each. The solar-only and wind-solar portfolios also experience a shift in consideration. On one hand, the solar-only portfolio demonstrates the best adequacy performance metrics, and

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third cheapest portfolio. However, it causes an expected 5% increase in annual fossil dispatch. On the other hand, the wind-solar portfolio exhibits the second-best adequacy performance, has the 2nd to last costliest option before the wind-only, and is expected to reduce fossil dispatch by 1%.

Based on these results, decision makers in the CRB are required to determine an optimal decision given several tradeoffs, including emissions, initial financial investments, and grid adequacy. From a climate perspective, the optimal choice is the wind-only portfolio. To offer additional considerations, decision makers can further analyze the financial performance of the portfolios by including variable operating costs and tax implications, as well as the broader impact of removing dams on regional economic and transportation networks.

As the energy supply in the CRB relies on over 50% hydropower generation, future work can further evaluate the substitution of additional dams. Recognizing that some substitution portfolios may improve emissions, either by a large or marginal extent, opens the discussion about conducting basin-level analyses to identify other climate beneficial opportunities.

The contribution of this study in is advancing a straightforward and supplementary climate performance method that can accompany any energy portfolio analysis. Though GENESYS is a specialized energy model for the CRB, any energy model that extracts the dispatch can be used to analyze substitution comparisons.

V. CONCLUSION

Evaluating the performance of the system with emphasis on climate metrics, such as fossil fuel dispatch as a proxy for emissions, is a valuable step in considering energy decisions in the food-energy-water nexus [35]. When considered alongside adequacy and financial metrics, emission performance metrics can tip the scales in favor of one decision that would have otherwise been avoided; or worse, that a negative climate impact would have occurred given the wrong decision. The key is for decision stakeholders to fully understand and review a broad range of performance metrics.

The fact that substitution portfolios may reduce fossil fuel dispatch, and therefore GHG emissions, provides meaningful insight that food-driven considerations may have additional non-food benefits in the nexus. The outcome shows that there are pathways to improve both survivability of migratory fish and reduce GHG emissions by choosing the wind-only portfolio, or to achieve marginal reduction with the wind-solar portfolio.

The results presented in this study relate to the CRB as GENESYS is tailored to the energy system in the Pacific Northwest. Though our findings are not universal, the presented methodology is valuable to other scholars and decisionmakers in their efforts to study the impacts of substituting hydroelectric dams. Future studies can identify additional climate-beneficial dam substitutions and expand on the research to further develop financial and emission models for additional metric considerations.

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