ENERGY SUPPLY READINESS ACROSS CLIMATE CHANGE AND ENERGY DEMAND SCENARIOS IN THE COLUMBIA RIVER BASIN

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By

Hong Liang

with Samantha Garcia, Kenneth Ross and Cameron Bailey

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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.

ADVISOR
Juliane Queen, Department of Engineering Systems and Environment

ABSTRACT

The Columbia River Power system is the country's largest renewable energy system, spanning several states and two countries. It provides one of the fastest growing regions in the continent with clean, reliable energy and protects thousands of square miles of land from flooding. The reservoirs on the Columbia River and its tributaries are responsible for many critical functions, such as flood prevention and mitigation, water quality and quantity assurance, and salmon reproduction. Despite these other objectives, the Columbia River Power system is the backbone of the region's energy supply, providing baseload when other renewable energy sources, namely wind and to a smaller extent solar, are unavailable. When hydropower cannot fill the gap, natural gas must instead, increasing reliance on fossil fuels. The objective of our project is to analyze the energy output of the Columbia River Basin across multiple different climate change and energy demand scenarios to understand the impact that each of these possible futures has on the region's ability to transition to a cleaner energy future while meeting potentially growing demands. By utilizing multiple scenarios, uncertainty around hydrometeorological and socioeconomic conditions can be quantified and addressed.

In this study, we analyze outputs in the middle of the 21st century from the California and West Coast Power System (CAPOW) model, customized to reflect each climate change and energy demand combination. Energy demand scenarios are quantified by Shared Socioeconomic Pathways (SSP) and climate change scenarios by CMIP5 Representative Concentration Pathways (RCP), providing projected trends until the end of the century. By varying low, middle, and high pathways across both the SSPs and RCPs, we can gain insights into the Pacific Northwest's energy health. This research has the potential to identify shortcomings in the current energy infrastructure, project the benefits and consequences of alternative development pathways, and

increase understanding of the Columbia River Power system's greatest sensitivities (climatic or socioeconomic). Future work can build off of this knowledge to design more robust reservoir operating policies in the Columbia River Basin.

INTRODUCTION

The Columbia River Basin (CRB), a network of 1,243 miles of rivers running into the Pacific Ocean, is a system that provides electricity, water, navigation, habitats and other natural resources to a wide swath of land. The system itself stretches across six US states (Washington, Oregon, Idaho, Montana, Nevada and Wyoming) and two Canadian provinces (British Columbia and Alberta) with over 400 dams. Considered the foundation of the Pacific Northwest's (PNW) power supply with 60% of all energy being hydroelectric, the CRB is a key contributor to the PNW energy market, in which consumers use over 170 million megawatt-hours of electricity [1][2]. The Bonneville Power Association (BPA), a federal organization in charge of 31 reservoirs' operation and energy transmission, oversees the 10 largest reservoirs in the Federal Columbia River Power System (FCRPS)[1]. Beyond the major function of producing renewable hydroelectric energy and outside the scope of this research, FCRPS reservoirs balance other objectives such as environmental protection of salmon runs, flood mitigation efforts, water quality and supply assurance, and other economic benefits [3]. Prioritizing these other demands could reduce hydropower production, creating cascading impacts on the energy system. These impacts include reducing generation from renewable energy, changing the price of electricity in the Pacific Northwest's Mid-Columbia energy market and the adjacent California Independent System Operator (CAISO) market. Changing climate conditions could also influence future hydropower production potential, causing cascading impacts on these energy systems.

One way of understanding these multi-sectoral impacts is through integrated water-energy system models such as the California and West Coast Power Systems (CAPOW) model. CAPOW uses stochastic simulation to generate possible temperature and streamflow time series that feed a reservoir operations model and unit commitment/economic dispatch model (UC/ED). The outputs of the UC/ED model include system costs and energy prices [5]. This paper uses CAPOW to analyze the potential benefits and consequences of alternative development pathways in the region under possible future climate scenarios in the years 2050-2059, representing a mid-century scenario for the CA and PNW region. These scenarios are represented by climate projections from the Coupled Model Intercomparison Project 5 (CMIP5) Representative Concentration Pathways (RCP), and population and energy growth scenarios informed by Shared Socioeconomic Pathways (SSP)[6][7]. This paper's research has focused on altering the CAPOW model to reflect scenarios combining a specific climate change and energy demand future and understanding the impact each potential scenario has on the CRB. The goal is to understand how these two sets of scenarios interact in shaping future socioeconomic benefits and consequences in the region with the goal of informing regional energy development.

BACKGROUND

A common finding throughout the literature we have reviewed was that the compounding effects of climate change are currently poorly understood. Renewables and combustible turbine energy accounted for 56% of electricity in the Western US in 2015, and climate change can impact the availability of these resources [8]. Streamflow, air temperature, water temperature, humidity, and air density will all be affected by climate change, and therefore the overall energy production capacity of the region, calling into question the viability of the region's power grid. These climatic variables can also influence energy consumption, as temperature drives demands for heating and cooling. Another source of uncertainty is the energy efficiency of future technology potentially altering both the generating power of the system and the amount demanded [9].

While these climatic and technological uncertainties are hard to plan for, they can be modeled physically. Socioeconomic projections of population growth and energy development are more challenging to project. Designed to aid analyses of climate change impacts with that societal factor, the Intergovernmental Panel on Climate Change's (IPCC) SSPs describe five possible global societal trends and development pathways that could influence regional and global development. Within our study region, the Northwest Power and Conservation Council (NPCC) is one of many regulatory agencies, whose recent 2016 policy involves expanding the network of wind-powered generators in the region, drastically altering the energy market. We seek to model such possible energy development pathways as well as incorporate climate change projection data from the IPCC's RCPs into CAPOW's stochastic simulation of streamflow, temperature, energy production and energy prices in the basin. Defining the region's sensitivities to climatic and socioeconomic changes will indicate under what conditions the CRB is a robust energy system that can cheaply and cleanly meet its energy demands, and under what conditions the system needs to adapt.

METHODOLOGY

OVERVIEW

Modelling of the basin and its expected changes was achieved using the California and West Coast Power (CAPOW) systems model, sourced from https://github.com/samarthsing/CAPOW_Capstone, climate projection data sourced from CMIP5 RCPs, and energy demand frontiers sourced from SSPs.

CAPOW

The CAPOW framework was designed to simulate the operations of the West Coast power grid of the U.S., where bulk electric power is delivered to most of the Columbia River Basin. There are two major markets for wholesale electricity on the West Coast, the Mid-Columbia (Mid-C) covering most of the Pacific Northwest (PNW), and the California Independent System Operator (CAISO). Mid-C corresponds directly to the Pacific Northwest (PNW), while the major utility company service areas in California correspond to five zones (CA) in CAISO. This is a unit commitment and economic dispatch (UC/ED) model, which finds the cost-minimizing dispatch of electric generators in CA and the Pacific Northwest to meet both system's energy demands, assuming all available solar and wind energy is first dispatched, and all reservoirs obey federal operating guidelines. Primary inputs are hourly electricity demand, wind and solar power production and daily available hydropower production. In this study, we modified environmental parameters such as wind speed, streamflow and ambient air temperature, as well as the supply of solar and wind power and regional demand for electricity to represent nine possible future societal and climate scenarios. Each variable was changed with mathematical multipliers or delta shifts, showing the expected relative change in these inputs between the present year and 2050-2079.

CLIMATE SCENARIOS

By utilizing the CMIP5 Hydrology Projections released in 2013, multipliers were able to be calculated to represent CMIP5's RCPs. The chosen RCPs in this analysis are RCP 2.6, 4.5, and 8.5 shown in Table 1 [10]. These RCP's represent pathways of CO_2 emissions resulting in 2.6, 4.5 and 8.5 W/m^2 by the end of the century, which correspond to roughly 2℃, 2.4℃ and 4.3℃ of warming from pre-industrial global temperature levels. These were chosen to represent low, middle, and high global pathways for climate change in terms of emissions and expected increase in global temperatures.

Table 1: RCP Descriptions

RCP	Global Temperature Increase	Emissions Description
2.6 (Low)	~2 °C	Strong Decline
4.5 (Middle)	~2.4 °C	Slow Decline
8.5 (High)	~4.3 °C	Rising

To reflect these RCPs within CAPOW, multipliers and delta shifts were derived from requests on https://gdo-dcp.ucllnl.org/. Multipliers and delta shifts were computed by finding the quotient or difference between the average (and for some variables, standard deviation) of climatic variables over the time period 2050-2079 and the period 1990-2019. The final results yielded multipliers on the mean and standard deviation of streamflow in the CRB, an expected additive shift in temperature change for the region, as well as a multiplier for annual temperature standard deviation. Streamflow projections were utilized instead of precipitation to more directly model the volume flowing through CRB reservoirs.

ENERGY DEMAND SCENARIOS

A similar approach to the climate scenarios was utilized to establish future energy demand, this time informed by IPCC SSPs. The SSPs applied within CAPOW are SSP1, SSP2, and SSP5, again to represent low, middle, and high global pathways for energy demand. These SSPs model things explicitly left out of consideration for RCPs, including population growth, economic growth, technological development and other socioeconomic trends [11]. SSP1 represents a sustainable approach for the rest of the decade, SSP2 an intermediate, middle of the road, and SSP5 shows continued reliance on fossil fuel development.

RESULTS

ENERGY PRICE

First, we investigate the influence of the RCPs and SSPs on energy prices in the future. Figure 1 shows the average energy price on each calendar day of the 10-year simulation for the state of California and Figure 2 shows the same for the Pacific Northwest according to the different combinations of RCPs and SSPs. The RCPs among various pathways show little impact on the price, while the SSPs have a significant impact. SSP1 is considered as a sustainable approach for the future and the price effects on energy are more cost effective per megawatt hour compared to the other SSPs. SSP2 is the middle ground pathway and the prices for energy are found to be closer in line with SSP5 but slightly lower. While SSP5 is considered the path with continued heavy reliance on fossil fuels, this pathway has the most expensive prices for energy usage.

Figure 1 also shows differences in price seasonality across the SSPs. In SSP1, prices begin rising in August, while in SSP2 and SSP5 they start rising in June. Under SSP5, some of the highest prices occur in the summer, when they are highest in the winter for SSP1 and SSP2. SSP5 also shows more variance in prices from June to September, regardless of the associated RCP. While one might hypothesize that this is because higher and more variable summer temperatures lead to cooling demands exceeding heating demands, this effect should be captured by the RCPs not the SSPs. Further investigation would be needed to understand this response, but design implications could include a need to adapt hydropower operations to store more water for the drier summer to meet rising summer demands, allowing for lower prices.

Figure 2, displaying the same plot but for the PNW region, mirrors the same trends as the CA region. Again, SSPs are the driving factor for variance across the scenarios, not RCPs, and seasonality changes for SSP2 and SSP5 compared to SSP1. The similarities in Figure 1 and Figure 2 also suggest that despite different climates, both the CA and PNW region's energy production is resilient to climate change. However, these interdependent markets both share a large degree of sensitivity to changing socioeconomic and energy demand scenarios.

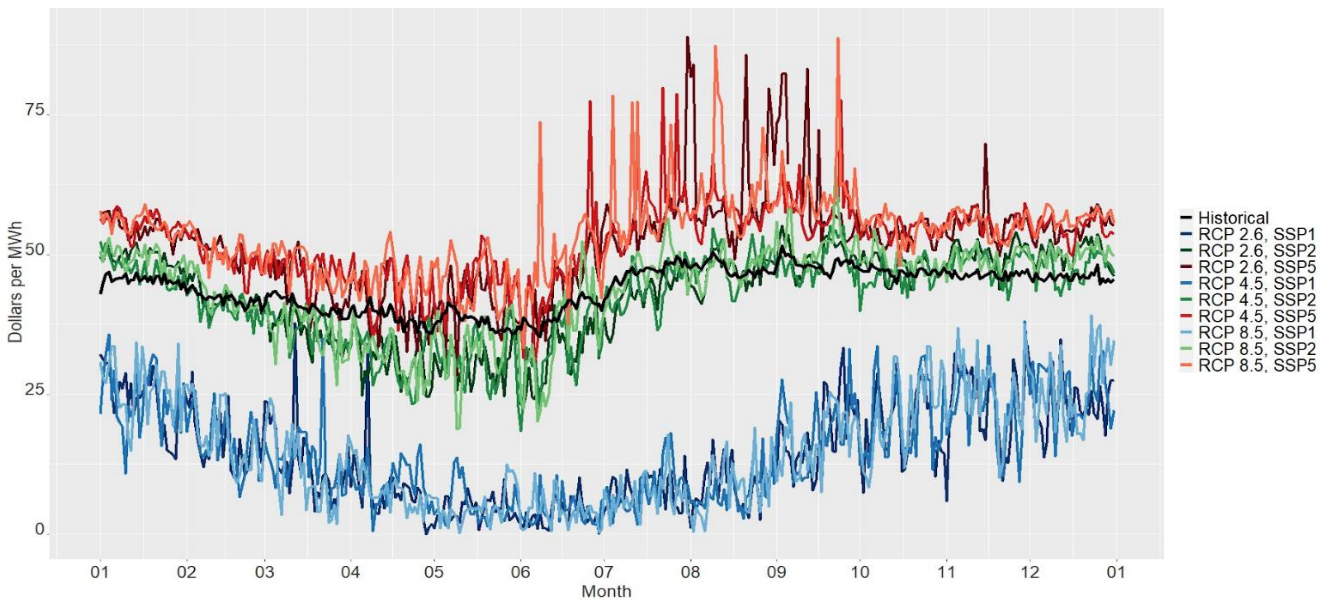


Figure 1: CA Region Daily Dollars per MW Averaged Over 2050-2059

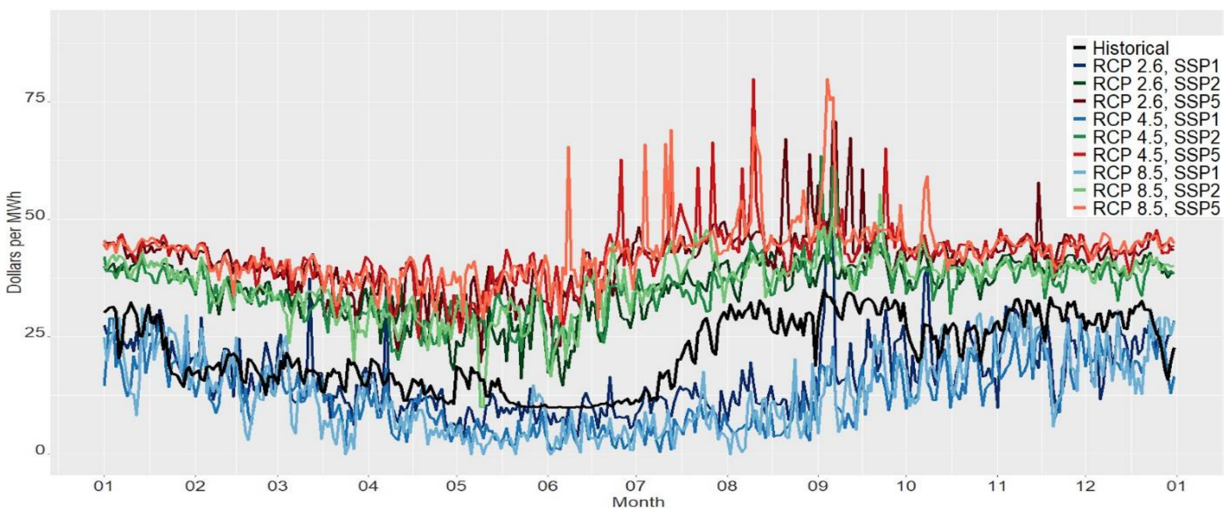


Figure 2. PNW Region Daily Dollars per MW Averaged Over 2050-205

ENERGY SOURCE

We also investigate changes in energy production in both regions. Figure 3 display average daily generation from fossil fuels in each region and SSP/RCP combination. In general, we observe that under each climate scenario, the PNW region generates less electricity using fossil fuel generators. Sources include natural gas, oil, and imports from fossil fuel generators across regions. As population increases from SSP1 to SSP5, demand for electricity and thus power generated from these sources also increases. Within a given SSP, fossil fuel generation across the three RCPs does not vary significantly in either region, at least for this projected decade of 2050-2059. This again shows that energy demands are less sensitive to climate change the socioeconomic change.

Across all climate scenarios, demand for fossil fuel energy is significantly diminished under SSP1. Both regions get nearly all their energy from renewable sources. Most of the stress on the system is placed under wind energy, with the least energy being generated from hydroelectric dams. While solar energy is not applicable to the PNW region, solar comes in between hydro and wind in terms of energy demand for California under SSP1. For SSP2, demand is more even across all sources of energy, with a majority still coming from renewable sources. Fossil fuels have the greatest demand under SSP5. The PNW region sees a more even distribution among its energy sources, but in California there is a pronounced reliance on fossil fuels under these scenarios. Comparing these to historical performance, energy needs typically peak during the summer months across all sources for both regions. In California, there will likely be increased reliance on solar energy regardless of the scenario. Perhaps most significantly, both regions have used fossil fuels for a large portion of their energy, which is not the case under SSP1. Under SSP5 there is more reliance on wind and fossil fuels than the historical for both regions.

Figure 4 shows the sum of daily generation from hydro, solar and wind power across the two regions in the simulated decade. Note the range on the y axis differs across SSPs, with SSP1 generating about twice as much from renewables as SSP2 and SSP5. All SSPs primarily increase their production from wind power, with the role of hydropower as baseload becoming less crucial in SSP1. Even in the most pessimistic SSP5, the total energy generation from renewables exceeds that of fossil fuels, showing that renewable energy has the potential to remain the dominating producer in the region regardless of population change. Once again, the climate scenarios are less influential, with no noticeable differences in renewable generation across RCPs.

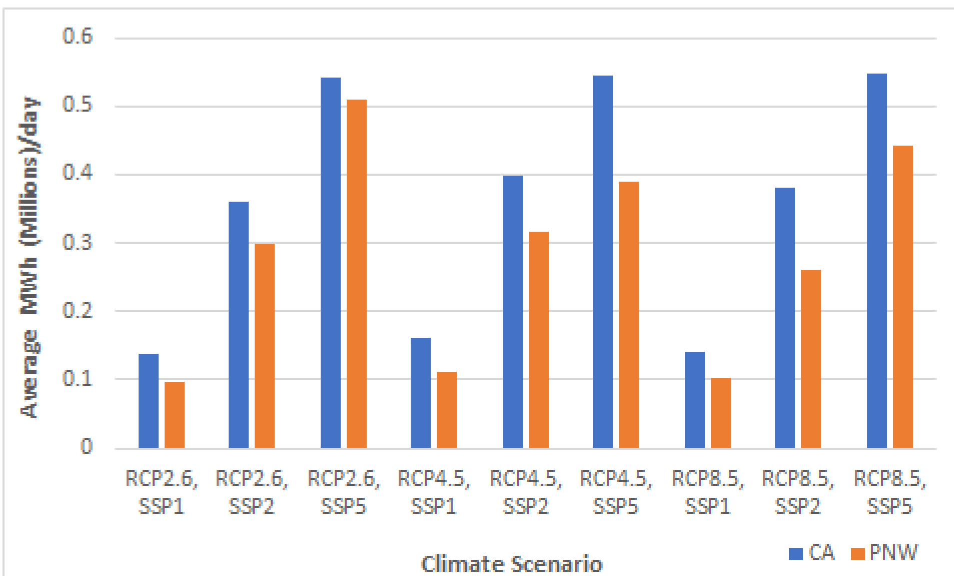


Figure 3: Fossil Fuel Consumption by Region and Scenario

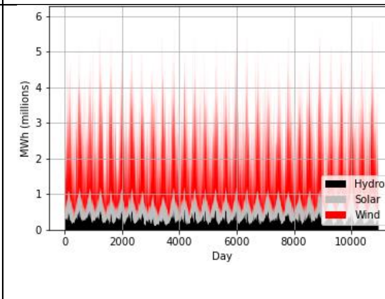
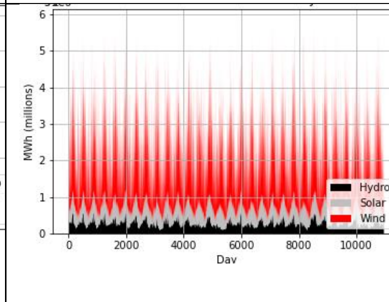
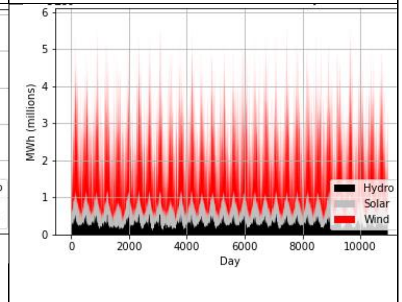
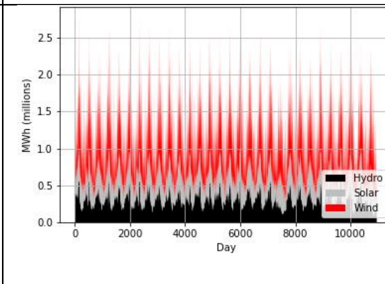
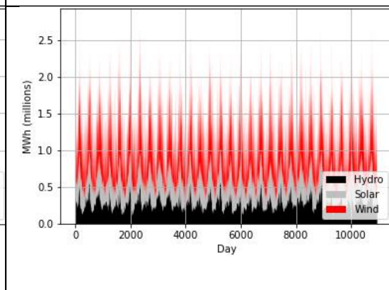
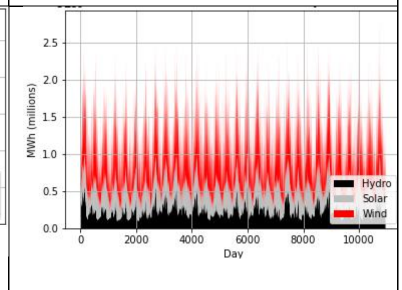
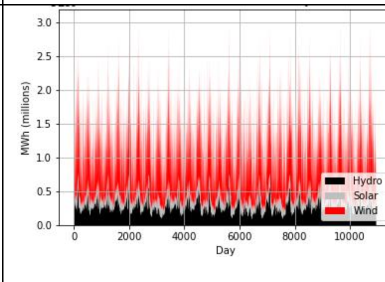
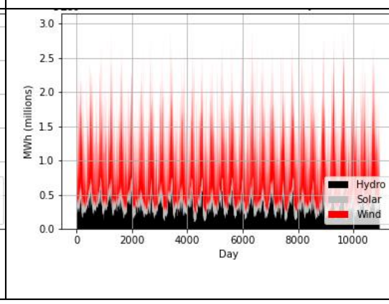
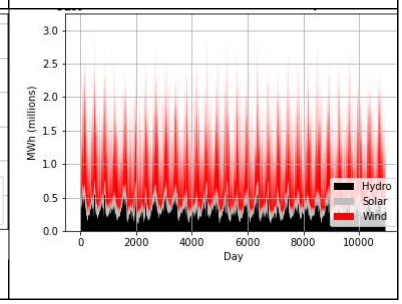
	RCP 2.6	RCP 4.5	RCP 8.5
SSP 1			
SSP 2			
SSP 5			

Figure 4: Hydro, Solar, and Wind Production Across Scenarios

DISCUSSION

Energy demand projections from population growth, and energy supply projections in both renewables and fossil fuel sources have shown to be more impactful on energy prices and generation in CAPOW than climate projections. Specific values in price per MWh and total MWh generated show little variation across the RCPs, while energy prices and generation increase as socioeconomic conditions move towards more “unsustainable” development. However, because we only considered a short segment of time, it is important to consider that climate change scenarios may be more important later in the century despite seeming insignificant in this research. We also focused on average conditions in this study, but it is possible that changing climate extremes could have a greater influence on short-term energy shocks, as we saw in Texas this past year.

These findings are also under the assumption that the regions' grid infrastructure remains unchanged throughout the decade including the 2050-2059 timeline. While the PNW and CA regions are connected through transmission lines and show similar price sensitivities in Figure 1 and Figure 2, future infrastructure might be built to capitalize on the renewable energy-rich PNW region. Our findings also have implications for future reservoir operators for the CRB's reservoirs. Operators may conclude that climate change considerations should be minimal in their models, but that socioeconomic changes could influence the timing of peak energy prices and demands. This suggests they should adapt the seasonality of their operations in response. However, the future energy production also shows that regional reliance on hydroelectric energy may diminish over time as Wind produced energy, and to a lesser extent Solar, become more prevalent. The SSPs detail how energy production, and its sources, change over time. The PNW and CA regions might undergo more specific changes not specified in the generalized SSPs, so while these trends are telling, the CRB operators should still remain aware of regional deviations from global SSPs.

CONCLUSION

The pricing for energy usage for California and the Pacific Northwest has shown that regardless of climate change scenarios, the SSPs have a larger impact on the cost than RCPs. SSPs carry enormous significance in both regions and are the dominant influencer for CA and PNW's energy production and prices. These regions have a large capacity for renewable energy growth, but depending on the next 30 years of energy demand trends, there is still a large amount of uncertainty. However, this research suggests that the CA and PNW regions may continue their energy production frontiers with little threat from climate change.

FUTURE WORK

DIRECT POLICY SEARCH

Referenced earlier in this paper, reservoirs within the CRB operate with more objectives than energy production. These other objectives, such as flood mitigation, salmon population management, water supply reliability, etc., build complexity into the system. Reservoir operators must meet criteria for all these objectives, with a reservoir operating policy dictating the operation of the reservoirs. These policies can be found using a method called Direct Policy Search, utilizing multi-objective evolutionary algorithms (MOEA). A direct and immediate application of this research is to use the climate and energy demand sensitivity results to search for policies that will be effective in the future. Searching for policies with an MOEA ensures that all objectives are not only met but optimized, resulting in policies that are robust to uncertainty across scenarios. Our results suggest that reservoir operations should adapt to changes in energy price seasonality that may occur in the future, but this could have consequences for these other objectives. Searching for adaptive operations with DPS could find effective strategies for balancing these tradeoffs.

CONTINUING RCP AND SSP ANALYSIS

This research used three different RCPs and three SSPs, yielding nine unique combinations that represented climate change and energy demand scenarios. The selected pathways were intended to cover as much uncertainty as possible, however there is further research to be done purely by using all the available pathways. SSPs 3 and 4 were not used, as well as multiple RCPs such as 1.9, 3.4, 6.0. Some combinations of SSPs and RCPs do not exist, however there are combinations that can yield further information on the ability of the CRB to prosper through the 21st century.

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REFERENCES

[1] Tan, S. (2017). Computationally Efficient Hydropower Operations Optimization for Large Cascaded Hydropower Systems Reflecting Market Power, Fish Constraints, Multi-Turbine Powerhouses, and Renewable Resource Integration. https://ecommons.cornell.edu/handle/1813/56992J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Northwest Power and Conservation Council. (2016). *Seventh Northwest conservation and electric power plan* (1st ed.). https://www.nwcouncil.org/sites/default/files/7thplanfinal_chap07_demandforecast_1.pdf

[3] Federal Columbia River Power System (2001). The Columbia River System Inside Story, Second Edition. https://www.bpa.gov/news/pubs/GeneralPublications/edu-The-Federal-Columbia-River-Power-System-Inside-Story.pdf

[4] Labadie, J. (2004). Optimal Operation of Multireservoir Systems: State of the Art Review. *Journal of Water Resources Planning and Management*. *https://ascelibrary.org/doi/10.1061/(ASCE)0733-9496(2004)130%3A2(93)*

[5] Su, Y., Kern, J., Denaro, S., Hill, J., Reed, P., Sun, Y., Cohen, J., & Characklis, G. (2020). An open source model for quantifying risks in bulk electric power systems from spatially and temporally correlated hydrometeorological processes. *Environmental Modelling and Software*. https://www.sciencedirect.com/science/article/abs/pii/S1364815219309739?via%3Dihub

[6] Brekke, L., Wood, A., & Pruitt, T. (2014). Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Hydrology Projections, Comparison with preceding Information, and Summary of User Needs. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado. https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf

[7] Riahi, K., Vuuren, D., Kriegler, E., Edmonds, J., O'Neill, B., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlík, P., Humpenöder, F., Silva, L., Smith, S., Stehfest, E., Bosetti,V., Eom, J., Gernaat, D., Masui,T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., & Tavoni, M (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Global Environmental Change, Volume 42. International Institute for Applied Systems Analysis. ISSN 0959-3780, DOI:110.1016/j.gloenvcha.2016.05.009

[8] Bartos, M. D. and Chester, M. V. (2015). Impacts of climate change on electric power supply in the Western United States. Nature Climate Change Vol. 5.

[9] Watts, R.J., Richter, B.D., Opperman, J.J., & Bowmer, K.H. (2011). Dam reoperation in an era of climate change. Marine and Freshwater Research, 62(3), 321. DOI:10.1071/MF10047

[10] SENSES (2020). Climate Change Scenarios: Mitigation. European Research Area for Climate Services. https://climatescenarios.org/primer/mitigation

[11] Hausfather, F. (2018). Explainer: How 'Shared Socioeconomic Pathways' explore future climate change. Carbon Brief. https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change