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Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation

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A B S T R A C T

Here we translate the impacts of climate change on hydropower generation, and discuss implications on greenhouse gas (GHG) emissions and operation in California. We integrate a model of major surface-water reservoirs with an electric grid dispatch model, and perturb it by projected runoff based on representative concentration pathways (RCP4.5 and RCP8.5). Results show that climate change and variability is expected to decrease the average annual hydropower generation by 3.1% under RCP4.5, but have negligible impact under the RCP8.5. Model simulations indicate more inflow, caused by more future extremes, in the future that does not necessarily translate to more energy production because of reservoir spillage of water. While overall volume of future available water for energy production may be similar or higher, the delivery of this volume is expected to be significantly more variable in the future climate than the historical average, which has many implications for hydropower generation. Our results show that the expected changes in future climate leads to increases in grid GHG emissions, load-following capacity, fuel usage, and costs for the RCP4.5 due to generation shortfall, and very slight increases in the same metrics for the RCP8.5 case due to variability causing decreased efficiencies in load-following power plants.

1. Introduction

Concerns over the impacts of climate change on the physical and economic environments have driven the development and deployment of a wide range of advanced technologies. Electrification has been determined to fulfill a key role in the decarbonization of many services [1] and therefore many of the advanced technologies have been centered of providing carbon free electricity. This has driven the deployment of renewable resources such as wind and solar power in many areas, with many states in the U.S. deploying renewable portfolio standards [2]. California in particular has very aggressive renewable portfolio standards, with a 50% goal by 2030 [3].

Managing the integration of renewable resources for carbon reduction on the electric grid requires the use of dispatchable generation. In many regions, hydropower fulfills a significant portion of this role on the electric grid. Hydropower generation is ideal for providing dispatchable generation due to a number of characteristics over other resources which can provide these services such as natural gas combined cycle plants. These include but are not limited to:

- No need for fuel input in the conventional sense to provide generation, compared to fossil fuel input requirements for dispatchable thermal power plants.
- No efficiency penalties or emissions increases when operating at part load or during ramping and start up events.
- Ability to ramp and start up over very short timescales
- No greenhouse gas emissions in operation while performing grid services.

Climate change and variability, however, is expected to impact precipitation and runoff in many regions which serve as the inflows to surface reservoirs at hydropower plants. These impacts include

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but are not limited to changing the timing of runoff and the overall magnitude of precipitation and runoff which affects the overall potential contribution of hydropower to the electric generation portfolio. These impacts can jeopardize the ability of hydropower to perform load-balancing services for the electric grid. To compensate for the shortfall in these services, other resources may need to operate and be dispatched to keep the electric load balanced, especially with more renewable resources on the grid. These other resources may not have the same advantages as hydropower, especially with respect to greenhouse gas emissions.

Depending on the severity of these impacts, they need to be taken into account for the planning of strategies for emissions reduction. This study seeks to provide an example of one method for accounting for hydropower generation under future climate simulations, and the corresponding impacts on emissions and grid design. This has been achieved by combining a water reservoir network model with a detailed grid resource dispatch model, forced with inflows simulated from climate model projections.

2. Background

The effects of climate change and variability on precipitation, temperature and runoff have been studied extensively in the literature over the last decade [4–6]. In the western United States, the observed increase in droughts and heatwaves [7], shifts in runoff timing [8] and substantial increase in anthropogenic water demand [9] have raised concerns on climate impacts on energy production. Many studies have examined how climate change for a given region impacts surface runoff and hydropower generation [10]. The primary gap in the literature is a translation of these effects to grid operation and emissions impacts by coupling these results with the constraints of the electricity system. This study aims to address this important research gap. Current studies in the literature which have examined hydropower in the context of climate change are described as follows.

Hamlet [11] performed a study which examined the projected effects of climate change on energy supply and demand in the Pacific Northwest region of the U.S, a large component of which is hydropower. This study incorporated climate scenarios for 2010–2039, 2030–2059, and 2070–2099 to examine changes in annual and seasonal hydropower generation, as well as changes in electricity demand due to cooling loads and used the ColSim model to simulate hydropower reservoir operations in 20 reservoirs in the state. This study found that annual hydropower production in the Colombia River Basin was reduced by 2.0–3.4% by 2040, and 2.6–3.2% by 2080 with the largest reductions occurring in the summer during the times of peak air conditioning loads.

Kao [12]examined the impact of climate change on 132 federal hydropower plants in the U.S. for 18 different study areas across the country ranging from the pacific northwest to the southeast. This study used the United States Geographical Survey (USGS) WaterWatch runoff to provide observational runoff data, and used a combination of global climate models, regional climate models, and hydrologic models for each region along with climate scenarios from the Intergovernmental Panel on Climate Change Assessment Report 4 (IPCC AR4) reports. This study, however, did not take into account the constraints of reservoir operation and made projections primarily based on runoff volume. It was found that in the Pacific Northwest regions, average annual hydropower generation increases by 1.7% over 2010–2024 and by 3.3% over 2025–2039, but did not account for operational issues at the reservoir level. Hydropower in the Western Power Administration, Southwest Power Administration, and Southeastern Power Administration regions were also projected to increase overall, but with high variability.

Madani [10] investigated the impact of climate change on high elevation hydropower in California for 137 high elevation hydropower plants using an Energy-Based Hydropower Optimization Model (EBHOM) and dry, wet, and temperature warming only climate scenarios. The EBHOM methodology optimizes hydropower generation revenue based on on-peak and off-peak pricing within the constraints of reservoir capacity. This study predicted a reduction of 19.7% in hydropower generation for the dry climate scenario, an increase in 5.8% for the wet scenarios, and a decrease of 1.3% for the temperature warming only cases relative to the 1985–1998 levels.

Vicuna [13]also examined the impacts of climate change on high elevation hydropower in California, particularly in the Sierra Nevada region. This study examined a hydroelectric system consisting of 11 hydropower reservoirs operated by the Sacramento Municipal Utility District using climate change data from four global climate models (GCMs) and emissions scenarios. This study predicted hydropower generation to be reduced by 10% for two of the climate change scenarios, but increased by similar levels for the other climate change scenarios.

Other studies have also been performed. Wang [14] examined the vulnerability of hydropower generation to climate change in China, Schaefli [15] examined impacts of climate change on hydropower in the Swiss Alps. Mimikou [16] performed one of the first studies on this topic for a multipurpose reservoir in Greece and Robinson [17] also performed one of the first studies on this topic for systems in the southeast U.S. The topic of climate change impacts on hydropower have been discussed in many papers regarding the future role of hydropower in a climate affected system [18–20].

Overall, the topic of climate change impacts on hydropower has been examined for many regions from a wide range of perspectives such as generation and hydropower plant revenue. While there are many studies on the topic, a key aspect that is currently missing from the literature on this topic is the implications of changes in hydropower generation on the electricity system, greenhouse gas emissions, and electricity system operation.

Translating the impacts of climate change affected runoff on hydropower generation to electricity system emissions and operation impacts requires coupling of climate models and reservoir models with a detailed electric system dispatch model. This study integrates these types of models to provide insight into the impacts of climate change on hydropower generation and the electricity system, and their implications for carbon reduction strategies for the electricity system.

3. Approach

3.1. Electric grid modeling

The electric grid is modeled using the Holistic Grid Resource Integration and Deployment (HiGRID) model [21], developed by the University of California, Irvine. The HiGRID model is a large scale, integrated model of the electricity system which captures changes in technical and economic aspects of the system including but not limited to grid resource dispatch, grid resource operation, greenhouse gas and criteria pollutant emissions, and the levelized cost of electricity due to a wide variety of perturbations.

This model has been used to examine perturbations such as increased variable renewable penetration [21], electrification and grid-integration of light-duty transportation through plug-in vehicles [22,23], and increased water infrastructure-related electric loads due to the reliance on alternative water supply measures to secure water resource supplies under climate change [24]. For this particular study, the perturbation of hydropower generation in a