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Climate change impacts on high-elevation hydroelectricity in California

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SUMMARY

While only about 30% of California's usable water storage capacity lies at higher elevations, high-elevation (above 300 m) hydropower units generate, on average, 74% of California's in-state hydroelectricity. In general, high-elevation plants have small man-made reservoirs and rely mainly on snowpack. Their low built-in storage capacity is a concern with regard to climate warming. Snowmelt is expected to shift to earlier in the year, and the system may not be able to store sufficient water for release in high-demand periods. Previous studies have explored the climate warming effects on California's high-elevation hydropower by focusing on the supply side (exploring the effects of hydrological changes on generation and revenues) ignoring the warming effects on hydroelectricity demand and pricing. This study extends the previous work by simultaneous consideration of climate change effects on high-elevation hydropower supply and pricing in California. The California's Energy-Based Hydropower Optimization Model (EBHOM 2.0) is applied to evaluate the adaptability of California's high-elevation hydropower system to climate warming, considering the warming effects on hydroelectricity supply and pricing. The model's results relative to energy generation, energy spills, reservoir energy storage, and average shadow prices of energy generation and storage capacity expansion are examined and discussed. These results are compared with previous studies to emphasize the need to consider climate change effects on hydroelectricity demand and pricing when exploring the effects of climate change on hydropower operations.

1. Introduction

Hydropower facilities in California generated on average 37,000 gigawatt hours (MWh), or 15%, of the annual in-state electricity generation between 1983 and 2001; ranging annually between 9% and 30%, depending on hydrological conditions (McKinney, 2003). Hydroelectricity's very low cost, near-zero emissions, and load-following capacity are some of the reasons for its great popularity (McKinney, 2003; Pew Center on Global Climate Change, 2009). The State of California has the second largest hydropower system in the United States with a total hydroelectric capacity over 14 gigawatts (GW), representing 25% of California's electricity generation capacity (McKinney, 2003). California also relies on hydroelectricity imports from the Pacific Northwest, including Canada and the states of Oregon and Washington (Aspen Environmental Group and M. Cubed, 2005).

In-state hydropower is generated by four types of hydropower systems: high-head, low-storage hydropower plants; low-head multipurpose dams; pumped-storage plants; and run-of-the-river units (Pew Center on Global Climate Change, 2009). While only about 30% of the state's usable water storage capacity is at higher elevations, high-elevation (above 300 m) hydropower units generate, on average, 74% of California's in-state hydroelectricity (Madani, 2010). Madani and Lund (2009) have identified 156 high-elevation (above 300 m) hydropower plants, most of them located in Northern California. Hydroelectric generation is generally their only purpose, and only small amounts of water are necessary to produce substantial quantities of electricity due to their vertical drops of hundreds of meters (Pew Center on Global Climate Change, 2009). They have been designed to take advantage of the snowpack acting as a natural reservoir so that their human-made reservoir is usually small. Their limited storage capacity may make them sensitive to snowpack volume and runoff timing variations (Madani and Lund, 2010).

Climate across the California region can be very different, due to the great differences in altitude and in latitude of the state. According to Kauffman (2003), five major climate types can be observed in close proximity in California; namely Desert, Cool Interior, Highland, Steppe, and Mediterranean. Much of California has warm, dry summers and cool, wet winters (Zhu et al., 2005). In terms of electricity demands this corresponds to high demands in summer for cooling and in winter for heating; whereas, the lowest demands

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occur in spring and fall, when neither great heating nor cooling is required. Precipitation is very uneven throughout the year, with around 75% of the annual average 584 milimeters (mm) occurring between November and March (Zhu et al., 2005) and falling as snow in the Sierra Nevada mountain range (Moser et al., 2009). This situation results in spatially uneven runoff, with more than 70% of California's average annual runoff occurring in northern California (Madani and Lund, 2009).

California's twenty-first century hydrology is expected to be altered by climate change and statewide average temperatures raise of 1.5–5 °C: part of the winter precipitation falling as snow will turn to rain; higher temperatures will lead to a shift in timing of the snowmelt peak flow to earlier months; peak flow's intensity will be reduced; and winter runoff is increased (California Climate Change Center, 2006; Cayan et al., 2008, 2009; Moser et al., 2009; Mirchi et al., 2013). Hydrological changes and variations in the annual runoff pattern create a big concern for California's hydropower system, which may face water shortages in summer when the demand is the highest (Medellin et al., 2006; Moser et al., 2009; Madani and Lund, 2010; Blasing et al., 2013). These changes can significantly alter California's hydroelectricity generation, depending on the system's storage and generation capacities as well as their spatial distribution.

The expected changes should be less problematic for low-elevation (below 300 m) multipurpose hydropower systems benefitting from large human-made reservoirs, than it is for high-elevation units with small human-made reservoirs. Studies of low-elevation multi-purpose reservoirs in California show that the low-elevation hydropower system is not vulnerable to flow timing changes due to warming (Tanaka et al., 2006; Medellín-Azuara et al., 2008; Connell-Buck et al., 2011). This is indeed because of the large storage capacity of this system which provides flexibility in operations. Yet this system is directly affected by changes in flow magnitudes under climate change which might result in lower or higher levels of hydroelectricity production with dry and wet climate warming, respectively. Relying mainly on natural snowpack reserves, high-elevation hydropower systems have a limited flexibility in operation. If their storage capacity cannot accommodate hydrological changes, these high-elevation hydropower systems may be vulnerable to climate change (Madani and Lund, 2010).

Most studies assessing the impacts of climate change on hydropower generation in California have focused on large-scale, low-elevation systems (e.g., Tanaka et al., 2006; Medellín-Azuara et al., 2008) or on a few individual high-elevation hydropower units (e.g., Vicuña et al., 2008, 2011; Madani et al., 2008). High-elevation systems are nonetheless generating 74% of California's in-state hydroelectricity on average, which has prompted recent research on the impacts of climate change on high-elevation hydropower systems (e.g., Madani and Lund, 2007, 2010; Duffy et al., 2009; Madani, 2009). These studies suggested that the current storage and generation capacities enable the system to adapt to climate warming to some extent. In case of dry warming, lower hydropower generation is expected. Nevertheless, the revenue losses in percentage are less than the generation losses due to price variability and the non-linear relationship between hydroelectricity generation and pricing. In case of wet warming, the system cannot fully take advantage of increased flows due to its limited storage and generation capacities. While generation is increased to some extent, the revenues do not increase significantly as increased generation mostly occurs in months with average lower hydropower prices.

Beside its effect on power supply, climate change is expected to affect power demand and pricing. This is because of the temperature changes which can increase the need for cooling in warmer months of the year and decrease the need for heating in colder months. So, some researchers have focused on climate change impacts and energy demand in California (Franco and Sanstad, 2006; Miller et al., 2008; Aroonruengsawat and Auffhammer, 2009; Guégan et al., 2012a). These studies suggest that in general, climate change will result in increased demand, peak load, and average pricing in California. Based on these studies, California is expected to face electricity supply deficit in peak electricity demand periods and with extreme heat, which is expected to occur more frequently with climate change.

Rising energy demand, coupled with reduced hydroelectricity generation, could lead to a substantial impact on the hydropower operations. Therefore, a comprehensive analysis of climate change on hydropower operations, that considers climate change on supply and demand/price side simultaneously is required in order to evaluate the adaptability of California's hydropower system to climate change. Nevertheless, previous research on the climate change effects on hydropower systems operations and adaptability have examined climate change effects on hydropower supply and demand/price independently, leaving a gap in our understanding of the implications of climate change for hydropower operations in California. To bridge the gap, this paper examines the impacts of climate warming on California's hydropower system, considering simultaneously the impact of climate change on the hydroelectricity supply and pricing. The study focuses on high-elevation single-purpose snowpack-dependant hydropower system (including plants above 300 m) which is the major in-state hydroelectricity producer and is expected to be more vulnerable to climate warming and snowpack losses due to its limited storage capacity. The low-elevation hydropower system which provides one quarter of in-state hydropower supply in California is not the focus of this study as hydroelectricity generation is an ancillary benefit of the system, composed of large multi-purpose reservoirs.

2. Method

California's Energy-Based Hydropower Optimization Model (EBHOM) (Madani and Lund, 2009) is used in this study in order to evaluate the adaptability of California's high-elevation hydropower system to climate change. EBHOM is a monthly-step non-linear hydropower revenue optimization model that finds optimal hydropower operations for 137 high-elevation hydropower plants throughout California. Assuming that hydropower operation costs are fixed at a monthly scale, EBHOM maximizes revenue as a surrogate for net revenue (Madani, 2009). EBHOM performs all storage, release, and flow calculations in energy units. It provides a big picture of the system and is a more convenient alternative to conventional volume-based optimization models that usually require detailed information such as streamflows and, storage operating capacities at each individual plant of the system (Madani et al., 2008). EBHOM's reliability has been tested against the traditional volume-based hydropower optimization model developed by Vicuña et al. (2008) on the Upper American River system in a collaborative study by UC Davis and UC Berkeley (Madani et al., 2008). Both models predicted the same changes in generation and revenue with respect to the historical case. Despite the fact that EBHOM is very simplified compared to traditional optimization models, it provides a reliable picture of a complex large-scale hydropower system.

Fig. 1 shows a flowchart of the EBHOM's modeling procedure. The input data required to run EBHOM are: runoff data and frequency of hourly electricity prices for each month of the year. EBHOM has the basic information (i.e., elevation and generation capacity) of 137 high-elevation hydropower plants in California. To estimate the available energy storage capacity at each power plant, EBHOM uses the No Spill Method (NSM) (Madani and Lund, 2009), which is applicable when: plants are operated for net