Climate Warming and Adaptability of High-Elevation Hydropower Generation in California

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Abstract
California’s high-elevation hydropower system is composed of approximately 150 hydroelectric plants. Most of these plants have reservoirs that have relatively small storage capacities compared to the average storage capacity of California’s water resources and have been designed to take advantage of snowpack. With climate warming, changes in the runoff patterns from snowpack to rain will affect the adaptability of high-elevation hydropower system to new climate conditions. In this paper, we investigate the effects of climate warming on the adaptability of the California hydropower system. We use a stochastic optimization model to simulate different climate warming scenarios. We found that the storage capacity and generation levels of high-elevation hydropower plants vary significantly under different climate scenarios. This study suggests that a No-Spill Approach to investigate the climate change effects on generation.

No-Spill Approach
In this approach the basic assumption is that storage capacity at high elevation has been enough to accommodate the historical mean runoff without water spill from the reservoirs. Therefore, all mean-year water could have been stored behind the reservoirs during months when the demand for electricity was low and released later when energy prices are higher. This assumption will be helpful in estimating the aggregated energy storage capacity at each elevation range. With this No-Spill assumption, the available energy storage capacity can be estimated by finding the area between the monthly historical runoff and monthly generation curves when they both are expressed in percentage terms. In month \( i \), the runoff percentage \( \text{runPercent}(i) \) and generation percentage \( \text{genPercent}(i) \) can be calculated by dividing the average monthly runoff in month \( i \) (average runoff \( (i) \)) and the average monthly generation in month \( i \) (average generation \( (i) \)) to the average annual runoff and average annual generation, respectively.

\[
\text{runPercent}(i) = \frac{\text{average runoff}(i)}{\text{average annual runoff}} \quad \text{and} \quad \text{genPercent}(i) = \frac{\text{average generation}(i)}{\text{average annual generation}}.
\]

In percentage terms, the total difference between the two curves for a year period (12 months) must be zero. In the 12 month period there are months when the runoff percentage exceeds the generation percentage value (e.g. when runoff is stored in the reservoir) and months when the generation percentage value exceeds the runoff percentage value (e.g. when hydropower is generated by releasing stored water). Therefore, the storage capacity as a percent of total inflow is:

\[
\text{Storage Capacity Percent} = \sum_{i=1}^{12} \left( \text{runPercent}(i) - \text{genPercent}(i) \right) = 0.
\]

Multiplying the storage capacity percentage by the average annual generation gives the average annual energy storage capacity. Multiplying the storage capacity percentage by the average annual runoff gives the volumetric water storage capacity which is directly used for hydropower generation. Since the relation between power generation and water storage is not linear (generation depends on turbine head which changes continuously with storage), this study applied calculated as a percentage of energy. Turbines head in high-elevation hydropower facilities results from potential drops, rather than storage elevations.

Here, the runoff data were obtained from several U.S. Geological Survey’s (USGS) gauges representing selected elevation ranges. These sample gauges were selected in consultation with the California Department of Water Resources’ chief hydrologist. For each elevation range, the mean monthly discharge and mean annual runoff were estimated.

After estimation of available energy storage capacity and average monthly energy runoff at each hydropower plant, a linear optimization model was developed to investigate the adaptability of the hydropower generation at different climate warming scenarios (Dry, Warm, Wet, No-Dry/Wet). Six different objectives were considered:

1. Maximization of Revenue
2. Minimization of Shortage
3. Maximization of Shortage
4. Maximization of Revenue with Shortage Penalties
5. Maximization of Revenue with Spill Penalties
6. Maximization of Revenue with Spill and Shortage Penalties

Results and Discussion
Unlike any scenario, revenue is highest when the model only maximizes revenue. For all objective functions annual value is lower than the revenue maximization case. Volumes will be the highest under wet warm climate if the model maximizes revenue and generation. This indicates that the estimated storage capacity is enough to handle the extra runoff for the warm wet climate and can store water for when energy demand is higher. While maximizing the revenue, the model suggests no generation in months when the price is low and generation in months with higher prices. The model assumes that there is enough storage capacity of each hydropower plant to cover the demand for energy. However, it is critically low because the total storage capacity of all hydropower plants in California is small compared to the total energy demand. Moreover, demand will be affected by climate warming which will affect energy prices. Revenue under the No-Dry/Wet climate warming is always less than the base and wet cases and more than the dry case.

Limitations
The No-Spill Approach overestimates storage capacities and generation levels. This method was used because of lack of energy storage capacity data. Perhaps later studies can include a more realistic representation of storage capacities. In California there is big and variable in hydrology. Assuming the same hydrology for an entire climate range is not a realistic assumption. Also, it is more accurate to consider more than a few gauges at each elevation range. Defining a reasonable objective function for an optimization model is always a big challenge. Although, different objectives have been defined here, they may all be far from the real objective. In the real electricity market, revenues are not linearly related to monthly generation as the electricity price changes all the time based on supply and demand. With climate warming, demands are likely to increase in winter months from higher temperatures. This has some effects on the prices. Here, the model optimizes generation based on perfect information about the future hydrological pattern and energy prices. This kind of management is impossible in practice as there is always some risk associated with decisions in the operation of the electricity sector because future hydrological conditions perfectly. A stochastic optimization formulation might help with this problem.

Conclusions
In absence of good information about energy storage capacities at high-elevation in California, this study suggested a simple approach for estimating the adaptability of high-elevation hydropower generation to climate warming. California’s hydropower system, which has functioned historically as a natural reservoir. Moreover, energy storage is expensive to build and maintain. In conclusion, the model’s predicted generation data are compared with the historical generation to investigate the adaptability of the hydropower system to climate change.

Method
One hundred fifty-eight high-elevation (above 1,000 feet) hydroelectric plants are considered in this study. Since runoff patterns change by elevation, three different elevation ranges has been used (1,000-2,000 feet, 2,000-3,000 feet, and above 3,000 feet). Monthly hydropower generation information from U.S. Energy Information Administration database for the period 1982 to 2002 was used to calculate the average monthly hydropower generation and the maximum generation capacity of each power plant. The maximum value of monthly generation was calculated for each power plant on a monthly basis. This period was considered as the monthly generation capacity of each power plant. To estimate the energy storage capacity of each power plant, we used 150 hydroelectric plants in California. Estimation of climate warming effects by conventional simulation or optimization methods is almost not possible. Thus, this study suggests No-Spill Approach to investigate the climate change effects on generation.