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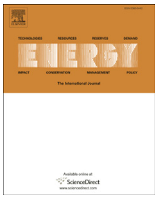

Projecting changes in annual hydropower generation using regional runoff data: An assessment of the United States federal hydropower plants

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ABSTRACT

Federal hydropower plants account for approximately half of installed US conventional hydropower capacity, and are an important part of the national renewable energy portfolio. Utilizing the strong linear relationship between the US Geological Survey WaterWatch runoff and annual hydropower generation, a runoff-based assessment approach is introduced in this study to project changes in annual and regional hydropower generation in multiple power marketing areas. Future climate scenarios are developed with a series of global and regional climate models, and the model output is bias-corrected to be consistent with observed data for the recent past. Using this approach, the median change in annual generation at federal projects is projected to be -2 TWh, with an estimated ensemble uncertainty of ±9 TWh. Although these estimates are similar to the recently observed variability in annual hydropower generation, and may therefore appear to be manageable, significantly seasonal runoff changes are projected and it may pose significant challenges in water systems with higher limits on reservoir storage and operational flexibility. Future assessments will be improved by incorporating next-generation climate models, by closer examination of extreme events and longer-term change, and by addressing the interactions among hydropower and other water uses.

1. Introduction

In the United States, federal hydropower plants (i.e., owned and operated by federal agencies and marketed through DOE [Department of Energy] PMAs [power marketing administrations]) account for approximately half of installed US conventional hydropower capacity, and are an important part of the national renewable energy portfolio. The 132 federal hydropower projects generated an annual average of 120.6 TWh over the period from 1971 to 2008 [34], approximately 3% of the national combined total across all different sources of energy (e.g., nuclear and coal). More important, most of the hydroelectricity generated from these federal projects is sold to public bodies, such as municipalities, non-profit organizations, and other public corporations or agencies, at the lowest possible rates consistent with sound business principles, not fully for revenue [21].

Despite its higher initial capital investment, hydropower is a favored source of electricity generation owing to its operational flexibility and low maintenance costs (i.e., the "fuel" is generally free of charge, and renewable). Therefore, when conditions allow, utilities will try to optimize the usage of existing hydropower capacity before switching to other fuel-dependent energy sources to maximize revenue, especially during daily peak load periods. While hydropower operation is controlled on shorter time scales (hourly, daily, monthly) by variables such as water usage allocations, daily energy demand, pool elevation, turbine efficiency, flood protection, and other environmental constraints, on longer time scales (annual and longer) it is mainly water availability that dominates the

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Nomenclature

BCSD	bias-corrected and spatially downscaled
BPA	Bonneville Power Administration
CCSM3	community climate system model version 3
DJF	winter, December/January/February
DOE	Department of Energy
EBHOM	energy-based hydropower optimization model
EIA	Energy Information Administration
GCM	global climate model
HM	hydrological model
HUC8	8-digit hydrologic unit
IBWC	International Boundary Water Commission
IPCC	Intergovernmental Panel on Climate Change
JJA	summer, June/July/August
MAM	spring, March/April/May
NHAAP	National Hydropower Asset Assessment Program
NWIS	National Water Information System
ORNL	Oak Ridge National Laboratory
PMA	power marketing administration
PRISM	parameter-elevation regressions on independent slopes model
RCM	regional climate model
Reclamation	Bureau of Reclamation
RegCM3	regional climate model version 3
SEPA	Southeastern Power Administration
SON	fall, September/October/November
SWPA	Southwestern Power Administration
TVA	Tennessee Valley Authority
US	United States
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VIC	variability infiltration capacity
WAPA	Western Power Administration

amount of hydropower generation. Therefore, high interannual streamflow variability presents challenges for business planning. For instance, the difference in total US hydropower generation between a wet year, such as 1997, and a dry year, such as 2001, can be as much as 40%, with such variation causing significant uncertainties in managing water usage, reservoir operation, and sales of power [28].

Given the direct linkage between streamflow availability and climate change, this issue may be further complicated in the future in response to continued global warming. To evaluate potential climate change impacts on hydropower, two analytical components are required: (1) a calibrated water resources relationship that can help translate streamflow into hydroelectric energy potential, and (2) future climate change scenarios, such as those that are generated from GCM (global climate model) projections. However, because US federal hydropower plants are widely distributed across the entire country, with diverse hydrologic conditions and different operational objectives, development of a uniform model to simulate their responses to climate change would require substantial resources.

Important progress has been made in assessing the potential impacts of climate change on hydropower generation on smaller spatial scales. Robinson (1997) [33] used a Reservoir Depletion Model to study how the hydropower systems of Duke Power and Virginia Power in the southeastern United States might react to a stylized 2 °C increase in temperature and 10% decrease in precipitation. Mimikou and Baltas (1997) [27] used a runoff-based water balance model with three GCM-derived future climate scenarios to study the sensitivity of annual hydroelectric energy production of a large multipurpose reservoir in northern Greece. Christensen et al. (2004) [6] analyzed the effect of climate change on the water resources of the Colorado River Basin in the United States using three downscaled climate projections generated from the Parallel Climate Model [40]. Vicuna et al. (2008) [42] used a linear programming model with four GCM-driven scenarios to investigate how climate change may impact an 11-reservoir system in the Upper American River Basin in California. Hamlet et al. (2010) [18] used two climate scenarios (constructed from projections of 20 GCMs) and a Columbia Simulation reservoir model (designed and modeled for 20 selected major reservoirs in the Columbia River Basin in Washington state in the United States; [17]) to evaluate the potential effects of climate change on the seasonality and annual amount of hydropower generation in the Pacific Northwest region. Other studies related to the assessment of climate and hydropower were reported by Refs. [1,19,35,38,43,24].

Although these studies have laid foundations for examining climate change impacts on selected hydropower plants, assessing impacts across large spatial scales remains a major challenge. For instance, it is still unclear how climate change impacts on hydropower generation at regional and national scales can be estimated (e.g., joint responses to larger-scale extremes like droughts). Given the complexity of surface water storage, management, and distribution systems, and the proprietary nature of existing hydropower models and data [22], it would likely be very costly and time-consuming to develop a large-scale energy–water model through a conventional reservoir-based approach. Even a full computational model could be built (with hundreds of hydropower plants), it will likely entail a large number of site-specific parameters that are challenging to calibrate and validate. Therefore, a simplified approach is required in the interim. An example is the EBHOM (energy-based hydropower optimization model), in which a simplified energy flow method has been used to evaluate climate change impacts on more than 135 high-elevation hydropower plants in California [22,23]. Another example is demonstrated by Markoff and Cullen (2008) [24], in which regression is used to predict the average annual streamflow and hydropower generation from the winter/summer precipitation fraction and temperature change so that the assessment can be expanded to cover more climate change models.

In the present study, a runoff-based alternative approach was developed to project the change in annual hydropower generation of the US federal hydropower plants. The assessment includes a series of hydro-climatic models and statistical techniques, including GCM projection, RCM (regional climate model) simulation, HM (hydrological modeling), historic runoff–generation relationships, and a US national hydropower data set. The methods and results are described in the following sections.

2. Methods

2.1. Scope and study area

Federal hydropower in the United States is generated from 132 plants that are owned and operated by the USACE (US Army Corps of Engineers), the Bureau of Reclamation (Reclamation), or the IBWC (International Boundary Water Commission) (Fig. 1). The