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Vulnerability of the US western electric grid to hydro-climatological conditions: How bad can it get?

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ABSTRACT

Large-scale assessments of the vulnerability of electric infrastructure are usually performed for a baseline water year or a specific period of drought. This approach does not provide insights into the full distribution of stress on the grid across the diversity of historic climate events. In this paper we estimate the Western US grid stress distribution as a function of inter-annual variability in regional water availability. We softly couple an integrated water model (climate, hydrology, routing, water resources management, and socioeconomic water demand models) into an electricity production cost model and simulate electricity generation and delivery of power for combinations of 30 years of historical water availability data. Results indicate a clear correlation between grid vulnerability (unmet electricity services) for the month of August, and annual water availability. There is a 21% chance of insufficient generation (system threshold) and a 3% chance that at least 6% of the electricity demand cannot be met in August. Better knowledge of the probability distribution of the risk exposure of the electricity system due to water constraints could improve power system planning. Deeper understanding of the impacts of regional variability in water availability on the reliability of the grid could help develop tradeoff strategies.

1. Introduction

1.1. Background

Water is essential in all sectors of the economy. Besides the commonly known uses in the residential, commercial, industrial, and agricultural sectors, water is critical for the generation of electricity. Water scarcity affects electricity generation in three ways: 1) it reduces the energy source of hydropower generation, thereby reducing the ability to generate electric power over a period of time; 2) it may constrain the rejection of heat from thermoelectric power plants into the river resulting in a reduction in plant capacity (derated capacity) [2]; and 3) it could also reduce the thermodynamic efficiency of power plants during conditions of low flow and high water temperature, thereby requiring more energy to reject the heat from the steam cycle in power plants. Due to recent droughts in California, Texas, and the Southeast, there are growing recognition of and attention placed on the exposure of the power grid to prolonged drought conditions, particularly in the context of climate change, because the frequency and severity of droughts are expected to increase. In this paper, we focus on the water-energy nexus from the perspective of electricity generation and power operations constrained by water availability.

1.2. Previous work on the water-energy nexus: geophysical and grid modeling approaches

As of 2010, hydropower contributes 37% to the installed electricity generation capacity in the Western United States (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, Wyoming), while 17% of the installed capacity requires fresh surface water (i.e., no groundwater, no grey water, no ocean water) either for once-through cooling, wet recirculating, or wet cooling (large evaporative cooling towers) technologies [37]. To date, most approaches found in the literature that focus on the water-energy inter-dependencies quantification and vulnerability assessments are based either on geophysical models or on engineering models.

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Geophysical approaches allow analysts to explore the impacts of climate change on electricity generation capacity or potential hydropower generation. The maximum generation capacity of thermoelectric plants requiring fresh surface water has been the subject of previous assessments of vulnerability conducted under climate change conditions [3,34,35,39,40]. Potential hydropower generation has also been the subject of large-scale vulnerability assessment under climate change conditions [4,19]. Note that reasons other than low summer flow and high stream temperature could decrease capacities and/or the potential generation of water-dependent power plants—reasons like environmental flows (dissolved gas, fish migration) and changes in operations.

Some studies couple geophysical models with engineering models [33]. They comprise hydro-climate model that informs the water routing model, which in turn constrains electric power flow modeling. Vulnerability assessments under specific historical conditions such as the Dust Bowl (1934), Northwest drought (1977), and California drought (1956), using the existing and projected future grid infrastructures examined the negative impacts on these rare stress conditions [33].

Many energy-centric studies analyze data surveys, records, or models associated with a specific water-energy interdependency process [3,10]; for example, the link between thermoelectric cooling needs and water withdrawals [12,21,27,36], nuclear power plants and water withdrawals [22,34], energy needs for water supply systems [30], or bioenergy needs for electricity generation [32]. These types of water-energy dependencies can then be used to inform or constrain electricity operations models that explore the impacts on power flows through the grid. Alternatively, the projected water availability can be used to constrain an electric capacity expansion model to explore the build-out of the electric grid into the future [1,27]. These approaches assume conditions of a given water year, which neglects potential water deficits or oversupply of water from the previous year, a phenomenon that we are evaluating in this paper.

The variability of the water budget over several years needs to be considered in order to capture likely water availabilities, particularly when exploring future climate impacts on the water cycle. This paper will address this gap by studying extreme hydro-climatology factors such as drought conditions and their impacts on the operations of the electric grid. Thus, this paper provides new insights into this water-energy nexus from a risk-based hydro-climatological perspective based on coupled geophysical and engineering grid models.

1.3. Significance of this research

Previous work focused on the interactions among climate and hydrology systems, and the production and transmission of electric power; it explored various aspects for scientific reasons to gain insights into complex system phenomena, as well as to inform engineering communities about how climate via the hydrology pathway may affect current grid operation and future build-out of the power plant fleet and the transmission grid. However, only as of 2014, did the notion of grid stress testing and the development of grid stress scenarios under climate change conditions and related droughts come into being [43]. Grid planners in the Western US power grid are increasingly interested in exploring severe stress scenarios to better understand how resilient the electricity grid must become to provide reliable power services in spite of extreme natural conditions. This desire for deeper understanding is further motivated by the deployment of more variable renewable resources (such as wind and solar technologies), which reduce the level of certainty that grid operators have sufficient capacity available to meet the electric load.

To address these severe climate-hydrology conditions, this study combines the two approaches of geophysically based (usually top-down) and electric power flow modeling (usually bottom-up); it aims to investigate the impact of historical inter-annual hydro-climate variability on generation capacity and how variability further affects generation dispatch in order to look at its impact on actual grid performance. This requires a departure from the long-term resource adequacy assessment of the commonly used approach that treats water resources and extreme weather events as separate, specific, single events (e.g., average year, one extreme drought, high or low hydropower cases, etc.). Instead, the spatial and temporal variability of extreme events between regions should be considered as a portfolio of vulnerabilities. Finally, the findings will put in perspective vulnerability assessments of grid operations under climate change conditions with respect to similar assessments under historical inter-annual variability.

1.4. Specific objectives

In this paper, we estimate the impacts of water availability on electricity generation and transmission in the Western US grid for a range of historical water availability combinations, which generates a distribution function of the grid stress. We specifically address the following questions:

1. What is the relationship between water availability and the reliability (expressed as unserved electric energy without mitigating actions in operations) of the Western Interconnection (Western Electricity Coordinating Council [WECC] region)?
2. What is the value of inter-regional coordination of water-energy joint management and what regional patterns of droughts are most impactful for Western Interconnection reliability?
3. What are the grid operational risks of not addressing regional co-variability in water availability during extreme events?

To address these questions, an analytical framework is developed to explore the reliability space of the WECC region as a function of a new grid-centric drought severity metric that is specifically defined to capture and characterize the impact of water scarcity on the electric grid. The technical approach involves coupling climate, hydrology, and socioeconomic water demand models with an electricity production cost model that seeks cost-optimal electric generation dispatch within the WECC region (Fig. 1). The hydrologic regions offer a regionalization approach for analyzing the inter-regional, inter-annual and inter-seasonal availability of water-dependent energy generation. The grid simulations are performed using balancing area zones. A mechanism was developed that maps the hydrology results from the hydrologic regions to the grid balancing area zones, thus enabling the study of interactions between water availability and grid impacts (Fig. 1).

The following sections present: 1) description of the modeling framework, which includes the derivation and definition of WECC-based and regional water-scarcity grid impact factors; 2) experimental approach; and 3) and discussion of the role of inter-annual variability in regional water availability in the reliability of the grid. We also discuss opportunities for water-energy tradeoffs.

2. Domain and modeling tools

2.1. Western US grid and hydro-climatology

2.1.1. Western US grid and grid management regions

The Western US electric grid stretches from Western Canada south to Baja California in Mexico, and reaches eastward over the Rockies to the Great Plains (Fig. 1). It is commonly referred to as the