The impact of wind power growth and hydrological uncertainty on financial losses from oversupply events in hydropower-dominated systems

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Highlights

- Oversupply can lead to financial losses when renewable energy is curtailed.
- Oversupply losses will increase as a function of installed wind capacity.
- Adding transmission capacity is not a cost effective solution to oversupply.

Abstract

The rapid expansion of variable renewable energy (e.g., wind and solar) can make it more difficult to balance electricity supply and demand at a grid-scale. While much attention has focused on the risk of unexpected generation shortfalls, periods of oversupply (when supply is greater than demand) also present challenges that can lead to financial losses for utilities and/or consumers when renewable energy is “curtailed”. A unique form of oversupply occurs in hydro-dominated systems. Although hydropower is thought to offer a highly flexible resource that can complement variable renewable energy, seasonal variability in streamflows and the presence of environmental regulations can create complex oversupply conditions if renewable energy is plentiful. In this study, an integrated hydro-economic model is developed to assess the frequency and severity of financial losses arising from oversupply in the U.S. Pacific Northwest, a hydro-dominated system with rapidly growing wind power generation. Present value losses over 25 years (2016–2040) are evaluated under several future scenarios including increased wind capacity, electricity price uncertainty, and expanded transmission capacity for moving excess electricity to export markets. Results indicate that oversupply losses will increase as a function of installed wind capacity, with the extent of this increase sensitive to future electricity prices. In the case of adding transmission capacity to alleviate oversupply losses, the cost of this infrastructure is substantially more than the associated reduction in losses and is therefore difficult to justify.

1. Introduction

Wind power capacity worldwide is increasing at a rapid rate, with installed global capacity having increased roughly 2400% from 2000 to 2015 [1]. Nonetheless, an ongoing challenge with increasing wind capacity is managing wind power’s variability [2,3]. Wind speeds can change dramatically on multiple time scales, and existing power systems sometimes struggle to accommodate these sudden changes [4,5]. One challenge associated with the variability of wind is generation “oversupply”. Oversupply occurs when the total electricity generation in a region exceeds internal demand [6,7]. In general, generation oversupply happens due to the presence of some combination of “must run” thermal generation (e.g., nuclear) and hydropower that cannot be turned off or sufficiently ramped down, and variable renewable energy.

During oversupply events, excess electricity that cannot be exported to another region or stored via batteries or pumped storage [8] must be curtailed in order to maintain the integrity of the electricity grid. Often, renewables like wind and solar power are curtailed because it is the most economically and/or viable way to balance load and generation [6,9]. Without significant improvements in transmission capacity, energy storage, and demand side

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management, oversupply is likely to become a greater challenge in the future as wind and solar capacity increases [7–12].

Many studies have addressed the issue of renewable energy curtailment from an economic perspective. Some point out that it wastes energy, leading to economic losses for both utilities and society [11,13,14]. Others, however, have concluded that, given the cost of transmission and energy storage options, renewable energy curtailment may be a socially optimal choice [10]. The range of conclusions drawn from previous studies suggests that oversupply problems in different systems can be very distinct. The financial losses associated with curtailment may depend on a number of factors, including complex interactions between different types of generation, the price of electricity in deregulated markets, as well as climatic and environmental factors, making for challenges in both characterizing the problem and solving it.

Power systems in Germany and China, as well as regional energy systems in the U.S. (e.g., PJM Interconnection and ERCOT (Electric Reliability Council of Texas) and MISO (Midcontinent Independent System Operator)) have experienced generation oversupply due to the combination of must run thermal generation and greater renewable capacity, in particular wind power [8,9,15]. Another form of generation oversupply can occur in hydropower-dominated systems, especially in situations where high levels of renewables are present [9]. Hydropower, due to its operational flexibility, is often regarded as an ideal resource to compensate for the intermittency and unpredictability of wind power [16,17]. However, as more wind penetrates the electricity mix, hydroelectric dams may be limited in their ability to dramatically reduce generation to accommodate increase in wind power, especially if the operations of dams are constrained by multi-purpose obligations or environmental regulations.

Oversupply problems in hydropower-dominated systems are unique because they are a product of both hydrological variability and wind variability. Study of this issue has been limited, however, partly because accurately characterizing the frequency and severity of oversupply losses requires a modeling approach that integrates both the complexity of the reservoir system (accounting for both watershed hydrology and dam operating rules) and the larger power system (including alternative thermal sources, variable load and renewable production as well as transmission constraints). In order to facilitate exploration of oversupply problems in hydropower-dominated systems, a transferrable methodological approach is needed.

The goal of this study is to develop an integrated modeling framework that couples multi-scale stochastic time series modeling with a mass-balance reservoir network model to facilitate a probabilistic assessment of financial losses from oversupply. This integrated modeling framework is then applied to a hydropower-dominated system in the U.S., the Bonneville Power Administration control area. Loses from oversupply are quantified over an ensemble of 25-year trajectories (2016–2040), and the sensitivity of oversupply losses to various factors is explored, including: (1) the rate of wind capacity growth; (2) investment in additional export transmission capacity; and (3) fluctuations in wholesale electricity prices. The results of this work provide an improved understanding of the key factors driving financial losses from oversupply in hydropower-dominated systems. They also inform the development of better system planning strategies that accurately value the economic benefits of oversupply mitigation strategies (i.e., construction of additional export transmission capacity).

2. Methods

A primary goal of this study is to gain a probabilistic understanding of financial losses caused by oversupply events in hydropower-dominated systems. To do so, the following approach is taken. First, the study area of interest is chosen. Then an integrated modeling framework is developed, and its ability to replicate observed instances of oversupply and accurately estimate associated financial losses is validated. A sensitivity analysis is performed in order to understand the relative impacts of wind capacity growth and electricity prices on oversupply losses. Finally, present value losses are evaluated over an ensemble of 25-year trajectories (2016–2040) assuming gradual growth in wind capacity, and the question of whether investment in additional transmission capacity represents an economically viable mitigation strategy is answered.

It should be noted that “financial losses” discussed in this work differ from “economic losses”. We define financial losses simply as the monetary value of curtailed wind power production. This value does not include the broader economic losses that may include impacts to other system participants (i.e., customers in adjacent systems) or potential externalities.

2.1. Study area

Perhaps the most prominent example of oversupply in hydropower-dominated systems is the U.S. Pacific Northwest, where hydropower meets more than 60% of regional electricity demand [18]. Most of the Pacific Northwest’s electric power system is operated by Bonneville Power Administration (BPA), a federal power marketing organization that is in charge of power plant operations, transmission, and grid balancing [18]. Within BPA’s footprint there are 31 federal hydroelectric dams and many additional non-federal dams, 1 federal nuclear plant and other non-federal thermal plants [18]. This system has experienced rapid growth in wind power capacity and is already experiencing oversupply issues, with two major wind related oversupply events occurring in 2011 and 2012. Thus, BPA is a logical choice for the application of the proposed modeling framework.

Oversupply events in the BPA system occur as a result of a complex interaction between snowmelt-driven hydrology, wind power availability, limited export transmission capacity, and environmental regulations on the operation of hydroelectric dams (see Fig. 1). During periods of high streamflow (peak summer snowmelt), hydroelectric dams in BPA’s system, including many found in the Federal Columbia River Power System (FCRPS), a network of hydroelectric dams spanning several states, produce massive amounts of hydropower. In response, thermal power plants are shut down or ramped down to their operational limits [19–21] in order to maximize the use of hydropower. Nonetheless, with wind power capacity in the region growing quickly, the combination of summer hydropower production and wind power can create periods of system-wide generation oversupply. With limited transmission capacity for exporting excess electricity to other systems (i.e., California and British Columbia), resolving oversupply issues in the BPA system is a challenge that ultimately falls to generators within the system.

As a first recourse, dams reduce hydropower production (thereby maximizing the use of wind power) and store water for release at a later time. Ultimately, however, storing inflows drives reservoir levels higher and exhausts the ability of dam operators to store any additional water. The next recourse available to dam operators is to “spill” water (i.e., discharge it from reservoirs without generating electricity). In the FCRPS, however, environmental regulations on flows downstream of some hydroelectric dams limit the dams’ ability to spill water in order to accommodate high wind energy penetration. Specifically, spilling large volumes of water can cause elevated downstream levels of total dissolved gases [22], a violation of federal water quality standards. Thus, the combination of high reservoir levels and water quality regulations can,
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