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Analyzing storage for wind integration in a transmission-constrained power system

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HIGHLIGHTS

- Storage and transmission reduce wind curtailment, but transmission is more effective.
- The energy value of storage and transmission is greater than the sum of the parts.
- The arbitrage value of storage diminishes in terms of both energy and capacity.
- Energy storage may provide greater value when collocated with wind instead of load.
- The energy arbitrage value of storage alone does not justify the investment.

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ABSTRACT

High levels of energy from variable generation sources such as wind and solar photovoltaics (PV) can result in significant curtailment, in which the wind and PV energy cannot be used to serve demand. Adding transmission and energy storage can assist in reducing renewable curtailment, but the relative merits of each enabling technology individually or combined is not well understood. Thus, we compare the role of transmission and storage in reducing curtailment, as well as reducing generation costs from conventional sources. Using a high-fidelity model of the electric power grid, we examine a scenario in which the western portion of the U.S. and Canada reaches 37% energy from wind and 12% energy from solar PV. In the case studied, we find that transmission is generally more effective than energy storage in reducing curtailment, due to the curtailment patterns of wind. However, the interaction between transmission and energy storage shows that the two technologies act symbiotically, meaning that their combined energy value is greater than that of each individually. This analysis demonstrates that fully realizing the benefits of wind resources located far from demand centers will require an effective method to deliver wind power at the right times to the right locations.

1. Introduction

Wind energy capacity in the world totaled 487 GW in 2016, with the United States surpassing 82 GW [1,2]. Declining capital costs, improved performance, and favorable policies have prompted continued growth in the industry. The U.S. Department of Energy's Wind Vision Study set out to examine the costs and benefits from wind energy if robust growth continues [3–6]. Specifically, the Wind Vision Study Scenario analyzed a future in which wind generation serves 35% of total U.S. electricity consumption in the year 2050. Analysis of this scenario demonstrated significant health, environmental, and economic benefits. Additional detailed grid modeling showed that over 35% wind generation (with 12% PV generation) was operationally feasible in the Western U.S. [7]. However, it also showed that absent significant transmission upgrades to accommodate wind resources in the Rocky Mountain states, a high amount of wind curtailment can be expected. Curtailment occurs when wind energy is available, but unable to be used to serve demand. Curtailment can occur for many reasons, including insufficient ability to transport wind energy to demand centers, or the inability to reduce conventional generation to accommodate wind output [8]. In the case of [7], the curtailment is almost entirely the result of insufficient transmission capacity.

The fact that the best wind resources are often far-removed from demand centers is not unique to the Western U.S. [9–11]. Grid studies identify insufficient transmission access as a primary driver for wind energy curtailment [12]. Nevertheless, even if transmission appears an economic method to boost wind utilization, there are often barriers to deployment of large-scale transmission lines. These barriers include the

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substantial effort required to plan, site, permit, and construct large transmission lines, which often cut across great distances [7,13,14].

Where transmission expansion may be difficult or impossible, energy storage is widely discussed as an alternative strategy for wind energy integration [15,16]. Previous analysis has demonstrated the ability of energy storage to avoid curtailed energy and increase the value of wind generation [17–21]. However, the value of avoided curtailment alone is not enough to justify storage deployment, due to the current high cost of storage [18–20]. The economics of storage can improve with the addition of other value streams, such as storage provision of firm capacity, participation in reserve markets, or when high levels of wind penetration make low-cost energy abundant [16,19,21]. Even still, this previous analysis has generally found that transmission is a more cost-effective approach to wind integration compared to energy storage [18,22,23]. Again, this is largely due to the capital cost of storage, but also because transmission is more effective at delivering power during periods of high wind compared to storing energy for later, which incurs an efficiency loss [23]. However, declining storage costs motivate continued examination of the potential benefits of storage in wind integration.

For instance, previous analysis begins to show the tradeoffs associated with siting wind, transmission, and storage [20,22,23]. Storage co-located with wind may be able to reduce transmission costs needed to deliver energy from remote wind resources [24,25]. However, storage co-located with wind may not be able to take full advantage of system arbitrage because storage can be impeded by transmission congestion, making storage deployment less economical [25].

Previous studies have indicated the complex considerations in siting wind, transmission, and energy storage. In this analysis, we build on these studies using a high-fidelity model of the synchronous power grid comprising the western portion of the U.S. and Canada (known as the Western Interconnection) to evaluate the role of energy storage and transmission capacity in a high wind scenario. We evaluate the potential for storage to reduce wind curtailment and demonstrate the challenges of using shorter-duration (with 8 h charging ability at rated power capacity) storage to relieve transmission congestion from remote wind resources. We also demonstrate the importance of comparing the benefits of siting storage remotely, where it can avoid curtailed wind energy, to siting storage closer to load, where it can provide different and potentially more valuable grid services. Our analysis begins to untangle the considerations between using transmission and storage to integrate wind at a high renewable energy level of nearly 50% using state-of-the-art modeling techniques. Although we focus on a specific geographic area, the results and insights in this analysis should be applicable to other wind-heavy systems with transmission congestion.

2. Methods

2.1. Model and input data

The operation of the electric power grid on an hourly or sub-hourly timescale presents a challenge in minimizing generation costs while maintaining reliability and adhering to various physical and institutional constraints. We use the PLEXOS production cost model to simulate the commitment and dispatch of the power plant fleet to meet demand at every time step [26]. PLEXOS is a proprietary model; however, the software has been broadly accepted and validated externally, and is used increasingly widely by utilities and researchers alike [27–29], especially to observe the effects of wind generation on electricity and market operations [30–32].

The PLEXOS model is formulated as an optimization problem to minimize the sum of fuel cost, start-up and shutdown cost, and variable operation and maintenance cost under many constraints. Although the model can be configured deterministically or stochastically, we use the deterministic capability over several scenarios. PLEXOS uses the many inputs supplied by the user (discussed later in this section) to minimize cost over the simulation horizon. We use a simulation horizon of one day (with an additional day of lower-resolution foresight) at hourly resolution. PLEXOS solves each day chronologically before moving onto the next day. PLEXOS uses a mathematical solver, in this case, Xpress MP, to compute the mixed-integer linear program. We execute all simulations of PLEXOS version 7.200 R03 on a Windows workstation with 192 GB of RAM and 3.0-GHz processors.

PLEXOS requires many types of input data, including generator parameters, network topology, and time-varying profiles such as electric demand and the weather-dependent generation patterns of solar and wind resources. We start with the model developed in [7], which relies on public datasets from the Western Electricity Coordinating Council (WECC) and previous analysis [33,34]. This dataset contains every generating unit in the Western Interconnection, with unit-specific characteristics such as heat rate curves, ramp rates, start-up costs, minimum generation levels, outage rates, and availability data for the hydroelectric fleet. The dataset also contains transmission network topology and other detailed transmission data such as individual line capacity and voltage ratings. The network represents transmission projects in existence today, as well as a small number of anticipated builds before the year 2030. In our analysis we enforce the interface limits of 118 transmission paths from the WECC stakeholder review process, with optimal direct current (DC) power flow at a zonal level.

Table 1 shows the generating fleet used for this analysis, which captures a representation of the year 2050 from the Wind Vision Study Scenario, as discussed further in [7]. The location and amount of wind generators in this analysis, informed by the Wind Vision Study Scenario, totals 371 TWh of available wind generation annually. Interconnection-wide annual demand totals 1030 TWh. This represents a 37% possible penetration of wind energy (measured on an annual energy basis). Further, the scenario includes 12% energy from solar PV, leading to a total potential variable generation penetration close to 50%. Fig. 1 depicts the geographical distribution of the available wind generation, showing the annual average and hourly maximum penetration in each state. Here, annual penetration represents the total potential yearly contribution from wind generation relative to the total demand in that state, before any curtailment. The wind resource relative to load is the highest in the Rocky Mountain states, which are windy and more sparsely populated than coastal regions. In some states, annual potential wind generation actually exceeds annual demand, leading to penetrations greater than 100%. These high levels of wind indicate that these states must be net exporters of energy – using their wind energy to serve demand in other states.

The 2050 natural gas price, as modeled, varies by month and region, averaging $6.7/MMBtu. As gas prices are highly uncertain into the future, we also consider prices 25% higher and lower than that average

Table 1
Modeled generation fleet in the Western Interconnection.

Type	Capacity (GW)
Biomass	2.5
Coal	27
Concentrating solar power (CSP)	3.2
CSP with thermal energy storage (CSP-TES)	2.8
Gas CC	56
Gas CT	29
Geothermal	4.2
Hydro	49
Other (combined heat & power, engines, etc)	6.2
PV	49
Customer-sited PV	13
Energy storage (pumped hydro, battery)	5.6
Wind	116
Total (sum)	**366**
Peak load	188
Total Annual Load (terawatt-hours)	1030 TWh