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Timescales of energy storage needed for reducing renewable energy curtailment

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ABSTRACT

Integrating large amounts of variable generation (VG) resources such as wind and solar into a region's power grid without causing significant VG curtailment will likely require increased system flexibility via changing grid operation and deploying enabling technologies such as energy storage. This article analyzes the storage duration required to reduce VG curtailment under high-VG scenarios. The three analysis scenarios assume VG provides 55% of the electricity demand in the largely isolated Electricity Reliability Council of Texas grid system in 2050, with three different proportions of wind and solar generation. Across the three scenarios, 11%–16% of VG energy is curtailed without storage due to system-generation constraints. When 8.5 GW of storage capacity with 4 h of duration are added, curtailment is reduced to 8%–10% of VG. Additional storage duration further reduces curtailment, but with rapidly diminishing returns. At least half the potential avoided-curtailment benefits are realized with 8 h of storage, and the first 4 h provide the largest benefit. At VG penetrations up to 55%, there appears to be little incremental benefit in deploying very-long-duration or seasonal storage.

1. Introduction

Integrating large amounts of variable generation (VG) resources such as wind and solar into a region's power grid is challenging because of the mismatch of electricity supply and demand across various timescales. A number of grid-integration studies have been performed in the United States with differing levels of VG penetration and modeling fidelity [1–4]. A key finding of these studies is the potentially significant increase in renewable energy curtailment that occurs at increasing penetration [5–7]. This increase in curtailment can substantially reduce the value of VG and its cost-competitiveness.

Few integration and planning studies of high VG deployment have considered large-scale storage deployment in detail (examining storage size and configuration needed to minimize curtailment), typically because historical storage price projections preclude the economic use of storage compared with more cost-effective flexibility options.

The significant reduction in costs for energy storage observed recently and projected going forward warrants further examination of increased storage deployment in high-VG scenarios [8]. Greater storage deployment may occur as storage becomes cost-competitive with conventional peaking resources and as greater renewable deployment increases the value of storage [9].

A key element of using energy storage to integrate renewable energy and reduce curtailment is identifying the timescales of storage needed—that is, the duration of energy storage capacity per unit of power capacity. Most of the existing storage in the U.S. is in the form of pumped hydro storage with fairly long duration (typically 8 h or more) [10]. However, much of the current deployments is in the form of batteries, often with 4 h or less of storage. This deployment may be accelerated by regions that allow 4-h storage to receive credit for providing peaking capacity, which may disincentivize longer-duration storage [11]. This raises the question as to whether shorter duration storage will be sufficient to reduce curtailment. The tradeoff between long- and short-duration storage also needs to consider the mix of wind and solar generation.

This report analyzes the storage duration required to reduce VG curtailment under high-VG scenarios. It also examines the value of storage with varying durations and how these insights might be used to optimize storage sizing from the perspective of a storage developer. Section 2 briefly discusses the timescales of different

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energy storage technologies and their potential application in integrating renewable energy. Section 3 describes our methods. Section 4 shows our results, including the impact of storage duration on curtailment and value. Section 5 concludes and suggests areas for future work.

2. Timescales of energy storage

An energy storage device's size is defined by its power capacity and energy capacity. The power capacity reflects the rate at which the device can charge or discharge. Power capacity for energy storage is typically measured in kilowatts or megawatts, just as it is for conventional power plants. The energy capacity reflects the amount of stored energy, typically measured in kilowatt-hours or megawatt-hours. Linking these two metrics is storage duration: the amount of time the storage can discharge at its power capacity before depleting its energy capacity. Although this is a fairly straightforward measure, actual energy capacity ratings are complicated by limits on how the storage device can be used economically. For example, only a fraction of the rated energy capacity may actually be used to avoid degrading battery performance over its life [12]. For this analysis, we base power capacity on the devices' alternating current (AC) ratings, and we base energy capacity on the devices' economically usable discharge capacity at their AC power ratings.

The power and energy capacities of an energy storage device determine the applications for which the device is useful. These applications are often categorized by the timescale or duration of discharge needed for a particular grid service. Timescales of storage technologies that have been deployed at significant scale range from fractions of a second to many hours [10]. Several timescales have been identified for integrating renewable energy.

At the shortest timescale (seconds to minutes), significant storage has been deployed for providing operating reserves including frequency regulation, which responds to small random variations in normal demand [13]. Although individual renewable generators can demonstrate rapid, short-term fluctuations in output (e.g., from clouds passing over photovoltaic [PV] systems), grid-integration studies have found little inherent need for storage to address these problems, largely because diverse renewable generator locations minimize rapid fluctuations of aggregate renewable output [14,15]. The ultimate market potential for storage providing operating reserves is limited by the relatively small market size and competition from other resources, such as demand response and curtailed renewable energy [16,17].[1]

At longer timescales (up to several hours), storage has been deployed to provide peaking capacity and to shift energy from off-peak to peak periods. Such storage can enable thermal power plants to run at full output or avoid shutdown, thus increasing utilization.[2] Historically, this category is dominated by pumped hydro storage, with smaller contributions from compressed air energy storage (CAES), and thermal energy storage in concentrating solar power (CSP) plants [10]. Batteries are an emerging technology for providing peak power [18]. For renewable integration, several hours of storage can be used to address ramp events and curtailment that results from the daily mismatch of renewable supply and electricity demand.

[1] The technical potential for energy storage providing operating reserves in ERCOT is about 1900 MW, consisting of 1400 MW of responsive reserves (out of a 2800-MW total requirement, of which half is already provided by demand response) and 500 MW of regulation reserves [16].

[2] This is analogous to using storage to avoid renewable energy curtailment because both increase the utilization of capital-intensive power plants and lower their cost of energy.

At an even longer timescale, storage could provide capacity greater than that needed for daily shifting, or greater than about 10 h. Some pumped hydro plants (and proposed CAES plants) have capacities somewhat larger than 10 h, which enables the plants to perform daily shifting and provide additional arbitrage between weekday and weekend price differences [19]. Various fuel production and storage technologies have been proposed to provide capacity beyond a day or so, including hydrogen and methane (power to gas) [20]. These technologies could potentially address the seasonal mismatch of supply and demand associated with renewable generation. Seasonal mismatches are largely driven by high wind and solar conditions in the spring, which is the period of lowest electricity demand. Seasonal storage has been proposed as potentially important in scenarios that have renewables providing 100% or close to 100% of a system's electricity demand [21].

3. Methods and scenarios

This section discusses our methods for evaluating the ability of storage to reduce curtailment and our various VG penetration scenarios. Our scenarios are based on achieving annual average penetration of up to 55% VG on an energy basis. We use the U.S. Department of Energy (DOE) Wind Vision study as a baseline to study the potential role of energy storage at increased penetration of VG [22,23]. The study examines a nationwide penetration (on an annual energy basis) of 35% wind (and 10% solar) by 2050. However, the penetration varies regionally, with a 44% annual contribution from wind, along with 11% from solar, in the Electric Reliability Council of Texas (ERCOT) grid. The Wind Vision study assumes a relatively modest increase in transmission capacity between ERCOT and the rest of the United States. As a result, the study provides scenarios with VG contributions well over 50%, creating a useful test for the role of storage in mitigating curtailment in relatively isolated regions.

We develop three scenarios based on the ratio of wind and solar:

- **Wind Vision**: 44% wind, 11% PV
- **Equal Mix**: 27.5% wind, 27.5% PV
- **Minimum Curtailment** (the mix of wind and solar that produces the lowest level of curtailment): 38% wind, 17% PV (calculation of this ratio is described in Section 3.2).

3.1. Simulations

For this study, our main performance metric is the amount of curtailed renewable energy assuming the addition of various amounts of energy storage. To calculate the amount of curtailment in each scenario, we perform chronological simulations using NREL's Renewable Energy Flexibility (REFlex) model [24]. REFlex performs a chronological dispatch of aggregated thermal and hydro units assuming generator flexibility limits, including ramp rates and minimum generation levels. It also performs chronological dispatch of energy storage and measures the ability of storage to avoid curtailment.

In each hour, the REFlex model maintains an hourly supply/demand balance, and any renewable energy generation that exceeds what can be used by the system is counted as curtailed energy and does not contribute to the fraction of demand met by VG. A key factor in system dispatch to maintain supply/demand balance is the minimum generation level from thermal generators [25]. We use the 2016 price/net-load relationship to calibrate the aggregated minimum generation level for the fossil and nuclear (thermal)