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Spatial and geographic heterogeneity of wind turbine farms for temporally decoupled power output

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A R T I C L E I N F O

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Many regions with good wind resources and aggressive renewable energy portfolio targets have achieved installed wind turbine capacity that is difficult for electricity system operators to manage. The purpose of this paper is to compare the measured output of wind farms at various locations throughout Nova Scotia, looking specifically at factors that either facilitate or hamper integration of additional capacity into the existing grid system. Special emphasis is placed on the effects of aggregating wind farms that are separated by distance and geography, and consequently experience different wind conditions at different times. The results are presented using metrics that have significance to electricity grid system operators, and new metrics that are accessible, readily interpretable, and actionable in locating new wind farms. The principle findings are that over a distance of 540 km the majority of potential correlation and 10-min ramp-rate reductions are achieved; that up to 30% improvement in effective load carrying capacity of wind farms is available for the worst electricity load hours by strategic wind farm siting; and a new metric shows several hours time shift between existing farms over this span. This timeshift is equal to or longer in length than most electricity utilities' peak demand periods;

1. Introduction

As intermittent renewable energy makes up an ever larger share of the electricity supply, addressing the challenges associated with variable generation becomes an important component of system resource planning [1–4]. There are a number of approaches to deal with the problem of coordinating unscheduled variability, and these depend on the characteristics of the resource [5]. The most basic approach is to simply limit renewable energy via penetration caps or operation (i.e. curtailment) to levels at which grid impacts are manageable using conventional mechanisms [6,7]. Similarly, renewable energy variability beyond the capacity of existing grid stability mechanisms may be addressed by dedicating complimentary dispatchable resources such as fast-ramping fossil-fueled generation [8]. More slowly ramping resources may be leveraged by improved wind forecasts, which was demonstrated in the Canadian Maritime Provinces by considering multiple fields as a unit [9].

There are other approaches that extend renewable generation capacity limits without the need for additional dispatchable generation capacity. One of these is expanding the electric grid flexibility by adding energy storage [10–15], which has been found to be technically effective, though the economics are challenging. A variant to this is identifying and managing variable dispatchable loads such as desalination [16,17] where 'energy' is stored as stocks of processed material.

Another approach consists of understanding, maximizing, and relying on the effects of resource aggregation and transmission to smooth renewable outputs, and to export or import power locally to address oversupply or undersupply [18–22]. The efficacy of transmission relies on the spatial variability of renewable resources, i.e., the tendency for resources in different physical locations to rise and fall at different times. As a prescriptive measure, such analyses in general attempt to identify regions that have renewable resources that, when combined, minimize the cost imposed on the electric grid [23].

Nova Scotia, in southeastern Canada, has a relatively high penetration of wind turbine capacity, consisting of some 560 $MW_{installed}$ in a province where the 1st percentile electricity load in 2016 was just 760 MW, the average load was 1200 MW, and the 99th percentile load was 2100 MW. The province presently has only a 300 MW transmission intertie for import/export, making it almost an energy island. This combination of high renewable

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penetration rate, low average load, and near-island status has brought about concern that additional projects would hamper the ability of the electricity grid operator to insure reliable and stable electricity supply. Many untapped regions of Nova Scotia have highly economic wind resources, with annual average wind speeds exceeding 8 m/s [24] (7.5 m/s is often cited as economically viable, though newer technology is pushing down that threshold [25–27]).

To support further integration of wind turbine projects, this study focuses on the inter-variability of wind resources at locations throughout the province. The aim is to determine how additional wind farm capacity may be integrated into the electricity grid with minimal operational impact by strategic and informed siting. Further, this paper introduces methods and aims to identify principles which may be applied in other jurisdictions where wind resources are good but balancing resources are limited. Methodologically, this study will evaluate the effects of physical separation or regional distribution between wind farms on various aspects of the temporal variability of electricity production. It will qualify and quantify how wind farm location influences the ease with which wind farms can be accommodated by the utility, focusing on metrics already in use by grid managers, and new metrics devised for this purpose.

To accomplish this, we present the usage of 10-min timestep resolution measured power data from 11 wind farms located over a span of 540 km. The general approach of seeking complimentary renewable resources has been discussed by previous researchers.

Timeshifting of resource output (section 4.1) is not discussed or quantified in any of the reviewed literature, but the effects are discernable in timeseries plots in other jurisdictions by Refs. [21,28].

Inter-farm correlation as a function of distance (section 4.2) is examined by Refs. [20,28–31]. Among these [29], differentiate correlations by north-south and east-west separation, while [20] note that geographic or topographic differences seem to contribute to differences in the wind regime. The authors of [32] show correlations between wind farms, but don't explicitly tie those correlations back to location.

The effects of wind farm aggregation on ramp rates (section 4.3) are noted by various researchers, and are addressed in various ways. The authors of [33] express ramp rates as a cumulative distribution function of percent change of regional net load per hour. They observe changes through *time* as more wind is added, and differences between regional systems, but they do not examine the effects of regional heterogeneity of renewable resources. Ref. [21], do not treat it explicitly, but show production exceedance probability curves for individual wind farms within seven regions, along with aggregate production curves for those regions. Refs. [20,34] examine changes in ramp rates in the frequency domain and show that higher frequency variability is reduced as more sites are aggregated, and that maximum step change decreases with aggregation distance, an effect that improves when shorter time intervals are considered.

Changes in production curves (section 4.4) are likewise noted by various authors. The treatment in Ref. [28] is most similar to ours.; the authors show production curves of two wind farms, and the production curve for the array of 11 sites spanning 2400 km. For the combined resource both zero and full production are exceedingly rare, and outputs between 20% and 40% of capacity are most common. In Ref. [21], regionally aggregated wind resources are compared to their individual wind farms using generation duration curves, where scaled output is plotted against exceedance probably. Because they only consider entire regions, their results are difficult to quantify as a function of aggregation. In Ref. [30], the average UK wind speed and wind power output are compared to a typical turbine power curve. The wind resource aggregated across the UK produce relative outputs up to about 0.4 $MW/MW_{installed}$ at far lower windspeeds than the power curve would suggest (i.e., are more common . The authors of [32] observe a centralizing tendency of the wind speed probability density function (towards ~10 m/s) as separate wind farm sites are aggregated, and a reduction in the frequency of zero generation.

Our research also focuses explicitly on a metric of wind power availability/reliability used by electric utilities; the effective load carrying capacity (ELCC; section 4.5). This attribute of wind variable has been examined extensively by Ref. [35], but without examination of the effects of aggregation or spatial variability of wind resources. Subsequently [36] noted that ELCC of a combination of two wind fields was better than that of a single one. To our knowledge wind farm siting for ELCC optimization has not been systematically studied within academic literature.

2. Data sources

The principle data type required for this study is wind turbine electrical power outputs. Two types of power data were used, wind farm level and provincial aggregate electricity system data. We solely utilize measured power output data from operating wind turbines to insure fidelity of the analysis.

2.1. Wind farm data

The principle tool of evaluating spatial heterogeneity is a set of wind turbine output data measured at disparate locations around the province. Data was sourced from the provincial utility Nova Scotia Power Inc. (wind farms: South Canoe, Nuttby Mtn., Glen Dhu, and Sable), and from wind farm operators Colchester Cumberland Wind Farm Inc. (Spiddle Hill), Katalyst Wind Inc. (Wedgeport, Barrington, Ketch Harbour, Porters Lake, and New Glasgow), and Gardiner Mines Renewable Energy Inc. (Gardiner Mines). These organizations construct and/or operate wind farms throughout the province, and Nova Scotia Power Inc., the province's vertically integrated utility, is also the principle purchaser of generated electricity. Fig. 1 shows the location of Nova Scotia within Canada (inset), the locations of the wind farms, and the geography of the province. Additional information about each of the farms is provided in Table 1.

For 10 of the 11 farms, between 1 and 34 wind turbines were in operation for the full duration of 2016. The exception is Gardiner Mines where the first of three wind turbines entered service on January 14, 2016. With the exception of data from Nova Scotia Power farms, wind turbine data was taken directly from the wind turbines' SCADA systems on a 10 min timestep. Data from the four Nova Scotia Power farms were measured at transmission interconnection points and thus represent the net aggregated output of the wind farm. At Nuttby Mountain, both individual wind turbine and aggregated substation data was available. The two show very small inconsistencies averaging 2% and rarely exceeding 5%, which may be associated with equipment loads and transformer inefficiency when collecting and converting power from the wind turbines to the grid interconnection.

From each of the wind farms a selection of data was available. To address the issue of grid integration, the most interesting piece of information was the electrical power output, which in all cases was

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[3] Topographic map: by Zamonin - Source: At least one of the following Public Domain data sourcesETOPO1 (Resolution 1° = 1,8 km)SRTM 4.1 (Resolution 3' = 90 m), CC BY-SA 4.0, [https://commons.wikimedia.org/w/index.php?curid=47355838].