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RESEARCH ARTICLE

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How many offshore wind turbines does New England need?

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Abstract

The proliferation of countries and regions with 100% clean or renewable energy targets necessitates an analysis to determine the number of generating units and storage needed to meet real-time electricity demand on the electric grid. The coastal areas of New England have the capacity to produce a large percentage of the region's energy needs with offshore wind turbines. Here we model offshore wind turbine power production data using MERRA-2 reanalysis and lidar wind speed data sets. We compare this power production to the New England hourly grid demand over the course of one year. 2,000 10 MW offshore wind turbines could satisfy New England's grid demand for about 37% of the year. When combined with 55 GWh of storage, 2,000 turbines could satisfy grid demand for about 72% of the year.

KEYWORDS

electrical demand, grid, lidar, offshore wind, reanalysis, renewable energy, storage, wind energy

1 | INTRODUCTION

Wind energy continues to grow rapidly as a way for individual countries and states to meet their clean energy goals, achieving greater energy independence and reducing overall emissions. Twelve US states and territories, including New York, New Jersey and California, currently have plans to meet 100% of their energy needs with clean or renewable energy by 2050 (Energy Sage, 2019). For coastal regions, offshore wind has become an attractive opportunity for development because it requires less land area than land-based wind energy in states with a high population density, such as Massachusetts, New York and New Jersey. According to the National Renewable Energy Laboratory's (NREL) Assessment of Offshore Wind Energy Resources, the waters off the coast of Massachusetts have average turbine hub-height wind speeds of 9–10 $m \cdot s^{-1}$, some of the highest wind speeds found in US offshore areas (Draxl *et al.*, 2015). The high potential productivity and current plans to develop wind farms here motivate the study of this region.

The only offshore wind power plant currently operating in the US has an installed capacity of 30 MW and is located off the coast of Block Island, Rhode Island. In 2018, Vineyard Wind leased a 675 km^2 area off the coast of Martha's Vineyard, Massachusetts, to install 800 MW of offshore wind capacity (Bureau of Ocean Energy Management, 2019). In Virginia, approval has been granted to Dominion Energy to construct roughly 220 turbines to supply 2,600 MW of offshore wind power to the state (Dominion Energy, 2020). In comparison, Europe currently has 4,543 grid-connected offshore wind turbines installed, contributing 18,500 MW to meet energy demand (Wind Europe, 2019).

By analysing high-resolution mesoscale weather models, Dvorak *et al.* (2013) theorized that "the strong winds off the

[US East Coast] alone can theoretically power all of the annual coastal electricity demand from Florida to Maine." A quantitative comparison of wind power supply and grid demand is necessary to aid grid operators and utilities in determining how much turbine and storage capacity would be necessary to feasibly meet the power demands for that region, or if 100% offshore wind penetration is possible. This study follows other studies that attempt to quantify offshore wind resource capacity using reanalysis data and numerical weather predictions, including Manwell *et al.* (2002), Draxl *et al.* (2015), Musial *et al.* (2016), Doubrawa *et al.* (2018), James *et al.* (2018), Lee *et al.* (2019) and Schwartz et al., (2010), but extends the analysis by coupling the wind resource with the region's energy demand.

Meteorological conditions influence grid demand, necessitating heating, cooling and lighting, but these same conditions simultaneously impact the power supply from renewable sources (Bloomfield *et al*., 2016). Unlike temperature, precipitation and grid demand, which can be directly measured instantaneously, data describing the wind resource are often more difficult to obtain because direct wind speed measurements from cup anemometers or lidars at the study location are not always available. Instead, reanalysis data such as those from the National Aeronautics and Space Administration's (NASA) MERRA-2 global reanalysis data set can be used instead as a reliable wind resource estimate (Lahlou *et al*., 2019). The reanalysis data are derived from a retrospective analysis of global meteorological data using a weather/climate model incorporating observations from a wide range of land- and satellite-based instruments (Rienecker *et al*., 2011). By using hourly wind speed measurements from MERRA-2, changes in meteorological conditions that may impact hourly demand will be reflected by a change in the wind resource and turbine power production at the same time.

Here we estimate requirements for offshore wind power production to satisfy energy demand. The grid demand and wind speed data sets used in the study are presented in Section 2. We demonstrate the reliability of the wind speed data used in the analysis in Section 3. The methodology used to compare wind speed and grid demand is presented in Section 4. In Section 5 we quantify the number of turbines and storage capacity necessary to match demand for a certain percentage of the year and discuss the effects of interannual variability. In Section 6, we summarize the results and conclude the analysis.

2 | DATA

2.1 | Demand

To understand the grid requirements for the region of New England, we assess hourly demand data. The hourly demand data quantify the total power demand experienced by the grid operated by the New England Independent System Operator (NE ISO). NE ISO spans the states of Maine, Vermont, New Hampshire, Massachusetts, Connecticut and Rhode Island, providing power to 14 million people, about 4% of the US population (NE ISO, 2020). NE ISO has 8,000 miles of high-voltage transmission lines that transmit approximately 32,000 MW of electric power to New England's residents and businesses. The current resource mix is comprised of 49% natural gas, 30% nuclear power and 18% renewables, including 3.2% wind energy, 1.4% solar and 8.9% hydro; the remaining 3% is made up of coal and oil. NE ISO has decommissioned two nuclear power plants in the past five years, resulting in a loss of more than 1,200 MW of generating capacity. It intends to rectify this loss by increasing the capacity of zero-emission renewables such as wind and solar (NE ISO, 2020).

NE ISO measures the total demand from the grid at the start of each hour. The grid data used in the present study begin at 0000 UTC on October 17, 2016, and continues in hourly increments until 2300 UTC on October 16, 2017. This one year aligns with the time period during which lidar wind speed data were gathered.

The daily and seasonal cycles of grid demand correspond to human behaviour in reaction to meteorological conditions. Figure 1 shows the variability of daily grid demand as well as seasonal variations. In general, there are two daily peaks: one occurring around 0700 hours, which corresponds to the time that many people begin their days. As people wake up, they turn on lights and appliances, and businesses begin to use electricity for the workday. The next peak occurs at around 1800 hours. Turning on more lights as it gets dark, cooking, and watching television all contribute to this peak. In

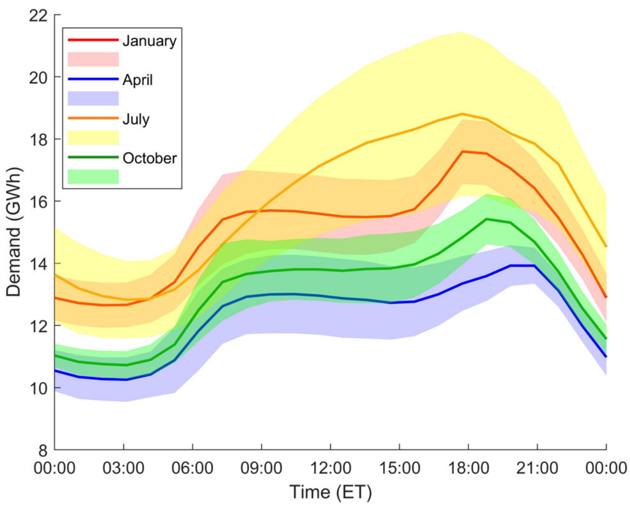

FIGURE 1 Average daily demand for representative months, 2016–2017. Shaded areas represent ± 1 SD (standard deviation) of the mean for each day of the month

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summer (June–September), only the 1800 hours peak appears, but the overall grid demand is higher due to the use of air-conditioning throughout the day (National Academies of Sciences, 2017). The summer displays slightly higher overall energy consumption than the rest of the year (Figure 2). However, wind speeds do not vary in the same predictable cycles (Bodini *et al.*, 2019).

2.2 | Supply

2.2.1 | MERRA-2

Estimates for hourly wind speeds at the reference site, the Bureau of Ocean Energy Management Lease OCS-A 0501, were gathered from the MERRA-2 reanalysis data set. The MERRA-2 data set assimilates numerous observations including temperature and wind from radiosondes, commercial aircraft, surface station pressure, and ship and buoy temperature, as well as satellite radiances (Rienecker *et al.*, 2011). Radiosonde measurements are taken at 72 vertical levels within the atmosphere, and linear interpolation is used to estimate wind speed at every altitude by assuming the wind speed changes linearly with altitude between two observed values. MERRA-2 outputs wind speeds at 2, 10 and 50 m. Linear extrapolation was used to estimate the hub height wind speeds at 120 m (Staffell and Pfenninger, 2016). MERRA-2 data have a horizontal resolution of 0.5° in longitude and 0.625° in latitude (Rienecker *et al.*, 2011) creating a 41 × 56 km cell around the lease location (Figure 3). A single average wind speed is assigned over this entire 2,300 km^2 cell. Wind speed data from the four cells surrounding the lease location were used to bilinearly interpolate an estimate of wind speeds at lease location of 41 ° N, 70.56 ° W. The reanalysis data have an hourly temporal resolution. MERRA-2 reanalysis wind speed data used in the present study were collected from Renewables.ninja (Pfenninger and Staffell, 2016) at 120 m and at the lease location hourly for the same one year period as the demand.

2.2.2 | Lidar

Limited offshore observations of wind speed and turbulence are available. During this study period, the Woods Hole Oceanographic Institute (WHOI) Air–Sea Interaction Tower (ASIT) hosted a profiling lidar located at 41.325 ° N, 70.56 ° W in the same MERRA-2 grid cell as the lease location. The Windcube V2 profiling lidar was mounted on a 13 m platform in waters 3 km south of Martha's Vineyard (Bodini *et al.*, 2019). The lidar measures horizontal and vertical wind speeds as well as wind direction and wind speed dispersion. Measurements are

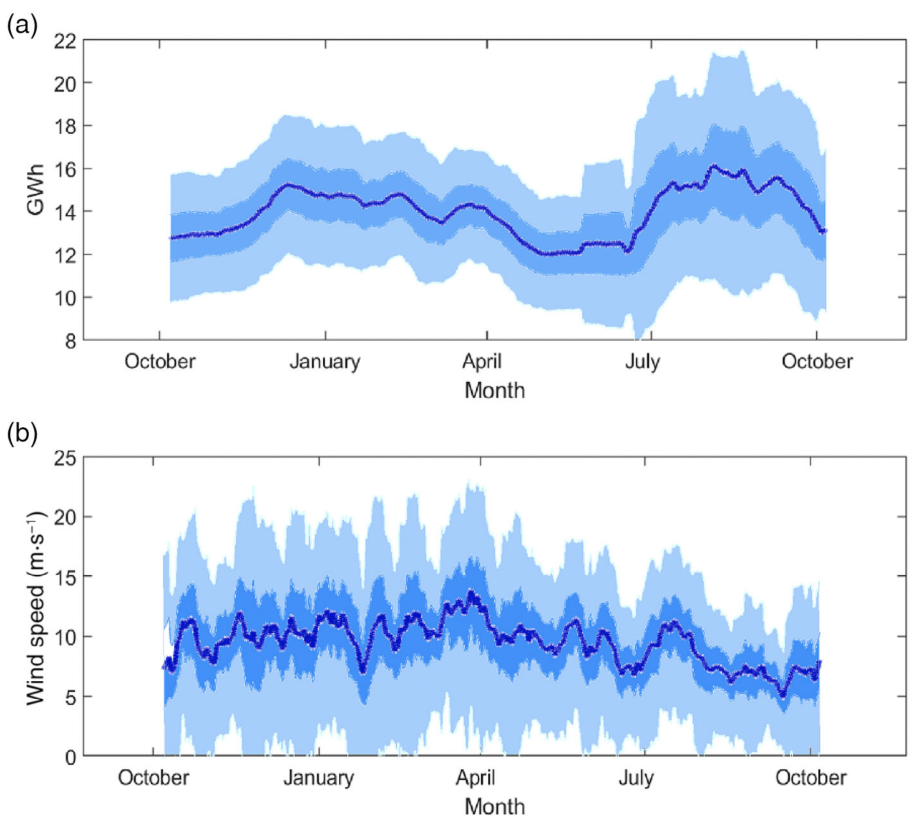

FIGURE 2 (a) Ten-day moving-averaged hourly grid demand (NE ISO, 2020); and (b) 10-day moving-averaged hourly wind supply over the course of year, 2016–2017 (Pfenninger and Staffell, 2016). The medium blue shaded areas represent 1 SD (standard deviation) of the moving average; the light blue band represents the full range of the data

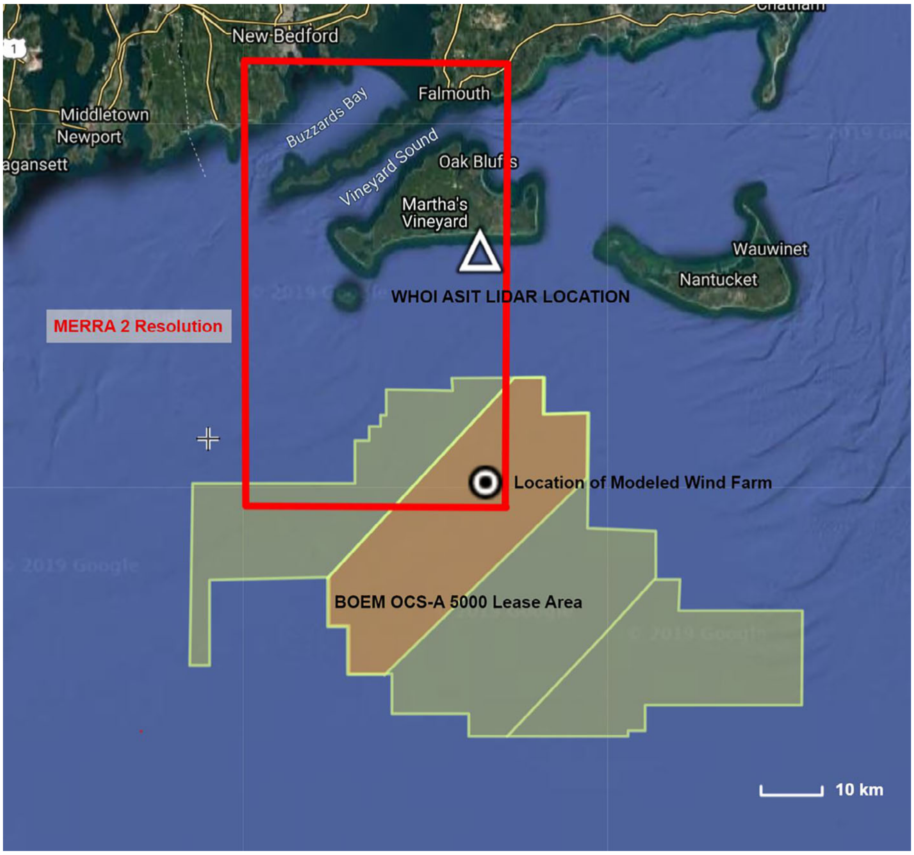

FIGURE 3 Lidar location at 41.325 ° N, 70.56 ° W at the white triangle labelled 'WHOI ASIT'. The red box represents the area encompassed by the MERRA-2 grid cell

taken at 53, 60, 80, 90, 100, 120, 140, 160, 180 and 200 masl. The lidar estimates wind speed measurements at every altitude approximately once *per* 5 s, averaged to 10-min intervals (Kirincich 2020).

3 | DATA SET VALIDATION

Because our renewable energy *supply* estimates rely on reanalysis estimates of wind speeds, we first validate these wind speed estimates at the lidar location by comparison with offshore lidar observations. At an altitude of 120 masl, the MERRA-2 windspeed data agree with lidar observations. The correlation of the daily average lidar data and the MERRA-2 wind speed data produced an $R^2 = 0.86$ (Figure 4b). Similarly, the Massachusetts Clean Energy Center found an $R^2 = 0.88$ correlation between the MERRA-2 and lidar daily average wind speed data sets at a height of 100 masl (Andriyanov, 2016). These values are similar but not identical because the validation was performed with wind speeds at different altitudes.

On an hourly basis, the agreement is less compelling. The correlation of the hourly lidar data and MERRA-2 wind speed data produced an $R^2 = 0.57$ (Figure 4a). This weaker agreement may be explained by the fact that MERRA-2 assigns a single average wind speed across the 2,300 km^2 cell while the lidar takes instantaneous wind speed measurements at a single point. Furthermore, the lidar is located in coastal waters that typically experience large wind speed gradients (Jiang and Edson, 2020). This level of agreement is adequate for this study because turbine capacity assessment requires knowledge of average wind speeds and temporal and spatial trends.

4 | METHODOLOGY

Estimates of hourly power supply from the as-yet-unbuilt wind turbines off the coast of New England rely on the convolution of a wind turbine power curve with the wind speed distribution at the location of offshore wind plant lease areas. The turbine chosen to represent the eventual installed turbines is the DTU 10 MW reference turbine, an idealized turbine used to provide a representative design model (Bak et al., 2013). The power curve for the DTU 10 MW reference turbine is shown in Figure 5. This reference turbine was chosen because Vineyard Wind has stated an intention to install 9.5-MW turbines (Dominion Energy, 2020).

As seen in Figure 6, wind speeds < 4 m·s^{-1} occur during 11% of hours in the study year. No power is produced during these times because the wind speeds are less than

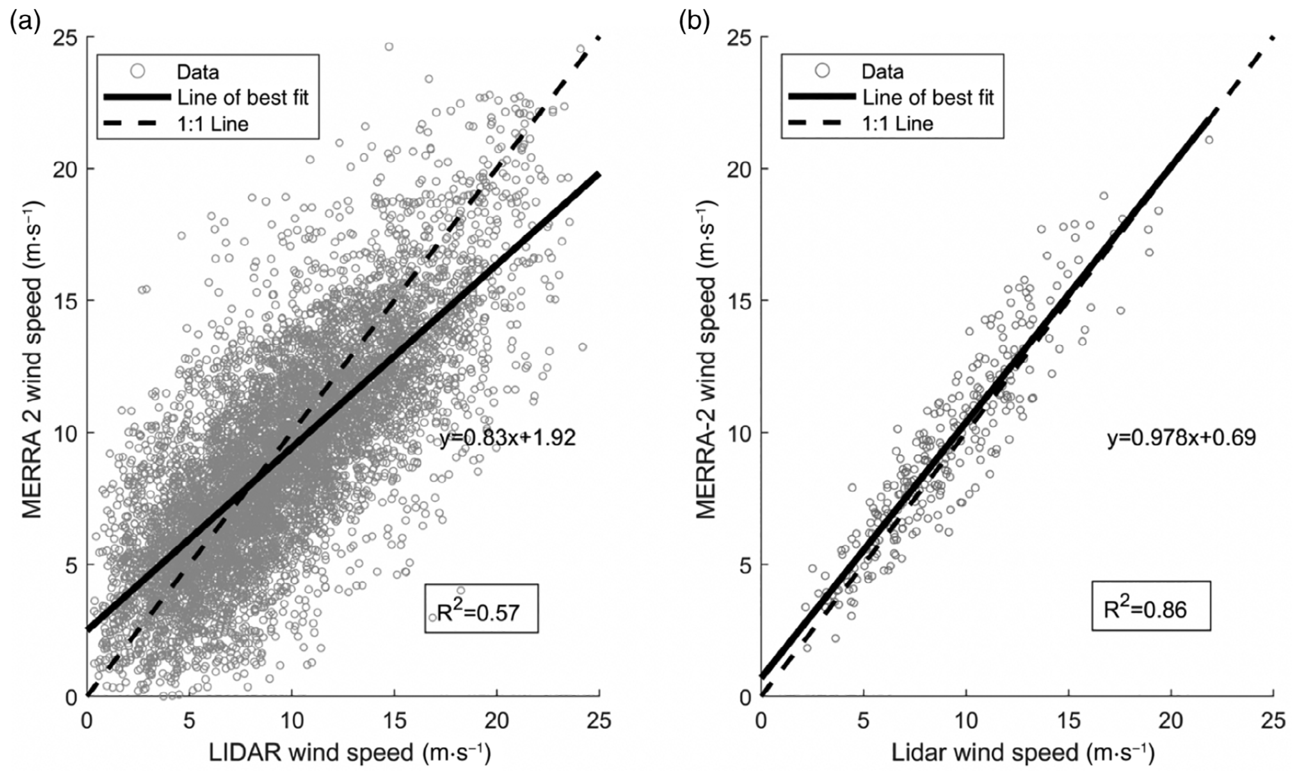

FIGURE 4 Validation of (a) hourly and (b) daily average wind speeds from MERRA-2 and lidar data sets at the lidar location. Wind speed data from October 17, 2016, to October 16, 2017 at an altitude of 120 masl

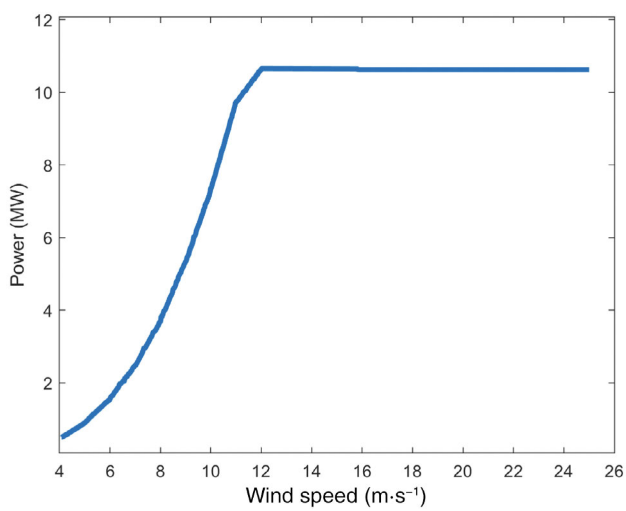

FIGURE 5 DTU 10-MW turbine power curve representing how power production varies with hub-height wind speeds (Bak et al., 2013). The turbine has a cut-in speed of 4 m·s^{-1}, a cut-out speed of 25 m·s^{-1} and a rated speed of 11.4 m·s^{-1}

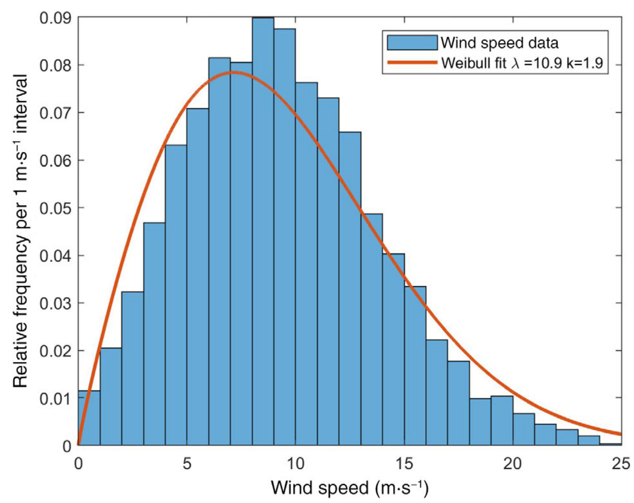

FIGURE 6 Probability density function showing the distribution of hourly wind speeds from October 2016 to October 2017 and a fitted Weibull distribution where scale parameter λ has units of m•s-1

the cut-in speed of the DTU 10-MW turbine. Hours of low wind speed are most prevalent during the middle of the day, while greater wind speeds are seen during night-time hours. Wind speeds > 25 m·s^{-1} exceed the cut-out speed of the turbines and only occur < 0.5% of the year. The average turbine hub-height wind speed is 9.8 m·s^{-1} for the region and year period studied.

A single turbine would not be installed alone, so generation losses incurred by each turbine experiencing wake losses from other turbines had to be accounted for. Due to the variability of wake losses, a standard loss of

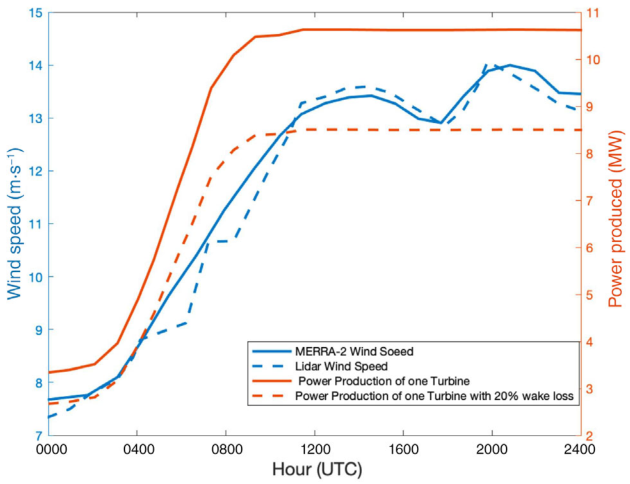

FIGURE 7 Hourly wind speeds from MERRA-2 and lidar data sets on August 1, 2017, with the corresponding power output of a single DTU 10-MW turbine calculated using MERRA-2 wind speed data and the turbine power curve

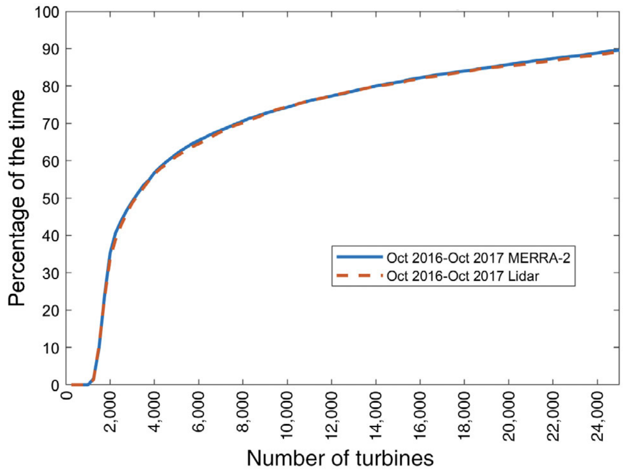

FIGURE 9 Cumulative demand generation curve showing the number of wind turbines required to match the percentages of full yearly demand comparing results from the MERRA-2 and lidar data sets

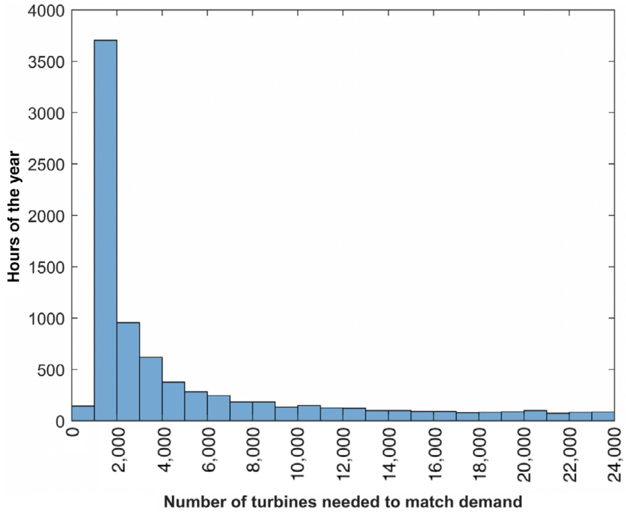

FIGURE 8 Probability density function showing how many hours *per* year an array of turbines would be required to fully match demand

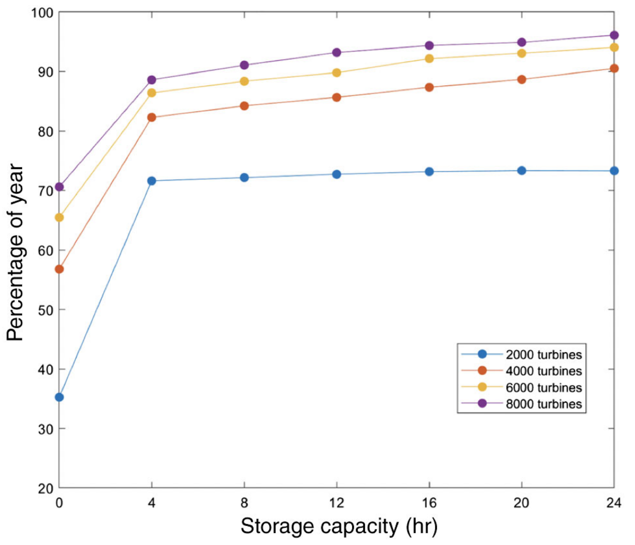

FIGURE 10 Percentage of yearly demand satisfied by a combination of hours of storage capacity and number of turbines

20% was assumed in accordance with El-Asha *et al*. (2017). The 20% wake loss assumption is a standard assumption based on measurements at the Horns Rev offshore wind farm in a range of stability conditions (Barthelmie *et al*., 2009). The wind turbine spacing at Horns Rev is 7D in the main direction, and 9.4–10.4D in the diagonal direction. The current agreements for Vineyard Wind, the first wind farm planned to be developed in this region, assume 1 nautical mile (1,852 m) spacing for the Vineyard Wind. For the 10-MW turbines here, the rotor diameter is 178.3 m, for a turbine spacing of at least 10.4D. If wakes at Vineyard Wind behave similarly to wakes at Horns Rev, then using the Horns Rev estimate of 20% wake loss is reasonable. In the present study, a 20% wake loss was applied for all figures and analysis involving the power production of multiple turbines. Of course, wake effects vary with inflow wind speed and atmospheric stability (Lundquist *et al*., 2019), but the refinement required to explore the effects of these variations will be explored in a future study.

By using each hourly wind speed to calculate a power output from the power curve shown in Figure 5, we estimate the amount of power produced by a single turbine at each hour of the study period. An example calculation for one day is shown in Figure 7. This power production value is multiplied by 0.8 to account for a 20% wake loss. The NE ISO hourly demand is divided by the power produced by one turbine to calculate the total number of turbines required to meet hourly demand at that time step, with the resulting distribution shown in Figure 8. For example, 3,710 hr in the one-year study period only required 1,000–2,000 turbines to fully satisfy grid demand. Less than 100 hr required 24,000 turbines to fully match demand.

5 | RESULTS AND DISCUSSION

5.1 | Cumulative demand

A modest number of wind turbines can contribute to a sizeable portion of NE ISO's power demand. As seen in Figure 9, during the study year, 2,000 10-MW wind turbines operating under normal conditions at 20% wake loss installed off the coast of New England could produce enough power to fully meet NE ISO grid demand for about 37% of the year, or 3,068 hr. If this number increased to 6,000 turbines, demand would be met for about 65% of the year. Beyond an installed capacity of 6,000 turbines, installing additional turbines continues to increase the percentage of time the demand is matched, but at a slower rate of increase. These diminishing returns seen with an increase in wind penetration are not unique to this region and were also observed in a study of offshore wind in Finland and California (Pitt *et al.*, 2005). The shape of the cumulative demand curve is the same regardless of whether MERRA-2 or the lidar observational data set provides the estimate of the wind supply.

The remaining hours that are unmet have large disparities between demand and supply. These hours represent high demand simultaneous with low wind speeds and, therefore, low wind power production, requiring a greater quantity of turbines to fully match demand. During hours where wind speeds are as low as 4 m·s^{-1}, even adding 20,000 more wind turbines may not be able to

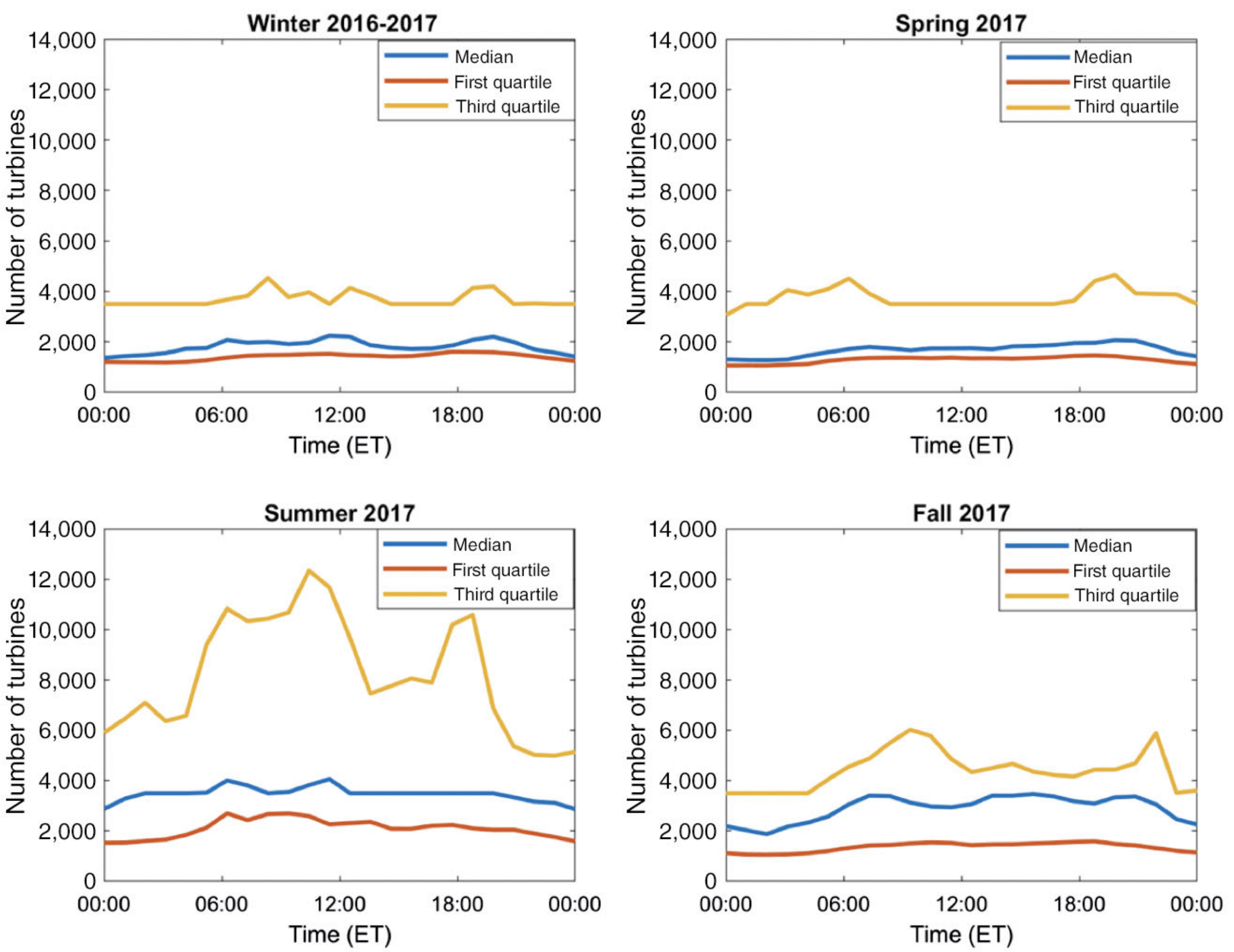

FIGURE 11 Number of turbines required to match diurnal grid demand for each season. Winter 2016–2017 is defined as December–February; spring 2017 is March–May; summer 2017 is June–August; and fall 2017 is September–November

fully satisfy grid demand. We can conclude that 100% of New England grid demand cannot currently be met by offshore wind alone.

The space requirements for this number of turbines can be estimated. At the time of this writing, Vineyard Wind plans to install 84 Vestas 9.5 MW turbines at the BOEM Lease OCS-A 0501, spanning 306 km^2, resulting in a density of 2.6 MW·km^{-2} (Dominion Energy, 2020). US offshore developers recommend a capacity density of 3 MW·km^{-2} (Musial *et al*., 2016). Massachusetts currently has 3,002 km^2 offshore in the lease areas shown in Figure 3, allowing 900 turbines to be constructed in that location alone (Bullard, 2018). To construct 2,000 turbines, 6,670 km^2 of offshore area is required.

5.2 | Storage

Large-capacity energy storage takes many forms, including advanced battery storage, pumped hydroelectric storage and flywheel energy storage. As of May 2019, the United States has 31.2 GW of rated power in energy storage compared with the total power of 1,098 GW in use (Center for Sustainable Systems, 2019). Here we quantify the amount of storage not by GW but by hours of stored capacity (Safaei and Keith, 2015). One hour of storage is equal to the average amount of electrical power that the grid will use in an hour. Over the course of this study period the average hourly demand on the NE ISO grid was 13.8 GWh. Therefore, for these purposes, 1 hr of storage could store 13.8 GWh while 4 hr of storage could store 55.2 GWh.

At any hour, an array of turbines may produce more or less energy than is needed, so having capacity to store excess electricity to use during a time with a power deficit allows an array of turbines to match demand a greater percentage of the time. From Figure 10, increasing storage capacity from zero to 4 hr with 2,000 turbines operating roughly doubles the percentage of yearly demand met from 37% to 72%. Smaller gains occur if hours of storage are further increased because the remaining hours of

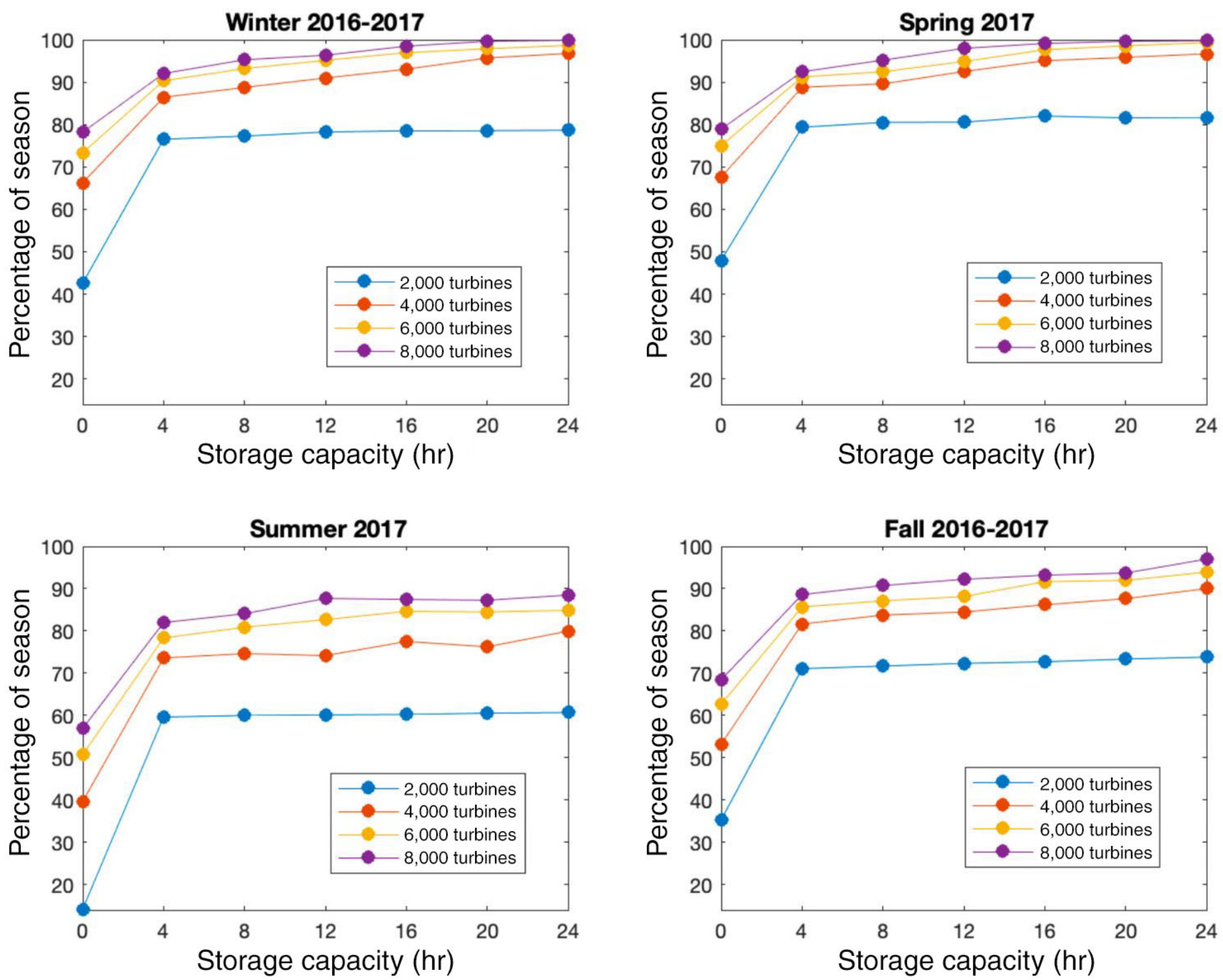

FIGURE 12 Percentage of total demand satisfied by a combination of hours of storage capacity and number of turbines for each season

unmet demand are hours where wind speeds are low and demand is high.

The storage calculation shown in Figure 10 modelled the hours of storage capacity as a battery charging and discharging. A deficit of power produced by an array of turbines would subtract from the quantity held in storage in order to satisfy hourly demand. Surplus production would add to the available storage until the storage capacity had been reached. Wind droughts can completely empty the battery for days, resulting in many hours of unmet demand and requiring sustained power surpluses to refill the storage.

Significant energy shortfall events (characterized by low wind speeds and high demand) can last hours or days, which can completely deplete the power stores (Malloy *et al*., 2015; van der Wiel *et al*., 2019). Once wind speeds increase again, it takes 2,000 turbines an average of eight days of surplus power production to refill 4 hr of battery storage. Even if the system has days or weeks of storage capacity, there may not be enough surplus energy produced at one time to refill the batteries to the full capacity. For example, a system with 20 hr of storage capacity may only receive enough surplus power from the grid to maintain around 8 hr of stored capacity. The remaining 12 hr of capacity are empty and therefore do not contribute to satisfying demand. Since energy storage is currently expensive, it would be in the best interest of a utility or grid operator not to install more storage than is functionally necessary.

5.3 | Seasonal variability

Wind speeds and grid demand vary seasonally, requiring different generating and storage capacities to satisfy demand. The degree of co-variability between wind speeds and demand determine times when offshore wind can best satisfy demand, and times when other sources of power generation will be necessary.

For example, as shown in Figure 2, July–October experience higher than average demand but lower than average wind speeds, requiring more turbines to satisfy grid demand (Figure 11). To meet daily demand peaks during the summer (June–August) and fall (September–November), around 4,000 turbines are required. During winter (December–February) and spring (March–May), wind speeds are faster generally, so 1,500–2,500 turbines would be able to satisfy median daily average grid demand.

This seasonal variability in wind speeds means that storage needs also vary. As seen in Figure 12, during winter and spring, a combination of 8,000 turbines and 20 hr of energy storage could satisfy grid demand 100% of the hours. During summer and fall, no combination of

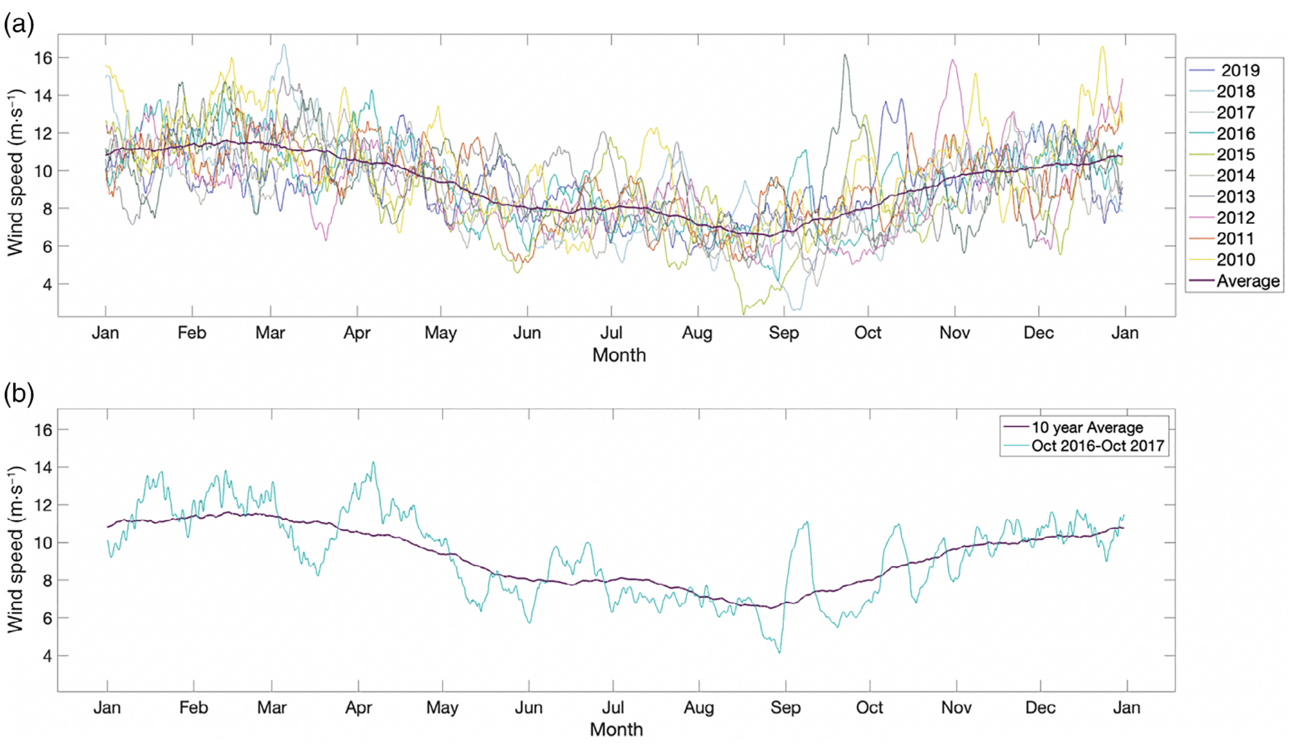

FIGURE 13 (a) Ten-day moving averages of MERRA-2 wind speeds for 10 years showing interannual variability; and (b) 10-day moving average of MERRA-2 wind speeds for October 2016–October 2017 compared with the average of 10 years

turbines and storage shown in Figure 12 could satisfy grid demand 100% of the hours. In reality, a mix of renewables would be implemented alongside offshore wind to provide power to the electric grid. Solar power, which produces more power during daylight hours and during summer and fall, has a higher covariance with demand, so incorporating solar generation may be useful in augmenting wind generation (Richardson and Harvey, 2015). Hydropower and nuclear power could also provide baseline power, lessening reliance on storage technologies.

5.4 | Interannual variability

Meteorological conditions cause wind speeds and grid demand to vary on an annual basis (Hamlington *et al.*, 2015; Lee *et al.*, 2018). Large interannual variability (IAV) of wind speeds (Figure 13a) contributes to uncertainty in the wind resource assessment and ability of offshore wind power to satisfy demand over the course of multiple years. Comparing any individual year in Figure 13a with any other reveals differences in wind speeds up to 6 $m \cdot s^{-1}$, which could certainly influence the wind resource. Wind speeds between October 2016 and October 2017 display significant variance from the mean (Figure 13b). And yet, this period is not unique as similar variances are shown in all years analysed. In an investigation of approaches for the accounting for IAV, Lee *et al.* (2018) conclude that 10 years of data are sufficient to account for the IAV of wind resources. Therefore, we assess 10 separate years of MERRA-2 to explore the variability of annual wind speed data.

By analysing the hourly comparison of wind speeds with grid demand for different years, we assess the effects of interannual variability. The procedure described in Section 4 was repeated using MERRA-2 hourly wind speed data and NE ISO hourly demand from 2018 and 2019. Figure 14 compares the resulting cumulative demand generation curves, showing the number of installed DTU 10-MW turbines required to meet the percentages of yearly demand. For each of the three years studied, 2000 wind turbines could meet demand for about 37% of the year. Since the cumulative demand curves are very similar across the three years, the effects of interannual variability do not significantly affect the results of the study. More years should be studied to fully address the impacts of interannual variability, but this was not done here because of difficulties obtaining NE ISO demand data for multiple years.

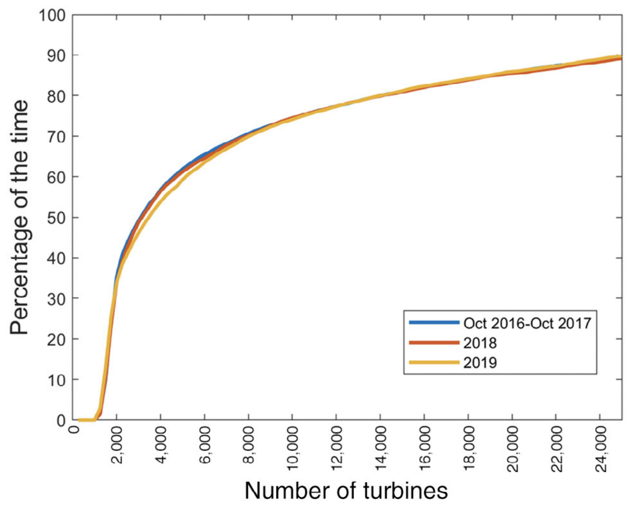

FIGURE 14 Cumulative demand generation curve showing the number of wind turbines required to match percentages of full yearly demand comparing results from three year periods

6 | CONCLUSION

New England has the wind resource capability to meet a large percentage of its power demand with offshore wind energy. By estimating power supply from either MERRA-2 winds or from offshore lidar observations from October 2016 to October 2017, and comparing these supply estimates with observed demand, we find that with 2,000 grid-connected turbines and 4 hr of energy storage, New England could match its power demand for about 72% of the year. Once 2,000 turbines have been deployed, increasing the number of turbines and hours of storage provides smaller marginal gains to the percentage of yearly demand met. The hours of remaining unmet demand tend to have a high grid demand concurrent with low wind speeds, and, therefore, low power production from the turbines. At such low wind speeds, even adding thousands more turbines may not be sufficient to power the grid, especially once the storage has been depleted. To fully satisfy New England's energy demand, we recommend implementing offshore wind power alongside a broad portfolio of power-generation technologies, including power sources that can immediately respond to changes in grid demand, lessening the reliance on expensive storage technologies. To account for interannual variability, we have repeated this analysis for three years and find similar results.

Because this first estimate relies on a general 20% wake loss, future analysis could incorporate a more sophisticated treatment of wind turbine wake and transmission losses from large offshore wind farms. Coupling this analysis with incoming solar radiation estimates from MERRA-2 and other models for solar resource estimation over the same period, or considering the influence of temperature on demand, would provide a more complete evaluation of the ability of variable renewable energy sources to satisfy grid demand.

At the time of the initial work for this analysis, MERRA2 was the preferred reanalysis product. Since that time, the ERA5 (Fifth European Reanalysis, Hersbach *et al*., 2020) has been released. Some investigations suggest that the ERA5 may be preferred for wind resource assessment (Olauson, 2018), at least in some locations. So once more offshore lidar data become available for off the US East Coast, then a multi-location assessment could consider which reanalysis product is optimal for this type of investigation.

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