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Assessment of fresh water wind resources on Lake Erie

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Abstract

Wind farms are better been built at locations with higher wind resource potentials. As the appropriate locations become fewer and fewer to build onshore wind farms, significant attention has been drawn to the wind energy industry to build offshore wind farms. The terrain effect has fewer effects offshore than onshore since the sea level is flat and no artificial buildings are built there. The coastal line of the Great Lakes is one of those areas that not only has great wind energy potential but is also near the high population coastal cities which is short of the land surface. This article makes the detailed statistical analysis of 1-year offshore wind data in Lake Erie from a Light Detection and Ranging system placed on a water intake crib 4 miles away from near the coast of Cleveland. For comparison purpose, a nearby onshore wind monitoring station's data have also been analyzed to study the wind and power characteristics. Specifically, the statistical analysis of the data includes Weibull shape and scale factors, the monthly average of the wind speed, turbulence intensity, and wind power density. In addition, two site-matching commercial wind turbines with 50 (Vestas® 39) and 80 m (Vestas® V90) hub heights have been chosen to estimate the 1-year energy output. The result shows great preponderances of building offshore wind farms than building onshore wind farms. This study gives guidance to the cost-benefit analysis to build the offshore wind farms in Lake Erie.

Keywords

Offshore wind, wind resource assessment, Light Detection and Ranging system, Lake Erie

Introduction

Wind Energy has been used by human beings long before the electric energy. Ancient wind turbines had been used by people to grind grain and to pump water for agriculture purposes. Modern wind turbine, however, is mainly used to produce electricity and is widely used for its worldwide availability, cost-effectiveness, and sustainability. Wind farms are usually built at locations with higher wind speed to get better energy output performance. However, there are also other factors, which need to be taken into consideration when planning to build a wind farm. Modern wind turbines become larger and larger, and the turbine's blade length can be over 40 m (Li and Yu, 2016). The blades' transportation is costly and highly depends on the road availability. On the contrary, the wind farms need to be built closer to the load center to reduce transmission cost and lost. Nevertheless, load centers are usually short of the land surface and may not have suitable wind conditions. According to the previous reasons, there is a growing interest in building offshore wind farms in recent years.

Offshore wind energy has great advantages over onshore wind farm such as (Henderson et al., 2003; Li et al., 2014; Wang et al., 2015a, 2015b): (1) Offshore wind is higher than onshore wind because the terrain is flat. (2) The transportation of larger parts is easier for an offshore wind turbine. (3) A significant amount of large cities are near the shoreline, which lack land surface. (4) Less noise and visual impact. The world's first offshore wind farm was established in Vindeby, Denmark (5 MW) in 1991 (Hsuan et al., 2014). Other European countries all started to develop offshore wind farm technology in late 20th century on all aspects. According to Leutz et al. (2012), the global offshore electric resource is around 37,000 TW h. The industry is expected to reach an installed capacity of 40 and 460 GW for offshore wind by the years 2020 and 2050, respectively. The United States has abundant coastal wind resources potential, and United States's first commercial offshore wind farm, Block Island Wind Farm has started to produce electricity in December 2016 (Wang

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Figure 1. Site map of monitoring wind data (water intake crib photo from McCarty, 2016).

Table 1. Wind turbine prototype data.

Name	Rated power (kW)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	Cut-out wind speed (m/s)	Hub height (m)
Vestas® V39	500	4	15	25	40.5/53
Vestas® V90	3000	3.5	15	25	65/80/105

et al., 2017). Compare with seawater wind farms; fresh water wind farms have more advantages such as less erosion and current force. In the United States, a plenty of large cities are near the Great Lakes, and some researchers have been down seeking to develop wind energy in the Great Lakes (Ashtine et al., 2016; Chiang et al., 2016; Mekonnen and Gorsevski, 2015). This study is mainly based on the preliminary study supported by the Lake Erie Energy Development Corporation (LEEDCo), a nonprofit economic development corporation that plans to build five to seven turbines off the Cleveland shoreline (Grewal and Grewal, 2013). This research made the detailed analysis of the offshore wind resources of the proposed offshore wind farm locations on Lake Erie and compared the data with a nearby onshore observation point. Two commercial wind turbines with different hub heights and rated power are used to estimate the wind energy output potential. The research gives guidance to future researchers for building offshore wind farms on Great Lakes.

Site description

Ohio is one of the pioneer states in developing wind energy resources. According to the National Oceanic Atmospheric Administration (NOAA), Cleveland has great energy potential on the north side near Lake Erie (Li and Yu, 2017a, 2017b). The dataset used in this research consists of both onshore and offshore locations shown in Figure 1. Data of the onshore site come from a ZephIR®-160 LiDAR (Light Detection and Ranging system), which is placed in an industrial area 4 miles away from the Lake Erie coastal line. The LiDAR is placed at an open terrain with no obstacles. The monitoring height was set as 70 m above ground level. The laser-based ZephIR® wind LiDAR is manufactured by Natural Power and is capable of measuring wind conditions at up to 200 m at up to five user-defined altitudes (Corrigan, 2014). The basic principle of LiDAR relies on measuring the Doppler shift of radiation scattered by natural aerosols carried by the wind such as water droplets, pollen, or dust (Li and Yu, 2017a, 2017b). Data of offshore site come from the same LiDAR, which put on a water intake crib 4 miles away from the coast of Lake Erie and the monitoring height was set as 50 m above water level.

Prototype wind turbines

Two commercial wind turbines Vestas® V39 and Vestas® V90 were chosen in this study to compare wind energy output at both lower height level and higher height level. These two wind turbines are both all three blades upwind horizontal wind turbines. The rated wind speed and cut-out wind speed are the same, but the cut-in wind speed is slightly different. These two wind turbines have different hub height styles to suit different terrain types as shown in Table 1. In this research,

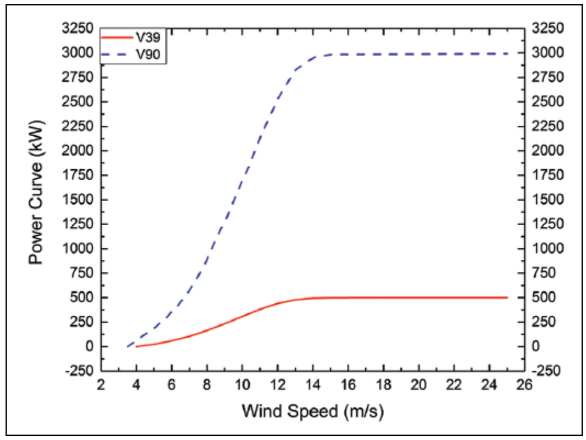

Figure 2. Prototype wind turbines' power curves.

Table 2. WSC of various terrain.

Terrain type	WSC
Lake, ocean, and smooth hard ground	0.10
Foot high grass on ground level	0.15
Tall crops, hedges, and shrubs	0.20
Wooded country	0.25
Small town with some trees and shrubs	0.30
City area with tall buildings	0.40

WSC: wind shear coefficient.

Vestas® V39 were chosen at 50 m hub height and Vestas® V90 were chosen at 80 m hub height. The manufacturer power curve of the two turbines is shown in Figure 2.

Analysis and result

Power law

As discussed in the "Site description" section, the monitored wind data of onshore site is 70 and 50 m for the offshore site. The prototype wind turbines' hub heights used in this research, however, are 50 and 80 m. To convert the monitored wind speed into targeted height's wind speed the power law is used at the first step. The power law is also referred to as Hellmann exponential law which is first proposed by Hellmann (1914). It correlates the wind speed at two different heights and is expressed as (Li and Yu, 2015)

$$v_2 = v_1 \left(\frac{h_2}{h_1} \right)^{\alpha} \tag{1}$$

where v_1 and v_2 are the wind speeds (m/s) at the heights of h_1 and h_2 (m), respectively. The exponent α is the Hellmann exponent or referred to as wind shear coefficient (WSC). The WSCs are mainly depended on terrain types and are listed in Table 2 based on former studies (Bañuelos-Ruedas et al., 2010; Fırtın Güler and Akdağ, 2011; Patel, 2005). The Power Law WSC was chosen as 0.25 for site B and 0.1 for site C according to the locations' terrain types.

Weibull distribution

The general form of the Weibull Density function of the Weibull distribution, which is a two-parameter function, is given as (Soler-Bientz, 2011)

Table 3. Locations and mean wind speed characteristics at 50 m.

		Mean wind speed (m/s)	Weibull shape factor k	Weibull scale factor c (m/s)	WPD (W/m²)
Onshore 41°36'07.8"N 81°29'48.7"W	50 m	5.29	2.17	5.97	162.76
	80 m	6.00	2.19	6.77	230.94
Offshore 41°32'53.7" N 81°44'58.7" W	50 m	8.21	2.37	9.36	561.88
	80 m	8.73	2.37	9.86	670.12

WPD: wind power density.

$$f(\mathrm{v}) = \frac{k}{c}\left(\frac{\mathrm{v}}{c}\right)^{k-1} e^{-(\mathrm{v}/c)\mathrm{k}} \tag{2}$$

where $f(\mathrm{v})$ is the probability density function, also referred to as pdf; v is the wind speed (m/s); c is the scale factor (m/s), and k is the shape factor. In this research, we use the maximum likelihood method (MLM) as the Weibull distribution can be fitted to time-serious speed data according to our 10-min time intervals of wind speed data availability (Saleh et al., 2012). Then the shape factor and scale factor could be calculated as follows (Carta et al., 2009; Seguro and Lambert, 2000)

$$k = \left(\frac{\sum_{i=1}^{N} v_i^k \ln(\mathrm{v}_i)}{\sum_{i=1}^{N} v_i^k} - \frac{\sum_{i=1}^{N} \ln(\mathrm{v}_i)}{N}\right)^{-1} \tag{3}$$

$$c = \left(\frac{1}{N}\sum_{i=1}^{N} v_i^k\right)^{1/k} \tag{4}$$

where v_i is the average wind speed in time step i and N are total of the number of nonzero wind speed data points.

According to the International Standard IEC 61400-12 and other international recommendations, two-parameter Weibull probability density function is the most appropriate distribution function of wind speed data (Bagiorgas et al., 2008; Rehman et al., 1994). This research is based on real wind data up to 5 years (Onshore site: May 2011–April 2012; Offshore site: January 2006–December 2010) in 10-min time intervals. The yearly mean wind speed, Weibull shape and scale factor, and wind power density (WPD) are all shown in Table 3. The mean wind speed of onshore site at 50 and 80 m are 5.29 and 6.00 m/s. The mean wind speed of offshore site at 50 and 80 m are 8.21 and 8.73 m/s, respectively. The mean wind speed of offshore site at both heights is larger than the wind speed of onshore sites. The incensement of wind speed for the onshore site is higher than that of offshore site. The Weibull shape factors of the offshore site are larger than that of onshore sites on both heights. The relatively high value of shape factor indicates that the variation of mean wind speed about the annual mean is small. Figures 3 and 4 show the wind speed histogram, Weibull distribution, and prototype wind turbines' power curve for both locations. The Weibull distribution and the frequency distributions of the wind speed matched very well on the monitoring site in this research as shown in Figures 3 and 4. Figure 3 indicates that the wind peak of the wind speed histogram is between 4 and 5 m/s for the onshore site and 7 and 9 m/s for the offshore site at 50 m height. By comparing the V-39 wind turbine's power curve with the wind speed histogram, we can see the wind speed of onshore site has seldom reached V-39 wind turbine's rated power; however, about 5% of the offshore wind speed are higher than the V-39 wind turbine's rated power. The same trend can be found for 80 m wind speed histogram in Figure 4. There is only 0.5% of wind speed that reaches V-90 wind turbine's rated power for the onshore site but 7% for the offshore site.

The wind compass rose diagrams, which were constructed using the measurements of wind speeds and corresponding wind directions, provide useful information on the prevailing wind direction and availability of directional wind speed in different wind speed intervals (Rehman and Al-Abbadi, 2008). The wind rose for both onshore site and offshore site at 50 m height are plotted in Figure 5. The effect of topography is obvious at both sites as the dominant wind directions of both locations are different. For the onshore site, the dominant wind direction of the year is from S. The percentage of wind speed from S is 13%. The second dominant wind direction comes from ENE, which reaches 9.5%. The wind directions for offshore site tends to be more stable compared to the onshore site, the dominant wind direction comes from SSW

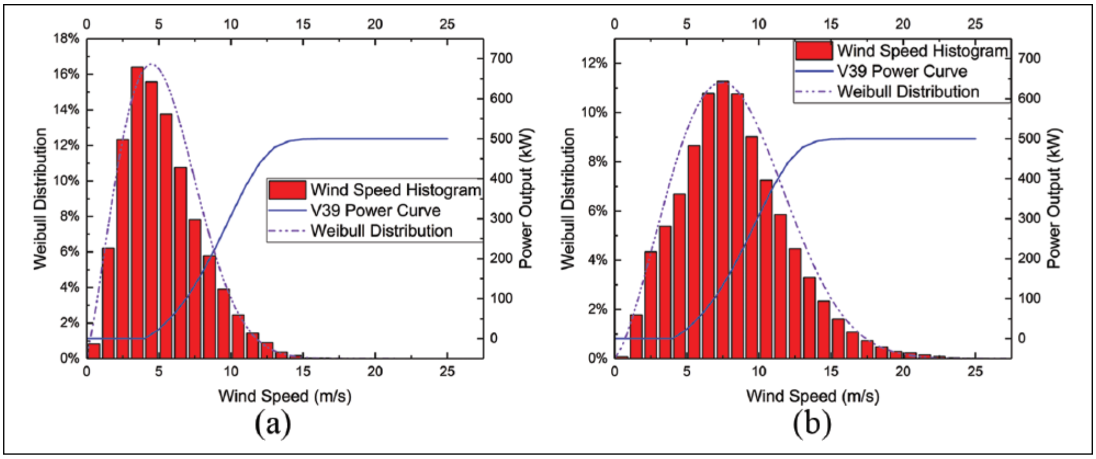

Figure 3. (a) Weibull distribution of onshore site at 50 m and (b) Weibull distribution of offshore site at 50 m.

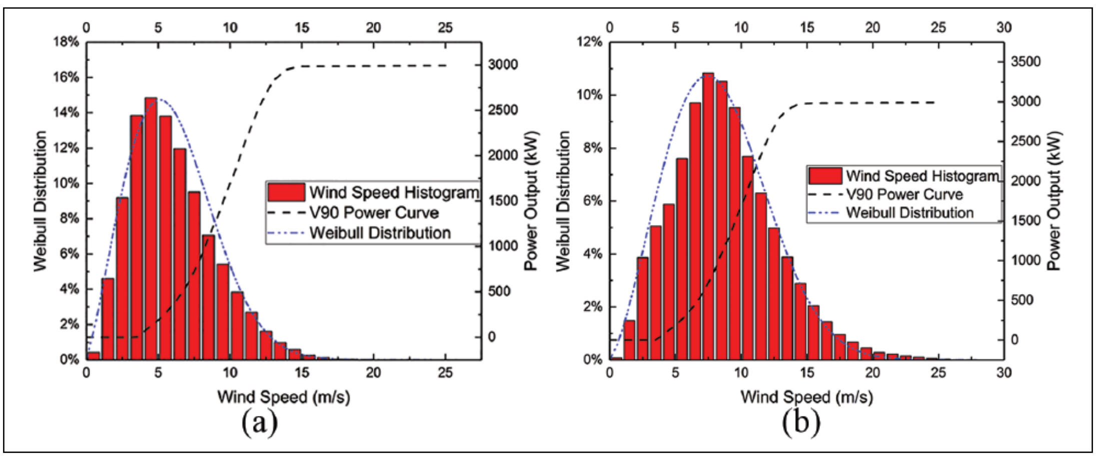

Figure 4. (a) Weibull distribution of onshore site at 80 m and (b) Weibull distribution of offshore site at 80 m.

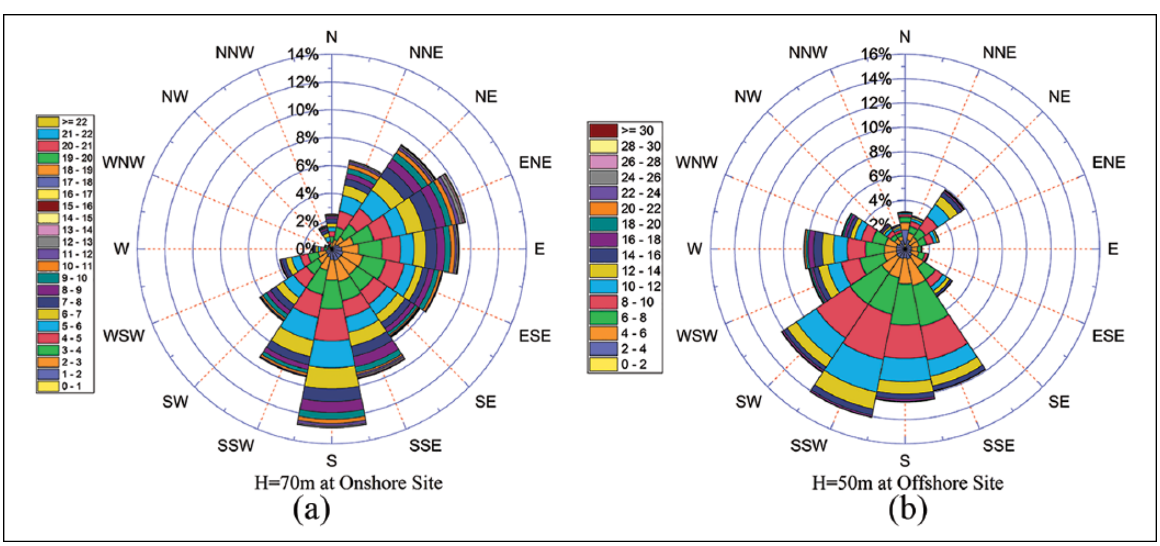

Figure 5. Wind compass rose of onshore and offshore sites: (a) 70 m at onshore site and (b) 50 m at offshore site.

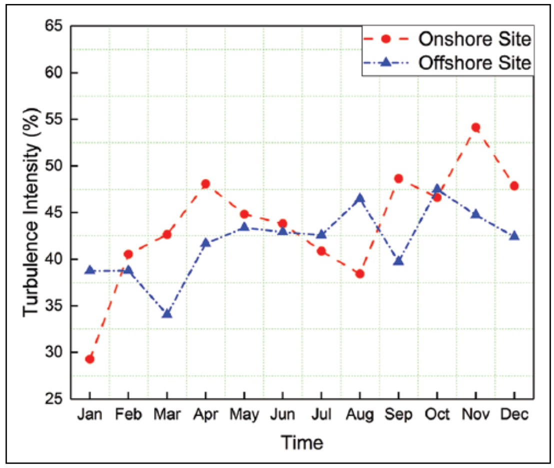

Figure 6. Turbulence intensity of onshore and offshore sites at 50 m height.

which reaches 14% and the second dominant wind directions are SSE, S, and SW which all reach 12%. The wind direction of the onshore site is more dispersive than the offshore site.

Turbulence intensity

As the near ground surfaces are covered with buildings, trees, and hills, the local wind speed turbulence is significantly affected by the terrain types. A statistical description needs to indicate the local turbulence. The concept of turbulence intensity (TI) is defined as the standard deviation of a horizontal mean wind speed over 10 min (Đurišić and Mikulović, 2012; Kumer et al., 2016). Its formal equation is shown as (Scientific, 1997)

$$TI = \frac{\sigma_u}{\bar{u}} \tag{5}$$

where TI is the turbulence intensity and σ_u is the standard deviation of the wind speed variations about the mean wind speed u (m/s). In this research, the mean wind speed is chosen in 10 min. The monthly TI of both onshore and offshore sites could be plotted in Figure 6 according to equation (5). In general, the annual average TIs of onshore and offshore sites are 43.81% and 41.91%, respectively. The highest value of TI occurs at onshore site in November and the lowest TI value occurs at onshore site in January. Both sites are characterized by a high level of wind turbulence but offshore site's TI is lower than the onshore site.

WPD

The WPD, which is based on Weibull shape and scale factors, is commonly used. The WPD equation is shown as follows (Peña et al., 2009)

$$\mathrm{p}(v) = \int_0^\infty \frac{P(\mathrm{v})}{A} f(\mathrm{v})\,\mathrm{dv} = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \tag{6}$$

where $p(v)$ is the WPD in W/m^2 and Γ is the gamma function which has a standard form of (Akpinar and Akpinar, 2004; Ohunakin et al., 2011)

$$\Gamma(x) = \int_0^\infty e^{-u} u^{x-1}\,\mathrm{du} \tag{7}$$

WPD, measured in watts per square meter, indicates how much energy is available at the site for conversion by a wind turbine. The annual average WPD of both sites at 50 and 80 m are shown in Table 3. The monthly variations of WPD at

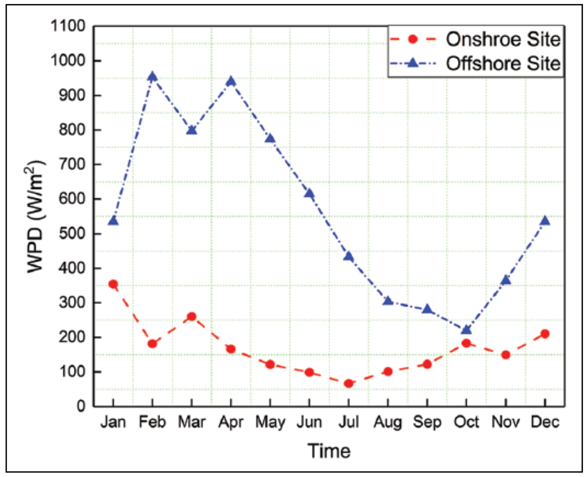

Figure 7. Wind power density of onshore and offshore sites at 50 m.

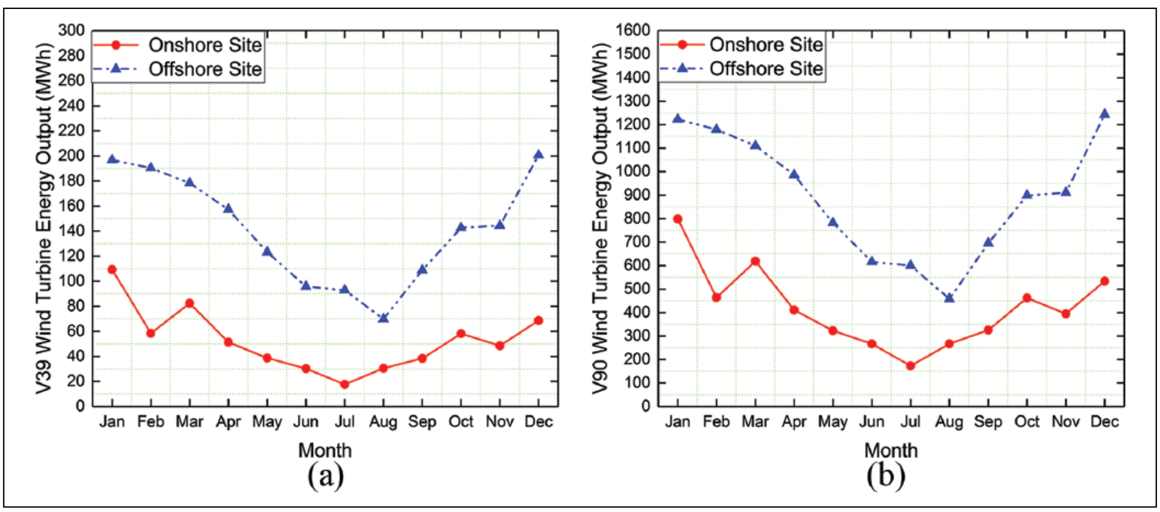

Figure 8. (a) V-39 wind turbine's annual energy output at onshore and offshore sites and (b) V-90 wind turbine's annual energy output at onshore and offshore sites.

50 m heights evaluated using equations (6) and (7) are shown in Figure 7. The WPD shows significant variations between the two sites. In general, the WPD of the offshore site is higher than the onshore site of all time of the year. The offshore site has the highest value of WPD in February, which achieved 953 W/m^2. The lowest value of WPD occurs at an onshore site in July and the value is 66 W/m^2. The figure also indicates that the offshore site has higher WPD in winter and lower WPD in autumn; however, the onshore site has higher WPD in winter and lower WPD in summer.

Energy output

According to previous studies (Bilgili et al., 2011; Green et al., 2011), the installation cost of an offshore wind turbine is about 1.5 times of a same size onshore wind turbine. This means without considering other factors, it is only worthwhile to build an offshore wind turbine if the energy output is 1.5 times higher than an onshore wind turbine. In this section, the annual energy output of both onshore and offshore sites are calculated using the former discussed V-39 and V-90 wind turbines. The annual energy output of the selected wind turbines for the two locations are shown in Figure 8. It shows that the wind energy output of both sites are lower in summer and higher in winter. The wind energy output of offshore site is much higher than the onshore site for both wind turbine types. At 50 m hub height, the annual energy output of V-39 at the onshore and offshore sites are 632 and 1701 MW h, respectively. At 70 m hub height, the annual energy output of V-90 wind turbine is 5036 and 10,701 MW h for onshore and offshore sites.

Conclusion

Offshore wind energy has great advantages over onshore wind energy, and many efforts have been put into by all countries around the world. This study, at the first of its kind, analyzes the offshore wind energy potential of Lake Erie near Cleveland shoreline and compared with an onshore site in the same region. The research is based on on-site monitored wind data over 5 years period in 10-min time intervals from the LiDAR system. The annual mean wind speed, Weibull shape and scale factor, TI, and WPD have been analyzed. The following conclusions could be made based on the discussion:

- The results indicate that at 50 m above ground level, the wind energy potential at the offshore location is 3.5 times higher than that near the onshore area where the annual average wind speed is 8.2 m/s and the annual mean power density equals 562 W/m^2.
- The TIs of the two sites are both at a high level of wind turbulence, but the offshore site is slightly lower than the onshore site.
- The annual wind energy output of the two selected wind turbines is calculated using 1-year wind data of the two sites. The energy produced by V39 at the offshore site is 2.69 times of onshore site. For the wind turbine at 80 m hub heights, the annual energy output by V90 at the offshore site is 2.12 times of onshore site's energy output.
- Although the cost of installing an offshore wind turbine is 50% higher than installing a same size onshore wind turbine, there are still economic benefits to build the offshore wind turbine in Lake Erie than to build the wind turbine at nearby onshore site.

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