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Onshore and offshore wind energy potential assessment near Lake Erie shoreline: A spatial and temporal analysis

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ABSTRACT

Choosing a proper location is a pivotal initial step in building a wind farm. As appropriate locations for onshore wind farms become more and more scarce, offshore wind farms have drawn significant attention. The coastal line of the Great Lakes is an area that has great wind energy potential. This research conducted detailed statistical analysis of the onshore, nearshore, and offshore wind energy potential of Lake Erie near Cleveland, Ohio. It analyzed the wind data collected in 10-min time intervals from three locations near the Lake Erie shoreline to assess wind characteristics. Statistical analyses of wind data include the Weibull shape and scale factors, turbulence intensity, and wind power density. In addition, the capacity factor and the potential energy output are estimated by using two commercial wind turbines, which are appropriate for the sites at 50 m and 80 m hub heights. The results show that offshore sites will produce at least 1.7 times more energy than the onshore and nearshore sites when using the same commercial wind turbine. Furthermore, offshore wind turbines could produce more power during peak hours in the spring and winter. This indicates that offshore wind turbines offer advantages over onshore wind turbines in Lake Erie.

1. Introduction

Wind energy has been used by human beings for centuries for pumping water and grinding grain, since 900 B.C [1]. Modern wind energy is used to produce electricity and is considered to be one of the most important renewable energy resources worldwide, due to wide availability, cost-effectiveness, and sustainability [2]. Natural and human-made land features, such as buildings, can affect onshore wind turbine performance. However, this effect is mitigated with offshore wind turbines, which are surrounded by a flat-water surface. However, the wind energy resources being used today come mostly from onshore wind turbines. Onshore wind farm development is mainly focused on choosing sites with higher wind speeds, but appropriate locations for onshore turbines are becoming more and more scarce. Meanwhile, there is a growing interest in offshore wind utilization, as the wind is normally stronger and more uniform at sea than on land [3,4]. The first offshore wind turbine was set up in Sweden in 1990, and other European countries began developing offshore wind farms in late 20th century, mainly because of the lack of space on land for the development of onshore wind farms [5]. Although the initial offshore wind energy projects date back to the early 1990s, the growth of this technology is just beginning to break out in recent years [6]. According to the study of Leutz et al. [7], the global offshore electric resource energy potential is around 37000 TWh. The global installed offshore wind energy capacity at the end of 2016, however, was only 14384 MW. The global annual wind report [8] states that the cumulative offshore wind energy production capacity around the world approximately doubled from 2013 to 2016, and this number is expected to continue to grow.

Coastal wind sources in the United States are abundant and offshore wind has the potential to become a major energy source for domestic applications [9]. The United States began to build its first commercial offshore wind farm, the “Block Island Wind Farm” in2015, and the wind farm began to generate electricity into the grid in December of 2016. However, offshore wind energy development in the U.S. is in its early stages, with several projects currently in the planning phase, including the Cape Wind project (Massachusetts), the Blue-water Wind project (Delaware), the LIPA offshore wind park (New York), and the Galveston offshore wind

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project (Texas) [3,10,11]. Offshore wind energy has several advantages over onshore wind energy [12,13]. First, offshore wind allows for development in populous regions where there is little land available, but the local energy demand is high. Offshore wind turbines can also be larger, by removing restrictions on transporting turbine components by road [14]. These offshore turbines reduce visual and noise impacts of wind farms, and may reduce local opposition to development of wind farms. Finally, offshore turbines experience lower wind shear (i.e. the boundary layer of slower moving wind close to the surface is thinner), thus allowing for the use of shorter towers. The freshwater offshore wind turbine, in the meantime, has additional advantages such as reduced erosion and current forces, and less complex water conditions. Although there are significant advantages to offshore wind turbines, there are also disadvantages when compare to onshore wind turbines [15,16]. Construction of offshore wind turbines is more complex and costly, and these projects will be affected by waves, currents, corrosion, and possibly ice loads. Offshore turbines also require higher cost foundations, towers, underwater cables, and operation and maintenance is more difficult and costly than for onshore turbines [17]. The U.S. Department of Energy (DOE) estimates that offshore wind turbines are currently 1.5 times as expensive as similarly sized onshore turbines [18]. Therefore, it is important to know the characteristics of wind resources in the proposed region, including the probability of wind availability in the region, and how many hours in the year wind speeds between 3.5 m/s and 25 m/s (typically wind turbine cut-in and cut-out wind speeds) can be expected [19].

However, plain average wind speed maps cannot provide a precise forecast of wind power because of the non-linear relationship between wind speed and production [20]. To assess the wind energy potential at a specific site, long-term wind speed records need to be statistically analyzed [21]. Wind turbine installation at a site is viable only after an accurate analysis of site feasibility has been conducted [22]. Generally, at least one year of wind data records is needed to predict the long-term seasonal mean wind speed with an accuracy of 10% with a confidence level of 90% [19] for a target wind farm location. Chancham et al. [23] presented an offshore wind resource assessment, and an offshore wind power plant optimization, in the Gulf of Thailand. This study used the Weather Research and Forecasting atmospheric model to create wind resource maps at three different altitudes above sea level, and validated the results using 13 met masts installed along the coastline. The results show that there is the potential to install 6000–8000 MW wind turbines in the Gulf of Thailand. Junkai Liu et al. [24] presented a statistical analysis of twenty years of wind data on a 15-level, 325 m met tower in Beijing, and evaluated the wind energy potential. The authors analyzed the monthly and diurnal variation separately, and found that the wind speed had significant seasonal and diurnal variations, and that diurnal variations varied with height. Solyali et al. [25] investigated the wind resource availability in Northern Cyprus. The study presented the monthly and diurnal average wind speed based on 10 min time intervals between 2007 and 2014 at 30 m above the ground level. The researchers found diurnal wind speed forms a reversed bell shape of all heights, with no obvious seasonal variation. Boudia and Guerri [26] used ten years of wind data from a meteorological station to evaluate the wind power potential in the coastal area of the Mediterranean Sea in Algeria. Wind speeds at 10 m above the ground level were used to plot the annual and seasonal daily variation. The results showed that the wind speed is higher in early afternoon from 12:00 to 18:00 and lower at night. The seasonal Weibull distribution of the wind speed indicated that the windiest season is spring. Finally, Jiang et al. [27] evaluated offshore wind resources using QuikSCAT Level-2 satellite measurements. A nine-year average monthly wind power density map was depicted in their study. The seasonal variations showed that the wind power density in the east and South Seas reaches a peak in October, while the maximum wind power density of the yellow Sea occurs in August. The previous researches, however, mostly studied a specific terrain type. The wind resources for both onshore and offshore in the same region were not compared in parallel. Additionally, seasonal and diurnal effects were studied separately, which may have overlooked the influence of the large heat capacity of offshore water.

In the United States, there are several large cities near the Great Lakes, and some researches have been seeking to develop wind energy in the Great Lakes [10,28,29]. In Lake Erie specifically, an offshore wind demonstration project carried out by the Lake Erie Energy Development Corporation (LEEDCo), is planned to be built in 2018. Six of 3.45 MW turbines are planned to be built off the Cleveland shoreline with a total output of 20.7 MW [30]. At this time, it is important to know the future energy production potential of offshore wind turbines to ensure reliable operation of the power grid when integrating renewable energy. However, it is not possible to tell the future energy production with great accuracy, thus historical wind data and simulation methods are used together to forecast new wind energy production [31]. This research is the preliminary study of the LEEDCo project, and it focuses on assessing the Lake Erie wind energy resource and potential energy output. This study is the first of its kind to make a detailed comparison and analysis of the onshore, nearshore, and offshore wind energy potential of Lake Erie near the Cleveland shoreline. Wind data of three monitoring sites recorded from Light Detection and Ranging (LiDAR) systems and anemometers have been statically analyzed in this research. Extrapolation of the wind speed at different heights using the power law has been used to determine the wind data at 50 m and 80 m. Two commercial wind turbines, Vestas® V39 and Vestas® V136, are chosen to calculate the potential energy output at the three sites. Vestas® V136 has the same rated power output as the wind turbine proposed for the LEEDCo project, and Vestas® V39 is chosen for comparison at a lower hub height. Capacity factors and annual wind energy outputs have also been calculated for the three locations, for both wind turbine prototypes. Additionally, this research compares the offshore, nearshore, and onshore wind resources in the same region, which offers a chance to study the detailed wind speed characteristics for different boundary layers. The results show great advantages to constructing offshore wind turbines in Lake Erie compared to onshore wind turbine in the same area. Additionally, this research conducts a spatio-temporal analysis of the wind speed, WPD, and the energy output at the three locations using a 2D contour plot. The results show significant atmosphere stability effects at different sites both seasonally and over diurnal cycles. The offshore wind turbine could produce more energy during the peak hours of demand in the spring and winter. Electricity generated during peak demand periods is more valuable than electricity generated during off peak hours both economically, and for reducing greenhouse gas emissions. This indicates that the offshore wind turbines offer both higher total energy output, and higher value energy output.

2. Methodology

2.1. Power law

The wind speed near the ground varies with height is referred to as wind shear. In the atmospheric surface boundary layer extending to no more than 150 m above the ground surface, the power law is used to calculate the wind speed at target height from the known wind speed at another height [32]. The power law is also referred to