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Effect of island topography and surface roughness on the estimation of annual energy production of offshore wind farms

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ABSTRACT

Accurate information on the wind flow characteristics within a given site is a prerequisite for making precise prediction of the wind energy production of offshore wind farms. Two typical methods of taking field measurements at an actual site are employed. The first is to install an offshore meteorological mast, and the other is to use onshore meteorological towers on the coast or on adjacent islands. This study explores the feasibility of predicting the annual energy production (AEP) from an offshore wind farm by analysing the full-scale data measured at an adjacent island by using WindPRO and WAsP software. These software programs are used to model the topology of the island and to predict the wind resources and the energy production of wind turbines by using at least one set of measured wind data. The effects of the island topography and roughness on the prediction of the AEP are obtained, and the predicted AEP affected by inaccurate island shape modelling is analysed. When wind velocity data obtained at a height of 60 m are used, the prediction error of AEP decreases to 38% compared with that measured at a height of 30 m owing to inaccurate modelling of the island terrain. Therefore, in order to reduce the prediction error of AEP caused by inaccurate terrain information of the island it is desirable to increase the height of the wind measuring tower. Inaccurate roughness modelling of the island has little influence on the prediction of AEP.

1. Introduction

Estimated in March 2012 to exceed 7 billion, the world population continues to rise although the energy resources of the land are being rapidly depleted [20]. In this regard, the world's nations are competing to search for energy resources in the ocean and in nearby offshore areas [7,10,11]. In particular, large-scale offshore wind farms have been installed in seas and on coastlines. In late 2012, instruments with just less than 5 GW of offshore wind energy capacity were installed in Europe. Moreover, additional instruments of 4460 MW capacity were under construction at that time, and installation of about 18,000 MW capacity instruments is planned. The WindEurope (previously EWEA) has forecast that by 2020, 40 GW of offshore wind capacity could be operational in European waters, producing 148 TW/h if the appropriate framework conditions are in place. This amount is sufficient for providing electrical power to 39 million households. By 2020, offshore wind will represent 30% of the new installations in the annual wind market [9]. Developing an onshore or offshore wind farm is usually a complicated and time-consuming process involving developers, landowners, investors, utilities, the public, and various local authorities. Although each wind energy project is unique and has different characteristics, the basic features and related steps have much in common. In practice, the steps are iterative and overlap each other depending on the specific project circumstances. The key steps of development and planning of a wind farm include site selection, detailed wind assessment, feasibility studies, financing, construction, and operation.

In the Republic of Korea, hereafter referred to as Korea, development projects on offshore wind farms have not been performed satisfactorily. However, feasibility studies of developing offshore wind farms in the areas of Incheon, Busan, Jeju Island, and the southwest coast are currently under way. In particular, a 5 GW offshore wind power project is in progress near the South Jeolla Province; thus, the scale of the domestic offshore wind farm market in Korea is expected to continuously increase in the near future. Prior to the development of an offshore wind farm, it is necessary to

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survey wind resources for a feasibility check. The most accurate wind resources survey requires installation of a high-rise offshore meteorological tower, which could cost millions of dollars. Therefore, it is desirable to survey wind resources through the following procedure. Firstly, wind resources are actually measured by a wind measuring tower installed on an adjacent coast or island near the planned site. Secondly, these data are used to conduct a preliminary feasibility check of the planned site based on its predicted energy production. Finally, depending on the results, the wind resources are assessed in detail after installing an offshore meteorological tower. The most important factor to be considered in the development of a wind farm is the sites wind resources. In addition, the energy generated from wind turbines is known to vary considerably depending on the annual wind resources in the area of concern, the local wind climate, and the topological characteristics. Therefore, prior to developing a wind farm, it is essential to conduct a precise survey on the wind resources near the region as well as an in-depth analysis of its cost effectiveness.

Several recent papers have interpreted wind energy resources from a commercial and economical perspective [12,21,25] and most recently Lim and Jeong [17]. In a study on the technical and industrial feasibility of offshore wind farms in the Puglia area in Italy, Pantaleo et al. [21] reported that investment in a large scale offshore wind farm may bring 27% of the internal rate of return. Stockton [25] conducted an economic feasibility study on a utility-scale wind farm in Hawaii, United States of America. In that study, it was concluded that a utility-scale wind farm on the island of Oahu, the neighbouring island of Molokai, would be capable of supplying electricity at 34% less cost than that generated by burning fossil fuel (coal).

Interestingly, Cavallaro and Ciraolo [8] applied a multicriteria approach in their feasibility study of a wind energy farm in Salina Island, Italy, in which the wind resources and electricity capacity were considered on the basis of economical, technical, environmental, and social criteria. The common aim of the aforementioned studies was to predict energy production and to investigate cost-related issues by selecting areas suitable for wind energy development projects. These economic feasibility studies provide important data and information for industrialists and businesses interested in operating a wind energy business in a specific area.

From a wind engineering perspective, wind speed near the ground surface is greatly influenced by the surface of the surrounding areas. Moreover, the predicted wind resources can be influenced by the surface topography and roughness of the areas surrounding the wind measuring tower location. Therefore, it is important to determine the effects of topography and roughness variations on the predicted wind resources and energy productions of a wind farm. However, it is often not easy to obtain the topographic information required without an additional and specific topographic survey, which could be costly and time consuming. Therefore, the primary focus of our paper is to determine the relationship of the uncertainty error of the terrain and the annual energy production (AEP) estimation. Secondly, on the basis of this relationship, the probable range of the AEP estimation is assessed and predicted. If the AEP estimation proves to be inaccurate, it is necessary to improve the accuracy by obtaining more precise topographic information. Finally, owing to the tidal range, the geographic effect could be an effective parameter for predicting the AEP value. Therefore, in the future, the tidal effect could also be considered in predicting the AEP estimation range.

In this study, the annual energy production is estimated for a priority target. An additional objective is to quantitatively assess the prediction error of the AEP induced by inaccurate topography and the surface roughness of the site. For this purpose, wind data from a 60 m high wind measuring tower and the real-scale geometry of an island are used in this study. The tower is installed on an island located 39 miles (about 70 km) from the southwest coastal region, one of the strongest candidate sites in South Jeolla Province, Korea. The basic information required in developing wind energy resources in a given area are annual and seasonal wind speeds and wind direction. Meteorological properties such as annual and seasonal pressures, temperature, and moisture of the area are also required.

This paper is organised as follows. In Section 2, the sensitivity analysis method is outlined, which includes the base shape of the island, wind statistics, topological changes, layout of the wind turbines, and a description of the wind energy prediction method. In Sections 3.1 and 3.2, the effects of inaccurate shape modelling of the island on the predicted wind energy production are described. Section 3.3 gives an account of the effect of terrain when the ridge of the island is cut. Section 3.4 presents an analysis of the effects of island surface roughness, and a discussion and the major conclusions are presented in Sections 4 and 5, respectively.

2. Sensitivity analysis method

2.1. Base shape of the island

To analyse the prediction sensitivity of offshore wind energy generation, an island on the southwest coast Korea was selected as the base shape (Fig. 1). For this purpose, a 60 m-high measuring tower was installed on the ground 30 m above sea level on the ridge of the island, and wind velocity sensors were installed at heights of 30 m, 40 m, 50 m, and 60 m from the ground. Then, wind velocity data were measured for one year. Fig. 1 shows the shape of the island and location of the wind measuring tower. This basic shape of the island follows the shape defined in the 1:25,000 scale numerical topographic maps distributed by national geographic information (National Spatial Information Clearinghouse (NSIC), http://www.nsic.go.kr). In the base shape, Roughness Class 2 was selected to represent the surface roughness of the island. Table 1 shows the roughness lengths derived from the terrain classification of Davenport (see Ref. [27]). In the table, the roughness length z_0 is defined via the mean-velocity log law.

$$\frac{U}{u_*} = \frac{1}{\kappa} ln\frac{(z-d)}{z_0} \quad (1)$$

here, u_* and d are the friction velocity (τ_{wall}/ρ) and the zero-plane displacement, respectively [16].

2.2. Wind statistics

A key step in developing a wind farm at a particular site is to conduct appropriate analysis on wind statistics. For this purpose, Weibull and Rayleigh probability density functions are widely adopted. Among them, the general form of the Weibull distribution for wind speed, which is a two-parameter function, is given in Eq. (2) [24]; [1,29].

$$f(\nu) = \left(\frac{k}{c}\right)\left(\frac{\nu}{c}\right)^{k-1} exp\left[-\left(\frac{\nu}{c}\right)^{k}\right] \quad (2)$$

here, $f(\nu)$ is the probability of the observed wind speed ν, k is the dimensionless Weibull shape parameter (or factor), and c is the Weibull scale parameter; all have reference values in units of wind speed. The corresponding cumulative probability function of the Weibull distribution is given in Eq. (3).