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Designing an index for assessing wind energy potential☆

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ABSTRACT

To meet the increasing global demand for renewable energy, such as wind energy, an increasing number of wind parks are being constructed worldwide. Finding a suitable location requires a detailed and often costly analysis of local wind conditions. Plain average wind speed maps cannot provide a precise forecast of wind power because of the non-linear relationship between wind speed and production. We suggest a new approach to assess the local wind energy potential. First, meteorological reanalysis data are applied to obtain long-term low-scale wind speed data at specific turbine locations and hub heights. Second, the relation between wind data and energy production is determined via a five parameter logistic function using actual high-frequency energy production data. The resulting wind energy index allows for a turbine-specific estimation of the expected wind power at an unobserved location. A map of the wind power potential for Germany exemplifies our approach.

1. Introduction

Because of increasing energy demand worldwide and the willingness to reduce greenhouse gas emissions, renewable energies, such as wind energy, are rapidly growing: The global cumulative installed capacity of wind energy increased from 6 GW in 1996 to 318 GW in 2013 and is expected to reach 596 GW in 2018 [17].

Planning a new wind farm begins with the search for a suitable location. Besides suitable surface conditions and legal aspects, geographical wind conditions and timing are also important. Timing influences the financial success of a wind farm project since revenues generated from renewable energies are generally based on a regulated country-specific feed-in tariff system. To reduce governmental subsidies, the amount of compensation paid to operators decreases annually based on the commission date. Therefore, the delay of a project increases the costs and uncertainty of the expected outcome. Finding a suitable position by measuring wind speed at various locations and heights is very time-consuming and costly. Hence, the expected energy production at possible locations has to be derived using different tools.

There are many studies which pertain to deriving detailed long-term wind speed maps for individual countries (e. g., U.S. [1], Spain [14], Germany [12], and Greece [20]), continents (e. g., Europe [33]), or even the world (e. g., [2]). These maps of long-term average wind speeds are a rough indicator for average local wind conditions, but they are inadequate for deriving the expected wind energy production. The reason is the non-linear relationship between wind speed and production: It is possible that a stable wind speed of around 3 m/s over the year, which is smaller than the typical cut-in speed where turbines start, leads to zero production. A wind speed with high fluctuations around the mean of 3 m/s, however, leads to much higher production.

To overcome this problem, a long record of high-frequency wind speed at the turbine location and hub height is required. Then, the wind power production can be estimated by transforming the high-frequency wind speed to wind power production via a wind power curve (e. g., [6,29]). However, from the perspective of installing a turbine at a new location, the requirement of long-term high-frequency wind data can hardly be fulfilled. The wind power curve given by the turbine producer requires instantaneous mast wind speed to derive production, which, in most cases, are not recorded. Hence, wind production cannot be estimated via the wind power curve and the linkage between wind speed at a higher scale (e. g.,

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hourly averages) and true production deserves further investigation.

In this paper, we propose a new way to estimate the long-term wind energy potential of a new location by applying an index, which mainly consists of two steps: First, we derive lower scale wind speed data at the turbine location at hub height by processing meteorological reanalysis data. These data are available throughout the world at low spatial and temporal scales, so our approach is feasible globally. Second, we estimate an analytic production function based on real production data, which converts the meteorological reanalysis data into production data. Based on local wind speed data derived for an unobserved location, this production function provides an estimate of the turbine's low-scale energy production. By aggregating the estimated production to a larger time scale and long-term historical data, the proposed wind energy index is able to assess the long-term wind energy potential for any location.

The remainder of the paper is organized as follows: in the next section, we describe how wind speed at the turbine location is derived, how the production function is estimated, and how the wind energy index is constructed; in Section 3, we apply and evaluate our approach to data for Germany and include an energy production map, which estimates the long-term wind energy potential for each location in Germany; and Section 4 provides further discussion and conclusions.

2. Methods

2.1. Framework

To measure the potential of wind power production at a specific location, we develop a quantitative and objective wind energy index that represents the actual wind energy production of a certain turbine type. To obtain such an index, there are several necessary steps.

First, the type of database to calculate the wind energy index has to be chosen. A possible database is energy production data from wind farms in the neighborhood with similar wind conditions and turbine characteristics. Alternatively, wind speed data can be applied directly. If wind speed data are chosen for the database, they have to be transferred to the wind turbine position since they are usually not available for every location. This means that the data have to be horizontally interpolated to the turbine location and vertically extrapolated to the turbine height. The most crucial decision is how local wind speed data can be transformed to a wind energy index that reflects actual wind energy production.

The aforementioned steps are described in greater detail in the following sections.

2.2. Database

In principle, the analysis can be built on production data or wind speed data. Production data of nearby wind farms have the advantage that they reflect the true fluctuations and do not require transformation, which might cause an estimation bias. Nevertheless, equal geographical and technical conditions have to be assumed.[1]

Another way of analyzing the energy potential is to derive a wind energy index based on wind speed data, which are more readily available than production data. The most common dataset used in the analysis of wind resources is weather station data because it objectively measures the actual wind speed at certain locations. Using weather station data for this aim, however, comes under criticism: the availability of such data is often limited; the historical data records might not be complete; weather stations may not be located at a reasonable distance to wind farms; and the time series record of weather station data is frequently no more than 25 years [21]. In Germany, free wind speed data are available since 1996 for 64 weather stations with three measurements per day (6:00 a.m., 12:00 p.m., and 6:00 p.m.) from the German Meteorological Service (DWD). The data, however, are measured in Beaufort units, which is too imprecise of a measurement.

An alternative dataset that has been recommended in the wind power analysis is reanalysis data, such as the Modern-Era Retrospective Analysis for Research and Applications (MERRA) data provided by NASA [9,21,31]. MERRA reanalysis data reconstruct the atmospheric state by integrating data from different sources, such as conventional and satellite data [16,28]. They offer a complete worldwide grid of wind data at a spatial resolution of 1/2° latitude and 2/3° longitude (about 45 km × 54 km in Germany) and an hourly temporal resolution since 1979. The wind data consist of a northward and an eastward wind component at three different heights (2 m, 10 m and 50 m above ground), which are helpful to derive the wind speed and wind direction at various turbine heights. Thus, reanalysis data could mitigate the problems that plague available weather station data.

Alternative reanalysis data sources, such as National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim), or Climate Forecast System Reanalysis (CFSR) are also possible, but so far there is no consensus on the superiority of one particular reanalysis model [10,19,24]. Further comparisons among these candidates are needed to determine the correct wind power potential. In the following, we apply MERRA data to obtain wind speed data at an unobserved location.

2.3. Horizontal interpolation

Every location lies within a rectangle spanned by the four nearest MERRA grid points. The wind speeds at these four points, i.e., the eastward and northward components u_h and v_h at heights of 2 m, 10 m and 50 m, are interpolated to the turbine's location weighted by their horizontal distance (inverse distance weighting). This approach assumes that the influence decreases with increasing distance. Given the rather short distances (maximum distance to the nearest grid point is about 35 km) and the regular pattern of the MERRA grid, inverse distance weighting is a reasonable candidate. Nevertheless, alternative interpolation methods such as Kriging, polynomial, or spline interpolation are possible [27].

After interpolating, the two components for each height are combined to obtain absolute values of the wind speed at the turbine's location at the three heights using the Pythagorean theorem:

$$V_h = \sqrt{u_h^2 + v_h^2}, \quad h = 2, 10, 50. \tag{1}$$

At this point, it is still possible to calculate the wind direction at height h, φ_{V_h}, at the turbine's location with the following equation:

$$\varphi_{V_h} = \tan^{-1}\left(\frac{v_h}{u_h}\right). \tag{2}$$

[1] In Germany, the *Betreiber-Datenbasis* (BDB) index is used to measure monthly fluctuations of wind energy production in 25 regions; however, it is often criticized because of its in-transparency and unreliability as the wind conditions are not homogeneous in the 25 regions. Moreover, it remains unclear how the index can be used to estimate the potential of an unobserved location. For more details, we refer to Betreiber-Datenbasis (2011) [4] and Bundesverband WindEnergie (2013) [7].