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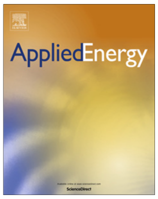

# Site assessment, turbine selection, and local feed-in tariffs through the wind energy index ☆

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## HIGHLIGHTS

- We present a wind energy index based on long-term reanalysis wind speed data.
- True production data are used to convert MERRA wind speeds to energy production.
- The index is applied to assess the wind energy potential of locations in Germany.
- The index can derive the required compensation such as a local feed-in tariff.

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## ABSTRACT

Since wind energy is rapidly growing, new wind farms are installed worldwide and a discussion is going on concerning the optimal political framework to promote this development. In this paper, we present a wind energy index, which is supportive for wind farm planners, operators, and policy-makers. Based on long-term and low-scale reanalysis wind speed data from MERRA and true production data, it can predict the expected wind energy production for every location and turbine type. After an in-sample and out-of-sample evaluation of the index performance, it is applied to assess the wind energy potential of locations in Germany, to compare different turbine types, and to derive the required compensation in terms of locally different feed-in tariffs. We show that in many parts of South Germany, profitability of new wind farms cannot be achieved given the current legal situation.

## 1. Introduction

Among all renewable energies, wind energy is the most environmentally friendly energy source (see Saidur et al. [1] and Asdrubali et al. [2] for two recent reviews) and it has experienced a rapid growth in the last decades: The global cumulative installed capacity of wind energy rose from 6 GW in 1996 to 370 GW in 2014 and is expected to almost double to 666 GW until 2019 [3,4]. The newly installed capacity in 2014 amounts to 51 GW worldwide, mainly driven by China (45%), Germany (10%) and the U.S. (9%).

This rapid growth requires an extensive search for locations suitable for wind energy production. On the one hand, topographical aspects and legal frame conditions play an important role, but local wind conditions and timing decide about the financial success of a wind farm project since governmental subsidies often depend on the year of commission.

One way of assessing the local wind conditions is using classical wind speed maps, which show the long-term average wind speeds for specific locations (e.g., U.S. [5] and Germany [6]). They are, however, only a rough indicator for the local wind energy potential because of the non-linear relation between wind speed and wind energy: A stable average wind speed of 3 m/s, which is lower than the typical cut-in wind speed that lets turbine start rotating, leads to zero production, whereas the same average wind speed with high fluctuations yields a much higher production.

When a record of high-frequency wind speed data measured at the turbine location is available, the wind power production can be estimated by the wind power curve, which converts wind speeds into the corresponding wind energy production (e.g., [7,8]). For example, Himri et al. [9] apply wind speed data measured every three hours at three locations in Algeria and derive the power curve and the resulting energy yield using RetScreen software.

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Dahmouni et al. [10] estimate the net energy output at one location in Tunisia by measuring the wind every 10 min in different heights and combining it with the power curve provided by the turbine producer. D'Amico et al. [11] use 10 min data from a local weather station and the turbine producer's power curve to derive a wind energy production indicator. However, from the perspective of installing a turbine at a new location, long-term high-frequency measurements of wind speed at various locations and heights are very time-consuming and costly and can hardly be conducted to compare potential locations.

As an alternative to the power curve, the wind power density (WPD) is often applied, which is the amount of energy that can be extracted out of the wind from a physical viewpoint. For example, Karsli and Geçit [12] derive the wind power potential of one location in Turkey from hourly wind measurements via the WPD. This approach is also applied by Ohunakin [13] using the Weibull analysis and by Gunturu and Schlosser [14,15] using meteorological reanalysis data. Gunturu and Schlosser [14] criticize, however, that the WPD overestimates the real on-site production and should be used only as an illustrative point. Hence, the linkage between wind speed at a higher scale (e.g., hourly averages) and true production deserves further investigation, and the expected energy production at potential locations has to be derived using different tools.

In this paper, we present a new way of assessing the long-term wind energy potential of a new location by applying a wind energy index, which exploits high-frequency reanalysis wind speed data and derives the turbine-specific relation between reanalysis wind speed data and true production data by using true wind energy production data. When aggregating the low-scale wind energy production to higher time scales, the wind energy index can predict the long-term wind energy potential of new locations. Since reanalysis wind speed data are globally available, our approach can be applied worldwide.

Besides the assessment of the wind energy potential of a new location, the wind energy index is also able to conduct a turbine type comparison for a given location to support the selection of the most suitable turbine type. So far, the turbine type is for example selected based on the capacity factor, i.e., the averaged produced power, which is derived from the local Weibull wind distribution and the wind power density, compared with the rated power [16]. Perkin et al. [17] discuss several other approaches and derive a theoretically optimal power curve for the local wind conditions based on Blade Element Momentum theory and multiple Evolutionary Computing algorithms and then search for the best suitable real turbine. Both of these approaches require again local high-frequency wind data, whereas our approach has the advantage that—after the function for each turbine type is derived once—the performance of different turbine types at a location can easily be derived from reanalysis wind speed data.

To support future wind power development, there are three different compensation schemes, which are widely discussed in the literature: feed-in systems (feed-in tariffs or feed-in premiums), quotas (tradable green certificates), and auctions. Butler and Neuhoff [18] compare the support schemes of the UK and Germany and find out that the German feed-in tariff mechanism leads to lower costs for consumers than the Renewables Obligation Certificates (ROC) scheme in the UK. Del Río and Linares [19] argue that regulators do not necessarily know the real costs and hence set the feed-in tariffs too high. They suggest to use appropriately designed auctions instead, which is also planned in Germany after 2016.

Nowadays, most of the EU countries have introduced feed-in systems. In countries such as Belgium, Sweden, and Norway, electricity from onshore wind energy is promoted through a quota system, based on the trade of certificates. Others have opted for a combination of feed-in tariffs and quota systems. In the UK, for example, quota obligations mostly apply for large scale renewables, while smaller systems are subject to feed-in tariffs. Table 1 depicts the support mechanisms for selected European countries and the resulting amount of payment or obligation.

The wind energy index suggested in this paper can also be used to derive the minimum compensation per MW h that is required to build a profitable wind farm. As a third application, we compare the expected revenues of a planned wind farm with its investment and operating costs. The resulting required compensation per MW h can either form the basis for an auction or can be used to derive location-dependent feed-in tariffs. Hence, the wind energy index can serve as a supportive tool for wind farm planners and policy-makers.

The remainder of the paper is organized as follows. In Section 2, we describe the methodology, i.e., the derivation and validation of the wind energy index as well as its application to site assessment, turbine type selection, and local feed-in tariffs. In Section 3, we exemplarily apply this approach to two different turbine types based on data for eight German wind farms. Section 4 provides further discussions and conclusions.

## 2. Methods

### 2.1. Framework

The wind energy index presented here is based on Ritter et al. [24]. The paper at hand focuses on a further validation and application of this index, so the framework is only briefly presented.

Deriving the wind energy index consists of several steps, which are illustrated in Fig. 1. First, reanalysis wind speed data are chosen for the underlying database. They have the advantage of being easily available worldwide on a high spatial and temporal resolution. For this reason, they are recently more and more applied in wind power analysis (e.g., [25–27]). The reanalysis data used in this study come from Modern-Era Retrospective Analysis for Research and Applications (MERRA) data provided by NASA [28], which provide a higher resolution and a good fit compared to other alternative datasets [26]. Nevertheless, MERRA data are known to systematically over- or underestimate the wind speed in different regions, so that a regional calibration is necessary [29–31]. The spatial resolution of the MERRA grid data is 1/2° latitude times 2/3° longitude (about 45 km × 54 km in Germany), the temporal resolution is hourly since 1979. The wind data are divided into a northward and an eastward wind component at three different heights (2 m, 10 m, and 50 m above ground) [32].

In the next two steps, the local wind speed data at the turbine's location and hub height are derived from the MERRA wind speed data. The wind speed components of the four nearest MERRA grid points at the three heights are horizontally interpolated weighted by their horizontal distance. Hence, northward and eastward components in 2 m,10 m, and 50 m at the turbine's location are obtained, which can be put together to absolute wind speeds at the three heights. At this point, even the wind direction could be inferred, which is not required for our approach. Then, the three wind speeds are vertically extrapolated to the turbine's hub height using the log wind profile (e.g., [14]):

$$V_z = \left(\frac{u_*}{\kappa}\right) \log\left[\frac{(z-d)}{z_0}\right], \tag{1}$$

where $V_z$ denotes the wind speed at height $z$, $u_*$ the friction velocity, $\kappa$ the von Kármán constant ($\sim$0.41) used for fluid modeling, $d$ the displacement height, and $z_0$ the surface roughness. The three unknown parameters $u_*$, $d$, and $z_0$, are calculated for each time step by solving the three dimensional equation system for the wind