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Wind resource estimates with an analog ensemble approach

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ABSTRACT

The wind resource and energy assessment is key to a wind farm development project. It allows for establishing the feasibility and economic viability of the project over the typical 10- to 30-year lifetime of a wind farm. Recent studies show that the accuracy of assessments has substantial room for improvement. Estimating and reducing uncertainty is important to secure financing and ensure the confidence of investors. A new method is proposed and demonstrated for the long-term estimation of the wind speeds at a target site, a key step in assessments. The method is based on ensembles made of analogs between a short-term observational record from the target site and a long-term historical record from a nearby site or an atmospheric model. It provides a high-quality long-term wind resource estimate, characterized by an accurate wind speed time series and frequency distribution. It also provides a reliable estimate of the uncertainty based on the actual physical processes determining the current atmospheric flow rather than the climatological wind distribution.

1. Introduction

Due to reasons ranging from climate change to geopolitical security, renewable energy has increasingly received attention for the past decades with some of the technologies becoming cost-competitive compared to conventional power sources [1]. Among those, wind energy is one of the fastest growing electricity generation sources in the world.

Together with the sector growth, wind turbine technology is evolving rapidly. Hub height now averages over 80 m, accessing stronger winds [2], while rotor diameters of 80–100 m are increasingly the norm [3]. These turbines produce more energy but also make the pre-construction assessment of the wind resource at candidate wind-farm sites more difficult, due to the lack of adequate wind observations at such heights.

Wind resource and energy assessment is key to the wind farm development process, as it allows for establishing the feasibility and economic viability of the project over the typical 10- to 30-year-long lifetime of the farm. Recent data show that the accuracy of assessments has substantial room for improvement. DNV KEMA [4] looked at actual power output of 89 facilities totaling 476 years of post-2000 operation and found an average overestimation of pre-construction energy estimates of 5–8%.

A comprehensive wind resource assessment usually entails the following tasks [4–6]:

1. *Site prospecting*: identification of a suitable site using cartography (wind maps, political maps, etc.).
2. *Measurement campaign*: characterization of the on-site wind resource by recording the winds for 1–4 years as close as possible to hub height, with temporary meteorological masts (possibly completed with remote sensing instruments).
3. *Microscale vertical extrapolation*: transfer of the measurements to hub heights.
4. *Long-term extrapolation*: extension of the measurements to the 10- to 30-year-long operation lifetime using historical observations (nearby tall towers, surface weather stations, rawinsonde stations, modeled data sets such as reanalyses) and (mostly) statistical methods.
5. *Wind-farm layout design*: establishment of turbine locations and relative wind resource estimation (e.g., using computational fluid dynamic models).
6. *Gross energy production estimation*: calculation of the potential wind power for the whole site.
7. *Energy losses assessment*: evaluation of losses due to various causes (equipment downtime, array losses, etc.).
8. *Uncertainty estimation*: careful evaluation of the uncertainty associated with every step above.

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Evaluating and reducing the uncertainties is of particular importance to secure financing and ensure the investor's confidence. The uncertainties drive the probability distribution of the expected energy production. A recent comparison of pre-construction energy assessments for about 200 North American utility-scale wind farms to the actual power output highlighted the following breakdown of contributions to the total energy production uncertainty [3]:

- Measurement accuracy: 19% (step 2).
- Vertical extrapolation: 13% (step 3).
- Historical wind resource: 18% (step 4).
- Spatial variation: 22% (step 5).
- Energy losses: 13% (step 7).
- Future variability: 15% (part of step 8).

These values obviously depend on many factors, including the project size, the terrain, and the availability of historical wind data. Estimating and constraining (if not reducing) these uncertainties is important.

Step 4 is the subject of this study. A widely used procedure for the long-term extrapolation of the wind measurements is the Measure-Correlate-Predict (MCP) method [5–7]. It establishes relationships of various complexities between concurrent wind measurements and historical wind data, then it uses these relationships to transform the historical wind data into a time series representing the long-term wind resource at the target site. Key requirements of such methods are that 1) the measurements correlate well to the historical data (i.e., in practice a correlation coefficient at least as large as 0.77 [6]), 2) the historical record is homogeneous, and 3) the measurements and historical data overlap for at least 9–12 months [7]. Caveats are that the first two conditions are sometimes hard to meet, and additionally MCP methods are usually not adequate to provide a wind frequency distribution [6]. Yet the wind resource uncertainties drive the probability distribution of the expected energy production. The energy production values with probabilities of exceedance of 50, 90 and 99% are used by lenders as a way of determining the level of risk in investing in a wind farm [3].

We hereby propose a new method for the long-term extrapolation step that provides a high-quality long-term wind resource estimation characterized by an accurate wind speed time series, a valid wind frequency distribution, and an estimation of this step's uncertainty – the latter based on actual physical processes determining the current atmospheric flow rather than the climatological wind distribution. The method is based on ensembles made of analogs between a short-term observational record from the target site and a long-term historical record from a nearby site or an atmospheric model. The strengths of the method lie in:

- Quality of results: the reconstructed long-term wind resource exhibits a good correlation with on-site wind observations, virtually no bias, and a low root-mean-squared error.
- Extent of results: a wind resource frequency distribution with uncertainty bounds that is based on actual physical processes rather than a more typical climatologically based value, and that is useful for the energy production estimation [6].
- Simple requirements: the necessary data already exist (i.e., reanalysis and 1–4 years of observations), and the correlation coefficient between the historical data and the observations does not need to be high (0.5 is acceptable), rendering more data sources “usable”.
- Ease of use: it can be run on a personal computer; for instance, a 10-year-long time series can be reconstructed in few tens of seconds.

Section 2 describes the testing sites and associated data used for the demonstration of the method, as well as the method's functioning and sensitivity to key aspects of the algorithm. Section 3 presents the results and compares them to a MCP reference. Section 3.3 discusses the direct relevance of this method for wind resource assessments and conclusions are drawn in Section 4.

2. Data sets and long-term wind resource estimation methods

2.1. Data for hypothetical wind farm sites

For the purpose of demonstrating the analog ensemble method, we established nine hypothetical wind farm target sites. Observations at all nine sites are hourly wind speed measurements at fixed heights above ground level, and constitute both a proxy for site measurements typically used in the wind resource assessment process, and data for validating the results. Their characteristics are listed in Table 1. Six sites coincided with locations where quality-checked, medium/long-term, near-hub-height wind measurements were publicly available. The remaining three sites coincide with locations where real mast measurements (i.e., step 2) were made. They are proprietary data and therefore not all results will be shown.

For each target site, meteorological fields from NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) were used as historical data [8]. MERRA is a freely available high-quality global reanalysis of weather occurring since 1979, and one of the few global atmospheric reanalyses that use data from the entire constellation of NASA Earth Observing System satellites. Native-resolution (0.5° in latitude × 0.67° in longitude, terrain-following hybrid sigma-pressure coordinate) hourly surface turbulent flux diagnostics and atmospheric single-level diagnostics were retrieved [9]. The planetary boundary layer height, temperature, specific humidity, and eastward and northward winds of the lowest layer came from the MERRA data collection *tavg1_2d_flx_Nx*, and the surface pressure came from *tavg1_2d_slv_Nx*. Data from the four grid cells nearest each site were bilinearly interpolated to the site's exact location. The lowest model level was used for all level-dependent variables (63 m AGL on average).

2.2. Analog ensemble method

Analog ensemble techniques have been used with success for short-term weather predictions [10–13]. In the context of the wind resource assessment, the analog ensemble method draws on the information contained in a long-term reanalysis (known as *historical data*) of multiple physical quantities that are related to available targeted wind speed observations (known as the *predictand*) collected over a short time period (known as *training period*; typically 365 days). The relationships derived within the training period are then applied to reconstruct the wind speed at the target site over the period for which there are no observations (hereafter referred to as *reconstructed period*; e.g., the past 20 years before the measurement campaign started).

More precisely, this is a three-stage process that is executed independently at every target site for every hour *t* of the reconstructed period, as sketched in Fig. 1:

1. The historical value of multiple physical quantities (known as *analog predictors*; e.g., wind speed, wind direction, pressure, etc.) is retrieved for a range of times (known as an *analog trend*) centered around time *t* (red star in Fig. 1) (in web version). The analog predictors are selected beforehand based on their known or anticipated correlations to the predictand.
2. Other historical cases over the training period with conditions analogous to those in the target window are identified (red marks in top series of Fig. 1) by looking at a temporal window (known as