Wind energy assessment for low complex terrain using reference meteorological mast

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Abstract. The wind flow distribution over semi-complex terrains is evaluated by the roughness factor of the topography and the terrain peculiarities. The energy yield from the turbines in the park is based on the wind parameters extrapolated from the on-site measurement point to wind turbine hub height. For the lower zones of the terrain, the wind shear is influenced by the boundary layer, which can hardly be modeled using only tall tower data and a linear numerical model. The implementation of a second mast (reference), however, gives enough reliable data about the wind parameters at the lower part of the location and is used to adjust the flow and directional behavior from the main mast. The current study shows that for the low complex terrains using the proposed methodology an improvement of the assessed energy yield from the farm with 3% might be anticipated. Furthermore, for more complex terrains where the effect of the orography on the wind shear is more significant the expected improvement should be higher.

1. Introduction

The wind is a renewable energy source, utilization systems of which are developing rapidly in the last decades. Thus, performing an accurate analysis of the site wind potential is essential for the profitability of the wind farm. Generally, wind parameters are registered with specialized hardware, installed on tall towers. When performing measurements with meteorological masts, it is necessary to install the measuring equipment far enough, so that it is not exaggerated by the disturbing wind flow around the mast. Therefore, it is essential to follow the relevant standards, applicable to wind measurements [1-3]. Also, when conducting wind measurements, the measuring equipment needs to be calibrated and allowing proper accuracy. In order to estimate the wind velocity distribution in height, it is needed to measure the wind parameters for at least three points above the earth surface. In flat and low complex terrain surfaces, the use of a 50 m mast is enough to determine the wind potential in the area of the site. However, in complex topographies it is required to use higher weather masts.

Once the wind parameters at the measurement point are determined, they should be extrapolated to the hub elevation of the wind turbine, which is at a higher height and can be spaced up to several kilometers. The land topographies as well as the site roughness factor [4-7] have the highest impact on the wind behavior over a given terrain.

In [8] the behavior of the wind shear is analyzed, when reaching a hill, and the results are accomplished experimentally. The behavior of the wind velocity distribution in height between two hills is even more complicated, when the developed flow between them is turbulent [9]. But, not only the topology of the terrain influences the behavior of the velocity profile. The presence of orographic elements on the terrain, such as tall grasses, shrubs or even forest belts and tall trees, have a substantial influence on the wind shear distribution [10].
The possibility of using empirical correlation for the foreseen of the data from the measuring point to the turbine tower height, is presented in [11]. The wind shear factors impact over the energy production from such turbines is presented in [12-13]. Recently, numerical modeling techniques for wind flow analysis over terrains are used [14-16]. Several studies indicate the specifics in the modeling of wind turbulent flows over terrains with varying complexity and further assessment of wind energy yield are presented in [17-22].

The performed analysis demonstrates that the effect of the ground boundary layer on wind shear distribution has a strong relation with the terrain roughness. Thus, the aim of the presented work is to reveal how the use of a second meteorological mast would improve the prediction of the distribution of the wind shear over the terrain, resp. refining the estimated energy production.

2. On-site wind data measurements
A semi-complex terrain is chosen in the presented study, and the elevation alteration among the higher and lower part of the site is 150 m. Two masts with a height of 20 and 60 meters (figure 1) are installed. The 60-meter high meteorological mast (Mast 1) is installed on the high part of the site, and the measurements of the wind-flow parameters are at three heights - 40, 50 and 60 m. The low mast (20 m) (Mast 2) is prepared with two measuring devices for wind speed, mounted at 10 and 20 m height. The low-lying sensor is used to determine the effect of the terrain boundary layer on the wind behavior in height. Photography of the two measuring masts is shown on figure 2.

![Figure 1. 3D orography of the terrain with the installation points of 60 and 20 masts.](image1)

![Figure 2. View of 60 m and 20 m measuring masts.](image2)
The measuring equipment is calibrated, and the operating range and measurement error are presented in table 1.

**Table 1.** Summarized technical information for the equipment, used for the on-site study.

| Sensor                  | Model         | Range            | Accuracy          |
|------------------------|---------------|------------------|-------------------|
| Cup anemometer         | NRG #40C      | 1 up to 96 m/s   | ±0.14 m/s         |
| Wind vane              | NRG 200P      | 0 up to 360°     | ±1°               |
| Temperature sensor     | TS 21         | -40 up to +70°C  | ±0.2°C            |
| Pressure sensor        | BP 20         | 15 up to 115 kPa | ±1.5 Pa           |

### 3. Wind data analysis

Mast 1 was used to monitor the wind potential for one year, and mast 2 was installed three months later. The average velocity at 60 m is 4.99 m/s, at 50 m - 4.80 m/s and at 40 m - 4.68 m/s. Based on this data, the wind shear profile is built for the high mast, using the two laws - logarithmic and power law:

- **Logarithmic law**

\[
U(z) = \begin{cases} 
\frac{u_*}{k} \ln \left( \frac{z}{z_0} \right), & \text{if } z > z_0 \\
0, & \text{if } z < z_0 
\end{cases}
\]  

where:

- \(U(z)\) - wind speed at certain height above ground, \(z\), m/s;
- \(z_0\) - surface roughness, m;
- \(k\) - von Karman’s constant (0.4);
- \(u_*\) - friction velocity, m/s.

- **Power law**

\[
U(z) = u(z_1) \left( \frac{z}{z_1} \right)^\alpha
\]

where:

- \(U(z)\) - wind speed at some height above ground, \(z\), m/s;
- \(z_1\) - height of the known wind speed, m;
- \(\alpha\) - power law exponent.

After constructing the wind shear, it is seen that the site roughness factor is 0.014, and the power law exponent, according to the above equation is 0.123.

The measured average wind speed for the considered period with the low mast shows an average wind speed at an elevation of 20 m to be 2.89 m/s, and that at 10 m - 2.15 m/s. The lower velocity is due to the less altitude at which mast 2 is installed. Using the same approach to calculate the wind shear as for mast 1, for the roughness factor is obtained 1.47 m, and for the power coefficient - 0.445. The variance in the two profiles in height is significant. This is mostly because the velocity sensor, mounted at a height of 10 m, is in the zone affected by the ground boundary layer and thus registers significantly lower velocity, which affects the profile behavior in height. The aim of the current study is to assess the error in determining the energy production only when using a low mast on weakly complex terrains, as well as the enhancement when using a reference high mast.
Data for the change of the average wind speed by months, for the studied period, for the two masts at the indicated heights, is presented on figure 3. It is seen a good correlation between the average velocity, both between the individual sensors on one measuring mast and between the two masts. The relation coefficient between the two masts is 89%, which is an indicator of a relatively stable height profile of the wind for the site.

The wind frequency distribution in several directions is shown on figure 4. It is seen that the predominant wind direction is from East and West. The correlation coefficient between the two masts with respect to the wind rose is over 80%, which evidently is acceptable.

On figure 5 are presented the average measured wind shear for both masts, as well as foreseen data in height up to 100 m, using the logarithmic and power laws. It must be noted that when the wind velocity is measured at several heights above the earth's surface, and when at least two measuring instruments are outside the shadow of the boundary layer, the two laws give similar values for an elevation of 100 m. Nevertheless, when the measurements are up to 20 m high and one sensor, as well as higher locations, falls partially or completely in the shadow of the boundary layer, the difference in extrapolated speeds at 100 m is over 30%, which would significantly compromise a prefeasibility study.
The average turbulence intensity for the corresponding mast at wind velocity of 15 m/s is shown on figure 6. For Mast 1 it amounts to 0.090, and for Mast 2 - 0.109. Both masts fall into class C, which determines the turbulence as low.

![Figure 6. Average turbulent intensity as velocity of 15 m/s for: a) 20 m meteorological mast; b) 60 m meteorological mast.](image)

### 4. Numerical study

Measurements from a high meteorological mast, for not less than 1 year, are usually used as an input data for calculating the energy production from a wind farm. The measurements usually last at least two years, and it is obligatory to correlate the data with long-term ones, either from other masts or from the local meteorological stations of BAS (Bulgarian Academy of Sciences).

In the presented numerical analysis, two cases will be assessed - determining the production from a given site when using each of the masts separately, and when using mast 1 as the main and mast 2 as the reference.

The numerical modeling is performed with the WASP software package. This is a specialized software, used to predict wind behavior on the terrain using a linear model. The aim of the study is to determine how the use of reference measurements can more accurately predict the production from a given terrain with semi-complex geometry.

A three-dimensional surface of the site has been built by digitizing a topographic map. The wind masts and wind generators are situated on it. The numerical modeling used a wind generator type Vestas V90 with an installed capacity of 2.0 MW. The height of the wind turbine hub is 100 m.

#### 4.1. Analysis of the energy production using the high meteorological mast (mast 1)

The data from the field measurements with the high mast (mast 1) were used as input data for the numerical study. The conducted numerical analyses shows that the wind velocity in the vicinity of the high mast is 5.66 m/s (Location 1), and for the location of a wind generator in the vicinity of the low mast is 5.50 m/s (Location 2). Summarized data about the wind generators for the two locations is presented in table. 2.

| Wind Generator | Velocity, m/s | Altitude, m | Energy production, GWG |
|----------------|--------------|-------------|------------------------|
| Location 1     | 5.74         | 182         | 4.407                  |
| Location 2     | 5.50         | 30          | 4.048                  |

#### 4.2. Analysis of the energy production using the low meteorological mast (mast 2)

The data from the field measurements with the low mast (mast 2) were used as input data for the numerical study. The conducted numerical analyses shows that the wind velocity in the vicinity of the
high mast is 5.79 m/s (Location 1), and for the location of a wind generator in the vicinity of the low mast is 5.59 m/s (Location 2). Summary information about the wind generators for the two locations is presented in table 3.

Table 3. Summarized data from numerical study

| Wind Generator | Velocity, m/s | Altitude, m | Energy production, GWG |
|----------------|---------------|-------------|------------------------|
| Location 1     | 5.79          | 182         | 4.302                  |
| Location 2     | 5.59          | 30          | 3.980                  |

When comparing the results of the numerical studies, it is seen that when using input data in the studies from a high mast, the annual production is 2.3% lower compared to the use of the data from the low meteorological mast (Fig. 7).

![Figure 7](image)

*Figure 7.* Results from the numerical solutions with the use of input data from a) 20 m meteorological mast; b) 60 m meteorological mast.

5. Conclusions

The presented study reveals the opportunity of using reference wind measurements in the assessment of energy production from a wind farm installed on low complex terrain surfaces. Two masts with a height of 60 m and 20 m, equipped with calibrated equipment, were used. The distance between the masts is about 4 km. A correlation was made with respect to the average velocity registered by the two masts, as the correlation coefficient is over 90%. In addition, a correlation was made with respect to the frequency distribution of the wind in the directions. A high correlation coefficient was also found - over 80%.

The numerical results show that the use of data only from the low meteorological mast leads to some inaccuracy due to the low-lying sensor in the shadow of the boundary layer. With low complex terrain surfaces, this can increase the expected energy production by about 3%. In more complex terrains, however, where the wind shear is strongly influenced by the terrain roughness, this increase will be significantly higher. The proposed methodology can be successfully used for flat and low complex terrains. For very complex terrains methods other than linear extrapolation need to be used.

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