Impact assessment of terrain specifics on wind energy production over semi-complex terrains

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Abstract. Estimated energy production for a wind farm depends on the wind shear who is influenced by both the roughness factor and terrain specifics. Tall towers measurements allow accurate determination of the velocity profile around the mast. Away from the point of measurements the reliability of the extrapolated data depends on complexity of the terrain and the extrapolation technique applied, as the error may exceeded 30 %. In terms of this, the use of one high mast to predict the energy potential is inaccurate. However, installing more than two tall masts is expensive. Therefore, a novel approach is used to analyse the wind potential for semi-complex terrains - one tall and one short (reference) masts. The novelty in the study here is that the short mast collects wind data for high and low terrain points. The data collected shows that the complex character of the terrain significantly increases the thickness of the surface boundary layer making the data obtained with 20 m masts quite unreliable. However, the 20 m mast data provides useful information for boundary layer that is used for refinement of the tall tower wind shear. Thus, the use of high and short masts improves the estimated energy production.

1. Introduction

Over the last few decades, there has been a significant increase in the share of energy produced from renewable energy sources. The energy produced from a renewable energy resources reduces the amount of carbon emissions generated compared to the conventional use of liquid fuels [1].

The use of the wind potential for the production of electricity has its specific features. The production of energy from a given site depends on both the terrain features and the roughness factor of the terrain [2, 6]. These two factors have a significant effect on the wind behavior over the terrain, which also further determines the micro-sitting of the wind turbines. Therefore, the determination of significant factors influencing the wind shear change is essential for accurate wind energy assessment.

In a number of works [2-11], a discussion is made on the factors influencing the wind behavior over terrains with different complexities. In [12], special attention is paid to the fact that, in the case of extrapolation of wind speed data from a measurement height to a wind turbine hub height, if the terrain features are not taken into account, the inaccuracy in energy production may reach 38 %. It turns out that the greatest discrepancy between real and estimated energy production occurs in cases where wind data from the point of measurement to the wind turbine hub height is incorrectly extrapolated. Several approaches are used, most notably those using a reference mast (second) or...
numerical modeling approach with a very precise adjustment of roughness factor and terrain specifics in the numerical model.

In many works [13-18] the specifics of the use of numerical methods in modeling of wind flow on both semi-complex and complex terrains are mentioned. All studies show that numerical modeling using linear models can only be considered valid in flat or low complex terrains. For complex terrains, the error may exceed 30%. The use of renormalization group (RNG) or Large eddy simulation (LES) software turbulent models much more accurately describes the wind flow behavior over complex terrain, but the timing of computing procedures is significant and is less applicable to large-area terrains.

Due to the above, the study explores the possibility of using reference measurements in determining the wind shear for a given semi-complex terrains and further refining the parameters in the numerical models with a view to precise the energy estimation model.

2. On-site measurements and site specifics

The purpose of the study is to show how the semi-complex terrain orography affects the wind shear over the terrain and respectably the energy yield. Semi-complex orography site was selected (Fig. 1), as the terrain is located in central part of northern Bulgaria. The altitude in the south ranges from 120 to 172 m. In the northern part the terrain is open at a low altitude in the range of 21 to 32 m. The on-site wind measurements are performed with two types of masts – one tall tower (60 m) and one short mast (20 m) both equipped with calibrated measuring equipment. The team estimated that the use of two high masts equipped with calibrated equipment is expensive, which is why a novel approach is accepted where one high and one short meteo masts are used here. Initially, the low mast was installed in the high parts of the terrain and after a certain period is moved to the low part. This was done in order to determine the wind characteristics in the surface boundary layer which significantly affect the wind shear. The distance between the two masts is 4.2 km (Mast 1 and 60m tall tower), making them particularly suitable for analyzing the influence of the relief on the wind shear. After a certain measurement interval the short mast was dismantled and subsequently installed on the low point of the terrain (Mast 2 location). The distance between Mast 2 and 60 m tall tower is 5.5 km.

![Figure 1. 3D map of the surface with location of three measuring masts](image)

The installation spot of the masts is made according to the terrain topology with a view to minimizing the shading of the equipment from the measuring mast. For this purpose it is necessary to know the prevailing wind direction for the site. 30 year long term data have been used to establish the prevailing wind direction. The data are collected with the 10 m mast owned by the Bulgarian Academic of Science meteorological services. The prepared wind atlas shows that for the site east and west winds have the highest degree of frequency. Light shading is expected, in cases where the prevailing direction is north-south.
The measuring period with the tall tower is one year (June, 2017 up to June, 2018) until the mast 1 measures the wind parameters for the indicated location for four months (May, 2017 up to August, 2017) and then moved to point 2 (Mast 2) where the measurements continued for the next 6 months (Figure 4).

All wind measurements have been performed in accordance with the current standards and norms. The mast is equipped with calibrated in a certified laboratory equipment. The 60 meters mast is equipped with two wind speed sensors installed at a height of 60 meters, one at 50 meters and one sensor at 40 meters. The wind direction sensors are installed at two heights - 60 and 50m.

In addition to the high mast, two sensors for measuring ambient air temperature and atmospheric pressure are also installed. The 20 m mast is equipped with two wind speed sensors at heights of 10 and 20 meters and one wind vane at a height of 20 meters. Also two sensors for measuring ambient air temperature and barometric sensor are installed.

Summarized technical information for the measuring equipment is presented in table 1.

Table 1. Technical specification of measuring equipment

| 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   |

With the installed measuring equipment on both masts, 10 minutes readings of wind parameters were collected over a one-year period. The quality control of the raw wind data indicates that the icing of the measuring equipment is not observed, so all the data can be successfully used for the analysis of the wind in the vicinity of the site.

Fig. 2 a-c is a representation of a wind rose for the three masts locations based on the collected on-site data.

Figure 2. Directional distribution: a) 20 m mast (Mast 1); b) 20 mast (Mast 2); c) Tall tower (60 m mast).

There is a greater similarity in the wind rose between the 60 m mast and the one installed in point 1 due to the fact that the terrain features are similar and the masts are installed at approximately the same altitude. The analysis performed shows that Pearson correlation coefficient [25] between tall
tower and Mast 1 (linear correlation between both measurement locations) is over 72 %. The same correlation coefficient between tall tower and mast 2 is 53 %.

The lowest directional Pearson correlation factor is between the both locations of the small mast – 48%. This indicates that the low and high parts of the selected terrain are characterized by local features of ground wind.

Fig. 3 shows the shadowing impact of the tower over the measuring equipment (red circle). The effect is seen to be minimal and the data collected can be considered reliable. No further adjustments are needed.

Fig. 4 is monthly distribution of the average wind speed based on the collected on-site data with all masts. The average wind speed is as follow:
- Mast 1 (at 20 m) – mean speed 4.14 m/s;
- Mast 2 (at 60 m) – mean speed 4.99 m/s;
- Mast 3 (at 20 m) – mean speed 2.73 m/s;

Good correlation is observed both between individual anemometers installed on different heights of the same mast and between masts.

It is obvious that both local terrain specifics and altitude affect the mean wind speed. The lowest wind speed is registered with mast 2 installed 20 m above sea level. On a terrain 1, 20 m mast (Mast 1) registers significantly higher average wind speed, such as the altitude is 150 m. The elevation of the tall tower is the highest – 187 m. Including the height of the mast, the registered wind speed is 4.99 m/s or higher than the other two masts.

Fig. 5 a-c provides information on the wind shear for the three mast locations. Both logarithmic and power profiles are obtained in accordance with the following relations:

- Logarithmic law

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

(1)

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

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

(2)

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.

Fig. 5a illustrates the wind shears for the location of mast 1. The values obtained for the power law constant (0.221) and the roughness factor \( z_0=0.110 \) are based on the collected on-site data. The difference in wind speeds using the two laws at 100 m height is 6%. The relief of the site is semi-complex so the sharper wind shear is expected.

The wind shear for the mast 2 is of interest. The mast is installed at a low altitude and the relief around is slightly hilly. According to the wind speed records collected at a height of 10 and 20 m, the power law exponent is 0.475, and the roughness factor is \( z_0=1.69 \). The roughness factor here is 15 times higher than one obtained with the same mast on location 1 which significantly changes the behavior of the wind shear. Here the surface boundary layer is affected by the terrain specifics and the difference in mean wind speeds for both laws at 100 m is more than 27%. Also the surface boundary layer slowing down the average wind speed at 10 m which is the reason for distortion of the velocity profile. Its thickness compared to the first site is greater due to the more complex orography of the terrain in the vicinity of the mast.

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**Figure 5.** Wind shears a) 20 m mast (Terrain 1); b) 20 m mast (Terrain 2); c) 60 m mast
Also the surface boundary layer slowing down the average wind speed at 10 m which is the reason for distortion of the velocity profile. Its thickness compared to the first site is greater due to the more complex orography of the terrain in the vicinity of the mast.

In such cases, the recommendation is the use of at least two measuring instruments mounted outside the surface boundary layer in order to reliably build the velocity profile above the ground. As it was stated above the logarithmic law wind shear behavior of both short masts location are very close to the wind shear behavior of tall tower. The power law wind shears for both short masts shows greater discrepancy in terms with the tall tower power law profile. The general conclusion here is that power law approximation should be carefully used for prediction of wind shear for a semi-complex terrains.

Wind shear for the tall tower site is presented in Fig. 5c. The wind speed measurements at three heights were used to get more accurate information about the specifics of the orography. A difference of 0.3 % is established between the mean wind speeds at a height of 100 m obtained using both laws. The both profiles are pretty sharp and in accordance with local terrain specifics. In addition, a good match between the two profiles serves as a correction for the low mast profiles.

Conducted field measurements show that the wind shear at a given location depends on the obstacles encountered by the wind in its path. In the case of semi-complex terrains, the influence of the peculiarities of the terrain several kilometers beyond the measuring point must be taken into account. Thus, the orography in the vicinity of the three masts is carefully considered. The terrain specifics are presented in Fig. 6 a-c. It is obvious that the most significant change in elevation is between location 2 and the other masts locations. Due to the fact that the location of the mast 2 falls in the lowest part of the terrain, there is a reason for a serious discrepancy between the two laws wind shears.

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3. Numerical study

Usually single tall tower measurements are used to assess the annual energy production from wind farm. The numerical modeling technique is used to extrapolate the wind data from the measurement point to the hub of the wind turbines, taking into account the features of the relief. In a presence of flat terrains the wind shear easily can be extrapolated to the wind turbine hub height. For a semi-complex or complex terrains such approach cannot be applied and turbulence modeling is needed. Turbulence
modeling and subsequent numerical solution is a time-consuming procedure, with subsequent validation of the results obtained.

Some of the specialized software products (WAsP, WindPro, WindSim) can be successfully used for prediction of energy output by the wind farm, in case that the sites are not very complex in structure.

Other Fluent/Ansys products that are specialized in modeling of flow behavior can be “tailored” for the wind power industry, but the mathematical models they use to describe are very complex, and the time for calculations, especially considering large terrains, is significant.

In [19-23] various approaches have been used to model energy production from wind farms. In [24], particular attention is paid to the impact of different turbulent models on estimated energy production.

WAsP is a commercial software that uses a linear model for wind flow prediction. The model combines two models: physical model (atmospheric stability, factor roughness, natural change in geography of relief, etc.) and statistical model (Weibull wind parameters distribution). The physical model is used to determine the wind shear over the terrain. WAsP software was used to run the numerical procedures of this study.

The main purpose of the study is to show how the use of two reference data improves the forecasting of energy production from wind farms on semi-complex terrains.

The following novel approach is used - one-mast full-scale measurements serve as input to the numerical model by which the wind parameters of the other two masts are calculated. In this way, the results from the numerical solution are compared with the on-site data collected by two masts and appropriate adjustments are made if necessary. Two cases are considered:

- **Case 1:** A 20m mast (Mast 2) is used as the basis for the numerical simulations, after which the results from the numerical solutions are compared with those collected from the 20 m mast (Mast 1) and 60 m mast;

- **Case 2:** A 60 m mast is used as the basis for numerical simulations, then the results are compared with those collected from a 20 m masts (Mast 1 and Mast 2);

![Figure 7. Meteorological data collected with a) Mast 2; b) Tall tower (60 m mast)](image-url)
Fig. 7 a and b is a representation of the input meteorological data of 20m mast (Mast 1) and 60m mast (tall tower) used in the numerical procedure.

3.1. Case 1: 20 m mast (Mast 2) data used to predict the wind flow

Numerical simulations were performed using input data of a 20 m mast (Mast 2) located at the site with the smallest altitude. The data, by a numerical procedure are extrapolated to the heights of the other two measuring masts. Summarized information for the wind speed allocated by sectors is presented in table 2.

According table 2, the difference between the numerical results and on-site collected data with 60 m mast is 32.5%. For a 20 m mast, the gap between the results is 35.6%. The error in both cases is approximately the same, indicating that the linear discretization model accumulates the same error in height, i.e. keep the same wind shear disregarding the orography features of the terrain. Moreover in presence of complex terrains the error can be as high as 30-40 % which can have a detrimental effect on the financial profitability of the project.

Table 2. Comparative analysis between on-site data and numerical results (20 m Mast 2 is used as an input data)

| Sector | Average speed [m/s], 60 m mast | Average speed [m/s], 20 m mast 1 |
|--------|-------------------------------|----------------------------------|
|        | Numerical | Experiment | Numerical | Experiment |
| 1      | 1.13      | 2.97       | 0.99      | 2.61       |
| 2      | 2.07      | 3.19       | 2.01      | 3.01       |
| 3      | 3.63      | 3.92       | 3.17      | 3.21       |
| 4      | 4.45      | 4.25       | 3.58      | 3.30       |
| 5      | 3.68      | 3.90       | 2.91      | 3.37       |
| 6      | 1.92      | 3.49       | 1.51      | 2.95       |
| 7      | 1.45      | 3.84       | 1.22      | 2.86       |
| 8      | 1.24      | 4.14       | 1.07      | 3.59       |
| 9      | 1.19      | 5.23       | 1.03      | 3.59       |
| 10     | 1.84      | 6.99       | 1.62      | 5.84       |
| 11     | 2.28      | 5.15       | 2.05      | 6.58       |
| 12     | 3.81      | 3.35       | 3.30      | 3.77       |
| 13     | 5.30      |            | 4.37      |            |
| 14     | 4.45      |            | 3.54      |            |
| 15     | 2.35      |            | 2.14      |            |
| 16     | 1.47      |            | 1.36      |            |
| All    | 3.24      | 4.80       | 2.65      | 4.12       |

Turbulent intensity (TI) is also a parameter that influences the behavior of the vertical wind shear. Given that the turbulent wind intensity is more significant near the earth's surface (surface boundary layer), the TI by sectors in the vicinity of a 20 m mast is presented (Fig. 8). According to the presented results, the peak turbulent intensity reaches 0.25. For couple of sectors the wake effect of the mast is also clearly visible.

Figure 9 presents the turbulent intensity change in vertical direction, both by sector and summarized for all sectors. The average TI at 100 m height is 0.15 which is determined as the average for the respective location.
3.2. Case 2: 60 m mast (tall tower) data used to predict the wind flow

Numerical simulations were performed using 60m mast input data. Through the numerical procedure, the results of the on-site measurements are extrapolated to the points and heights of the two 20 m masts. The results are presented in table 3.

Table 3. Comparative analysis between on-site data and numerical results (60 m Mast is used as an input data)

| Sector | Average speed [m/s], 20 m mast 1 | Average speed [m/s], 20 m mast 2 |
|--------|-------------------------------|-------------------------------|
|        | Numerical | Experiment | Numerical | Experiment |
| 1      | 2.46      | 2.61       | 1.97      | 0.18       |
| 2      | 2.78      | 3.01       | 2.08      | 1.26       |
| 3      | 3.47      | 3.21       | 2.83      | 2.48       |
| 4      | 3.55      | 3.30       | 3.18      | 2.25       |
| 5      | 3.50      | 3.37       | 3.43      | 1.04       |
| 6      | 3.24      | 2.95       | 3.26      | 0.62       |
| 7      | 3.21      | 2.86       | 3.04      | 0.42       |
| 8      | 3.05      | 3.59       | 2.60      | 1.06       |
| 9      | 3.10      | 3.59       | 2.52      | 1.46       |
| 10     | 3.30      | 5.84       | 2.63      | 3.53       |
| 11     | 3.89      | 6.58       | 2.70      | 2.34       |
| 12     | 5.09      | 3.77       | 4.32      | 0.84       |
| 13     | 5.57      | 5.47       |           |            |
| 14     | 4.23      | 4.29       |           |            |
| 15     | 3.20      | 2.69       |           |            |
| 16     | 2.66      | 2.25       |           |            |
| **All** | **3.85** | **4.12**   | **3.54** | **1.94**  |

The mast 1 and the high mast are installed on a plate of approximately similar height, so the difference between the numerical solution and the on-site measurements is about 13 %. A greater discrepancy is observed between numerical and experimental measurements compared to mast 2, which is installed at significantly lower altitude - 44.8 %. This shows that the use of a linear model during numerical simulations for semi-complex terrains leads to significant differences between real and estimated energy production, especially where large differences in elevations are available.

The main conclusion that can be drawn here is that performing numerical modeling of wind flow using a high meteorological mast produces better results than using a 20 m mast. However, using a linear model to predict the flow in the vicinity of the surface boundary layer is inappropriate, with a
difference between numerical and experimental studies of more than 40%. The indicated mismatch rate applies to semi-complex terrains, and this can be significantly increased for complex terrains.

### 3.3. Energy production estimation

Wind farm energy production is determined on the basis of two factors - the wind potential of the site and the technical characteristics of the wind turbines.

Also here it is shown to what extent the disregard of the terrain features influences the energy production of the park.

For this purpose two studies are performed – estimation of wind farm energy production based on the preliminary obtained wind parameters via 20 and 60 m mast. Due to the fact that the terrain is conditionally divided into high and low parts, two wind parks are formed (Fig. 11a dotted line region). The wind farm consist of identical Vestas V90 wind turbines with an installed capacity of 3MW each. The power curve of the wind turbine is according Fig. 10. The turbines starts at 3 m/s reaching a rated power output of 3 MW at a speed of 14 m/s.

Fig. 11a is a numerical study of a wind flow distribution over the terrain when 20 m mast data are used as an input data in the model. A dashed line shows the location of the turbines in the park. Fig. 11b is also a numerical study of the wind flow distribution over the terrain with 60 m mast input data. There is a similar distribution of wind parameters over the terrain with two masts. However, using a 60 m mast resulting in a wind speed of about 32% higher than using a 20 m mast. In addition, obtaining similar velocity fields indicates the use of a linear model in the software.

Table 4 gives summarized information for the wind farm energy production – estimated energy production (numerical study) and energy produced as a result of real operation of the farm. It is obvious that when short mast is used to predict the flow over the terrain the estimated annual energy production amounts to 44.287 GWh/yr. When a 60 m mast is used to predict the wind flow behavior, the estimated power output is 105.725 or about 140% higher than the 20 m mast prediction.

The main conclusion that can be drawn is that the use of two masts alone in semi-complex terrains, without taking into account the orography of the terrain, leads to significant discrepancies in determining the wind farm's energy production.
In order to take into account the influence of the terrain on the velocity profile, the Authors make an adjustment of the wind shear obtained with 60 m mast with the specifics of the surface boundary layer obtained from the two points of the 20 m mast. Thus, the wind speed of the hub of the turbine is 5.4 m/s or about 5.4 % lower than that obtained from the 60 m mast. With the adjustments in the numerical model made the estimated energy production amounted to 94.480 GWh/yr. The energy output is about 10 % lower than estimated energy production with only 60 m mast data.

The wind farm has a complete year of operation. A SCADA systems is used to record data and manage operation of the wind farm. The energy produced by the farms amounted to 90.165 GWh/yr which is 4.6 % lower than the adjusted numerical model or 14.7% lower than using single 60m mast which is pretty significant discrepancy.

**Table 4.** Estimated annual energy production from the wind farm

| Case                                | Annual energy production, GWh/yr | Wind speed at hub height, m/s |
|-------------------------------------|---------------------------------|-------------------------------|
| 20m Mast 2 on-site data             | 44.287                          | 3.59                          |
| Tall tower on-site data             | 105.725                         | 5.71                          |
| Tall tower onsite data incl. reference data | 94.480                     | 5.40                          |
| Real energy production              | 90.165                          | 5.31                          |

**4. Conclusion**

The paper presents a detailed analysis of the effect of terrain orography on the wind shear distribution over semi-complex terrain. For this purpose, long-term wind measurements were carried out with one high and one short weather mast equipped with calibrated equipment. To assess the impact of the surface boundary layer, the short mast has been consistently installed at high and low elevation points of the terrain. The results from the analysis performed show that:

- The use of low mast only in complex terrains results in a difference of more than 27 % between the values of wind speed at 100 m height when using both log and power laws;
Specialized software products using a linear data extrapolation model do not take into account the terrain specifics. This results in significant distortion of the wind speed results, especially at a significant distance from the measuring point;

Measurement with an additional 20 m mast gives information about the wind speed in the surface boundary layer and can be successfully used to refine the wind shear of a 60 m mast;

Using only a high mast to determine wind energy output on semi-complex terrains can increase the estimated energy production by about 15%. The reference mast refines the velocity profile, especially for low altitude installed wind turbines. Thus, the difference between estimated and real energy production is no more than 5%.

The possibility of using low reference masts in determining the velocity profile and over complex terrains is yet to be explored.

Using single tall or short masts for energy yield prediction in a semi-complex terrains may lead to significant discrepancy with the real energy production. The impact of the surface boundary layer can be established only with simultaneous use of tall tower and also with presence of at least two sensors installed away from the shadow of the boundary layer. The short reference mast installed on the lowest part of the terrain can improve the wind shear of the tall tower and to refine the wind farm energy output.

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