EXPERIMENTAL VALIDATION OF WIND ENERGY ESTIMATION

by

Predrag M. ŽIVKOVIĆ [a*]**, *Mladen A. TOMIĆ*** [b]**, *and Vukman V. BAKIĆ*** [c]

[a] Faculty of Mechanical Engineering, University of Nis, Nis, Serbia
[b] Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia
[c] Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

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Wind power assessment in complex terrain is a very demanding task. Modeling wind conditions with standard linear models does not sufficiently reproduce wind conditions in complex terrains, especially on leeward sides of terrain slopes, primarily due to the vorticity. A more complex non-linear model, based on Reynolds averaged Navier-Stokes equations has been used. Turbulence was modeled by modified two-equations k-ε model for neutral atmospheric boundary-layer conditions, written in general curvelinear non-orthogonal co-ordinate system. The full set of mass and momentum conservation equations as well as turbulence model equations are numerically solved, using the as CFD technique. A comparison of the application of linear model and non-linear model is presented. Considerable discrepancies of estimated wind speed have been obtained using linear and non-linear models. Statistics of annual electricity production vary up to 30% of the model site. Even anemometer measurements directly at a wind turbine's site do not necessarily deliver the results needed for prediction calculations, as extrapolations of wind speed to hub height is tricky. The results of the simulation are compared by means of the turbine type, quality and quantity of the wind data and capacity factor. Finally, the comparison of the estimated results with the measured data at 10, 30, and 50 m is shown.

Key words: *wind turbine, modeling, CFD, combined methodology, measurement*

Introduction

The most assessments of the fuel resources, mostly fossil, clearly marks the fact that their resources, especially for oil, are close to the end. The global heating and pollution problem, mostly caused by large emissions of flue gasses from power plants and engines, arises constantly. Needs for energy constantly rises, so even the richest states experience the energy problems (as the two-day California energy system collapse). All this facts points to the necessity of transition to the sustainable development, especially to the usage of RES. Wind energy clearly takes its place, considering its large potentials, purity and availability. The present constrains are mostly of a financial nature.

Having all that in mind, the most important task is the siting of wind turbines (obtaining the best possible locations for installing of the turbines, considering the possibility for energy production and minimization of losses). For that purpose, the wind atlas method is developed, which became the best for use with the fast development of computers. The task itself is comparatively simple when the terrain considered is flat. But, in terrains with complex

* Corresponding author, e-mail: pzivkovic@masfak.ni.ac.rs

orography, situation is much more complex. With change of wind turbine position by only few meters, their potentials for energy production can be drastically altered. It is known that simple, linear models (as the one used for WAsP [1, 2]) cannot estimate correctly the wind energy potentials in the terrain where the ruggedness index (index that represents the terrain slope value) exceeds 0.3.

Terrains with complex orography (height differences and roughness of the terrain distribution) can have larger potentials than flat terrains. This is caused with the speed-up effect, which also depends on the main wind directions. The necessity of using more complex, CFD software, which solves the set of mass and momentum conservation equations, is obvious [3, 4]. The present practice is that the change of wind turbine location is justified if the energy production potentials increases at least for 1% (it can be concluded that the best locations are those where loses are less than 1%).

A number of researchers have estimated Serbia's wind potentials [5-8]. Important research was done on atmospheric turbulence [9] and the methods of measuring wind potentials in the complex mountainous terrains of Serbia [10]. There are some papers considering the wind influence on other RES [11], energy storage [12, 13], and advanced simulation models [14, 15].

Renewable energy sources

Sustainable development is one of the main goals for the future projecting. Energetically, it corresponds to the higher energy efficiency and using of RES. Both of the approaches lead to the preserving of the environment. Renewable energy can be considered as the constant source energy, meaning that it is produced faster than is being used. Nowadays, as renewable energy sources we usually consider:

- Solar energy
- Wind energy
- Energy of running water
- Energy of waves and tidal energy
- Sustainable biomass
- Geothermal energy

There are some other energy sources that can be considered as renewable, as municipal waste energy, waste heat recovery, *etc*.

Wind energy

Currently, there are 500 MW of granted licenses for installing wind turbines on about a dozen locations in northern parts of Serbia, divided onto 17 wind farm locations. Plans are to achieve 600 MW till the end of 2020 [16].

Wind turbines

There are many construction solutions for wind turbines, which can be compared according to:

- Rotor axis direction (horizontal and vertical)
- Rotor blades (one, two, three or more)
- Power regulation type (stooling or changing the blade angle)
- Constant or variable rotor speed (revolutions)
- Indirect or direct driving of the generator

Usually, three bladed wind turbines with horizontal axis and blade angle regulation are used. Usual rotor speed is 12-16 rpm, so the use of multiplier is needed, as the electrical network frequency is 50 Hz, or 3000 rpm. There are constructions with direct drive between turbine rotor and the generator, which yield up to 30% more power, but are more expensive.

Turbine siting

Siting of wind turbines considers the choosing the best location for installing of wind turbines in order of achieving maximal energy production, usually considered annually, thus referred as the annual energy production or AEP. There are many factors influencing energy production, which can be summarized as:

- Location conditions
  - Good wind potentials (usually average wind speeds of 6.5-7.5 m/s are needed)
  - Vicinity of the electrical network (turbines are connected with underground lines)
  - Available infrastructure (roads, bridges *etc*.)
- Wake loss minimization
- Environmental constraints
  - Noise level
  - Blade shading
  - Land use
  - Biological constraints (usually bird migration)
- Electrical network loss minimization.

Taking all this into consideration, global or regional mapping of wind potentials is obtained, known as wind atlases. Nevertheless, such global assessment is not of much importance for the projecting and financing of real wind farms. The reason can be found in the reason that the influences of the local orography and wind conditions are pretty difficult to transfer from the location of the data collecting, usually main meteorological stations in the domain of interest. There are not many papers on this subject, as the results are usually owned by the private investors. Thus, the necessity of performing minimum of 12-18 month measurements on the chosen micro-location obtained by the previous research becomes obvious. The measurements are performed with the use of measuring masts, usually of 50 m height, with measuring points at 10, 30, and 50 m height (sometimes 30, 40, and 50 m) in order to obtain data on vertical distribution of wind speed, as the wind turbine masts are currently up to 140 m in height.

Mathematical modeling

In order to obtain wind fields, it is necessary to have good knowledge about the atmosphere physics and its appropriate modeling. Wind meteorology can be successfully described by seven dominant physical properties: pressure, temperature, density, humidity, and three spatial wind components.

Temporal and spatial changes of those properties can be described by six conservation equations – continuity equation, Navier-Stokes (momentum) equations, energy equation, the first law of thermodynamics and the partial species equation for steam (humidity). With the addition of the equation of state and defined turbulence characteristics, such model is closed and unambiguous.

In order to predict wind speed fields, several mathematical models are in use. Most of those models are of diagnostic type, meaning that they are based on the already measured wind speed and direction data in at least one point (meteorological stations) for the period of at least 13 years, with minimal 10 minute sampling. This comes from the known fact that meteorological period is 32 years, of which 13 years is the least sufficient period which can reliably describe the wind characteristics. Such models are not able to predict the future wind data. Example of such full diagnostic model can be represented through the following set of equations.

– Continuity equation:

$$\frac{\partial}{\partial x_i}\left(\rho U_i\right)=0 \tag{1}$$

– Momentum equations:

$$U_j\frac{\partial U_i}{\partial x_j}-\frac{\partial}{\partial x_j}\nu_{\text{eff}}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)=-\frac{1}{\rho}\frac{\partial P}{\partial x_i} \tag{2}$$

– k-ε turbulence model equations:

$$U_j\frac{\partial k}{\partial x_j}-\frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\nu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]=P_k-\varepsilon \tag{3}$$

$$U_j\frac{\partial \varepsilon}{\partial x_j}-\frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\nu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]=\frac{\varepsilon}{k}\left(C_{\varepsilon 1}P_k-C_{\varepsilon 2}\varepsilon\right) \tag{4}$$

where

$$P_k=\nu_T\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}$$

$$\nu_{\text{eff}}=\nu+\nu_T$$

$$\nu_T=\frac{C_\mu k^2}{\varepsilon}$$

Modified set of model coefficients is:

$$C_\mu=0.0324\,,\quad C_{\varepsilon 1}=1.44\,,\quad C_{\varepsilon 2}=1.92\,,\quad \sigma_k=1.0\,,\quad \sigma_\varepsilon=1.85$$

Such system of equations could be simplified. Basic model, so called linear model, assumes stationary wind over large flat terrain with negligible roughness for neutral conditions (overcast sky). For such assumptions, only vertical change of wind speed is of interest. This assumption leads us to the well known logarithmic vertical wind profile, fully defined by the height above the terrain, effective surface roughness and the wind speed in the friction layer.

First software working under these assumptions is WAsP (Wind Atlas Analysis and Application Programme). It is analytical kinematic model based on the concept of mass conservation (continuity equation). It does not account for the pressure gradient changes in the vertical direction, which leads to the large difficulties in applying for the complex flows over hilly to mountainous terrain. That is why it is usually used combined with the more complex models, such as is used in the software WindSim. Vinča institute possesses both softwares. As linear models cannot calculate the losses on the leeward slopes of the terrain, most papers report the overprediction of the linear, comparing to the results obtained by the full set of equations model. The WAsP considers the slopes of the terrain through the ruggedness index (RIX), and results are acceptable for the values of RIX $\leq$ 0.3.

Basic principle of the WAsP software is to calculate the field of regional climatology considering the wind data collected from one or more meteorogical stations and orography of the chosen location. Such climatology is general, as being considered for flat frictionless terrain (horizontal extrapolation). Further, vertical extrapolation is performed, using slopes of the real terrain through the RIX, roughness and obstacles near the meteorogical station for the height of, usually, 10 m. Then we find the wind speed for the wind turbine hub height, usually about 100 m, calculate RIX, roughness and account for the obstacles on the location of the wind farm. It is obvious that such data can wary from reality for dozens of m/s if the conditions are not neutral, and the buoyancy forces must be taken into account. The methodology is presented in fig. 1.

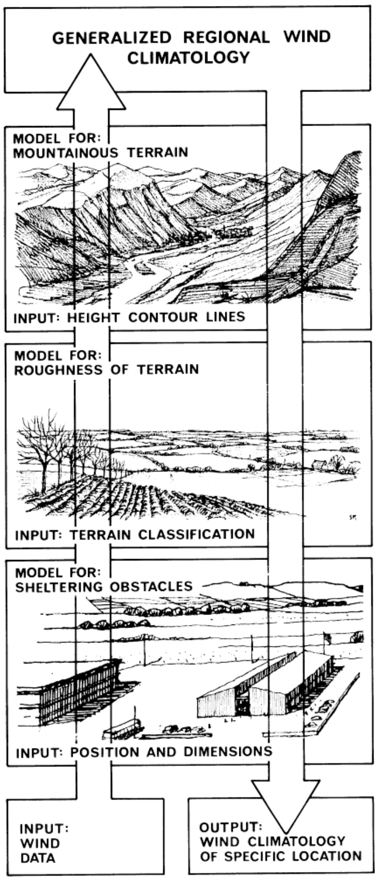

Figure 1. Wind atlas methodology; Regional climatology is calculated from raw data, which may be used to calculate wind climate at any specific site [1]

Mathematical model of the WAsP software is based on the balance of forces defined by the geostropic drag forces and the forces of surface friction in the atmospheric boundary-layer, for the neutral conditions. Such model is defined with the:
– Continuity equation:

$$\frac{\partial}{\partial x_i}\left(\rho U_i\right)=0 \tag{5}$$

– Geostropic wind equation:

$$U_g=\frac{U_*}{\kappa}\sqrt{\left(\ln\frac{U_*}{f\,z_0}A\right)+B^2} \tag{6}$$

– Logarithmic vertical wind profile:

$$U_z=\frac{U_*}{\kappa}\left(\ln\frac{z}{z_0}-\psi\right) \tag{7}$$

– Weibull distribution equations:

$$\frac{\partial}{\partial x_i}\left(\rho U_i\right)=0 \tag{8}$$

$$F\left(U\right)=\exp\left[-\left(\frac{U}{A}\right)^k\right] \tag{9}$$

Any software for wind energy estimation needs some of the basic data:
– At least one wind rose within the treated mezzo-micro region
– Digital model of height and effective roughness (minimum 100 × 100 m)
– Boundary conditions (initially logarithmic on the sides, later results from previous simulation – nesting technique).

Combined methodology

The CFD models are more precise, but they need much more computational time. Considering the need to obtain the results as soon as possible, the best micro-model was extracted from the larger macro-model.

The differences in wind energy estimations while using these different approaches are considerable. Many investigations were done on this subject, dealing with different aspects of the software operation.

Test model of Seličevica mountain [5] was chosen by its adequate orography, as can be seen in fig. 2. It was shown that the WAsP predictions are about 30% larger than WindSim [3] ones (estimated wind speed is in range 7.75-15.54 m/s for WAsP, and 4.96-12.64 m/s for WindSim), due to the neglecting of the second-order terms in the momentum equation, *i. e.* (6).

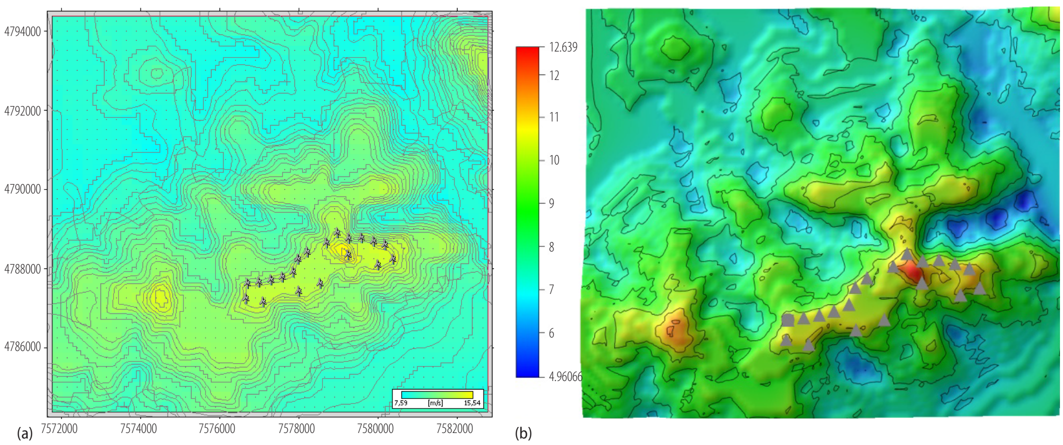

Figure 2. Mean wind speed fields obtained by simulations in WAsP (a) and WindSim (b)

For obtaining of the results the nesting technique is used. Simulations were done for the Enercon E82 wind turbine. It is very appropriate to use WAsP as the initial software on mezzo level estimations, and WindSim for more precise micro-level estimations, as the computational time for WAsP is about 20 times less than for WindSim.

In the previous papers [7, 8] results obtained by numerical simulation on over a dozen micro-locations are presented. The considered locations mainly covers the mountainous regions of Southern and Eastern Serbia.

Guševac micro-location

Mountainous regions of Serbia

Mountains of Serbia can be divided into several geotectonic areas. They are the Serbian-Macedonian mass, Carpathian-Balkan Mountains, Dinara Mountains, Vardar zone, and Kosovo and Metohia valley, fig. 3.

Carpathian-Balkan Mountains are situated in the eastern part of Serbia. They are located from the Danube River on the North to the Ruj Mountain on the southeast (border with Republic Bulgaria and Republic North Macedonia). Carpathian-Balkan Mountains extend in three parallel series, directed N-SSE (north-south south east).

Western series extend from Djerdap to the Ruj Mountain. Those mountains are mostly limestone and include Homolje, Beljanica, Kučaj, Rtanj, Ozren, Devica, and Suva Planina Mountains.

Middle series include Severni Kučaj, Stol, Veliki Krš, Crni Vrh, Tupižnica, Tresibaba, Svrljig, and Belava Mountains.

Eastern series include Miroč, Veliki Greben, Deli Jovan, and Stara Planina - Balkan Mountains.

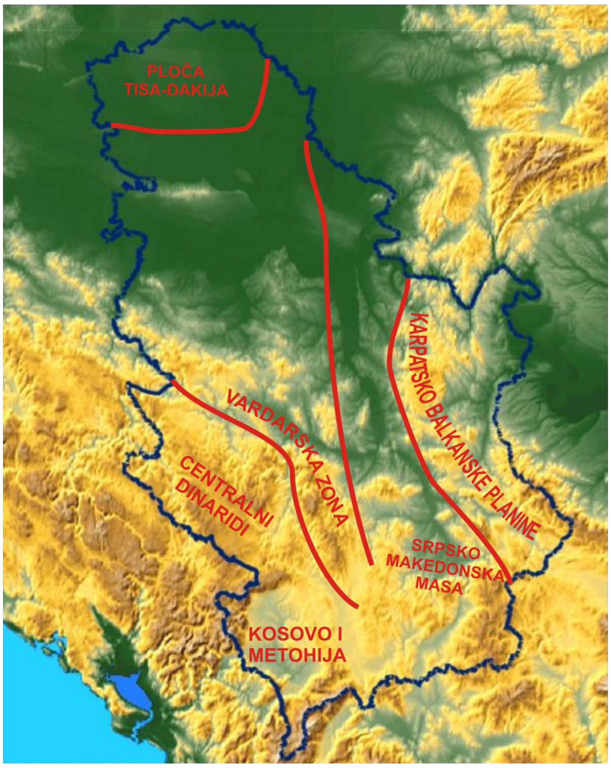

Figure 3. Mountainous regions of Serbia [17]

Wind in Serbia

Wind in Serbia is mainly generated by the interaction the warm current from the Genoa Bay and the cold currents from Siberia. Contact of those masses over the Carpathian Mountains generates the most intensive wind in Serbia – Košava wind, with gusts up to 60 m/s. Having in mind that most turbines produce energy in the range of 3-25 m/s, the more stable wind generated on the Balkan Mountain is long-term more energy proficient. One of the reasons is the tunnel effect between the mentioned series of mountains explained before.

Having this in mind, location on the slopes of the Tresibaba Mountain, near the village Guševac was chosen, fig. 4. Measurements were performed in the period April 2010 – July 2016. A 50 m measuring mast was erected on the location with elevation of 550m$_{asl}$ in cooperation with the firm Net Invest. Measurements of the wind speed and direction, temperature, barometric pressure and humidity were performed continually and averaged over 10 minute period, at the height of 10, 30, and 50 m.

Comparing the results

In order to compare the measured data to the data on the main meteorological station (MMS) Niš – Kamenički Vis with the data collected on the measuring site Guševac, mezzo model of the Svrljig Valley was chosen. It is defined by the Tupižnica and Tresibaba Mountain on the north, Stara Planina – Balkan Mountain on the north and east, Svrljig and Suva Planina Mountain on the south and Rtanj, Ozren Mountain and Niš valley on the west with area of about 6000 km^2. The RIX index for the chosen micro-model, including both the MMS Niš and the measuring site Guševac is in the rank 0-26.7%, which is within the acceptable limits.

Results are compared by the data measured in the period April 2010 – December 2011, for about 20 months, as this period is usual for validating estimated results. One set of the results is obtained by the stable data obtained from the MMS Niš (for about 15 years, needed at least 13), and other using data from the site Guševac. Simulations were performed using

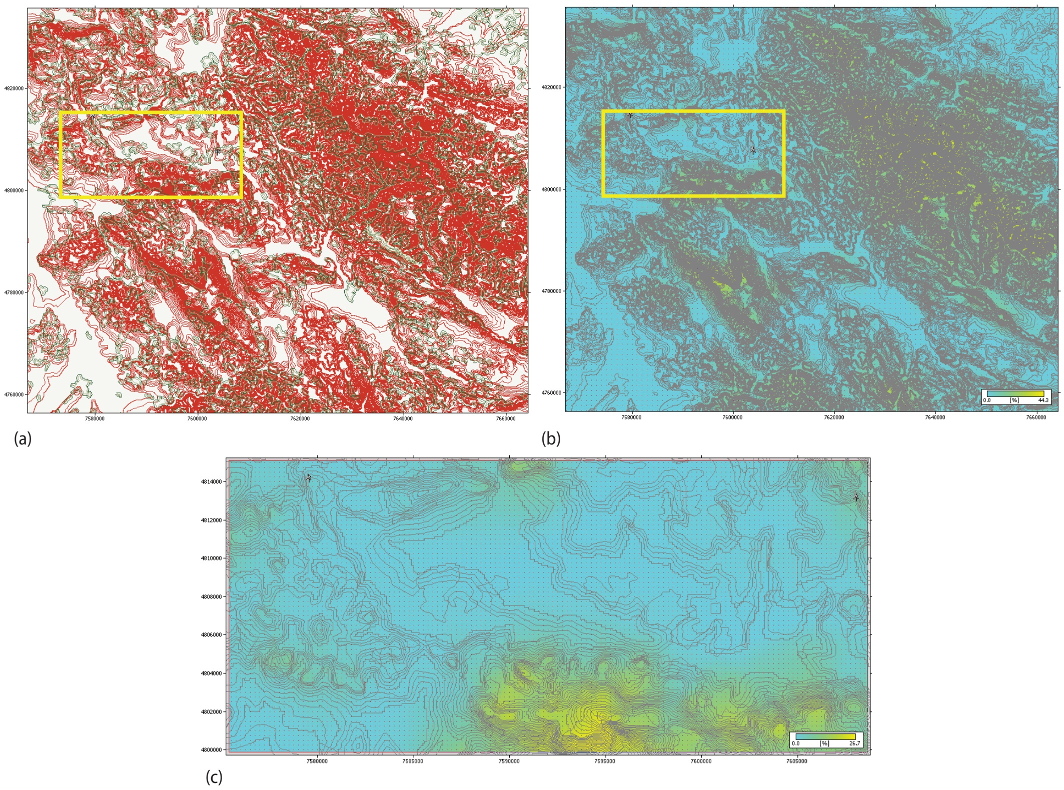

Figure 4. Orography (a) and RIX (b) fields for mezzo-model and RIX field for the micro-model (c)

WAsP 9.3 software, which is possessed by the Vinča Institute, for two wind turbines Enercon E82 (2MW), hub height 108 m. Results will be presented in the form of the Average wind speed and the annual energy production (AEP) fields, on the micro model.

Observed wind data

Wind data are presented in the form of the wind roses and Weibull histograms for the MMS Niš on 10 m and site Guševac on 10, 30, and 50 m height, fig. 5.

Maximum observed wind speed is 24 m/s for the MMS Niš on 10 m height and 15.2, 17.3, and 18.8 m/s for the site Guševac on 10, 30, and 50 m height, respectively. Discrepancy of the observed wind data is 0.93% for MMS Niš and 1.05, 0.53, and 0.35% for Guševac at 10, 30, and 50 m height, respectively.

Estimated wind climatology

Estimated wind speed and AEP fields are presented on figs. 6-9 for the wind data observed on the MMS Niš and Guševac at 10, 30, and 50 m height, respectively, with noted extreme values.

After the simulations for all of the observed wind climates were performed, two locations were chosen for comparison of the predictions, one near the MMS Niš – location Vetrila and other in the vicinity of the measuring site Guševac, with the same name, fig. 10. Summarized results are presented in the tab. 1.

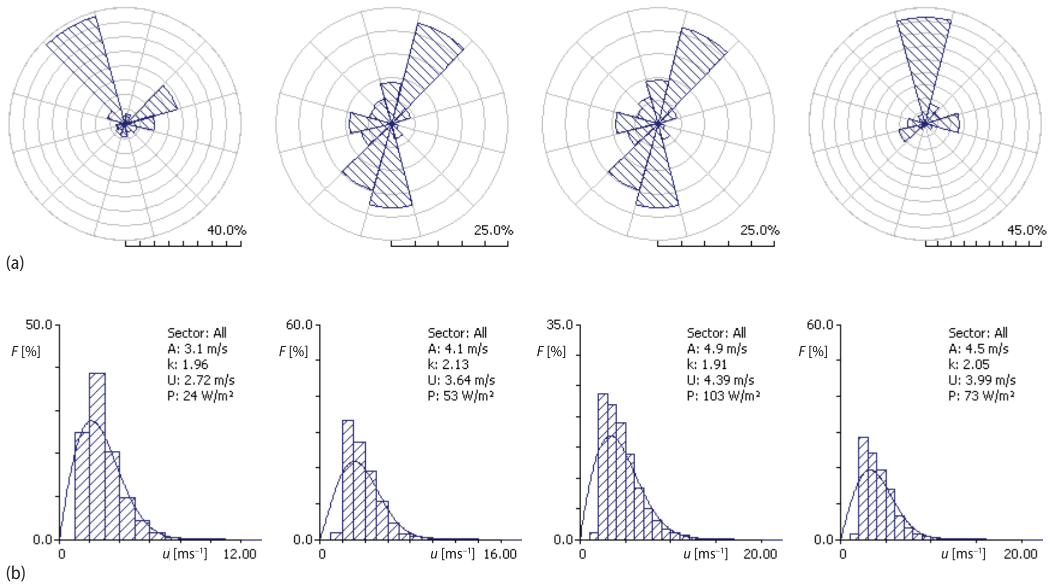

Figure 5. Wind roses (a) and Weibull histograms (b) for MMS Niš and Guševac at 10, 30, and 50 m, respectively

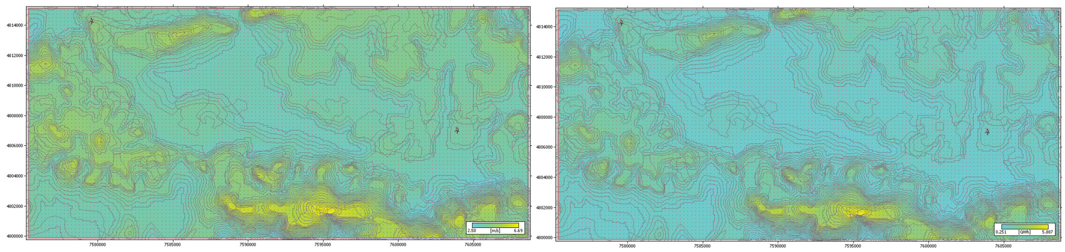

Figure 6. The MMS Niš – Wind speed (2.50-6.69 m/s) and AEP (0.251-5.887 GWh) fields

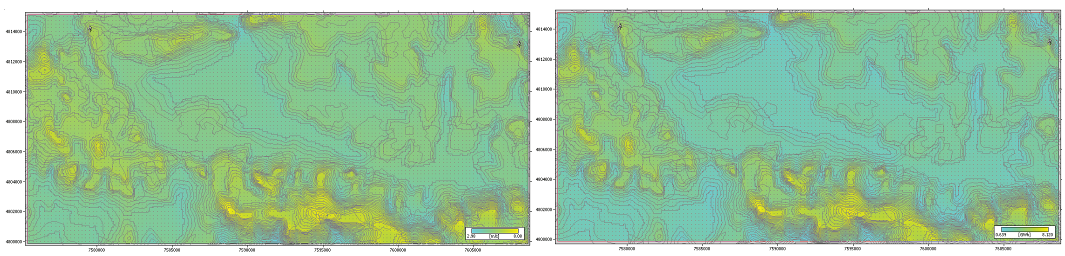

Figure 7. Guševac 10 m – Wind speed (2.98-8.08 m/s) and AEP (0.639-8.120 GWh) fields

One can notice that the predicted wind roses on turbine sites are strongly influenced by the chosen wind data, which can be explained by the using scalar RIX factor for modeling the wind speed, without calculation of the all components of the wind speed vector.

As presented in the tab. 1, it is obvious that the predicted AEP strongly depends on the data chosen, which leads us to the conclusion that the logarithmic profile is creating a substantial error.

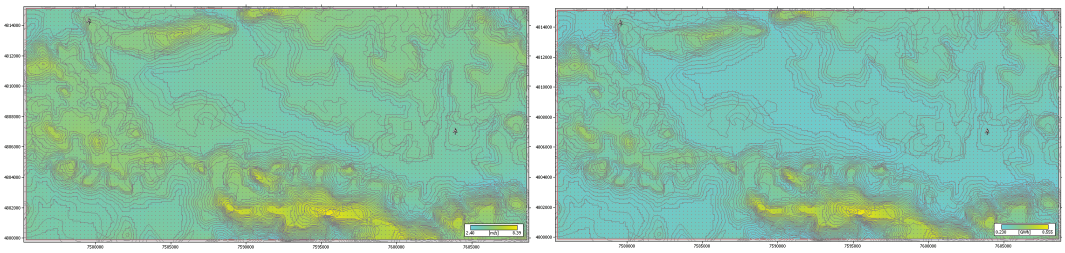

Figure 8. Guševac 30 m – Wind speed (2.40-8.39 m/s) and AEP (0.230-8.555 GWh) fields

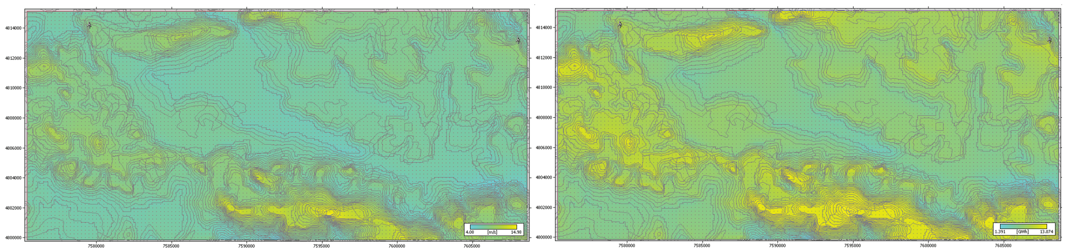

Figure 9. Guševac 50 m – Wind speed (4.08-14.98 m/s) and AEP (1.391-13.074 GWh) fields

Table 1. Predicted AEP for the locations Vetrila and Guševac

Wind data	Location	Position [m]	Elevation [m_{asl}]	Turbine	Height [m]	AEP [GWh]
MMS Niš	Vetrila	7579501, 4814000	565	E82	108	2.772
	Guševac	7608000, 4813000	660	E82	108	2.033
Guševac 10 m	Vetrila	7579501, 4814000	565	E82	108	3.412
	Guševac	7608000, 4813000	660	E82	108	3.626
Guševac 30 m	Vetrila	7579501, 4814000	565	E82	108	5.446
	Guševac	7608000, 4813000	660	E82	108	5.928
Guševac 50 m	Vetrila	7579501, 4814000	565	E82	108	9.789
	Guševac	7608000, 4813000	660	E82	108	10.297

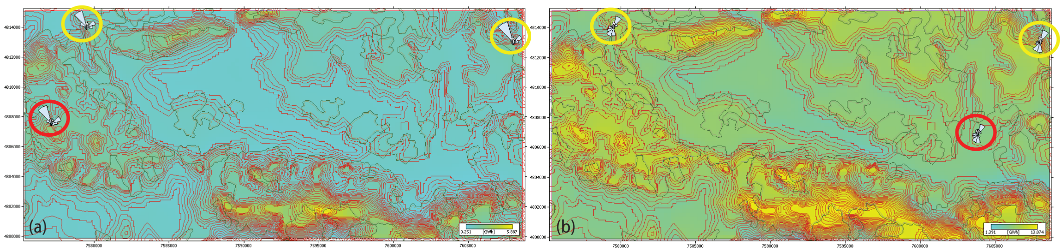

Figure 10. The AEP fields with observed wind roses on MMS Niš and Vetrila 10 m and predicted wind roses on chosen locations for wind turbines – Vetrila (a) and Guševac (b)

Conclusion

This paper presents extensive study of wind potentials of the Central Eastern Serbia. The wind measurements were performed for about six years, of which first 20 months are used for comparison in this study, as period of about 1.5 years is usually used for validation of previous estimation by the numerical simulation. The observed wind climate can be seen on the following fig. 11, at the measuring site Guševac, for the height of 50 m.

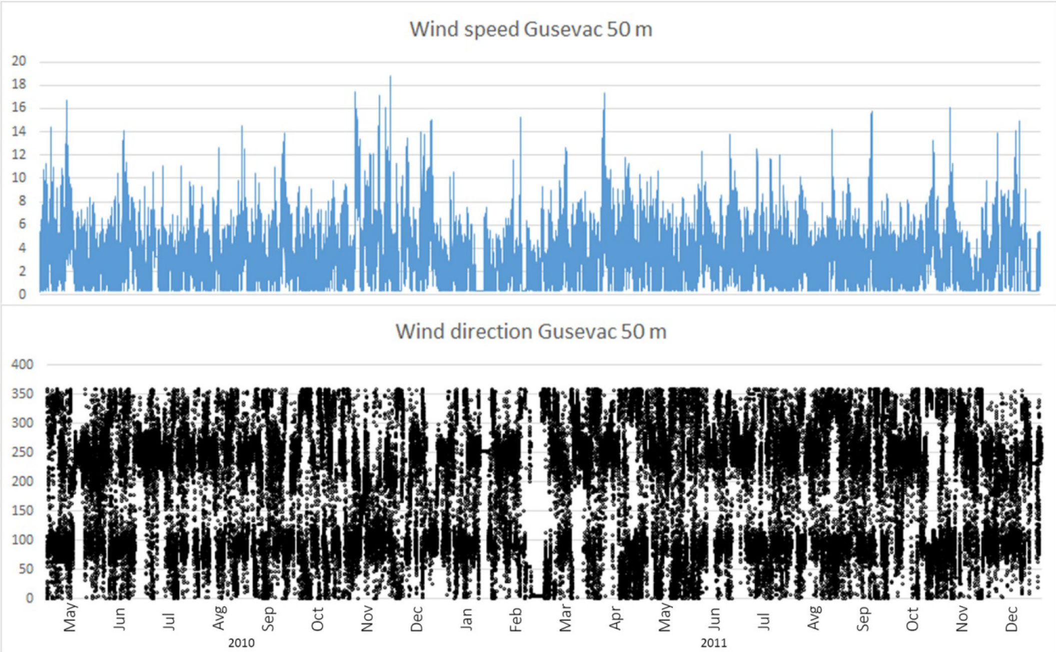

Figure 11. Observed wind speed and direction for the site Guševac 50 m

Numerical simulations have shown strong dependence of the results from the location of the data collected. Estimated wind roses from the MMS Niš extrapolated to the location of the measuring site Guševac are more similar to the basic data, than to the observed data on site, and vice versa. It shows that climatology transfer from the data collecting sites (MMS) to the location of the desired wind farm is not very precise.

Significant increase of the wind potentials for the data collected on the site Guševac 50 m can be also associated to the inadequacy of the data transfer methodologies. From the other hand, the RIX index reaches the value of 0.3, which is the reported limit for the used software WAsP. Finally, it can be concluded that the locations of the best potentials are adequately estimated, and the computation time is on the level of an hour, which is very important for achieving decision making data.

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