Zeszyty Naukowe Wydziału Elektrotechniki i Automatyki Politechniki Gdańskiej Nr 51

XXVI Seminarium

ZASTOSOWANIE KOMPUTERÓW W NAUCE I TECHNICE 2016

Oddział Gdański PTETiS

WIND RESOURCE ASSESSMENT AND ENERGY YIELD PREDICTION FOR THE SMALL WIND TURBINE ON THE SZUBIENICZNE HILL

Michał PACHOLCZYK[1], Dariusz KARKOSIŃSKI[2]

Politechnika Gdańska, Wydział Elektrotechniki i Automatyki
1. tel.: 58 347 2534, e-mail: micpacho1@student.pg.gda.pl
2. tel.: 58 347 1286, e-mail: dariusz.karkosinski@pg.gda.pl

Abstract: The goal of this study is to preliminary assess the wind resources on the Szubieniczne Hill in order to predict the annual energy production for planned small wind turbine. The analyzed site is located close to the Gdańsk University of Technology campus, in complex urban environment additionally surrendered by forested hills. The assessment is based on Computational Fluid Dynamics simulations which allow to evaluate the wind energy potential on the entire area of interest. Simulations are integrated with a long-term local wind measurements from nearby AARMAG weather mast. The study provides micro-scale wind maps of the analyzed area which are then used to a calculation of annual energy production and to proposed wind turbine located at the hill cost-effectiveness evaluation.

Keywords: computational fluid dynamics, wind resource assessment, wind turbine, annual energy production.

1. INTRODUCTION

Wind power is one of the most commonly used renewable energy source. In order to extract power available in the wind the variety of the wind turbines have been designed. Wind turbines became important part of the Power Production System all around the globe, especially within European Union. They are also important part of the of the Micro and Smart Grids which goal is to substitute the centralized power distribution systems. However, development of the electrical grids with distributed power generation and energy storage requires further researches conducted in specialized research facilities. Therefore, in 2010 Electrical and Control Engineering Faculty of Gdańsk University of Technology (GUT) has launched the project of Research Laboratory on the Innovative Power Technologies and Integration of Renewable Energy Sources LINTE ^ 2. In [1] authors proposed extension of LINTE ^ 2 capabilities by concept of correlated wind and water power plant located on the nearby Szubieniczne Hill (54°22'08" N, 18°37'01" E). The goal of this study is to preliminary assess the wind resources on the Szubieniczne Hill in order to predict the annual energy production (AEP) for planned small wind turbine. The Computational Fluid Dynamics (CFD) is widely used for this purpose. Many specialized CFD commercial software packages have been introduced to the industry (e.g. WAsP, GH WindFarmer, WindSim, UrbaWind, TopoWind).

The area of interest in located in the highly urbanized environment which is very challenging to simulate due to the high non-linearity of the flows in the cities. In the literature, there are two main approaches for wind maps producing in such a locations. First, is to explicitly model the geometry of all the building enclosed in the area of interest. Such a methodology is applied for example in commercial code UrbaWind. In [2] authors reproduced the wind flows at the campus of Massachusetts Institute of Technology by introducing into the calculation domain shapes of the campus facilities. However, such a approach requires much more denser mesh grid and thus, is more computational resources demanding what may limit the calculation domain. The exact dimensions of all the buildings, which are often hard to acquire, have to be known as well. In addition, in the most of the studies the terrain in the domain is assumed to be flat which is not a case in the Szubieniczne Hill vicinity. The second approach is to represented buildings and other urban forms, as well as forest, water areas etc. by using appropriate roughness parameters in the wall functions. As indicated in [3] it is popular option to use products which apply this methodology, such as WindSim or TopoWind for wind resource assessment in urban environments. In [4] authors established the annual mean wind speed and mean wind power density maps for entire city of Singapore (710,3 km^2). In [5] wind resources of the Metropolitan Area of Barcelona

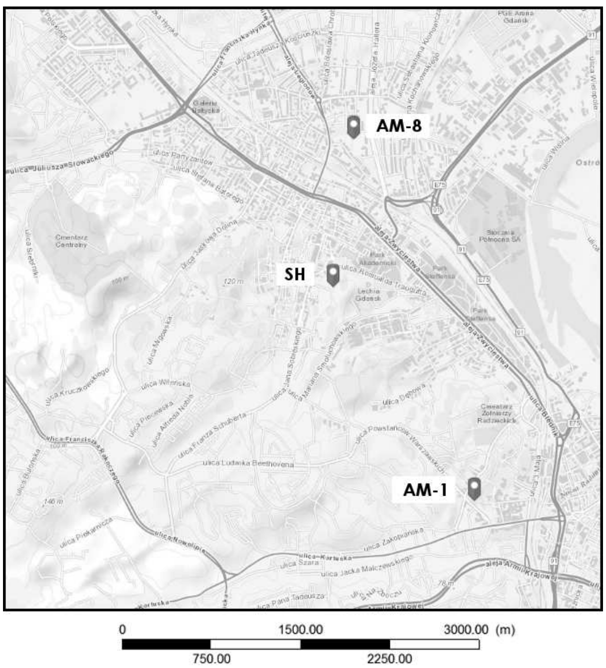


Fig. 1. Area of the interest. North-West corner set to 54°23'24" N, 18°34'30" E

have been mapped by use of this approach. The results have been then used as initial conditions for calculations with explicitly modelled city structures. From the other hand, as mentioned in [3] most of the software applying second approach are developed and designed for the wind resources assessment in rural areas (e.g. [6]) and therefore may introduce significant uncertainties in the estimated urban wind potential.

In this study, to assess the wind conditions at the Szubieniczne Hill the second approach has been chosen. In the general-purpose CFD software ANSYS Fluent the methodology used within specialized products has been applied. The entire area of interest has been shown in Figure 1 with Szubieniczne Hill marked as “SH”. The domain size is set to be 5 km x 5 km with the North-West corner located at 54°23'24" N, 18°34'30" E.

2. INPUT DATA

In order to estimate wind conditions at the site location at least one climatology data has to be present in the calculation domain. In this study reference wind speeds and directions have been extracted from the ARMAGG weather station located at 54°22'48.5" N, 18°37'11" E and marked in the Figure 1 as “AM-8”. The anemometer is placed at a typical 10 m height agl. Data from “AM-1” (anemometer at 3 m agl) are used in the verification purpose. Data from both sites have been collected from Jan 2014 to Dec 2015 and hourly averaged. (© Data included in this paper have been provided free-of-charge and are the property of the ARMAAG Foundation). The AM-8 wind speeds histogram and corresponding wind rose with total 8 direction are plotted in the Figure 2.

The Weibull probability distribution is widely used in the wind power industry as an accurate representation of the wind speed regimes [6]. The wind probability distribution function (PDF) is defined as

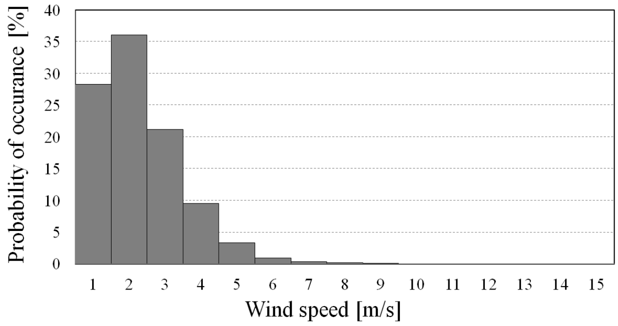
$$p(U) = \left(\frac{\alpha}{\beta}\right)\left(\frac{U}{\beta}\right)^{\alpha-1} e^{-\left(\frac{U}{\beta}\right)^{\alpha}} \qquad (1)$$

where: U – wind speed, α – Weibull shape factor, β – Weibull scale factor.

Raw data collected from the station “AM-8” were converted into Weibull PDF sector by sector with maximum likelihood algorithm and presented in Table 1. The probability of occurrence (“Time”) of the wind blowing from a particular direction has been presented as well.

3. NUMERICAL SETUP

The simulations are conducted using 3D steady Reynolds Averaged Navier-Stokes (RANS) equations with the standard k-ε turbulence model and performed for each of 8 directions. The computational domain used in this study is set to 5 km x 5 km and 1200 m height. Orthography data are extracted from the NASA database (SRTM) with fine resolution of 90 m x 90 m at the Equator. The first grid layer height is set to about 1 m and then 44 prism element layers are introduced with growing ratio of 1.1, reaching approximately 720 m agl in total. Above this level, the unstructured tetrahedral mesh with face size of 90 m is set. At the ground level average horizontal face size is about 50 m. This result in a grid with 570,863 cells in total.



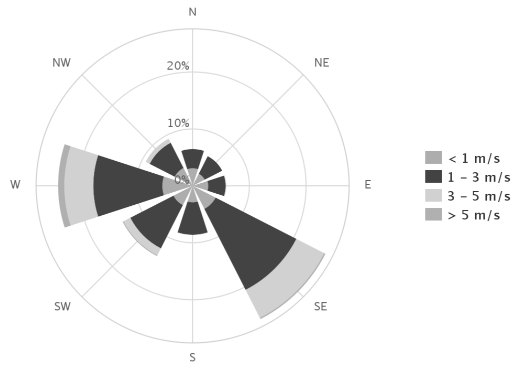


Fig. 2. Wind speeds histogram and wind rose for AM-8

A flow boundary condition either as velocity inlet or pressure outlet is imposed on a particular faces of the computational domain, depending on the wind direction simulated. In case of directions N, S, W, E side faces are set to symmetry. Top boundary is set to a symmetry as well. At the bottom boundary the standard wall functions is used in combination with the sand-grain based roughness modification. The roughness lengths z_0 extracted from the Corine Land Cover database (2012) are combined with parameters k_S (roughness height) and C_S (roughness constant) by a relationship given in [7].

Similar to the commercial codes, the CFD model is initialized based on the free stream wind velocity presented above Atmospheric Boundary Layer (ABL) [8]. In this study, for all the directions ABL is set to 500 m agl and above this level the wind blows with constant speed of 10 m/s. Below the ABL a logarithmic mean wind speed profile under neutral atmospheric condition is imposed

$$U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) \qquad (2)$$

where: z – height coordinate, u_* – friction velocity, κ – von Karman constant, z_0 – roughness length.

Table 1. AM-8 reference values

	U_{mean} [m/s]	α	β	Time [%]
N	1,05	2,01	1,18	6,46
NE	1,07	2,17	1,21	5,86
E	1,14	1,67	1,27	5,92
SE	2,13	1,96	2,40	26,26
S	1,35	1,91	1,52	8,66
SW	1,70	1,63	1,90	13,84
W	2,22	1,55	2,47	23,71
NW	1,47	1,51	1,63	9,29

Turbulent kinetic energy k and turbulence dissipation ratio ε at the inlet boundary are given by

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}}\left[1-\left(\frac{z}{z_{ABL}}\right)\right]^2 \tag{3}$$

where: C_μ – k-ε model constant, z_{ABL} – ABL height.

$$\varepsilon(z) = \frac{1}{\kappa}\frac{u_*^3}{z} \tag{4}$$

In this study, the commercial CFD software ANSYS Fluent has been used. In order to assign the inlet profiles User Defined Function (UDF) has been created. Similarly, to assign the roughness parameters at the bottom boundary wall another UDF was used. The ANSYS Fluent software does not allow k_s to be higher than distance between the central point of the wall-adjacent cell to the wall [7]. Therefore, k_s was set to be 0,41 and roughness constant C_s values were changed instead. Calculations were carried out at the Academic Computer Centre in Gdańsk.

4. WIND RESOURCE ANALYSIS AND ANNUAL ENERGY PRODUTION ESTIMATION

Numerical simulation results for wind resources analysis are presented as the wind and power density maps at a height of 18 m above the ground level for each computed direction. The height of 18 m was chosen regarding a hub height of the SWP-25kW wind turbine proposed in [1]. As mentioned in section 3 simulations were performed with the assumption of free stream velocity above the ABL. Therefore, in order to obtain actual wind maps the modelled wind speed fields have to be scaled by the measured values [8]. The procedure is as follow: the calculated wind speed at the mast location is weighted with measured mean wind speed. This ratio is then applied to the entire modelling domain and mean wind speed map is generated. This assumption may not be valid in whole area of interest but according to [8] is quiet commonly used in commercial codes. Based on the weighted mean wind speeds the power density maps with consideration of Weibull shape parameter for each direction can be calculated as follow

$$P_w = \frac{1}{2}\varrho\beta^3\Gamma\left(1+\frac{3}{\alpha}\right) \tag{5}$$

where: ϱ – air density, β – Weibull scale parameter calculated as $\beta = U/\Gamma(1+1/\alpha)$ with U being mean wind speed, Γ – gamma function.

The examples of the wind and power density maps for NW direction are presented in the Figure 3 and 4, respectively. The directional mean wind speeds for "WS" location at the hub height are summarized in Table 2.

In order to estimate the directionless mean wind speed at the particular site directional mean wind speeds have to be weighted with the probability that the wind is coming from that direction. In this study the assumption that probability of directional occurrence at any location is exactly the same as at the "AM-8" site (Table 1) has been made. This however is not valid, especially for large and rough domains due to wind direction shifts not considered in this study. Commercial codes beside directional mean wind speed, transfer the wind roses as well [2]. Thus, this part of the methodology has to be further developed. Nevertheless, the similar assumption has been made in [3]. Therefore, total mean wind speeds for "WS" and "AM-1" calculations, as well as Annual Energy production estimation have been performed with this assumption. The directionless mean wind speed for "WS" location at wind turbine hub height was calculated to be 2,86 m/s. Calculated mean wind speed at the verification site "AM-1" was 1,16 m/s and was found to be in the good agreement with the measured value of 0,88 m/s.

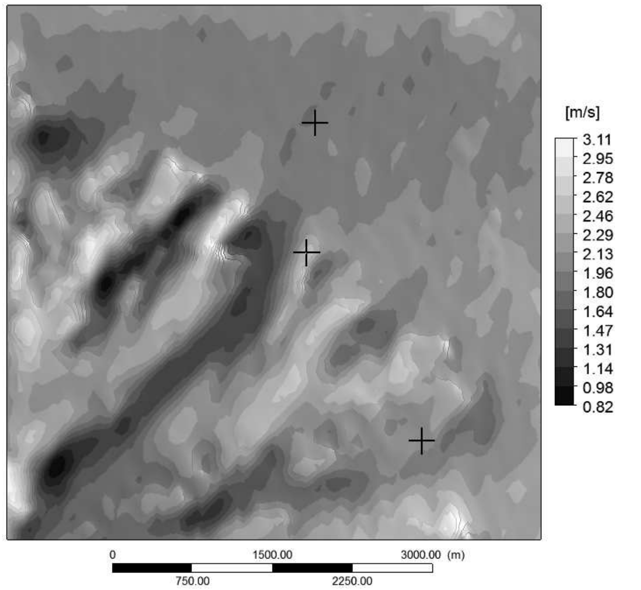


Fig. 3. Mean wind speed map for NW direction

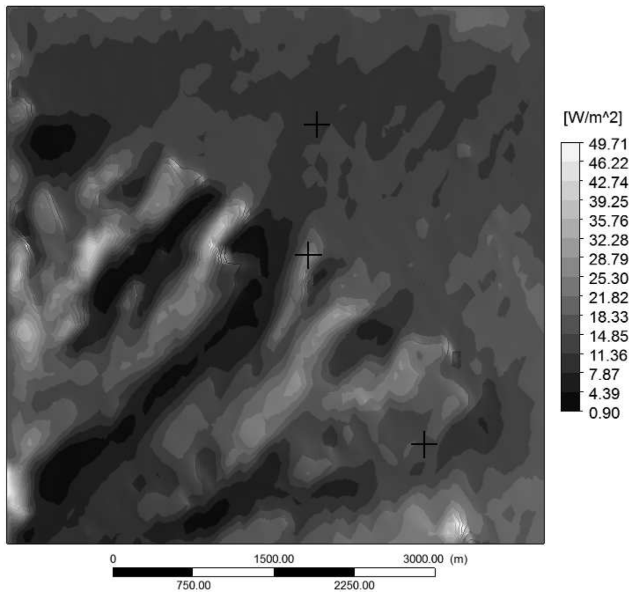


Fig. 4. Mean wind power density map for NW direction

The calculation of the combined hourly mean power P_h [kW] can be performed by taking into account the wind turbine power curve P_T as well as the wind speed PDF $p(U)$ over one year period (eq. 1). P_h is then given by [3]

$$P_h = \sum_{U=U_{cutin}}^{U_{cutout}} P_T(U)p(U)\Delta U \tag{6}$$

where: U_{cutin}, U_{cutout} – cut in and cut out wind speed for SWP-25kW wind turbine, respectively.

The idealized SWP-25kW wind turbine power curve P_T is

$$P_T(U) = \frac{1}{2}\varrho S U^3 C_p \quad (7)$$

where: S – rotor diameter, C_p – power factor

In Table 2. directional values of the P_h are presented ($P_{h,\theta i}$ [kW], where θ_i indicates the wind direction). The mean annual energy production with consideration of the probability of the winds blowing from all analyzed direction can be expressed by

$$E_{ad} = \frac{8760}{10^3}\sum_{i=1}^{\theta_{max}} P_{h,\theta_i} p(\theta_i) \quad (8)$$

where: θ_{max} – total number of wind directions, $p(\theta_i)$ – probability of wind blowing from θ direction.

The AEP for the SWP-25kW wind turbine located at the Szubieniczne Hill was calculated to be 14,223 MWh per year which is about 8 times less than declared by the manufacturer when the turbine is operating in the optimal conditions. The summarized results of AEP for each direction are presented in Table 2.

Table 2. Summarized AEP results for WS

	U_{mean} [m/s]	$P_{h,\theta i}$ [kW]	$E_{ad,\theta i}$ [MWh]
N	1,70	0,1105	0,0625
NE	1,80	0,1249	0,064
E	1,89	0,3064	0,1589
SE	3,29	1,8281	4,206
S	1,83	0,1896	0,1439
SW	2,64	1,1159	1,353
W	3,86	3,5681	7,4114
NW	2,47	1,0115	0,823
Total	2,86	8,255	14,223

5. CONCLUSION

In this study, the general-purpose CFD software ANSYS Fluent has been used in order to preliminary assess the wind energy potential at the Szubieniczne Hill. Methodology used in specialized CFD software has been applied. As the result the wind and power density maps were obtained. Simulation results at the verification site were found to be in good agreement with measured values.

Based on the CFD simulations AEP for SWP-25kW wind turbine located at the Szubieniczne Hill has been estimated. Calculated values show that wind conditions are not suitable for wind turbine of that size. Therefore, other types of wind turbines should be considered.

Methodology presented in the study should be further developed especially in means of wind rose transferring. The number of analyzed sectors should be increased. Denser mesh as well as higher order discretization schemes could be introduced.

5. REFERENCES

1. Karkosiński D., Pacholczyk M.: The concept of two-propeller wind and pumped storage plant on the Szubieniczne Hill, Zeszyty Naukowe Wydziału Elektrotechniki i Automatyki Politechniki Gdańskiej, No. 45, Gdańsk 2015, pp. 35-39 – in Polish.
2. Kalmikov A., Dupont G., Dykes K., Chan C.: Wind power resource assessment in complex urban environments: MIT campus case-study using CFD Analysis, AWEA 2010 WINDPOWER Conference, Dallas, May 2010, pp. 1-28.
3. Romanic D., Rasouli A., Hangan H.: Wind Resource Assessment in Complex Urban Environment, Wind Engineering, No. 2, 2005, pp. 193 -212.
4. Hyun-Goo K., Jia-Hua L.: Wind Mapping of Singapore Using WindSim, Journal of Environmental Science International, No 7., 2011, pp. 839-843. – in Korean.
5. Caniot G., García M., Sanquer S., Naya S., Pozo E.: Smart City 360°, Springer International Publishing, 2016.
6. Hwang Y., Paek I., Yoon K., Lee W., Yoo N., Nam Y.: Application of wind data from automated weather stations to wind resources estimation in Korea, Journal of Mechanical Science and Technology, No. 10, 2010, pp. 2017-2023.
7. Toparlar Y., Blocken B., Vos P., van Heijst G., Janssen W, van Hooff T., Montazeri H., Timmermans H.: CFD simulation and validation of urban microclimate: A case study for Bergpolder Zuid, Rotterdam, Building and Environment, No. 83, 2015, pp. 79–90.
8. Berge E., Gravdahl A., Schelling J., Tallhaug L., Undheim O.: Wind in complex terrain. A comparison of WAsP and two CFD- models, European Wind Energy Conference & Exhibition 2006, Athens, Feb 2006.

OCENA ZASOBÓW ENERGETYCZNYCH WIATRU I PREDYKCJA ROCZNEJ PRODUKCJI ENERGII DLA MAŁEJ TURBINY WIATROWEJ NA WZGÓRZU SZUBIENICZNYM

W artykule przedstawiono wstępną ocenę zasobów energetycznych wiatru dla Wzgórza Szubienicznego. Wyniki symulacji zostały wykorzystane do estymacji rocznej produkcji energii dla proponowanej małej turbiny wiatrowej typu SWP-25kW. Analizowana lokalizacja znajduje się w bezpośrednim sąsiedztwie Laboratorium Innowacyjnych Technologii Elektroenergetycznych i Integracji Odnawialnych Źródeł Energii LINTE^2, proponowana turbina miałaby uzupełnić infrastrukturę badawczą laboratorium. Wzgórze Szubieniczne otoczone jest przez silnie zurbanizowane obszary oraz zalesione wzgórza. Taka lokalizacja stwarza wiele problemów w procesie modelowania i symulacji. Ocena zasobów energetycznych wiatru została przeprowadzona z wykorzystaniem metod Numerycznej Mechaniki Płynów. Wyniki zostały skorelowane z dwuletnimi pomiarami wiatru ze stacji meteorologicznej „AM-8" dostarczonymi przez Fundację ARMAGG. Wyniki obliczeń wskazują, że warunki wietrzności na Wzgórzu Szubienicznym nie sprzyjają instalacji proponowanej turbiny.

Słowa kluczowe: zasoby energetyczne wiatru, numeryczna mechanika płynów, turbina wiatrowa.