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A METHODOLOGY OF WIND TURBINES SELECTION FOR THE GIVEN WIND CONDITIONS

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Abstract: The following paper presents a methodology of wind turbines selection with a axis of rotation based on measurements of wind conditions specific for the wind power sector. Basic properties and characteristics used in the wind power sector, as well as a proper measurement campaign along with determining the necessary instrumentation and the methodology of its use, are the basic parameters that determine the decision of wind farm investment. The main goal of those activities is to gather the accurate meteorological data in sufficient amount using a measurement tower situated at a possible future location of a wind farm. This method is used to identify the direction, speed, gust and energy of the wind. Measurements were made in northern Poland using a measurement system based on a 80-meter-high telescopic mast. The system was equipped with instrumentation necessary to measure and record the basic wind parameters, and was made by the Windhunter Serwis Ltd. Company headquartered in Koszalin. The reliability of measurements was verified using the statistical methods based on the *Weitbull's* distribution and the windrose. Thus, the energy potential of the raw air stream was determined with a possible future use in a wind farm sitting.

Keywords: wind power, wind conditions, wind turbines

1. INTRODUCTION

The measurement campaign is a key process to evaluate a given location in terms of usefulness for sitting a wind farm. The complex planning of various aspects of the measurement campaign can significantly lower the risk of mistake or uncertainty in the forthcoming stages like financing and execution of the wind farm investment process. A proper selection of instrumentation, in accordance with the international standards and suitable for a given location and its landform, natural and infrastructural barriers, inclination and other factors influencing the wind, is an extremely important aspect.

2. BASIC INFORMATION CONCERING THE EXECUTION OF MEASUREMENT CAMPAIN OF WIND PARAMETERS

2.1. Methodology of measurements

The reference document for the correct methodology of obtaining the bankable wind measurement comes from the International Electrotechnical Commission (IEC Switzerland - Geneva). The guidelines for the measurements are included in the standard IEC 61400-12-1: Wind turbines: Part 21-1: Power performance measurements of electricity producing wind turbines [1]. The appendix G of this standard covers the correct installation of instrumentation for measurement purposes on a meteorological mast of the tubular or lattice type. According to the guidelines included in the standards IEC 61400-12-1 [1] and EN 61400-12-1(2006) [2], it is an international practice in wind

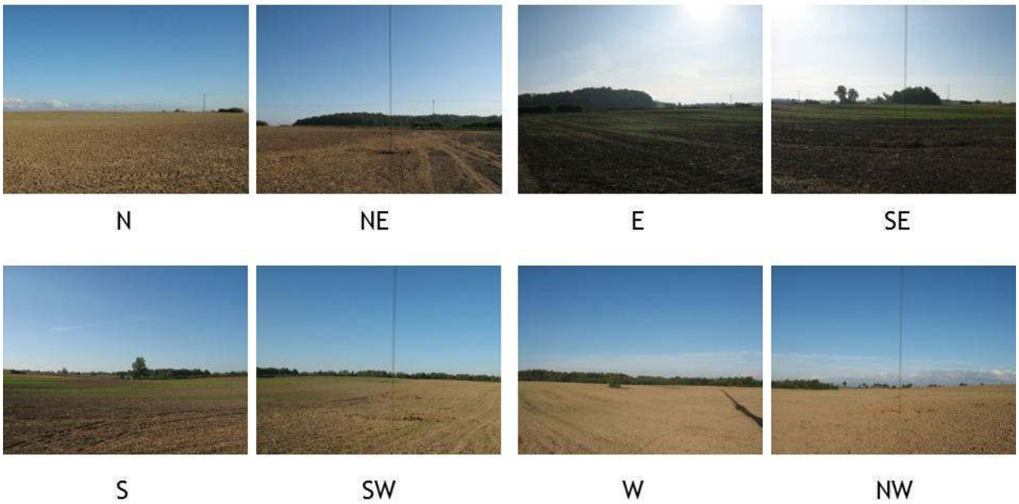

Fig. 1. Exemplary panoramic photo of location for measurement mast sitting

measurements that only measurements conducted using the measurement mast or tower can be classified as the bankable, and serve in the forthcoming stages of the project as a reference for obtaining a full or partial financing of the project. A document classified as a bankable is also an expertise of wind conditions. It includes a compilation of the measurement data from all the sensors, the shading effect and other analysis like:

- landform analysis,
- measurement uncertainty analysis,
- air density analysis,
- wind-force distribution analysis,
- productivity of a set of wind turbines analysis
- and other.

The bankable expertise also includes data that allows to evaluate the investment in terms of the wind turbine selection, Weitbull's distribution and windrose.

2.2. Landform and sitting

One of the basic tools for the sitting of a future wind farm are the topographic maps, identification of solid barriers, identification of land roughness, assumptions on wind conditions, selection of height and power of a wind turbine. In terms of orography there are only two types of landforms [3]:

- simple – plane with relatively small inclination;
- complex – with inclination over 17° and complicated topography.

But the only undeniable method to confirm a proper sitting is the site visit, also known as the local vision (Fig. 1). It provides confirmation in a form of photographical records, compass data, GPS data as well as a full and detailed description of all the barriers present at the specific location.

Distances between specific solid obstacles is measured and recorded using rangefinders. Those obstacles that may influence the wind are usually industrial buildings, residential buildings, forests, individual trees, chimneys, other wind turbines, observation towers, communication towers, hills, mountains, heaps, bridges etc.

2.3. Execution of measurement campaign of wind conditions

The necessary condition to conduct a proper measurement campaign is to use a high-end instrumentation to register data and a robust measurement mast or tower. Nominal heights of measurement masts of different types range between 2 and 160 meters. Typically the masts are of a lattice of tubular (telescopic) type. Another condition is to use instrumentation with a proper quality. It determines the precision of a wind conditions measurement. The following list presents an influence of measurement precision on a wind power estimation:

- wind speed: each ±1% change of wind speed change means ±3% change of power,
- wind direction: no direct influence, non-optimal arrangement of wind turbines in a farm,
- atmospheric pressure: each ±1% change of pressure means ±1% change of power,
- air temperature: each ±1˚C of temperature change means ± 0.35% change of power,
- air humidity: at 40˚C each ±1% change of humidity means ±0.05% change of power.

The basic instruments used for the wind conditions measurement are the anemometers, wind indicators, thermometers, hygrometers, barometers and data recorders.

It should be emphasized that such expertise are cost-intensive. On average their costs exceed 100,000 PLN (or ~24,000 €; or ~26,000 $). Minimal duration of the measurement campaign is 12 months. Longer investigation however, significantly increase the bankability of the end-report.

For the location in northern Poland, wind speed measurements were performed at four different heights: 80, 78.5, 58.5 and 30.5 meters, and Thies First Class anemometers by the Thies Clima Company were used. Wind direction was measured at two different heights: 76.65 and 29 meters, and Thies Compact wind indicators by the Thies Clima Complany were used. Temperature and humidity were measured at a height of 10 meters using KP thermo- and hygrometer by the Galltec Mess Company. All the measurements from the mast were recorded using Meteo 32 wind logger by the Ammonit GmbH Company. A summary of those measurements is presented in Tab. 1.

Tab. 1. Description of instrumentation of measurement mast for investigated location

Instrument	Height, m	Type	Orientation
Anemometer A1	80.00 m	Thies First Class (4.3350.10.000)	-
Anemometer A2	78.50 m	Thies First Class (4.3350.10.000)	270°
Anemometer A3	58.50 m	Thies First Class (4.3350.00.000)	268°
Anemometer A4	30.50 m	Thies First Class (4.3350.00.000)	270°
Wind indicator WF2	76.65 m	Thies Compact (4.3129.10.012A)	181°
Wind indicator WF2	29.00 m	Thies Compact (4.3129.10.012A)	185°
Thermometer T1	10.00 m	Galltec Mess KP	7°
Thermometer H1	10.00 m	Galltec Mess KP	7°
Data Logger	5.50 m	Ammonit Meteo 32	-

2.4. Validation of results obtained during measurement

The correctness, accuracy, proper validation and analysis of measurement data are the key elements to determine the usefulness of specific location in terms of its wind power potential. A summary of measurement period and its presentation in graphical or tabular form is the main goal of the end-report. A typical end-report consist of the following data: geographical coordinates of the measurement mast location, measurement location map, photographical report of the location, measurement data, statistics and monthly wind speed, wind direction distribution and wind direction frequency, temperature and pressure data. Analysis summarizing the measurement period is conducted basing on the data from the measurement mast location. It covers full measurement data from different heights and instruments. Validation of measurement data aims to check its and to determine the operating status of instruments installed on the mast. End-report is usually obtained using the Windographer that presents data in a graphical form: monthly average wind speed (Fg 2), *Weibull's distribution* (Fig. 3), windrose (Fig. 4), proportion of total wind energy (Fig. 5), temperature distribution (Fig. 6) and air density (Fig. 7). The following figures present compilation of data acquired during measurement campaign at a specific location in northern Poland.

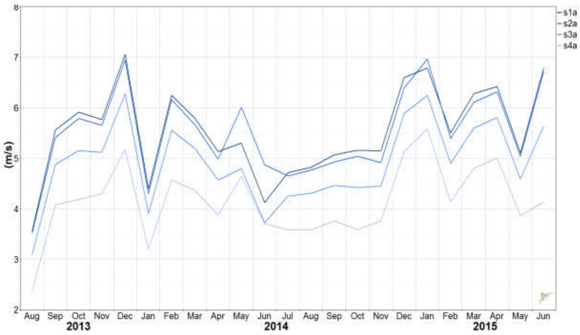

Fig. 2. Monthly average wind speed

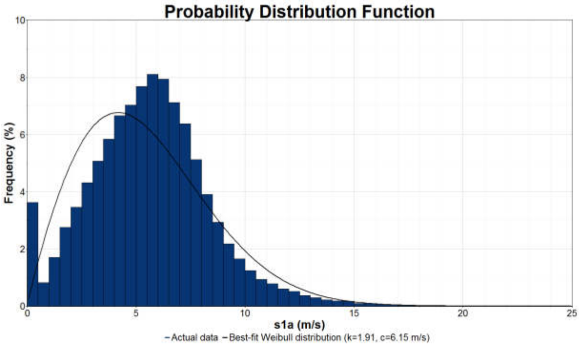

Fig. 3. Weibull's distribution for anemometer placed at the height of 80 meters

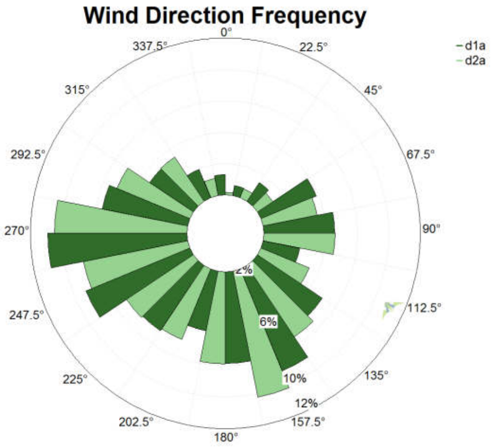

Fig. 4. Wind direction frequency – windrose

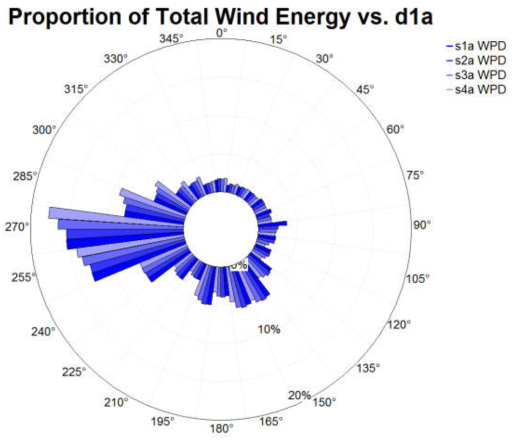

Fig. 5. Proportion of total wind energy

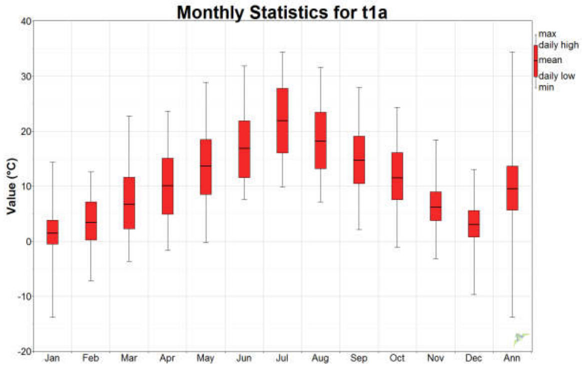

Fig. 6. Monthly average temperature

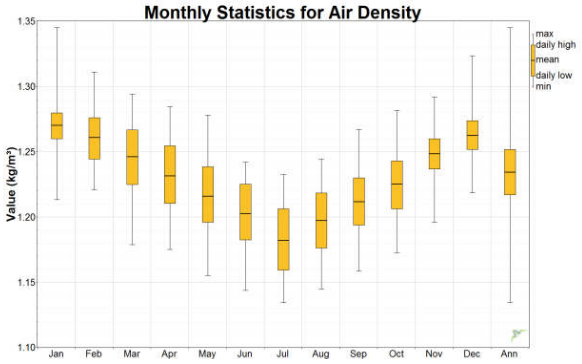

Fig. 7. Monthly average air density

3. SELECTION OF WIND TURBINE FOR A GIVEN WIND CONDITIONS

Within the scope of the measurements, obtained wind conditions were used to select a wind turbine suitable for the investigated location. An important step of this process is to determine a proper type of a wind turbine. There are a few basic solution and the division between them is based on different criteria:

- axis of rotation (vertical, horizontal),
- tip-speed ratio λ; low speed $\lambda \leq 5$, intermediate speed $1.5 \geq \lambda \leq 3.5$ high speed $\lambda \geq 3.5$,
- output power: small power from 50 up to 250 kW, medium power from 250 up to 750 kW, high power from 750 up to 1500 kW and very high power over 1500 kW.

Division may also consider design details i.a. number of blades, tower type, axis of rotation, rotational speed adjustment method [6]. In the wind power sector, the wind turbines with parallel (horizontal) axis of rotation with respect to wind direction are used. Basic assumptions for utilization of this type of wind turbine are presented below.

3.1. Conversion of kinetic energy of the moving air into electricity

The air mass obtains its kinetic energy due to temperature difference between various parts of the world. Temperature change causes pressure difference that results in horizontal air movement on a given area. The air mass pushes the wind turbine blade and the rotor starts to spin. As a result, the wind speed behind the blade is smaller. This is strictly connected to the pressure difference in the vicinity of the rotor, which is much higher just before it and with the air pressure drop behind the rotor, which at some distance equates to atmospheric pressure. The phenomenon presented above is described by the Betz's model from 1920 known as the blade stream theory [7]. According to this law, theoretically it is impossible to recover more than 59.3% of wind kinetic energy by using the wind turbine [8, 9, 10, 11]. The maximum power is obtained when the highest wind speed behind the turbine equals $v_2 = \frac{v_1}{3}$. Then the power received by the wind turbine can be calculated according to the following formula:

$$P_{th} = \pi \cdot r^2 \cdot \frac{\rho}{4} \cdot \left(v_1 - \frac{v_1}{3}\right) \cdot \left[v_1^2 - \left(\frac{v_1}{3}\right)^2\right] = \frac{8}{27} \cdot \pi \cdot r^2 \cdot \rho \cdot v_1^2 \text{ [W]}, \qquad (1)$$

where:
v_1 – wind speed before the turbine, m/s,
r – radius of wind turbine blade, m,
ρ – air density, kg/m^3.

In order to compare the different technical solutions of the wind turbines, a parameter $P_{u,th}$ called the "theoretical normalized power" was introduced. It represents a power of a turbine presenting zero resistance against the wind. A quotient of P_{th} and $P_{u,th}$ represents a so-called theoretical coefficient of wind utilization:

$$c_{p,max} = \frac{P_{th}}{P_{u,th}} = \frac{\frac{8}{27} \cdot \pi \cdot r^2 \cdot v_1^3 \cdot \rho}{\frac{1}{2} \cdot \pi \cdot r^2 \cdot v_1^3 \cdot \rho} = \frac{16}{27} = 0.5926\,. \qquad (2)$$

In practice, this coefficient is calculated according to the following formula:

$$c_p = \frac{1}{2} \cdot \left[1 - \left(\frac{v_2}{v_1}\right)^2\right] \cdot \left(1 + \frac{v_2}{v_1}\right), \qquad (3)$$

where: v_2 is the wind speed behind the wind turbine in m/s.

The c_p coefficient depends on the tip-speed ratio λ of a wind turbine, number of blades Z, start-up torque M and rotor diameter D. The dependency of power coefficient for both horizontal and vertical axis of rotation on tip-speed ratio, for a given number of blades, is presented in fig. 8. When the real efficiency of a turbine is established, it is now possible to calculate the theoretical power on the shaft of a wind turbine:

$$P_{th} = \frac{1}{2} \cdot A \cdot \rho \cdot v^3 \cdot c_p \; [W]. \tag{4}$$

An important parameter in terms of a wind turbine efficiency is its torque M. This quantity is also called the start-up torque, because for a given wind speed at which the turbine is starting-up, it should always be greater than the friction torque. It applies for every weather conditions. A number of blades is also an important factor in terms of the start-up speed:

- for 1 and 2 blades, start-up speed ranges between 5 and 6 m/s,
- for 3 blades, start-up speed ranges between 3 and 4 m/s,
- for 4 and more blades, start-up speed equals 3 m/s.

The dependency of torque M (relative C_M) on tip-speed ratio is presented in fig. 9 [3, 6, 12, 13].

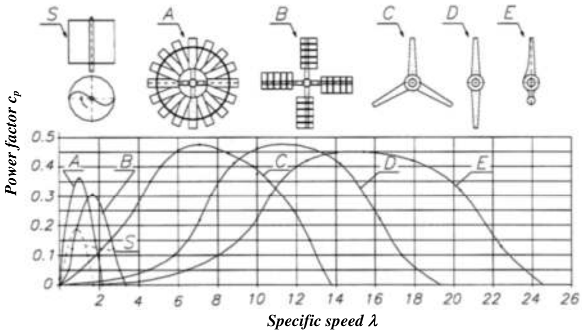

Fig. 8. Power coefficient c_p as a function of tip-speed ration and number of blades [3]

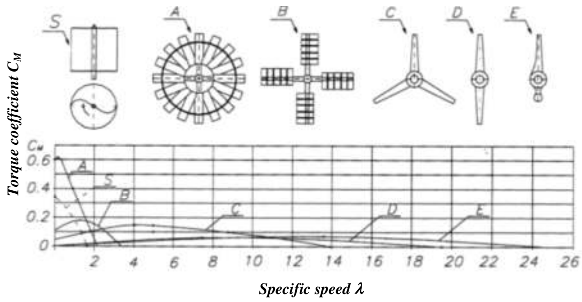

Fig. 9. Power coefficient C_M as a function of tip-speed ratio and number of blades [3]

The torque M is calculated according to the following formula:

$$M = C_M \cdot A \cdot \frac{\rho \cdot c^2}{2} \cdot R \, , \tag{5}$$

where:
C_M – torque coefficient from Fig. 9,
A – area covered by the moving blades, m^2,
R – radius of the blade, m.

Now it is possible to calculate the mechanical power of the wind turbine:

$$P_M = M \cdot \Omega \, , \tag{6}$$

where: Ω – angular speed: $\Omega = \frac{\pi \cdot n}{30} \left[\frac{rad}{s}\right]$.

A value to the C_M coefficient is especially important in case of low speed devices demanding high torque. This dependency is characteristic for the 3 bladed wind turbines. During calculations that serve the selection of the wind turbines, it is assumed that the total efficiency of the system takes into account aerodynamic coefficient of wind utilization, mechanical losses of the transmission and the generator, and ranges between 23 and 46 %. One of the important parameters that determines the proper operation of the wind turbine is the diameter of the rotor D. This quantity can be determined basing on the power demand. It is calculated according to the following formula [3, 6, 12, 13, 14]:

$$D = \sqrt{\frac{8000 \cdot P_{el}}{\pi \cdot \rho \cdot c_p \cdot c^3}} \; [m]. \tag{7}$$

The rotor diameter determines the rotational speed of the blades:

$$n = \frac{60 \cdot v_{max}}{\pi \cdot D} \left[\frac{m}{s}\right], \tag{8}$$

where: v_{max} – the highest linear speed of the wind turbine blade tip.

It is also assumed that the height of the tower cannot exceed:

$$H = H_p + 0.9 \cdot D \; [m]. \tag{9}$$

3.2. Device selection basing on the wind measurement calculations

Basing on the calculation made for the wind turbine situated at the height of 80 meters, it can be concluded that the energy of the raw wind stream per 1 m^2 of area A, equals 214.375 W. For this height, the typical rotor diameter is 100 m. Using equation (7) it is possible to estimate the output power basing on the measurement campaign data. The real system efficiency c_p = 0.46 (46 %) and operation time τ = 8000 h, are assumed. By modifying the equation (7), the following formula for the system power is obtained:

$$P_{el} = \frac{D^2 \cdot \pi \cdot c_p \cdot c^3}{8000} = 774.11 \; [\text{kW}]. \tag{10}$$

This means that each year (assuming 8,000 h of operation) the turbine can produce 6,192,865 kWh of electric energy, basing on the conditions at the height of 80 m. Taking the equation (9) into account, it can

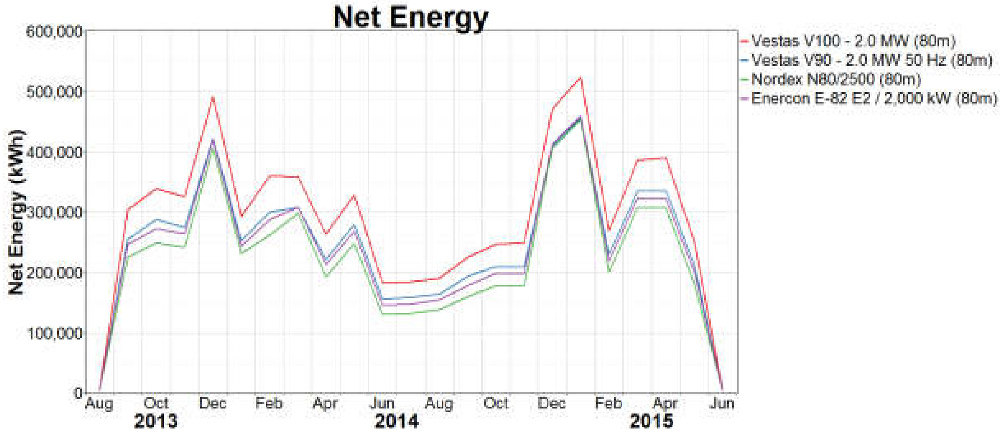

Fig. 10. Wind turbine selection basing on the productivity of 4 different models

Tab. 2. Net energy produced by 4 different wind turbines

Month	Net Energy, kWh			
	Vestas V100 - 2.0 MW (80m)	Vestas V90 - 2.0 MW 50 Hz (80m)	Nordex N80/2500 (80m)	Enercon E-82 E2 / 2,000 kW (80m)
Aug 2013	6,316.29	5,389.02	4,418.45	5,367.74
Sep 2013	303,609.75	254,841.34	225,186.17	247,229.41
Oct 2013	338,729.28	287,671.03	249,239.09	272,635.38
Nov 2013	325,379.88	274,549.63	241,501.81	264,115.09
Dec 2013	491,583.16	422,253.59	405,429.31	418,719.16
Jan 2014	292,744.84	252,981.39	231,330.98	243,911.83
Feb 2014	360,325.00	299,760.81	261,764.22	287,264.47
March 2015	358,442.66	307,963.66	297,563.66	307,900.63
Apr 2014	263,007.00	221,657.30	192,611.83	212,566.17
May 2014	328,946.53	279,399.53	247,415.08	267,853.66
Jun 2014	182,059.89	155,203.88	129,986.90	145,033.03
Jul 2014	184,300.69	158,615.55	131,840.83	147,819.03
Aug 2014	190,760.23	163,864.14	138,136.25	154,526.09
Sep 2014	225,376.23	193,027.67	159,786.48	177,953.63
Oct 2014	247,109.97	209,583.52	178,638.70	198,787.48
Nov 2014	248,723.05	208,672.78	176,953.08	197,735.83
Dec 2014	471,382.75	409,527.31	405,500.94	412,399.81
Jan 2015	524,713.94	456,629.38	453,230.78	459,883.09
Feb 2015	269,080.00	229,931.61	200,767.22	219,085.00
March 2015	385,572.38	334,741.59	307,926.06	323,638.72
Apr 2015	389,809.06	335,752.25	307,186.97	322,935.03
May 2015	252,131.91	212,407.14	181,418.06	201,467.52
Jun 2015	5,131.86	4,328.62	3,627.97	3,963.38
Overall	6,645,279.00	5,678,732.50	5,131,335.00	5,492,696.00

be assumed that the wind turbine with the diameter D = 100 m can be used. Fig. 10 shows how much energy can be produced by the different wind turbines: Vestas V 100 with maximum power of 2 MW, Vestas V 90 with maximum power of 2 MW, Nordex N80 with maximum power of 2,5 MW, Enercon E – 82 with maximum power of 2 MW. All the systems has the same height – 80 meters. The Vestas V100 2 MW turbine with blade length of 49 m and rotor diameter of 100 m shows the highest productivity in kWh that covers the demand obtained using the equation (10). Therefore it is assumed that for the given location the Vestas V100 turbine is the best one.

Table 2 presents the net energy production possible to obtain with 4 different systems. The results obtained confirm that the Vestas V100 turbine is the optimal choice.

4. CONCLUSIONS

This paper presents the scope of measurements conducted in order to determine the wind condition for a given location. The expertise is based on wide and long-lasting measurements at given location in northern Poland. Data obtained in the field is very time- and cost-intensive. Conducted measurements show that the location is proper for a wind farm, and the presented turbine selection process lead to the optimal choice for the given wind conditions. Measurements show that the examined location is suitable for production of electricity using the wind turbines. Estimated annual income from a single Vestas V100 - 2.0 MW (80 m) turbine, assuming price 0.53 PLN per 1 kWh, and annual production (data for 2014) of 3,500,315 kWh (average real efficiency $c_{rz} = 0{,}23$ (23%)):

$$0.53 \cdot 3500315 = 1{,}885{,}166.95 \text{ PLN}. \qquad (11)$$

While conducting the measurements of the wind conditions at a given location it is very important to follow the guidelines included in this elaboration. It allows to minimize the measurement uncertainty and provide high quality data about the wind conditions.

Nomenclature

Symbols

a – coefficient of absorption
h – convection heat transfer coefficient, W/(m^{2}K)
r – reflectivity
R – heat resistance, (m^{2}K)/W
T – temperature, K
u – ratio
U – heat transfer coefficient, W/(m^{2}K),
δ – cover thickness, m
ε – emissivity
σ – Stephan-Boltzman constant for black body, $\sigma = 5.76 \cdot 10^{-8}$ W/(m^{2}K^4)
λ – conduction, W/(mK)

Indices

A – air
C – roof cover
e – equivalent
H – horizon
R – room

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Biographical note

Michał Jakubowski received his M. Sc. Degree in Mechanical Engineering (specialisation: Operation of the motor vehicles) from Mechanical Faculty, Technical University of Koszalin in 2003. In 2014 he completed postgraduate studies at the University of Gdańsk in scope of the company's management controlling. His professional career remains firmly linked with management, sales and marketing. He currently works as a business development manager in Windhunter group.

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