Preliminary assessment of the wind conditions as a potential for using wind micro-installation to improve air quality in Poland

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Abstract. Poland has been struggling with the problem of exceedance of the permissible levels of air pollutions such as particulate matter (PM10, PM2.5) and benzo(a)pyrene (BaP) for several years. In the years 2007-2015 the concentrations of PM10 and BaP exceeded the European Union (EU) limit values. The vast majority of the country is characterised by wind energy zones described as very favorable and favorable. Facing the current legal regulations, wind micro-installations are becoming an opportunity to use the potential of wind energy in Poland. The micro-installations market in Poland is constantly growing. In 2017 there was recorded a nearly ten-fold increase in the number of micro-installations of renewable energy sources connected to the network in regard of 2015. The analysis based on available wind energy resources and available technologies of small wind turbines on the market showed that by installing a 10 kW turbine in the zone with the most favorable wind conditions (1000 kWh/m^2/year) one can avoid 93 kg of dust emissions to the air and 140 kg of CO and 6222 kg of CO_2. The calculated reduction of dust emissions for 3 kW wind turbine in area of Rabka-Zdrój is about 0.8 kg, in the case of BaP 0.0003 kg, and for CO_2 47.3 kg.

1 Introduction

In recent years, the EU Member States have managed to significantly reduce the concentrations of such pollutants as: SOx, CO, NOx, Ni, Pb. However, countries such as Poland, Bulgaria, Italy and others still face the problem of exceeding the permissible concentration standards of particulate matter (PM10, PM2.5) and benzo(a)pyrene (BaP). As indicated by the European Environmental Agency (EEA), the main reason for exceeding the permissible concentration standards of PM10, PM2.5 and BaP in Europe is the combustion of solid fuels in households. Other significant emitters of substances harmful to human health are: road transport, agricultural and industrial processes, energy production and distribution [1]. The research objective of this study is to assess the wind conditions as potential for using wind micro-installations to improve air quality used currently available data. In Poland, the assessment of air quality in terms of health protection is carried out in 46 zones designated in accordance with the Regulation of the Minister of Environment regarding zones in which the air quality is assessed [2]. The assessment is carried out by the Chief Inspectorate for Environmental Protection under the State Environmental Monitoring (SEM). In 2017, the level of the annual permissible concentration of PM10 in air (40 μg/m^3) was exceeded in 10 zones. Basing on the 24-hour concentrations of PM10 in a year (50 μg/m^3) the exceedance was recorded in 34 zones. Regarding PM2.5, the exceedances of the average annual concentrations (25 μg/m^3) occurred in 19 out of 46 zones. The worst situation is definitely observed for BaP, as only three zones did not exceeded the permissible level of annual concentration (1 ng/m^3) [3]. The wind energy resources are varied on the area of the country. The highest wind energy potential occurs in the northern part of Poland, and the lowest in its south-western part. The use of wind energy resources by high-power installations is not always possible. Consequently, wind micro-installations, as a part of distributed energy system, have an opportunity to enhance the local energy security. In Poland, apart from measurement masts, the most widely used data for estimating the local wind conditions are obtained from the Institute of Meteorology and Water Management-National Research Institute. However, it should be noted that these data should be used only for the nearest area of measurement station due to high variability of wind conditions. Therefore, the preliminary assessment of wind conditions was based on the results obtained from own measurement station located in Rabka-Zdrój. Rabka-Zdrój is one of the most popular mountain health resorts in Poland. Unfortunately, the areas of health resorts in Poland have also significant problem with air quality especially in the winter period. The most important novelty of this paper is showing how the health resorts areas can use local renewable energy resources to reduce the problem of low emissions.

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2 Air pollution in Poland

According to the European Commission [4], Poland is required to provide annual report on the air quality assessment as well as the measurement results from the ground measurement station SEM to the European Commission via the EEA. Key air pollution data for period 2006-2015 are presented in country profile for Poland available on the EEA website [5]. The long-term data confirmed poor air quality in Poland. The main causes of the poor air quality are outdated and inefficient heating installations based on solid fuels, commonly used in households [6-8]. During the 10-year period of analysis of the concentrations of PM10 Poland did not reach the acceptable level defined by the European Union. The highest 24-hour PM10 concentrations in a year were recorded in 2010, 2011, 2006 and amounted to over 70 µg/m^3 (Fig.1).

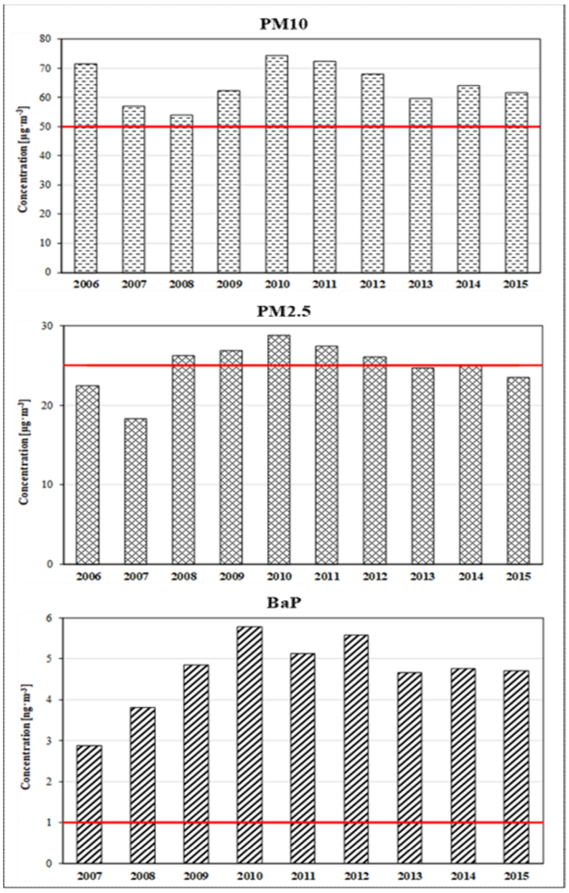

Fig. 1. Concentration of PM10, PM2.5, BaP in Poland [5].

In the years 2007-2015 the average level of BaP concentration in the air was 4.7 ng/m^3. In the analyzed period of time (except for 2007 and 2008), the concentration of BaP exceeded the admissible level at least four times. In extreme cases, the level of average annual BaP concentration was 6 ng/m^3. The PM2.5 annual average concentration was exceeded in 2008-2012. After 2012, the concentration of PM2.5 decreased and in the following three years was within the admissible standard. The presented data clearly show that in Poland the permissible level of concentration of BaP and PM10 is constantly being exceeded. The EEA exposure indicator for population living in urban areas in 2015 was: 99.1% for BaP, 80.6% for PM10 and 39.0% for PM2.5.

3 Wind energy in Poland

3.1 Wind energy resources

The distribution of wind speed in Poland is diverse. On the basis of many years of observations, the assessment of wind energy resources is carried out by the Institute of Meteorology and Water Management. According to the proposed division suggested by prof. Halina Lorenc in Poland one may observe five wind energy zones. The largest potential of wind energy resources, possible for effective and economical use, is located in the northern part of Poland: maritime areas (Poland's exclusive economic zone), coastal strip and the north-eastern edge of Poland (Suwalki Region) [9] (Fig.2). The aforementioned regions belong to the so-called extremely favorable zone. However, the vast majority of the country is characterized by wind energy zones described as very favorable and favorable. In Poland, there have been defined zones in which the frequency of winds exceeding 10 m/s is more than 40 days a year (Suwalki Region, Gdansk Coastal Region, the region of Poznan, Great Poland Lakeland and areas located on the southern part of Poland), less than 2 m/s is over 60% a year (the area stretching from Wloclawek to Szczecin and the southern part of the country).

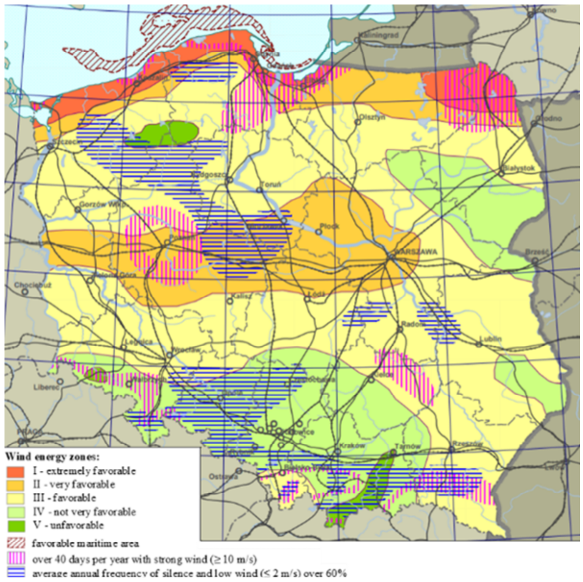

Fig. 2. Wind energy sources in Poland [9].

3.2 Wind micro-installations

Pursuant to the act on renewable energy sources, the term micro-installation should be understood as a renewable energy installation with a total installed electric capacity not higher than 40 kW, connected to a power grid with rated voltage lower than 110 kV or of reachable thermal capacity up to 120 kW [10]. For the purposes of this article, the term micro-installation will refer only to installations with a total installed electrical capacity not exceeding 40 kW. The final recipient using the electricity produced in micro-installations for personal use is referred to as a prosumer. From 2016 on, pursuant to the amendment of the RES Act, a new system of settlements for prosumers, the so-called discount system exists. The discount system is a system of the non-cash settlement of electricity collected and input into the network by a prosumer. The settlement within the discount system occurs in one-year period. Prosumer inputting 1 kWh of electric energy into the network can take 0.8 kWh from it – for the installed micro-installation capacity up to 10 kW, in the case of other micro-installations, the prosumer takes 0.7 kWh from the network. In addition, the prosumer does not pay any distribution fees or any other additional fees to the energy seller.

The micro-installation market in Poland is constantly developing. In 2017, there was a significant increase in the number of micro-installations connected to the network. In 2015, 3 153 micro-installations were connected to the five largest Distribution System Operators [11-13] (Table 1). In 2017, the number of prosumers increased almost tenfold, and the total number of micro-installations installed in Poland exceeded 28 000. Most micro-installations were located in the south-eastern part of Poland, while the smallest number of them was recorded in the Polish north-western extreme.

Table 1. Number of micro-installations connected to the five largest Distribution System Operators in Poland [11-13].

Distribution System Operator	Year		
	2015	2016	2017
Enea Operator	354	2 428	4 252
Energa Operator	749	3 227	5 414
PGE Distribution	1 088	5 266	9 335
Innogy Stoen Operator	26	148	539
Tauron Distribution	936	5 042	9 140
Total	3 153	16 111	28 680

4 Material and methods

Table 2. Technical parameters of small wind turbines available on Polish market.

	Type of wind turbine	Nominal power	Rotor diameter	Start wind speed	Rated wind speed	Number of blades
		kW	m	$m \cdot s^{-1}$	$m \cdot s^{-1}$	pcs.
1.	FD1000-2.7	1.0	2.7	2.0	9.0	3
2.	Flamingo AERO 4.4	1.6	4.4	2.5	7.5	3
3.	Energiewind 3 KW-FB	3.0	4.8	2.5	10.0	3
4.	Zefir D5	6.0	4.8	2.8	15.0	3
5.	Zefir D10	10.0	10.0	3.0	8.0	3

To estimate the reduction of pollutant emissions in the air through the use of small wind installations the values of useful wind energy at 10 m a.s.l. in Poland were used [14]. Furthermore, for the analysis used the data of average and maximum wind speeds, for winter period, obtained from the ground measurement station in Rabka-Zdrój. The analysis was conducted for five wind turbines with different nominal power (Table 2) available on the Polish market.

The upper limits of the ranges determining the amount of useful wind energy were adopted for the calculations. Poland was divided into three basic areas for which the following wind energy values were assumed: 1) Southern Poland: 500 $kWh/m^2/year$; 2) Central Poland: 750 $kWh/m^2/year$; 3) Northern Poland: 1000 $kWh/m^2/year$. The following formula was used to calculate the annual energy production from the selected wind turbines [15]:

$$E = K_e \cdot A \cdot \eta_t \tag{1}$$

where:
K_e – wind energy potential, read from the map [$kWh/m^2/year$]
A – surface of the wind turbine rotor [m^2]
η_t – efficiency of wind turbine: $\eta_t = 0,25$ [15]

The data of wind speed obtained from measurement station was presented in ranges with 0,5 m/s steps. For all determine ranges calculated the frequency of occurrence the wind speeds, wind power and wind energy. The energy efficiency of the analyzed wind turbines was calculated using:

$$E_{net} = E_c \cdot A \cdot \eta \cdot \xi \tag{2}$$

where:
E_{net} – net energy obtained from a wind turbine [kWh]
E_c – the total wind energy for designated speed ranges [kWh/m^2]
ξ – coefficient of wind energy utilization [$\xi = 0,3$]
η – mechanical and electrical efficiency: $\eta = 0,9$ [16]

The preliminary analysis of the possibilities to reduce air pollutants has been made for hard coal basing on guidelines developed by the Ministry of Environmental Protection, Natural Resources and Forestry (MEPNRF) [17]. The annual emission of NO_2, SO_2, CO, CO_2, BaP:

$$e = B \cdot w \tag{3}$$

where:
e – annual emission of pollution [kg]
B – the amount of fuel that should be burned to achieve the amount of energy produced by the wind turbine [Mg]
w – emission factor [kg/Mg of fuel]

The annual emission of dust:

$$e_{dust} = B \cdot w\ (100 - \eta_d)\ (100 - k) \tag{4}$$

where:
e_{dust} – the annual emission of dust [kg]
B – the amount of fuel that should be burned to achieve the amount of energy produced by the wind turbine [Mg]
w – emission factor [kg/Mg of fuel]
η_d – dust collector efficiency [$\eta_d = 0$]
k – content of combustible dust [k = 10%]

5 Results and discussion

In the case of choosing a small wind turbine, the key parameters are local wind conditions and terrain. Small wind farms are vulnerable to high wind instability due to low-altitude foundations. Therefore, the selection of a wind turbine should not be made only on the basis of medium speed, but also the distribution of the frequency of occurrence of individual wind speeds over time should be taken into account. The confirmation of these relationships are wind speed values obtained from measurement observations in Rabka-Zdrój (Fig.3). As a result, the average wind speed in January reached a constant level of 0.8 m/s while the wind speed course in particular days is varied and exceeds the determined average wind speed several times. In addition, when analyzing the frequency of distribution of individual wind speeds in the winter period (2017/2018), it can be observed that speeds between 0.5-1.0 m/s occur most frequently (Fig.4). Moreover, when considering the use of wind energy in the discussed area, it should be assumed that maximum wind speeds up to 4.0 m/s will occur most frequently, constituting over 90% of the analyzed time.

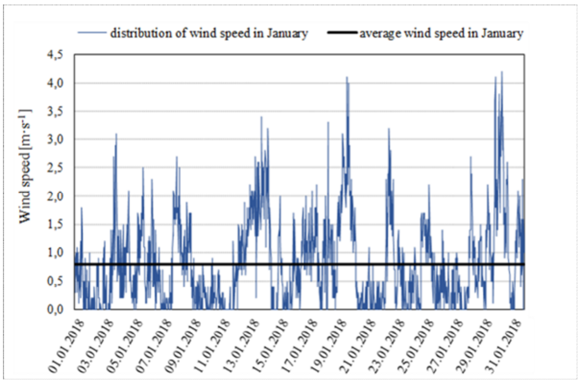

Fig. 3. The course of average wind speed measurements in January.

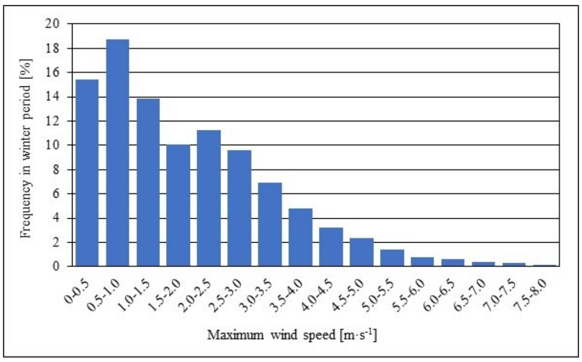

Fig.4. Distribution the frequency of occurrence the maximum wind speeds in winter period.

Due to the lack of wind speed in the annual period in Rabka-Zdrój, data from the winter period were used to estimate the reduction of pollutant emissions. It should be noticed that area of health resort is located in not very favorable wind energy zone with high annual frequency of silence and low wind. The analysis based on the distribution of average and maximum wind speeds confirmed the relationship between the amount of energy produced by the turbine and the frequency of occurrence the individual wind speeds. The energy production [kWh] for average wind speed for subsequent turbines is 2.7; 8.9; 8.4; 9.7; 42.2 and respectively for maximum wind speed: 45.4; 151.7; 149.9; 173.6; 753.6. The ecological effect, possible to achieve by using one wind turbine in the winter period, is higher for the range of maximum wind speed. The estimated reduction of CO_2 amount 0.84 kg for the turbine with the lowest nominal power and 13.34 kg for the turbine with the highest nominal power (Table 3). In case of the maximum wind speeds, these values are respectively to 14.33 kg and 237.99 kg (Table 4). In both analyzed variants, the BaP and NO_2 emission will be reduced to the smallest extent through the use of small wind turbines.

Table 3. Ecological effect [kg] for energy obtained from a wind turbines at average wind speeds in winter period in Rabka-Zdrój

Pollutants	Wind turbine 1	Wind turbine 2	Wind turbine 3	Wind turbine 4	Wind turbine 5
SO_2	0.010	0.034	0.032	0.037	0.160
NO_2	0.0004	0.0014	0.0013	0.0015	0.0067
CO	0.019	0.063	0.060	0.069	0.300
CO_2	0.84	2.80	2.65	3.10	13.34
Dust	0.014	0.047	0.044	0.051	0.222
BaP	0.00001	0.00002	0.00002	0.00002	0.00009

Table 4. Ecological effect [kg] for energy obtained from a wind turbines at maximum wind speeds in winter period in Rabka-Zdrój

Pollutants	Wind turbine 1	Wind turbine 2	Wind turbine 3	Wind turbine 4	Wind turbine 5
SO_2	0.172	0.575	0.568	0.658	2.856
NO_2	0.0072	0.0240	0.0237	0.0274	0.119
CO	0.322	1.078	1.065	1.234	5.355
CO_2	14.33	47.89	47.32	54.83	237.99
Dust	0.239	0.798	0.789	0.914	3.966
BaP	0.0001	0.0003	0.0003	0.0004	0.0017

The use of energy produced by small wind turbines allows to reduce hard coal consumption, and thus reduce the emission of hazardous substances into the air. The electricity generated by small wind turbines can be converted into thermal energy by the use of electric heaters, or provide a power source for compressors operating in heat pumps, and can be directly used for household needs. The analysis shows that with very favorable wind conditions, the 10 kW wind farm is able to reduce dust emissions by 93 kg, and CO_2 emission by more than 6 tonnes per year (Table 5). The same wind farm in a non-favorable area in terms of wind energy availability is able to reduce CO_2 emission by about 3 tonnes, and dust by 46 kg. For comparison, a 1.6 kW wind farm, which can be successfully used in households, achieves a reduction of emission of 0.7-1.5 tonnes for CO_2, 10-21kg of dust, 16-32 kg of CO and 8-17 kg SO_2, depending on the region in question. The amount of avoided emission due to the use of energy obtained from small wind turbines is greater for areas with more favorable wind conditions, and this is closely related to the possibility of installing a more powerful

Table 5. Ecological effect [kg] obtained for areas with different wind energy potential and using turbines of different nominal power

Wind turbine 1						
Pollutants	SO_2	NO_2	CO	CO_2	Dust	BaP
Southern Poland	2.71	0.11	5.09	226.01	3.39	0.0016
Central Poland	4.07	0.17	7.63	339.01	5.09	0.0024
Northern Poland	5.42	0.23	10.17	452.02	6.78	0.0032
Wind turbine 2						
Pollutants	SO_2	NO_2	CO	CO_2	Dust	BaP
Southern Poland	7.20	0.30	13.50	600.21	9.00	0.0042
Central Poland	10.80	0.45	20.26	900.31	13.50	0.0063
Northern Poland	14.41	0.60	27.01	1200.42	18.01	0.0084
Wind turbine 3						
Pollutants	SO_2	NO_2	CO	CO_2	Dust	BaP
Southern Poland	8.57	0.36	16.07	714.30	10.71	0.0050
Central Poland	12.86	0.54	24.11	1071.45	16.07	0.0075
Northern Poland	17.14	0.71	32.14	1428.60	21.43	0.0100
Wind turbine 4						
Pollutants	SO_2	NO_2	CO	CO_2	Dust	BaP
Southern Poland	18.23	0.76	34.18	1518.95	22.78	0.0106
Central Poland	27.34	1.14	51.26	2278.42	34.18	0.0156
Northern Poland	36.45	1.52	68.35	3037.89	45.57	0.0213
Wind turbine 5						
Pollutants	SO_2	NO_2	CO	CO_2	Dust	BaP
Southern Poland	37.20	1.55	69.76	3100.26	46.50	0.0217
Central Poland	55.80	2.33	104.63	4650.38	69.76	0.0325
Northern Poland	74.41	3.10	139.51	6200.51	93.01	0.0434

6 Summary

For many years, Poland has been struggling with the problem of poor air quality. Year by year, Polish cities are on the list of the most polluted cities in Europe. More and more often, the society is experiencing the intensified and negative effects of the poor state of air quality. In the years 2007-2015 in Poland the permissible levels of PM10 and the carcinogenic BaP levels were exceeded. The main reason for the high concentrations of pollutants in the air is the combustion of poor quality solid fuels in low-functional and obsolete heating devices. Therefore, the use of installations basing on the renewable energy sources, especially the development of prosumer energy, is an opportunity to reduce the emission of hazardous substances into the air. Over 60% of the country has favorable wind conditions that can be effectively used by wind farms. Unfortunately, the legal regulations in force since 2016 limit the possibility of using wind power installations. Therefore, wind farms become an opportunity to use wind energy resources in Poland, and the development of prosumer energy will contribute to ensuring local energy security. The analysis based on available wind energy resources and available technologies of small wind turbines on the market showed that by installing a 10 kW turbine in the zone with the most favorable wind conditions, one can avoid per year: 93 kg of dust emission to air and 140 kg of CO and 6.2 t of CO_2. In the case of the least favorable zone and the installation of the turbine with the lowest nominal power (1 kW), one obtains an ecological effect on the annual level of 3 kg of dust, 5 kg of CO and 226 kg of CO_2. Taking into account the state of air pollution in Poland, every activity, even the smallest one aiming at the reduction of pollutant emissions, is a key element of the integral system of long-term activities. Furthermore, the obtained results confirm that the use of wind farms can significantly contribute to the improvement of air quality in Poland, especially in rural areas.

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