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 pollutants 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 become 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/m²/year) one can avoid 93 kg of dust emissions to the air and 140 kg of CO and 6222 kg of CO₂. 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 CO₂ 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/m³) was exceeded in 10 zones. Basing on the 24-hour concentrations of PM10 in a year (50 μg/m³) the exceedance was recorded in 34 zones. Regarding PM2.5, the exceedances of the average annual concentrations (25 μg/m³) occurred in 19 out of 46 zones. The worst situation is definitely observed for BaP, as only three zones did not exceed the permissible level of annual concentration (1 ng/m³) [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/m³ (Fig.1).

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).

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 | 2015 | 2016 | 2017 |
|------------------------------|------|------|------|
| Enea Operator                | 354  | 2,428| 4,252|
| Energa Operator              | 749  | 5,227| 5,414|
| PGE Distribution             | 1,088| 5,266| 9,335|
| Innowy Stołec 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 |
|----------------------|---------------|----------------|------------------|------------------|-----------------|
| 1. FD100-2.7         | 1,0           | 2.7            | 2.0              | 9.0              | 3               |
| 2. Flemingo 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/m²/year; 2) Central Poland: 750 kWh/m²/year; 3) Northern Poland: 1000 kWh/m²/year. The following formula was used to calculate the annual energy production from the selected wind turbines [15]:

\[ E = K_e \cdot A \cdot \eta \cdot \xi \]

where:
- \( K_e \) – wind energy potential, read from the map [kWh/m²/year]
- \( A \) – surface of the wind turbine rotor [m²]
- \( \eta \) – efficiency of wind turbine: \( \eta = 0,25 \) [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:

\[ E_{net} = E \cdot A \cdot \eta \cdot \xi \]

where:
- \( E_{net} \) – net energy obtained from a wind turbine [kWh]
- \( E \) – the total wind energy for designated speed ranges [kWh/m²]
- \( \xi \) – coefficient of wind energy utilization \( \xi = 0,3 \)
- \( \eta \) – 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, National Resources and Forestry (MEPNRF) [17]. The annual emission of \( NO_2 \), \( SO_2 \), CO, \( CO_2 \), BaP:

\[ e = B \cdot w \]

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:

\[ e_{dust} = B \cdot w \cdot (100 - \eta_d) \cdot (100 - k) \]

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]
- \( \eta_d \) – 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.

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 CO₂ 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 NO₂ 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 |
|------------|----------------|----------------|----------------|----------------|----------------|
| SO₂        | 0.010          | 0.034          | 0.032          | 0.037          | 0.160          |
| NO₂        | 0.0004         | 0.0014         | 0.0013         | 0.0015         | 0.0067         |
| CO         | 0.019          | 0.063          | 0.060          | 0.069          | 0.300          |
| CO₂        | 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 |
|------------|----------------|----------------|----------------|----------------|----------------|
| SO₂        | 0.172          | 0.575          | 0.568          | 0.658          | 2.856          |
| NO₂        | 0.0072         | 0.0230         | 0.0237         | 0.0274         | 0.119          |
| CO         | 0.322          | 1.078          | 1.065          | 1.234          | 5.355          |
| CO₂        | 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 CO₂ 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 CO₂ 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 CO₂, 10-21kg of dust, 16-32 kg of CO and 8-17 kg SO₂, 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 | SO2 | NO2 | CO | CO2 | 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 | 452.32 | 6.78 | 0.0032 |

| Wind turbine 2 | Pollutants | SO2 | NO2 | CO | CO2 | Dust | BaP |
|---------------|------------|-----|-----|----|-----|------|-----|
| Southern Poland | 3.20 | 0.30 | 13.50 | 660.21 | 9.00 | 0.0042 |
| Central Poland | 10.80 | 0.45 | 20.26 | 900.83 | 13.50 | 0.0063 |
| Northern Poland | 14.41 | 0.60 | 27.01 | 1200.42 | 18.01 | 0.0084 |

| Wind turbine 3 | Pollutants | SO2 | NO2 | CO | CO2 | Dust | BaP |
|---------------|------------|-----|-----|----|-----|------|-----|
| Southern Poland | 8.57 | 0.36 | 16.07 | 714.30 | 10.71 | 0.0050 |
| Central Poland | 13.96 | 0.54 | 24.11 | 1071.45 | 16.07 | 0.0075 |
| Northern Poland | 17.14 | 0.71 | 32.14 | 1468.60 | 21.43 | 0.0100 |

| Wind turbine 4 | Pollutants | SO2 | NO2 | CO | CO2 | Dust | BaP |
|---------------|------------|-----|-----|----|-----|------|-----|
| Southern Poland | 18.23 | 0.79 | 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 | 3073.89 | 45.97 | 0.0213 |

| Wind turbine 5 | Pollutants | SO2 | NO2 | CO | CO2 | Dust | BaP |
|---------------|------------|-----|-----|----|-----|------|-----|
| Southern Poland | 37.20 | 1.55 | 69.75 | 3190.26 | 46.50 | 0.0217 |
| Central Poland | 55.80 | 2.33 | 104.63 | 6850.28 | 69.75 | 0.0225 |
| Northern Poland | 74.41 | 3.10 | 189.51 | 6200.51 | 93.01 | 0.0414 |

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 CO₂. 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 CO₂. 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.

Acknowledgement

Publication supported by the Polish Ministry of Science and Higher Education as a part of the program of activities disseminating science from the project „Organization of the First International Science Conference – Ecological and Environmental Engineering”, 26-29 June 2018, Kraków.

The scientific work was also financed from budgetary sources for years 2017-2021, as a research project under the “Diamantowy Grant” programme (grant agreement No. DI2016 003946).

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