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AN ANALYSIS OF ELECTRICITY GENERATION IN A WIND FARM IN NORTH-EASTERN POLAND – A CASE STUDY

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ABSTRACT: There are various methods of generating electric power. This article analyzes electricity generation in the Wronki wind farm in Poland. Wind farm specifications and turbine parameters were presented. The correlations between the wind farm's performance and wind speeds in 2014-2016 were analyzed. Turbine availability was estimated. The economic performance of the wind farm was analyzed by calculating the proceeds from the sale of generated electricity. The wind farm's environmental impact was determined by calculating the volume of CO_2, SO_2, NO_x, CO and dust emissions associated with the generation of equivalent amounts of electricity in a conventional power plant.

KEY WORDS: wind farm, electricity generation, wind speed, environmental protection

 JEL: Q01, Q21, Q42

Introduction

The wind turbine market has evolved dynamically in the last decade. Renewable energy sources have been classified into two main groups. In the first group, wind power is harnessed on a small scale to generate electricity for households, farms and telecommunications networks (Boczar, 2010).

These wind farms have an output of several to several dozen kilowatts, and most of them are connected to the power grid. The second group is composed mainly of foreign companies with extensive experience in wind turbine operation and manufacturers of wind turbine systems which can be operated in severe climates and which have been successfully implemented in hundreds of thousands locations around the world. This group includes large wind farms with nominal output of 10 MW and higher (Flaga, 2008).

Modern wind turbines have similar structural design. The most popular models have three aerodynamic blades made of glass fiber, carbon fiber and composite materials, and they are mounted on steel towers with a height of 50-100 m or even 150 m.

The aim of this article is to analyze energy efficiency depending on wind speed and turbine availability. The economic benefits resulting from obtaining electricity on the wind farm have been presented. The farm is located in north-eastern Poland, where there are excellent wind conditions. The article analyzes actual data gather in 3 years period on the wind farm „Wronki".

Wind turbine parameters

The analyzed wind farm is equipped with Vestas V90 wind turbines manufactured in Denmark. The turbines are mounted on towers with a height of 105 m. The nacelle has the weight of 70 Mg, the rotor – 41 Mg, and the tower – 285 Mg. The turbine has three blades, a rotor with a diameter of 90 m, and swept area of 6.362 m^2. Nominal rotational speed is 16.1 rpm in the range of 8.6 to 18.4 rpm. Power output is controlled by the OptiSpeed® system. The aerodynamic brake consists of three separate hydraulic actuators that control blade pitch. Cut-in wind speed is 4 m/s, and rated wind speed for a 3000 kW turbine is 15 m/s. Cut-out wind speed is 25 m/s. The turbine is equipped with the OptiSpeed® asynchronous generator with rated output of 3000 kW, 1000 V voltage and 50 Hz frequency. Turbine operation is controlled automatically with the use of microprocessors, and it is remotely monitored. Turbine output is controlled and optimized by the OptiSpeed® system, and blade pitch is controlled by the OptiTip® system. The operating temperature range of a standard turbine is – 20°C to 40°C (https://www.vestas.com).

Turbine structure

The rotor is one of the key components of a wind turbine which converts wind energy to mechanical energy. Mechanical energy is transferred to the generator via the the gearbox (https://www.vestas.com).

In many wind turbines, blade pitch is controlled by hydraulic actuators in a range of -5° to +90°. The rotor is mounted directly on the gearbox or the low-speed shaft which transfers mechanical energy to the generator via the gearbox. In turbines without a gearbox, rotor speed ranges from 1 to 30 rpm, and the gearbox increases that speed to 1500 rpm. The degree of speed transmission is determined by the type of generator. Most wind turbine generators are asynchronous devices.

The operation of a wind farm is controlled by a microprocessor system which collects data for calculations and monitoring. The nacelle is mounted at the top of the tower, and it houses the power transformer, generator, gearbox and control devices. The nacelle also contains lubricating and cooling systems, brakes, hydraulic drive train with pumps and other devices. The nacelle and the rotor are set into motion by electric motors and gears at the top of the tower. The tower is a tapered steel tube.

The structure of the Vestas V90 wind turbine is presented below (https://www.vestas.com).

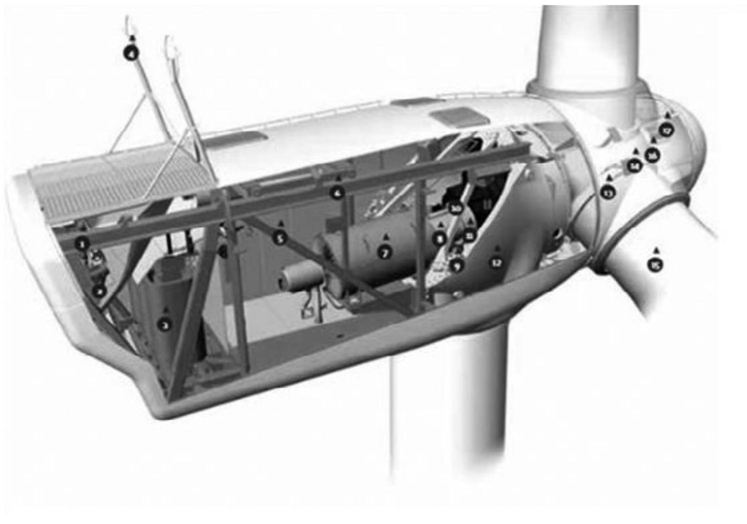

Figure 1. Cross-section of the Vestas V90 nacelle

Source: https://www.vestas.com [15-10-2017].

1. Oil cooler
2. Water cooler for generator
3. High voltage transformer
4. Ultrasonic wind sensors
5. VMP-Top controller with converter
6. Service crane
7. OptiSpeed generator
8. Composite disc coupling
9. Yaw gears
10. Gearbox
11. Mechanical disc brake
12. Machine foundation
13. Blade hub
14. Blade bearing
15. Blade
16. Main shaft
17. Hub controller

Description of the Wronki wind farm

The Wronki wind farm is situated in the Region of Warmia and Mazury near Gołdap, by national road No 65 from Węgorzewo to Gołdap.

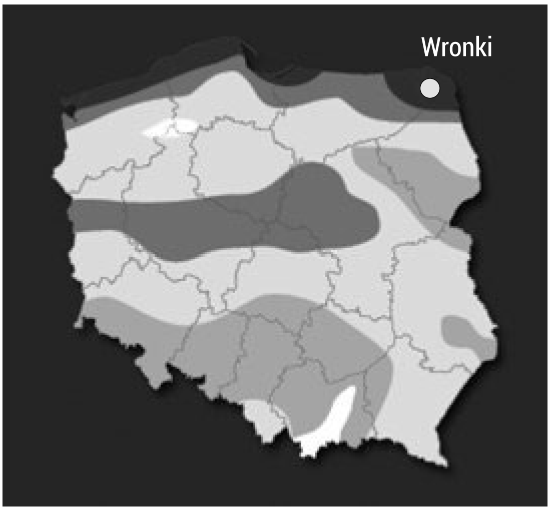

Figure 2. Location of the Wronki wind farm

The wind farm comprises 16 Vestas V90-3.0 MW wind turbines, and its total installed capacity is 48 MW. The wind farm has a transformer station, and it is connected to the 110 kV power grid. It was commissioned for use in 2010, and it has been in operation since 2011 (https://vortex-energy-group.com/pl/).

The wind farm is situated between plots of arable land in the vicinity of several farms. It is accessed by hardened dirt roads which had been built for the needs of the project. The roads provide local residents with access to the nearest town and farm fields (http://in-ventus.com/content).

Wind turbines are not marked with numbers in chronological order, and some numbers have been omitted. This is because a higher number of 2 MW wind turbines had been initially designed, but 16 3 MW turbines were ultimately installed with total installed capacity of 48 MW (http://goldap.wm.pl). The location of turbines in the wind farm is presented in figure 3.

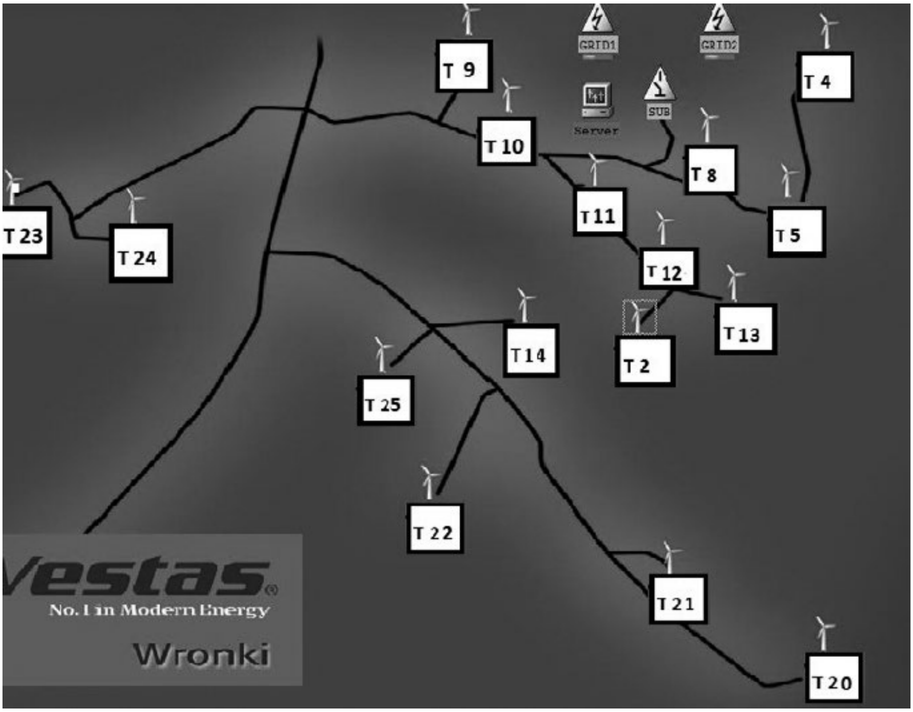

Figure 3. Location of turbines in the Wronki wind farm

Source: company materials.

The Wronki wind farm is managed by In.Ventus Sp. z o. o. sp. k of Poznań which designs and manages wind farms in Poland and Germany. The company manages several wind farms in Poland, including Mogilno, Wronki, Śniatowo, Dobrzyń and Inowrocław, and in Germany, including Lilet (Lubośny, 2017).

Analysis of electricity generation, wind speeds and turbine availability in the Wronki wind farm in 2014-2016

In a wind turbine, the rotor and the blades are propelled by wind energy. The rotor's mechanical energy is converted to electricity by a generator. The conversion of the wind's kinetic energy to electricity can be described with the following formula (Lewandowski, 2006):

$$P = C_p \cdot \eta_m \cdot \eta_{el}\, 0.5 \cdot \rho \cdot v^3 \cdot A$$

where:
P – power output of a wind turbine,
C_p – wind turbine power coefficient,
η_m – mechanical efficiency of the rotor and auxiliary systems,
η_{el} – electrical efficiency of the generator, transducers and transformers,
ρ – air density determined by temperature and humidity,
υ – wind speed,
A – swept area of a wind turbine.

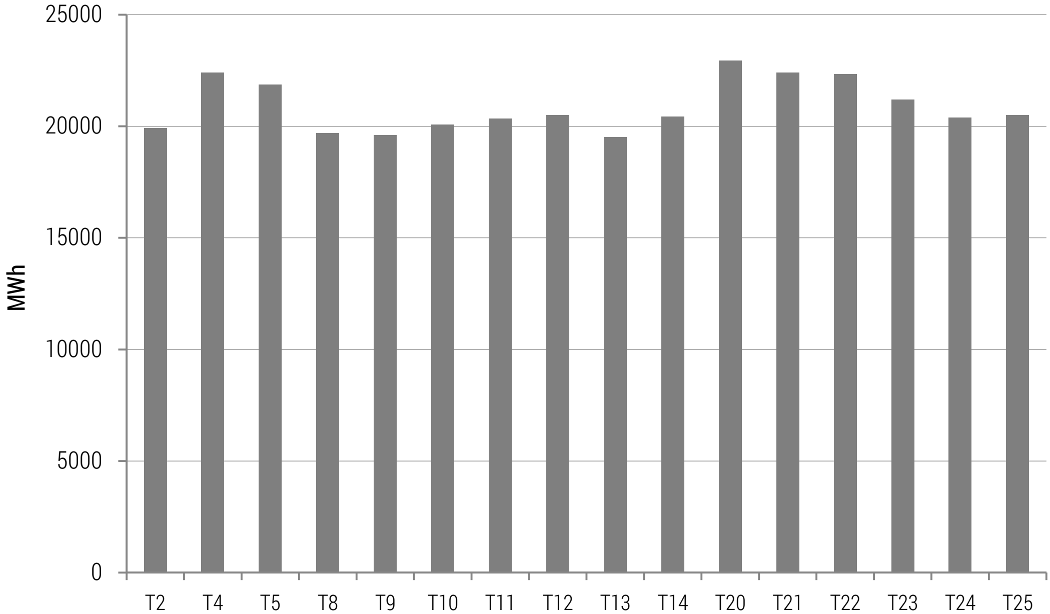

Figure 4. Energy output of each turbine in the Wronki wind farm in 2014-2016

Table 1. Energy output of the Wronki wind farm in 2014-2016 [MWh]

Turbine	T2	T4	T5	T8	T9	T10	T11	T12	T13	T14	T20	T21	T22	T23	T24	T25	Together
January 2014	1172	1195	1195	1161	1112	1118	1182	1193	1137	1152	1266	1258	1219	1116	1176	1152	18804
February 2014	773	832	832	667	688	746	679	708	755	795	468	851	872	874	858	761	12160
March 2014	657	741	741	652	672	680	648	710	680	611	783	752	743	706	681	678	11135
April 2014	407	462	462	395	385	397	403	423	395	401	480	449	462	421	433	417	6793
May 2014	435	486	486	422	408	407	396	410	433	437	520	422	484	484	485	453	7168
June 2014	353	392	392	346	347	352	362	345	321	373	412	344	404	349	377	364	5835
July 2014	379	454	454	382	341	338	340	394	408	394	460	438	455	422	206	374	6238
August 2014	384	411	411	340	367	366	387	404	359	371	457	429	444	401	375	366	6272
September 2014	405	475	475	401	364	287	359	389	409	399	468	439	458	424	410	381	6543
October 2014	485	822	822	747	746	761	777	696	779	782	742	780	825	791	809	778	12141
November 2014	689	713	713	604	566	564	612	632	666	687	754	727	693	655	681	640	10598
December 2014	754	820	820	743	786	798	781	571	709	768	855	817	841	813	699	775	12350
January 2015	1002	1064	1064	986	1000	1023	935	1009	969	1031	1104	1083	1067	936	634	1033	15940
February 02 015	552	570	570	546	549	561	571	558	512	559	543	619	609	586	595	566	9068
March 2015	686	746	746	675	669	674	687	686	636	703	785	726	756	735	741	696	11345
April 2015	626	749	749	685	691	698	701	698	626	705	765	731	741	689	659	676	11189
May 2015	427	498	498	450	411	429	437	446	344	447	513	503	497	480	466	442	7289
June 2015	262	258	258	253	225	240	254	248	214	214	282	268	211	270	272	225	3952
July 2015	437	508	508	435	444	441	444	461	402	431	506	497	434	465	439	424	7278
August 2015	304	410	410	310	347	337	331	388	390	368	438	423	416	390	405	393	6059

Turbine	T2	T4	T5	T8	T9	T10	T11	T12	T13	T14	T20	T21	T22	T23	T24	T25	Together
September 2015	416	485	485	177	393	400	424	416	430	401	504	481	486	475	322	446	6742
October 2015	586	652	652	548	524	527	567	598	550	579	673	640	602	567	575	572	9411
November 2015	754	826	826	762	773	801	807	772	720	773	869	825	846	797	781	790	12721
December 2015	924	1039	1039	966	997	998	1022	1009	848	945	1108	1054	1062	974	969	965	15919
January 2016	497	664	612	520	433	603	601	609	565	600	691	659	658	577	545	527	9361
February 2016	783	848	789	768	748	791	801	782	698	791	887	853	876	834	840	801	12890
March 2016	390	454	436	397	368	384	407	402	399	412	492	465	433	446	428	413	6726
April 2016	445	490	449	434	400	434	456	455	431	427	540	517	461	470	447	457	7314
May 2016	312	341	316	284	285	284	288	310	302	272	352	331	312	289	302	284	4863
June 2016	316	350	320	318	292	283	305	306	276	322	357	315	326	347	344	319	5096
July 2016	270	347	298	316	291	306	302	308	270	295	368	354	344	307	296	310	4981
August 2016	381	401	376	363	389	402	410	388	352	352	471	444	450	426	408	380	6393
September 2016	243	283	205	247	257	248	257	268	229	239	317	294	284	256	236	240	4102
October 2016	918	969	938	849	824	804	827	889	907	906	983	961	941	842	911	850	14320
November 2016	818	863	793	799	740	812	800	834	766	824	887	859	867	852	850	820	13185
December 2016	685	791	723	741	760	775	782	775	627	666	850	797	766	721	730	720	11909
Total [MWh]	19925	22409	21861	19692	19593	20068	20346	20488	19511	20435	22949	22408	22344	21188	20385	20489	334091

Source: author's own work based on company materials [2017].

The power of a wind turbine is a function of wind speed to the third power. The energy output of a wind turbine is determined by turbine power and its operating time.

The energy output (MWh) of the analyzed wind farm, average monthly wind speeds (m/s) and turbine availability (%) in 2014-2016 are presented in table 1.

In 2014-2016, the combined energy output of the Wronki wind farm was 334,091 MWh. The energy output of each turbine in the analyzed period is presented in figure 4.

The monthly power output of the wind farm in 2014-2016 is presented in figure 5.

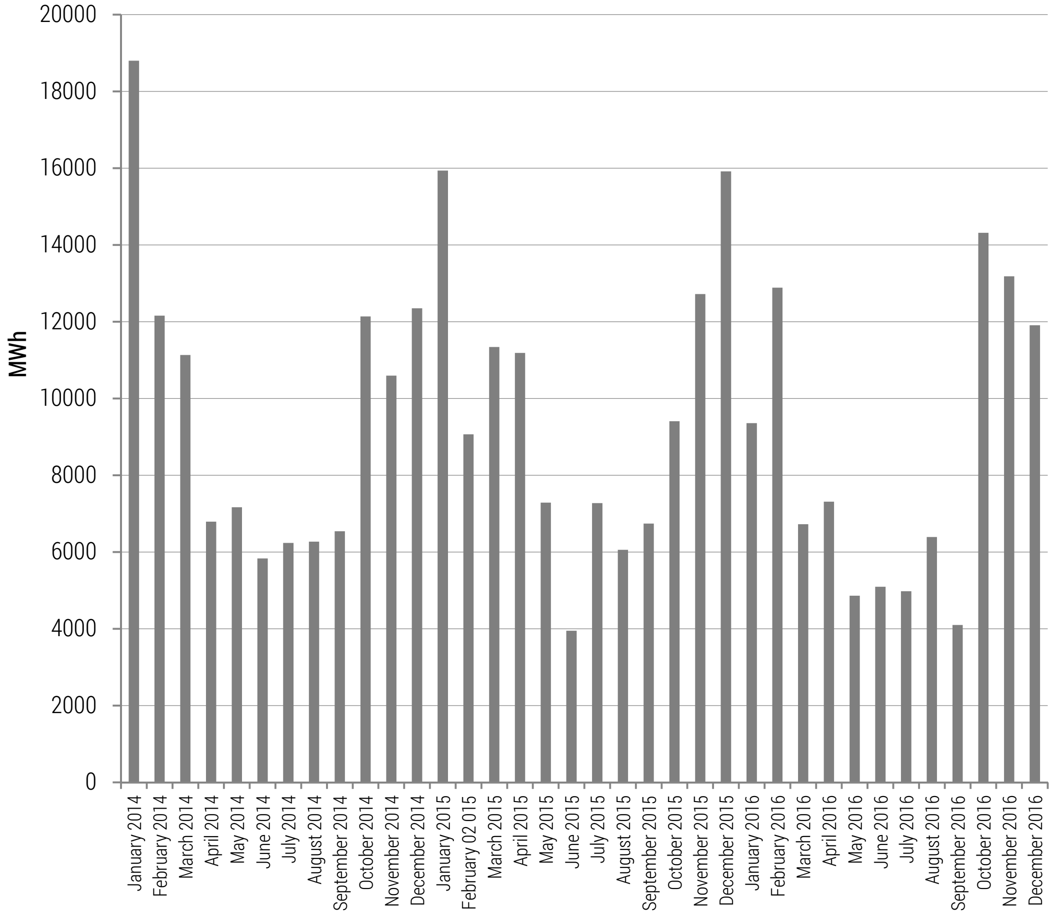

Figure 5. Monthly power output the Wronki wind farm in 2014-2016

Annual power output of the Wronki wind farm in 2014-2016:

- 2014 – 116,036 MWh,
- 2015 – 116,914 MWh,
- 2016 – 101 140 MWh.

The above data were analyzed to identify the turbine with the highest power output in the analyzed period. In 2014-2016, the highest amount of energy was generated by turbine WTG20 whose output reached 22,949 MWh at average wind speed of 7.62 m/s. The availability of turbine WTG20 was determined at 96.3%. Wind speed and turbine location are the critical determinants of turbine performance. In 2014, maximum energy output was 18,804 MWh in January, and minimum energy output was 5835 MWh in June. In 2015, maximum power output was 15,940 MWh in January, and minimum power output was 3952 MWh in June. In 2016, maximum power output was 14,320 MWh in October, and minimum power output was 4102 MWh in September.

Wind speeds in the Wronki wind farm in 2014-2016

Wind speeds measured in different turbines and at different heights over a period of three consecutive years (2014-2016) are presented in table 2.

The average wind speed measured in different turbines in 2014-2016 is presented in figure 6.

Table 2. Average monthly wind speeds in the Wronki wind farm in 2014-2016 [m/s]

Turbine		T2	T4	T5	T8	T9	T10	T11	T12	T13	T14	T20	T21	T22	T23	T24	T25	Average wind speed [m / s]
January 2014	2014-01	9,90	9,90	10,00	10,20	9,00	9,40	9,50	9,80	9,50	9,40	10,50	9,90	9,80	9,30	9,50	9,60	9,70
February 2014	2014-02	8,50	8,50	8,70	8,40	7,40	7,90	8,00	8,00	8,00	7,90	7,10	8,40	8,50	8,60	8,40	8,10	8,15
March 2014	2014-03	7,20	7,50	7,30	7,40	6,90	7,00	7,10	7,30	7,00	7,00	8,20	7,50	7,40	7,20	7,10	7,20	7,27
April 2014	2014-04	6,10	6,40	6,40	6,20	5,80	5,90	6,00	6,00	6,00	5,80	6,80	6,30	6,20	6,00	6,20	6,10	6,14
May 2014	2014-05	6,10	6,30	6,30	6,30	5,90	5,90	5,90	6,00	5,90	6,00	7,00	6,20	6,20	6,30	6,30	6,20	6,18
June 2014	2014-06	5,90	6,30	5,80	6,10	5,80	5,80	5,80	5,80	5,50	5,90	6,60	6,00	6,10	6,00	6,00	6,00	5,96
July 2014	2014-07	6,10	6,60	6,50	6,40	5,80	5,90	5,90	6,10	6,20	6,00	7,00	6,50	6,50	6,30	6,40	6,00	6,26
August 2014	2014-08	5,80	6,00	5,80	5,90	5,70	5,90	5,90	6,00	5,60	5,70	6,70	6,10	6,20	6,20	6,00	5,90	5,96
September 2014	2014-09	6,30	6,70	6,60	6,30	5,90	5,80	5,90	6,60	6,20	6,00	7,00	6,40	6,50	6,40	6,20	6,10	6,31
October 2014	2014-10	7,30	7,70	7,70	7,60	7,10	7,20	7,30	7,30	7,30	7,30	8,20	7,50	7,60	7,60	7,60	7,50	7,49
November 2014	2014-11	7,40	7,60	7,40	7,30	6,50	6,90	6,90	7,20	7,20	7,30	8,20	7,50	7,30	7,50	7,40	7,20	7,30
December 2014	2014-12	7,80	7,90	7,60	7,80	7,50	7,70	7,70	7,60	7,30	7,50	8,50	7,80	7,90	8,10	7,60	7,60	7,74
January 2015	2015-01	9,00	9,10	8,80	9,00	8,60	8,80	8,10	8,80	8,40	8,60	9,80	9,00	8,90	9,30	8,80	8,90	8,87
February 02 015	2015-02	7,10	7,00	6,90	6,90	6,50	6,80	6,80	6,90	6,50	6,80	7,70	7,10	6,90	7,20	7,00	6,90	6,94
March 2015	2015-03	7,60	7,60	7,70	7,50	7,00	7,10	7,20	7,30	7,10	7,30	8,20	7,50	7,50	7,80	7,50	7,40	7,46
April 2015	2015-04	7,50	8,00	7,70	7,90	7,50	7,60	7,60	7,60	7,10	7,50	8,40	7,70	7,80	8,00	7,50	7,60	7,69
May 2015	2015-05	6,20	6,40	6,30	6,40	5,80	5,90	6,00	6,10	4,70	6,00	6,80	6,30	6,30	6,50	6,20	6,10	6,13
June 2015	2015-06	5,30	5,30	5,20	5,40	5,00	5,10	5,20	5,20	5,00	5,30	5,80	5,50	5,40	5,50	5,40	5,20	5,30
July 2015	2015-07	6,40	6,60	6,40	6,50	6,20	6,30	6,30	6,30	6,00	6,30	7,20	6,60	6,50	6,70	6,30	6,30	6,43

Turbine		T2	T4	T5	T8	T9	T10	T11	T12	T13	T14	T20	T21	T22	T23	T24	T25	Average wind speed [m / s]
August 2015	2015-08	5,40	6,20	6,40	6,00	5,60	5,60	5,80	6,10	5,80	5,70	6,60	6,10	6,10	6,10	6,00	5,90	5,96
September 2015	2015-09	6,50	6,70	6,70	4,00	6,10	6,10	6,30	6,30	6,40	6,40	7,20	6,60	6,70	6,70	6,50	6,50	6,36
October 2015	2015-10	6,90	7,10	7,10	6,70	6,30	6,30	6,50	6,70	6,50	6,60	7,60	6,80	6,70	6,50	6,60	6,60	6,72
November 2015	2015-11	7,90	8,10	7,80	8,20	7,70	8,00	8,00	8,00	7,60	7,70	8,80	8,00	8,10	8,40	8,00	7,90	8,01
December 2015	2015-12	8,70	8,90	8,60	9,00	8,60	8,80	8,70	8,80	8,10	8,40	9,90	8,80	9,00	9,20	8,70	8,70	8,81
January 2016	2016-01	6,98	7,29	7,15	7,15	6,53	6,89	7,01	7,11	6,80	6,97	7,90	7,23	7,21	7,19	6,92	6,86	7,07
February 2016	2016-02	8,41	8,60	8,62	8,44	7,77	8,06	8,14	8,14	7,59	8,01	9,23	8,42	8,44	8,89	8,38	8,20	8,33
March 2016	2016-03	6,11	6,46	6,48	6,21	5,71	5,93	6,00	6,05	5,92	5,99	6,83	6,30	6,11	6,45	6,21	6,05	6,18
April 2016	2016-04	6,39	6,52	6,39	6,36	5,89	6,09	6,19	6,28	6,12	6,14	7,04	6,58	6,41	6,55	6,31	6,22	6,34
May 2016	2016-05	5,14	5,65	5,49	5,46	5,21	5,23	5,24	5,40	5,30	5,13	5,97	5,53	5,50	5,42	5,44	5,29	5,40
June 2016	2016-06	5,51	5,83	5,57	5,77	5,30	5,20	5,47	5,47	5,35	5,58	6,12	5,68	5,61	5,93	5,80	5,55	5,61
July 2016	2016-07	5,26	5,60	5,43	5,64	5,26	5,35	5,35	5,35	5,18	5,40	6,04	5,63	5,60	5,70	5,50	5,43	5,48
August 2016	2016-08	5,91	6,09	6,07	5,97	5,87	5,99	6,05	6,01	5,64	6,01	6,82	6,19	6,29	6,47	6,11	6,01	6,09
September 2016	2016-09	5,04	5,33	5,03	5,21	4,98	4,93	5,00	5,12	4,79	4,91	5,73	5,25	5,19	5,24	4,64	5,02	5,09
October 2016	2016-10	8,38	8,78	8,95	8,41	7,72	7,87	7,86	8,18	8,14	8,18	9,25	8,30	8,31	8,65	8,37	8,08	8,34
November 2016	2016-11	8,05	8,45	8,17	8,36	7,59	7,91	7,67	8,15	7,68	7,90	8,88	8,04	8,11	8,72	8,16	8,01	8,12
December 2016	2016-12	7,85	8,21	8,04	8,22	7,80	7,92	7,93	8,01	7,23	7,28	8,87	8,03	7,85	8,17	7,74	7,75	7,93
Together	V śr	6,89	7,15	7,03	6,96	6,55	6,70	6,73	6,86	6,57	6,72	7,62	7,04	7,02	7,13	6,91	6,83	6,92

Source: author's own work based on company materials [2017].

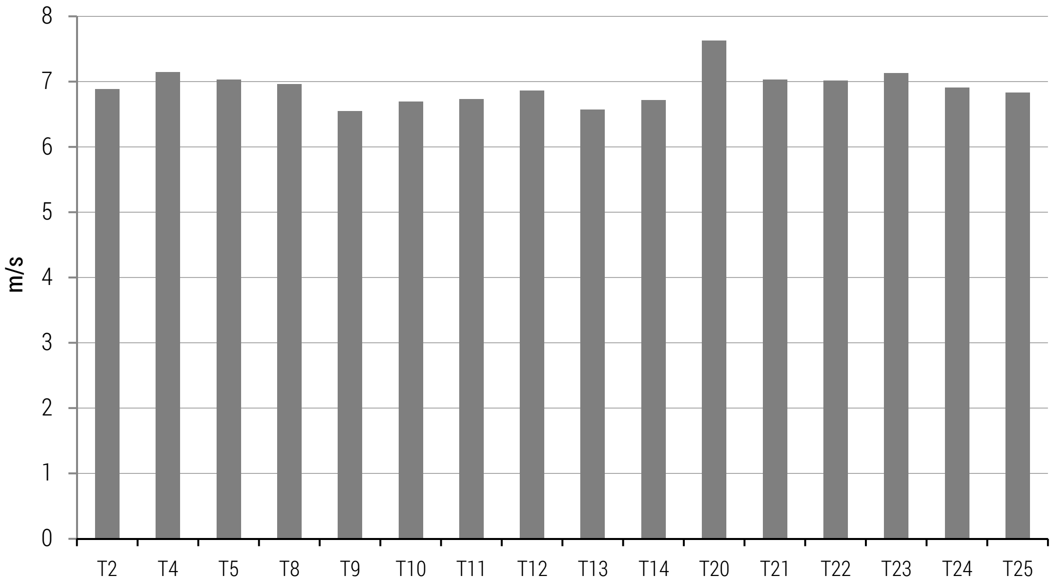

Figure 6. Average wind speed measured in different turbines in 2014-2016

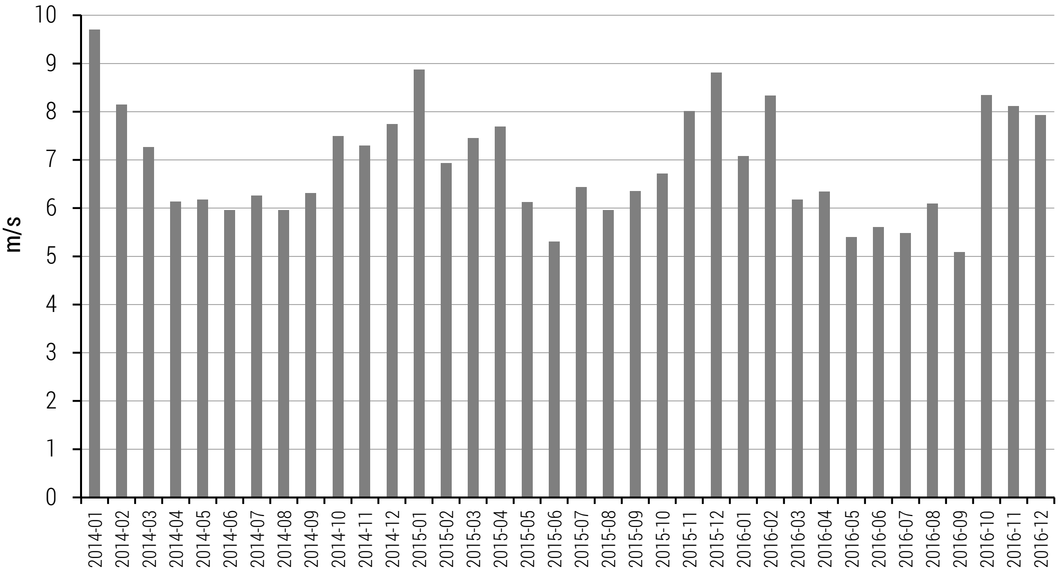

Figure 7. Average monthly wind speed in 2014-2016

Average annual wind speed in 2014-2016:

- 2014 – 7.04 m/s,
- 2015 – 7.06 m/s,
- 2016 – 6.67 m/s.

The data presented in table 2 indicate that average wind speed was 6.92 m/s in 2014-2016. In every analyzed year, wind speeds were higher in fall and winter months, which increased the wind farm's energy output in these seasons. In spring and summer months, winds were generally weaker, but sufficient for energy generation. The highest average wind speeds of 9.7 m/s and 8.9 m/s were noted in January 2014 and January 2015, respectively. In 2016, the highest wind speed of 8.3 m/s was noted in October and February. Average wind speed in the analyzed farm ranged from 6.8 m/s to 8.2 m/s, which is a highly satisfactory result. The Region of Warmia and Mazury is characterized by high wind speeds, and it belongs to the first energy zone according to the classification system of the Polish Institute of Meteorology and Water Management. The least windy months in the analyzed period were June (6.0 m/s and 5.3 m/s), August (6.0 m/s) and September (5.09 m/s).

The highest wind speed was registered by turbine T20 which is situated remotely from the remaining turbines in the wind farm. Turbine T20 is surrounded by empty space, and it is separated by a considerable distance from a forest. Somewhat lower wind speeds were registered by turbines 21, 22, 23, 24 and 25. These turbines are situated practically along the same line, they are surrounded by a forest on one side and by farm fields and pastures on the other side.

The remaining turbines are more clustered, and they occupy an area with variations in altitude. They are not situated in the vicinity of a forest, and they are surrounded by farm fields. The only exception is turbine T2 which is set in close proximity to trees.

Figure 8. Distribution of turbines in the Wronki wind farm. From the left: turbines T8, T4 and T5

Source: http://goldap.wm.pl.

Table 3. Turbine availability in the Wronki wind farm in 2014-2016 [%]

Turbine	T02	T04	T05	T08	T09	T10	T11	T12	T13	T14	T20	T21	T22	T23	T24	T25	Together
January 2014	99,9%	99,3%	98,0%	99,9%	99,5%	99,1%	99,9%	99,9%	100,0%	99,9%	99,7%	99,9%	99,9%	99,9%	98,2%	99,3%	99,5%
February 2014	99,9%	99,7%	100,0%	90,2%	99,7%	99,6%	99,4%	96,9%	99,3%	99,9%	67,3%	100,0%	100,0%	99,9%	99,7%	99,7%	96,9%
March 2014	99,9%	99,5%	97,3%	99,0%	99,7%	99,5%	96,6%	99,9%	99,9%	95,8%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,1%
April 2014	100,0%	99,9%	99,9%	98,3%	99,7%	99,9%	100,0%	99,4%	99,3%	99,7%	99,9%	99,9%	99,9%	100,0%	98,9%	100,0%	99,7%
May 2014	100,0%	99,9%	97,1%	98,6%	99,7%	100,0%	99,5%	99,9%	99,9%	99,5%	99,7%	97,9%	99,7%	99,4%	99,6%	99,5%	99,4%
June 2014	99,7%	97,5%	100,0%	99,7%	98,9%	99,7%	98,6%	99,1%	99,6%	99,9%	99,9%	95,1%	99,7%	99,0%	100,0%	99,6%	99,1%
July 2014	98,8%	99,9%	99,8%	99,6%	99,9%	99,7%	97,0%	99,9%	99,5%	99,3%	99,5%	99,6%	99,9%	95,9%	99,7%	99,5%	99,2%
August 2014	99,7%	100,0%	99,9%	97,9%	99,5%	99,6%	99,6%	99,9%	99,9%	99,9%	99,9%	99,7%	100,0%	98,9%	99,5%	98,5%	99,5%
September 2014	99,9%	99,9%	100,0%	99,7%	99,9%	92,3%	98,2%	99,9%	100,0%	100,0%	99,7%	99,1%	99,9%	99,6%	99,9%	98,1%	99,1%
October 2014	82,1%	97,4%	99,9%	99,7%	100,0%	98,5%	99,9%	93,5%	100,0%	100,0%	97,5%	97,7%	99,9%	99,9%	99,9%	99,7%	97,8%
November 2014	100,0%	99,4%	99,9%	99,9%	99,9%	97,3%	99,9%	99,9%	99,7%	99,9%	99,9%	99,6%	99,9%	99,7%	99,9%	99,9%	99,6%
December 2014	100,0%	100,0%	99,9%	100,0%	99,6%	100,0%	98,5%	87,3%	100,0%	99,9%	100,0%	99,9%	99,7%	99,9%	88,8%	99,9%	98,3%
January 2015	99,9%	99,7%	99,2%	99,9%	99,2%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,5%	93,3%	93,8%	99,9%	99,0%
February 02 015	100,0%	100,0%	99,9%	99,9%	99,7%	99,9%	99,9%	99,4%	99,9%	97,7%	99,8%	100,0%	99,7%	99,9%	99,9%	100,0%	99,7%
March 2015	98,1%	99,9%	99,7%	99,7%	100,0%	99,9%	100,0%	99,9%	97,1%	100,0%	99,9%	97,1%	99,5%	100,0%	99,9%	100,0%	99,4%
April 2015	100,0%	99,9%	100,0%	99,7%	99,9%	100,0%	100,0%	99,7%	99,9%	100,0%	99,9%	100,0%	99,2%	100,0%	100,0%	99,9%	99,9%
May 2015	99,1%	99,6%	99,9%	99,7%	99,9%	99,9%	100,0%	99,7%	99,5%	99,7%	99,9%	100,0%	99,7%	99,6%	99,9%	99,6%	99,7%
June 2015	99,4%	96,1%	99,7%	96,3%	99,4%	99,5%	99,5%	99,4%	95,3%	97,3%	99,7%	99,9%	96,6%	95,7%	99,4%	96,5%	98,1%
July 2015	99,9%	99,9%	99,9%	99,6%	99,9%	99,7%	97,7%	99,9%	99,7%	95,7%	96,7%	99,7%	93,8%	99,7%	98,8%	94,8%	98,5%
August 2015	89,6%	98,0%	99,7%	93,0%	99,7%	98,7%	96,6%	98,8%	99,7%	99,2%	100,0%	99,1%	99,0%	99,5%	99,5%	99,9%	98,1%

Turbine	T02	T04	T05	T08	T09	T10	T11	T12	T13	T14	T20	T21	T22	T23	T24	T25	Together
September 2015	99,4%	99,6%	99,6%	90,5%	99,4%	99,4%	99,4%	97,1%	99,9%	92,7%	99,4%	99,6%	99,6%	99,3%	77,1%	99,7%	97,0%
October 2015	99,7%	99,9%	98,5%	99,2%	99,5%	99,7%	99,7%	100,0%	98,4%	99,9%	99,9%	98,9%	99,9%	99,9%	99,9%	99,1%	99,5%
November 2015	100,0%	99,9%	99,7%	99,7%	99,6%	99,9%	100,0%	97,1%	99,9%	99,9%	99,9%	99,4%	100,0%	99,9%	93,0%	99,6%	99,2%
December 2015	99,9%	99,9%	99,9%	100,0%	100,0%	100,0%	99,9%	99,9%	99,9%	99,9%	99,9%	100,0%	99,9%	99,9%	99,6%	99,7%	99,9%
January 2016	97,4%	99,7%	100,0%	95,0%	93,5%	99,9%	99,4%	100,0%	99,9%	99,9%	100,0%	100,0%	99,9%	98,5%	95,9%	97,5%	98,5%
February 2016	100,0%	99,9%	99,9%	10,0%	10,0%	99,9%	99,9%	99,9%	99,9%	10,0%	100,0%	99,6%	100,0%	100,0%	100,0%	99,9%	83,0%
March 2016	100,0%	99,6%	100,0%	99,9%	99,9%	99,6%	99,9%	1,0%	100,0%	100,0%	100,0%	99,9%	98,9%	99,7%	99,9%	99,9%	93,6%
April 2016	99,9%	100,0%	99,9%	99,7%	97,3%	100,0%	100,0%	99,9%	99,4%	98,2%	99,9%	99,0%	96,1%	100,0%	97,5%	99,7%	99,2%
May 2016	99,9%	99,6%	99,9%	99,9%	99,5%	9,9%	1,0%	100,0%	99,9%	100,0%	100,0%	98,6%	97,8%	98,2%	99,9%	97,3%	87,6%
June 2016	99,6%	99,6%	98,5%	99,9%	99,7%	100,0%	99,6%	99,9%	95,1%	99,9%	99,6%	92,2%	98,8%	99,4%	99,6%	99,6%	98,8%
July 2016	9,6%	100,0%	99,7%	99,7%	99,6%	99,9%	98,8%	99,7%	100,0%	99,0%	99,6%	99,6%	99,7%	99,7%	9,9%	99,7%	88,4%
August 2016	98,9%	99,2%	99,9%	99,6%	99,7%	99,7%	98,9%	10,0%	99,6%	88,4%	99,5%	10,0%	100,0%	99,7%	10,0%	98,4%	82,0%
September 2016	99,9%	99,7%	97,5%	99,9%	100,0%	99,7%	99,9%	99,7%	100,0%	100,0%	99,7%	99,6%	99,6%	99,9%	99,7%	99,4%	99,6%
October 2016	99,9%	10,0%	99,7%	99,9%	99,9%	99,9%	99,7%	99,9%	99,9%	100,0%	10,0%	10,0%	99,7%	97,8%	100,0%	97,7%	82,7%
November 2016	98,7%	99,9%	1,0%	100,0%	96,9%	100,0%	99,6%	99,9%	100,0%	99,7%	99,9%	99,7%	99,6%	99,6%	99,7%	100,0%	93,4%
December 2016	99,9%	97,3%	10,0%	99,7%	99,1%	100,0%	10,0%	100,0%	99,7%	10,0%	99,9%	99,7%	96,9%	10,0%	100,0%	99,9%	77,0%
Together	96,3%	96,9%	94,2%	96,2%	96,9%	96,9%	94,1%	93,8%	99,4%	93,9%	96,3%	94,2%	99,2%	96,7%	93,2%	99,2%	96,1%

Source: author's own work based on company materials [2017].

Turbine availability in the Wronki wind farm in 2014-2016

Turbine availability in the analyzed period is presented in table 3. The availability of every turbine was expressed in percentage terms [%] as the amount of time when the turbine was able to produce electricity during the analyzed period (2014-2016).

The availability of each turbine in the analyzed wind farm in 2014-2016 is presented in figure 9.

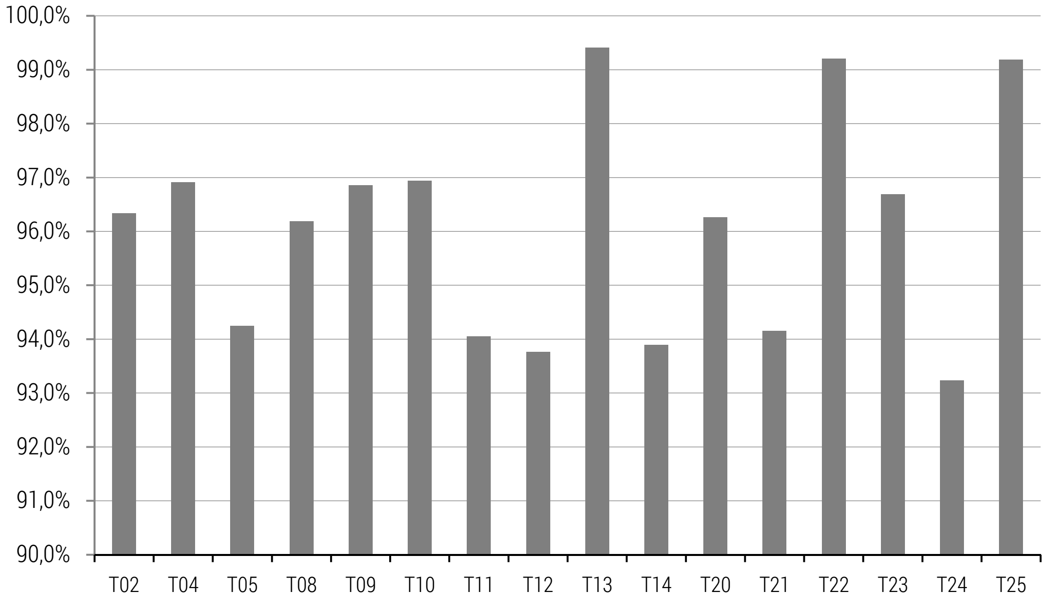

Figure 9. Average turbine availability in 2014-2016

Average annual turbine availablity in 2014-2016:

- 2014 – 98.9%,
- 2015 – 99.0%,
- 2016 – 90.3%.

Turbine availability is the amount of time that a turbine is able to produce electricity over a certain period. Regardless of wind speed, a turbine's status is set to RUN when the turbine is in operation or is waiting for cut-in wind speed. A turbine's operating time and availability decreases every time it is shut down for repair, inspection or maintenance.

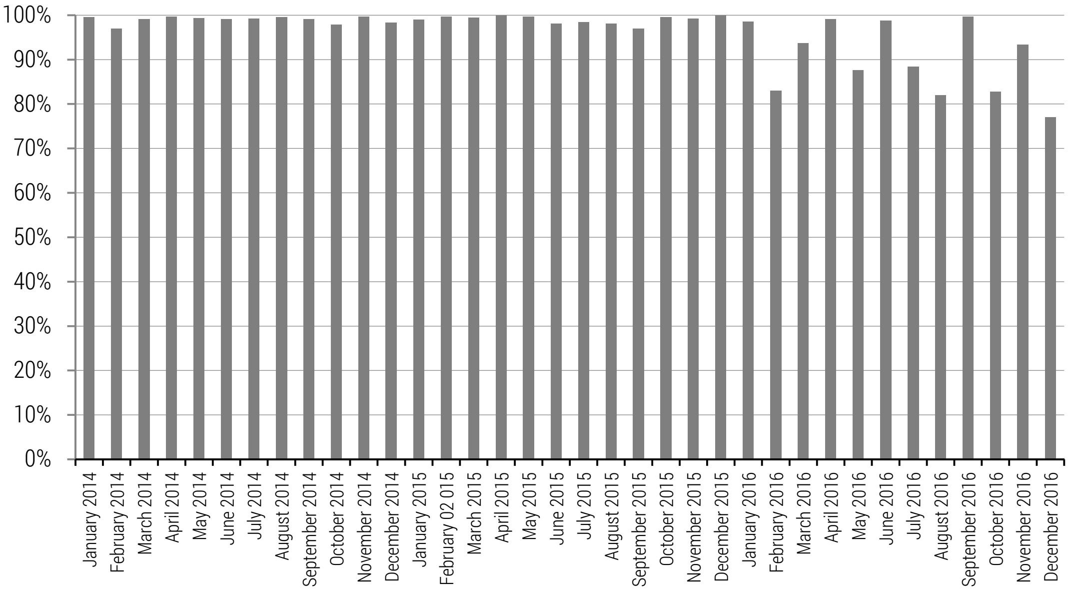

Figure 10. Average monthly turbine availablity in 2014-2016

In the analyzed wind farm, turbine availability approximated 100% on numerous occasions during the examined period. The lowest availability was noted when a turbine was shut down due to a failure of a critical component. The replacement required specialist equipment, trained personnel and cranes. The operation was prolonged due to strong winds and severe winter weather, which significantly decreased the turbine's availability in that month.

Economic performance

According to the Polish Power Exchange, the average price of 1 MWh of electricity was PLN 184.94 in 2014, PLN 158.97 in 2015 and PLN 169.70 in 2016. The average price of 1 MWh of electricity in 2014-2016 was PLN 171.20 (https://www.tge.pl). In 2014-2016, the Wronki wind farm generated 334,091 MWh of electricity, therefore, the value of production for the analyzed period based on the average annual price of PLN 171.20/MWh was PLN 57,196,379. The value of green certificates was not included in the above calculations because their price varies. The current price is around PLN 50 per 1 MWh, and it marks a nearly 80% decrease from 2014 when the prices of green certificates peaked at around PLN 250 per 1 MWh. In 2014-2016, the highest income of PLN 2,908,971.32 was achieved by turbine WTG20 ID 32487, and the lowest income of PLN 2,347,802.03 – by turbine WTG8 ID 32488.

Environmental impact

Unlike conventional power plants which emit considerable amounts of pollutants such as CO_2, SO_2, NO_x, CO and dust, wind farms generate clean energy and do not pollute the environment. Pollution emissions from coal-fired power plants in 2014 based on the data of the National Center for Emissions Management are presented in table 4. The above data were used to calculate pollutant emissions associated with the generation of equivalent amounts of energy in a conventional coal-fired plant.

Table 4. The amount of pollutants that would have been generated in the production of 334,091 MWh of electricity in a conventional power plant

Type of pollution		CO_2	SO_2	NO_x	CO	Dust
Emissions from conventional power plants	kg/MWh	831.500	1.572	1.049	0.235	0.064
Emissions avoided by the wind farm	Mg	277,7967	525.2	350.5	78.1	21.3

Source: author's own work [10-10-2017].

The data in table 4 indicate that significant amounts of CO_2, SO_2, NO_x, CO and dust emissions were avoided by the Wronki wind farm during the generation of 334,091 MWh of electricity in the analyzed period.

Conclusions

In 2014-2016, the Wronki wind farm generated 334,091 MWh of electricity, and its total revenue was calculated at PLN 57,196,379 based on the average price of electricity of PLN 171.20/MWh. Average wind speed was 6.92 m/s in the analyzed period. High average wind speeds in the evaluated wind farm confirm that the Region of Warmia and Mazury belongs to the first energy zone according to the classification system of the Polish Institute of Meteorology and Water Management. In 2014-2016, turbine T20 was characterized by the highest energy output of 22,948.8 MWh, and turbine T13 – by the lowest energy output of 19,511.0 MWh. The energy output of turbines in the Wronki wind farm was relatively similar, and the output of individual turbines did not deviate from the mean value of 20,880.7 MWh by more than 10%. Considerable variations in average wind speed and energy output were noted on a monthly basis. The highest wind speeds were observed between November and March, and the lowest wind speeds were recorded between May and August.

Wind farms significantly reduce pollutant emissions which are associated with the generation of equivalent amounts of energy in conventional coal-fired plants. Wind power is a renewable resource that is widely available and not confined to international trade agreements.

The article presents the data collected on the Wronka wind farm in the years 2014-2016 and analyzes the amount of energy produced by individual turbines depending on wind speed and turbine availability. This made it possible to estimate the economic benefits associated with electricity production. A comparison of pollutant emissions on a wind farm and a conventional power plant has been presented. This data may help potential investors to analyze the profitability of wind farms in long-time period.

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