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Development of the Wind Generation Sector and Its Effect on the Grid Operation—The Case of Poland

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Abstract: One of the main factors for changes in the structure of the energy mix in Poland is the development of renewable energy sources, in particular wind generation. In 2009–2020, the installed capacity of wind sources in Poland increased more than ninefold. At the same time, new legislation significantly curbed the development of onshore wind farms. Further development of wind energy in Poland will rely largely on offshore wind farms. The current state of development of wind power in Poland allows for analyses of the onshore part of wind energy development in Poland. The paper aims to conduct a detailed analysis of the Polish wind sector from an electric power generation perspective. This article presents a comprehensive discussion of the development of onshore wind generation in Poland. In particular, analyses address the production of electric power from wind. Various time horizons are taken into account, as well as the correlation of wind generation with demand for power in the Polish Power System (PPS). The results of the analysis indicate a high variability of wind generation throughout the month or year. The largest wind generation occurred during the night valley, which makes it difficult to operate the power system. In the winter months, wind generation is much greater than in the summer months. Monthly average values of the capacity factor for onshore wind farms (WFs) vary from 0.14 in August to 0.48 in February. Moreover, the coefficient of determination R^2 close to zero shows a lack of correlation between offshore wind power generation and real power demand in the PPS. The studied high variability of wind generation in PPS can be mitigated by the wide use of electricity storage systems. Moreover, the obtained results can be part of a model to describe the energy mix in Poland.

Keywords: wind energy; onshore wind farms; energy mix; Poland; wind generation profiles; grid operation

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1. Introduction

1.1. Background

The COP21 Agreement, signed in 2015 in Paris by all countries of the world, commits them to limiting the rise of average global temperature by 2 °C [1]. The main goal of the European Green Deal is climate neutrality of the European Union by 2050 [2]. Such initiatives have been undertaken in a situation where the generation of electricity and heat in Poland is based mainly on coal burning [3]. Poland ranks second in lignite production and first in hard coal production in the EU [4]. Energy sources using coal and lignite produce over 85% of electricity in Poland [5]. However, the shrinking reserves of fossil fuels [6], excessive carbon dioxide emissions by the manufacturing [7] and transportation sectors [8], climate change [9], and Poland's membership of the EU make RES increasingly significant [10].

Poland is making efforts to change its energy mix, based on goals of the European Green Deal [11]. In the case of Poland, technologies such as low-carbon coal technologies with CCS by 2050 [12], with non-carbon options including nuclear [13], biomass IGCC [14,15], photovoltaic, onshore, and offshore wind [16].

Embarking on energy transition has recently increased the share of electricity generated from renewable sources, especially wind, in Poland. The share of renewable energy sources in electricity generation increased more than five times in the period 2020–2016 in Poland [17]. This resulted in a reduction of the share of carbon sources by 12%. Further wind generation development, mainly by offshore wind farms, is considered a strategic project in Polish Energy Policy 2040 (PEP2040), which has been approved in 2021 [18]. The development of the wind energy sector and electricity generation profiles have huge impact on the power balance in the electric power grid in Poland. This aspect of wind power is the subject of this paper. The research problem discussed in this paper is determining the variability of onshore wind generation in Poland. It is assumed that the research will be carried out regarding the functioning of a large electric power system such as PPS.

1.2. Motivation

No publication has yet carried out a detailed analysis of Polish wind sector from electric power generation perspective. Currently, wind power development in Poland has reached a plateau. It means that the installed capacity of wind sources has been increasing only slightly. Therefore, an analysis that would verify existing concerns and set out the direction for further development of onshore and offshore wind power is much needed. This paper provides a comprehensive analysis of electricity generation from wind in various time horizons. Moreover, the analysis of the correlation wind generation and power demand in the Polish Power System presented here. These analyses are important for assessing the operation of the power system, but may also be helpful in building a market model for wind generation.

1.3. Review of Related Works

The production of electricity from wind has great potential and application possibilities all over the world [19]. As a key component of the energy mix in the transition period, wind generation has been a hot research topic in Poland. An alternative scenario to PEP2040 for the energy mix in Poland in 2040 is described in [20]. The concept of Energy Policy for Poland 2050, which may enable the transition to a low-emission energy mix, is described in [21]. On the other hand, the results regarding various scenarios of the energy mix until 2050 in Poland are presented in [22]. A comparison of various long-term scenarios for the Polish energy mix, resulting in different CO_2 emissions, is also discussed in [23]. An optimization model of an ideal Polish energy mix in terms of capital and operational expenses is proposed in [20]. Opportunities for the development of the renewable energy sector and its impact on the labor market in Poland are analyzed in [24]. Advantages and disadvantages of particular types of RES, as well as difficulties regarding the development of renewable energy in Poland, are presented in [25].

The history and general prospects for the development of the wind power sector in Poland are discussed in [26]. The current capacity of wind power generation in Poland based on wind speed variations is analyzed in [27]. The development in the wind energy sector in Poland in 2012–2013 is described and analyzed in [28]. Paper [29] presents issues related to the use of renewable energy sources, including wind, in Poland, while article [30] concerns the construction of offshore wind farms in the Baltic Sea area. The impact of wind energy sector on thermal power plants in the Polish energy system is analyzed in [31]. Legislation applicable in Poland related to investments in wind power plants is analyzed in [32]. Evaluation of the onshore wind development scenarios cost is conducted in [33]. The economic analysis regarding the investment in a wind farm in relation to the legislation in force in Poland is presented in [34].

1.4. Contributions and Paper Organization

The novelty of the paper can be highlighted as follows: (i) Detailed analysis of Polish wind sector from electric power generation perspective; (ii) Comprehensive analysis of electricity generation from wind in various time horizons; (iii) Analysis of the correlation wind generation and power demand in the Polish Power System.

The remaining part of this paper is organized as follows. Section 2 presents the characteristics of development of the Polish wind power sector. Section 3 analyses the energy mix, including wind source changes, in the last decade. Section 4 addresses electricity generation from wind and its impact on power grid operation. The last section concludes.

2. Stages of Development of Wind Power in Poland

2.1. Development of Onshore Wind Power—Prior to Poland Joining the EU

During the post-World War II period, after being brought into the Eastern Bloc (1945 to 1989), the Polish economy was developing for decades based on coal energy sources, owing to its large coal resources [35] and geopolitical reasons [36]. Economic transformation after 1989 [37] and Poland's European aspirations [38] made it possible to change this. As a result, in the early 21st century, wind power production started to grow [39]. This was facilitated by the adopted legislation. The "Energy Law" Act adopted in 1997 has laid down general directions for Poland's new energy policy [40]. That Act defined renewable sources, including wind energy processing sources. After that, the "Renewable Power Development Strategy" [41] adopted by the Parliament of the Republic of Poland in 2001 set out a priority goal for Poland, being to increase the share of renewable sources to 7.5% by 2010 and 14% by 2020 in the structure of consumption of primary energy. Regulation of the Minister of Economy [42] provided for quantities (percentages) of mandatory RES power purchases by power utilities. Selected paths of early stage of wind energy development in Poland are described in [43].

Before Poland joined the EU in 2004, the installed capacity of wind sources in Poland was 63 MW [44].

2.2. Development of Onshore Wind Power—After Poland Joining the EU

A key importance for the market of renewable energy, including wind energy, in Poland, was the implementation of successive Directives of the European Union (EU). Since Poland joined the EU in 2004, the most important was the Directive on the promotion of energy from renewable sources [45] which replaced prior Directives [46,47], as was subsequently amended by Directive [47]. The most important domestic regulations for the development of RES in Poland include the Act on Biocomponents and Biofuels [48] and the Act amending the "Energy Law" Act (since 2005), which introduced a system of certificates of origin as a system to support RES power [49], a new RES support system based on auctions, introduced in 2015 [50]. The Act [50] also defines the principles for the implementation of the national action plan for energy from renewable sources.

In the case of Poland, in accordance with the Directive [45], a goal was set out to generate 15% of energy from renewable sources in Poland by 2020. The projects to achieve the targets set out in Directive [45] were implemented largely based on the Responsible Development Strategy (with perspective to 2030) [51], Poland's 2030 Energy Policy [52], National Plan of Action for Energy from Renewable Sources [53].

Since 2015, RES auctions have been held in Poland to stimulate the development of such generating sources [54]. In recent years, Poland's government has been successively buying power through the auctioning system from installations that are yet to be built, including onshore wind farms (WFs), which has attracted investor interest [55].

In 2016, the Polish Parliament passed the Act regarding investments in wind power plants [32]. The Act specified, among other things, the minimum distance between wind turbines and buildings. This distance was determined to be ten times the height of the turbine tower. Introducing such a restriction without consideration of local contexts has led to a paradoxical situation where wind turbines cannot be situated, even in industrial and environmentally degraded lands. Therefore, in practice, the 2016 law significantly restricted wind power expansion [4].

For several years we have observed the dynamic development of renewable energy in Poland. In 2005–2016, energy from wind sources was the fastest growing category of RES in Poland, achieving a nearly 70-fold increase [56]. At the end of 2020, the installed capacity of onshore wind farms was 6347 MW [57].

The PEP2040 document anticipates further development of onshore wind farms, which would most likely involve legislative amendments [58]. The work aimed at relating the regulations that are now in an advanced stage [59]. Potential further growth of capacity of onshore wind farms is estimated at 6 GW [60].

According to Energy Regulatory Office (ERO) data [44], 1239 wind farms operated in Poland in late 2020, including 1111 with more than 10 MW capacity (89.7%) and 128 with capacity more than and including 10 MW. The power generated and fed by wind sources to the Polish Power System has also been steadily increasing. The largest onshore wind farm in Poland by installed capacity is FW Potęgowo with the capacity of 219 MW. A summary of the largest onshore wind farms in Poland is provided in Table 1.

Table 1. Poland's largest onshore wind farms.

Farm	Capacity	No. of Turbines/Turbine Power/Type	Year Built	Farm
Potęgowo	219 MW	81/(2.5 MW and 2.75 MW)	2020	Potęgowo
Margonin	120 MW	60/2 MW/Gamesa G90	2009	Margonin
Banie	106 MW	53/2 MW/Vestas V100	2016	Banie
Marszewo	100 MW	50/2 MW/Vestas V80 and V90	2013	Marszewo
Lotnisko	94.50 MW	30/3.15 MW/Alstom ECO 110	2015	Lotnisko
Karścino	90 MW	60/1.5 MW/Fuhrländer FL MD77	2009	Karścino

2.3. Development of Offshore Wind Power

Poland also has ambitions and strategy [18] (PEP2040) to join countries that have developed offshore wind power. Poland has access to the Baltic Sea, which offers a number of advantages for building wind farms: average wind velocities on the appropriate level [61], small depth [62], and low salinity [63]. Poland's maritime areas have been described in detail in [64], however it should be noted that Poland has 843 km of coastline [65]. The depth of sea waters in the Polish part of the Baltic Sea ranges from 10 to 100 m.

PEP2040 estimates that the potential of Offshore WFs by 2040 is about 11 GW, and generation capacity is close to 50 TWh annually [66]. The first Polish offshore wind farm is anticipated to be put into operation by 2025. The installed power of offshore winds farms is estimated to potentially reach 5.9 GW by 2030.

The implementation of offshore wind power is defined by a strategic project as part of PEP2040. Of key importance for Offshore projects is how far they can be balanced in the Polish Power System and development of grid infrastructure: offshore and onshore transmission lines, and offshore substations [16]. In several years from now, onshore wind farm will be joined by offshore farms on the Baltic, now in the design phase [56,67]. It is worthwhile to note that key legislation has been drafted and adopted to develop wind power in Poland, including the Act of 17 December 2020 on the promotion of power from offshore wind farms, and Regulation of the Minister of Climate and Environment of 30 March 2021 on the maximum price for electric power from offshore wind farms. These pieces of legislation provide funding for offshore wind farm projects, which is key to their implementation and thus achieving strategic economic targets. Table 2 shows a list of the most promising Polish Offshore WF projects.

Table 2. Characteristics of contemplated Polish Offshore WFs [16,68,69].

Name	Capacity [MW]	Average Wind Speed [m/s]	Depth Range [m]	Distance from Shore [km]	Name
Bałtyk I	1560	8.88	32–48	80	Bałtyk I
Bałtyk II	720	8.97	23–34	37	Bałtyk II
Bałtyk III	720	8.99	25–34	22	Bałtyk III
Baltica 2	1498	8.97	22–52	39	Baltica 2
Baltica 3	1045.5	9.02	33–39	33	Baltica 3
Baltic Power	1200	8.50	20–30	25	Baltic Power

3. Poland's Energy Mix

Change of Mix Structure

One of the major factors affecting changes in the structure of energy mix in Poland is RES development. The analysis of energy mix in the Polish Power System (PPS) started in 2009. At that time, RES constituted 5% of maximum capacity from all sources. The biggest single group within RES in terms of maximum capacity was hydropower. Figure 1 presents the structure of PPS energy mix in 2009.

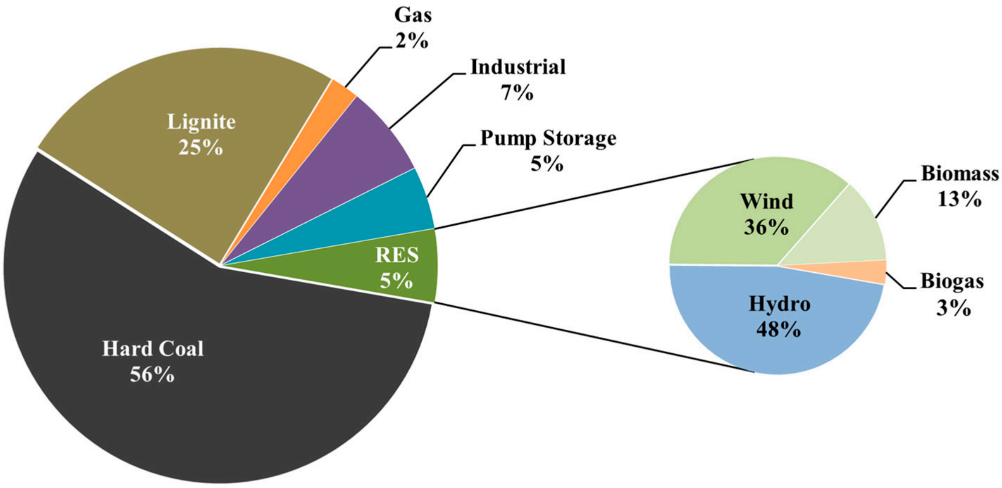

Figure 1. Structure of electricity generation sector in Poland in 2009 based on [55].

In the period leading to 2020, major changes occurred in the structure of energy mix in Poland. The share of RES in maximum power capacity from all sources increased from 5% in 2009 to 20% in 2020. This was largely due to onshore WF development, with capacity increasing from 720 MW in 2009 to more than 6350 MW in 2020 [55]. Thus, onshore WF is now the largest RES subgroup in Poland, corresponding to 64% of maximum capacity from such power sources. Among traditional energy sources, the share of gas-fired power plants increased from 2% in 2009 to 6% in 2020. No significant changes have occurred regarding industrial power plants and pumped storage power plants. Notably, the share of coal-fired power plants burning hard coal or lignite fell in 2020 in comparison to 2009. Figure 2 presents the structure of PPS energy mix in Poland in 2020.

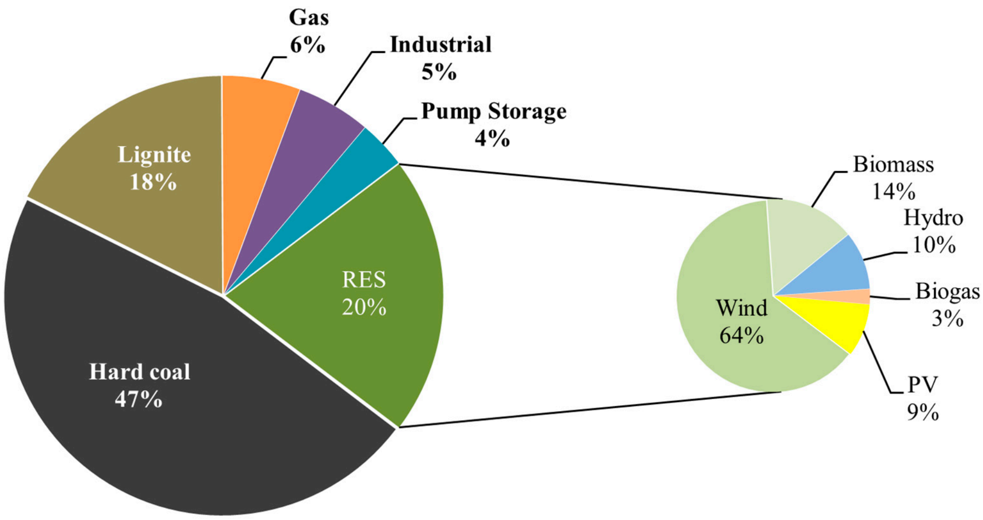

Figure 2. Structure of electricity generation sector in Poland in 2020 based on [55].

4. Installed Capacity of Wind Generation

Currently, in Poland, electricity from wind is generated in onshore WFs. Although there are advanced plans, no Offshore WFs have been built yet. However, several projects are underway to build these types of installations [16].

In 2009–2020, installed capacity of onshore WFs in Poland increased more than ninefold. The largest growth in capacity was in 2010–2013 by more than 35% year on year. In 2014–2016, the growth rate slowed down slightly to less than 20%. In 2017–2019 the development of onshore WFs was effectively stopped due to modification of the support system [55]. It was only in 2020 that a perceptible growth in installed capacity occurred, due to holding RES auctions. Figure 3 shows growth rates of onshore WF installed capacity in Poland in 2009–2020, with compound annual growth rate (CAGR). This rate was determined in accordance with the following formula [70]

$$CAGR = \left(\frac{X_E}{X_B}\right)^{\frac{1}{T_E - T_B}} - 1 \quad (1)$$

where X_B represents the baseline, X_E end value, T_B baseline year, and T_E end year.

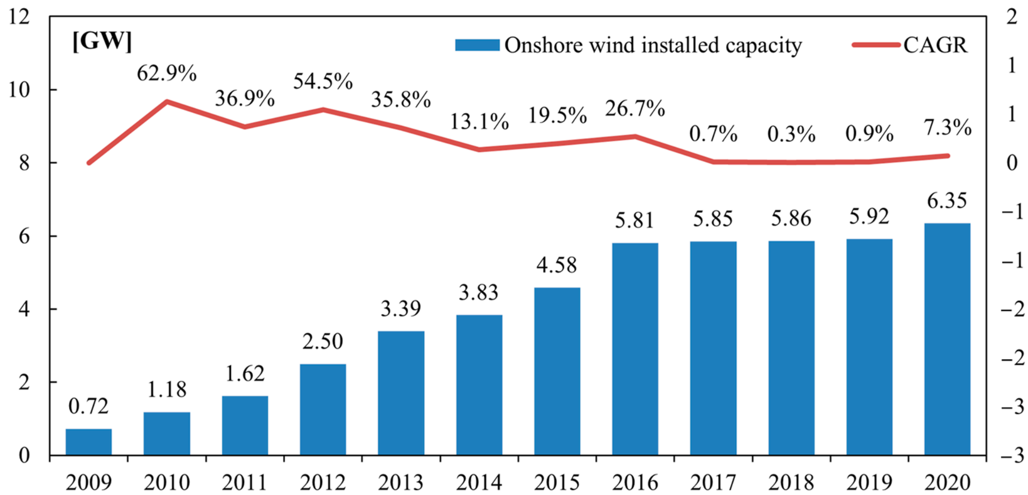

Figure 3. Onshore WF installed capacity in the PPS based on [57].

5. Analysis of Power Generation from Wind Sources and How It Affects the Operation of the Power System

The efficient and stable operation of wind farms is important for the realization of large-scale power systems [71]. To characterize the problem concerning PPS, comprehensive analyses of wind generation were performed. Statistical analysis of generation from wind farms was conducted based on historical data [72] for the last five years.

5.1. General Statistical Analysis

Figure 3 shows that onshore WF installed capacity in the PPS in 2016–2019 did not vary significantly. As a result, generation in that period was primarily affected by weather conditions. Meanwhile, the rise in generation in 2020 was also due to growth of installed capacity. The analysis is based on the data available on PSE S.A.'s (transmission network operator in Poland) website. The outcome of the analysis is presented in Table 3.

Table 3. Outcomes of statistical analysis of onshore WF generation in 2016–2020.

Parameter	Unit	2016	2017	2018	2019	2020
Installed capacity	[MW]	5807.42	5848.67	5864.44	5917.24	6347.11
Power generated	[TWh]	11,642.04	14,411.82	12,326.01	14,565.75	15,213.59
Capacity factor	%	22.82	28.13	23.99	28.10	27.29
Average hourly generation	[MWh]	1325.37	1645.19	1407.08	1662.76	1731.97
Maximum generation within hour	[MWh]	4891.73	5234.34	5195.93	5222.08	5729.17
Standard deviation of generation	[MWh]	804.23	946.83	838.06	945.85	903.83

The largest annual wind generation was in 2020. Among the years analyzed, 2020 also saw the largest maximum generation during the hour and maximum average value. Meanwhile, the biggest capacity factor was in 2019, despite the fact that the largest quantities were generated in 2020. In addition, standard deviation, which describes the hourly variability of wind generation, peaked in 2017.

5.2. Average Monthly Generation

Another aspect considered in comparing the profiles of wind generation across years was average monthly generation. Figure 4 presents average wind generation quantities in particular months of 2016–2020. A comparison of generation quantities in particular months reveals its significant variability, in particular for winter months. Maximum values in particular months occur for different years from the 2016–2020 range considered here.

Based on historical onshore WF generation data, a box plot was compiled that presents the capacity factor CF_{LFW}, and in particular, the months of 2020. Values for this factor were based on Formula (2), and the plot is presented in Figure 5.

$$CF_{\mathrm{LFW}} = \frac{P^{i,j}_{\mathrm{GLFW}}}{P^{i,j}_{\mathrm{OLFW}} \cdot T^{j}} \quad (2)$$

where $P^{i,j}_{\mathrm{GLFW}}$ represents real power generated by onshore WFs in i-th hour in j-th year, $P^{i,j}_{\mathrm{OLFW}}$ is the maximum capacity of onshore WFs in i-th hour in j-th year, and T^{j} number of hours in j-th year.

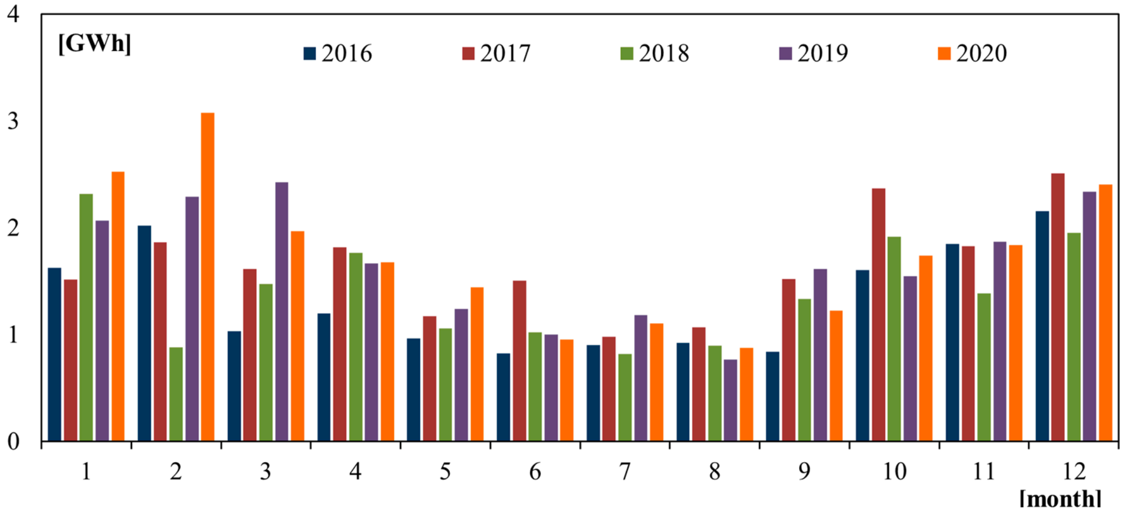

Figure 4. Average monthly wind generation in 2016–2020.

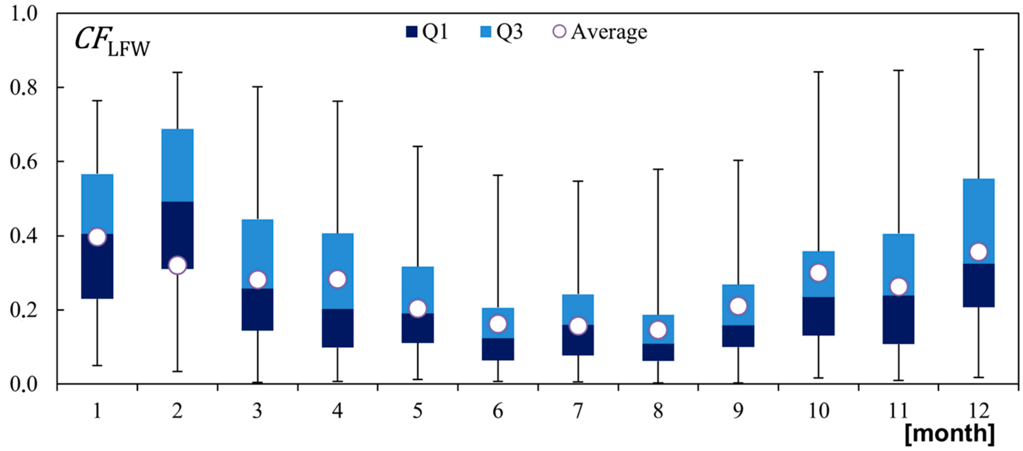

Figure 5. Box plot CF_{LFW} for 2020.

Further analysis considers the following summer months—June, July, and August—and the winter months include the rest of the year [73,74]. The shape of the box plot (Figure 5) indicates the high variability of wind generation throughout the year. In the winter months, wind generation is much more than in the summer months, as evidenced by the higher mean, and the average and maximum values for those months. In the winter months, the interquartile range is usually larger than in the summer months, which indicates larger wind generation variability in that period. Figure 6 presents the histogram of the capacity factor CF_{LFW} for 2020.

The histogram shows that the largest group in terms of the number of hours are CF_{LFW} values within the 0.05–0.1 range. For incrementing values of that factor, the numbers are gradually decreasing. For the summer months, there are values of the capacity factor above 0.6, which demonstrates lower wind generation in that period. Table 4 shows the results of statistical analysis CF_{LFW}, particularly the months of 2020.

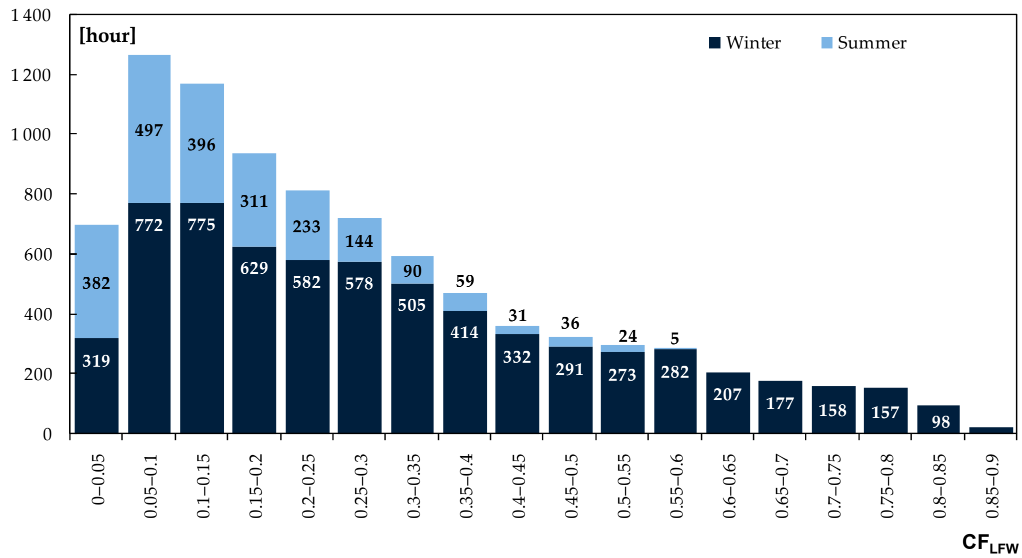

Figure 6. Histogram CF_{LFW} for 2020.

Table 4. Outcomes of CF_{LFW} statistical analysis for 2020.

Month	$\overline{CF}_{\mathrm{LFW}}$	max $\{CF_{\mathrm{LFW}}\}$	min $\{CF_{\mathrm{LFW}}\}$	σ_{LFW}	max $\{\Delta P^{i,j}_{\mathrm{GLFW}}\}$ [MW]	min $\{\Delta P^{i,j}_{\mathrm{GLFW}}\}$ [MW]
1	0.40	0.76	0.049	0.20	574.32	−761.42
2	0.48	0.84	0.034	0.23	601.02	−723.58
3	0.31	0.80	0.004	0.20	596.07	−754.02
4	0.26	0.76	0.007	0.20	1293.28	−694.50
5	0.23	0.64	0.012	0.15	612.38	−581.38
6	0.15	0.56	0.007	0.11	746.57	−661.10
7	0.17	0.55	0.005	0.11	604.58	−635.46
8	0.14	0.58	0.003	0.11	584.74	−814.75
9	0.19	0.60	0.003	0.13	685.79	−753.46
10	0.27	0.84	0.016	0.18	488.05	−615.62
11	0.29	0.85	0.010	0.22	642.54	−659.67
12	0.38	0.90	0.018	0.23	526.37	−529.25

The data in Table 4 indicate the strongly variable nature of onshore WF operation, as evidenced by monthly average values of the capacity factor for onshore WFs $\overline{CF}_{\mathrm{LFW}}$. It varies from 0.14 in August to 0.48 in February. Standard deviation of the onshore WF capacity factor σ_{LFW} is largest for the winter months, which is supported by box plot analysis (Figure 5). Hourly changes in wind generation $\Delta P^{i,j}_{\mathrm{GLFW}}$ demonstrate the extent to which wind generation affects the operation of Centrally Dispatched Generating Units (CDGU), which must reduce or increase their generation quantities by up to 1300 MW within one hour.

5.3. Relationship between Onshore WF Generation and Power Demand

A linear regression model and a correlogram were used to assess the relationship between wind farm production on land and power demand in the Polish Power System. Figure 7 presents the correlogram for 2020, which is the result of the analysis.

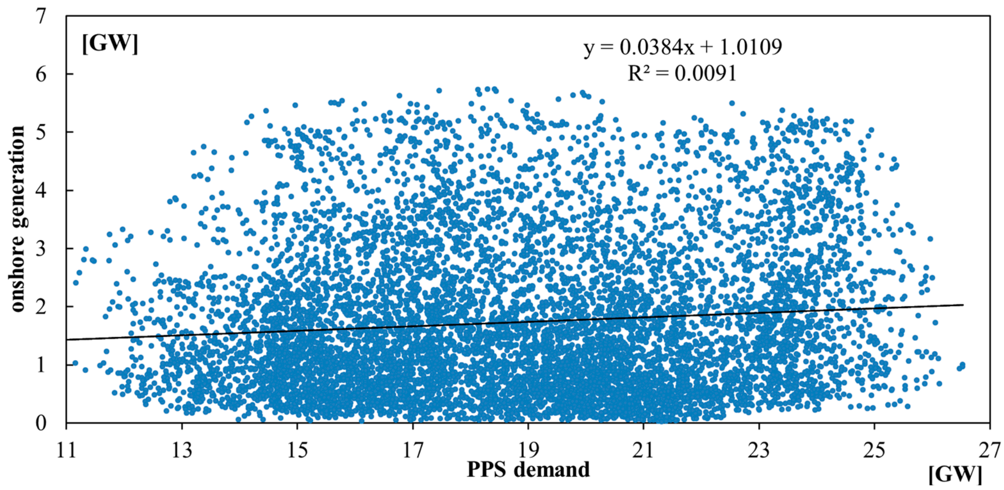

Figure 7. Correlogram of onshore generation and power demand in Poland, 2020.

The correlogram shape shows a total lack of correlation between offshore wind power generation and real power demand in the PPS. The coefficient of determination R^2 close to zero and almost zero slope ratio of the regression line demonstrate a lack of correlation. Stanisz's scale was applied to assess the strength of correlation between the studied quantities [75].

Table 5 presents the outcome of analysis of linear regression for wind generation for 2016–2020. The outcome shows no correlation between wind generation and power demand in the examined range, as proven by the coefficient of determination R^2 close to zero in each year.

Table 5. Outcomes of analysis of linear regression for onshore WF generation in 2016–2020.

Year	Linear Regression Equation	R^2
2016	y = 0.01x + 1.1384	0.00070
2017	y = −0.002x + 1.6838	0.00003
2018	y = −0.007x + 1.5464	0.00040
2019	y = −0.004x + 1.4789	0.00090
2020	y = 0.038x + 1.0109	0.00091

5.4. Daily Profile of Wind Generation

In the next step, aggregate wind generation values were compared to the daily profiles presented in Figure 8. Profiles for 2017, 2019, and 2020 are situated higher in comparison to the profiles for 2016 and 2018, which corresponds to the outcome of wind generation analysis in the annual scale (Table 3).

The analysis of profiles demonstrates that the highest wind generation occurred during the night valley. Meanwhile, it would fall significantly during the morning and evening peaks. The shape of the daily profile of wind generation across the years did not vary significantly. Statistical analysis of average daily generation profiles for wind farms was conducted, and the outcome is presented in Table 6.

The analysis consisted of the aggregation of onshore WF generation data for the year to compile daily profiles, which are shown in Figure 9, with PPS power demand profiles presented separately for the winter and summer months.

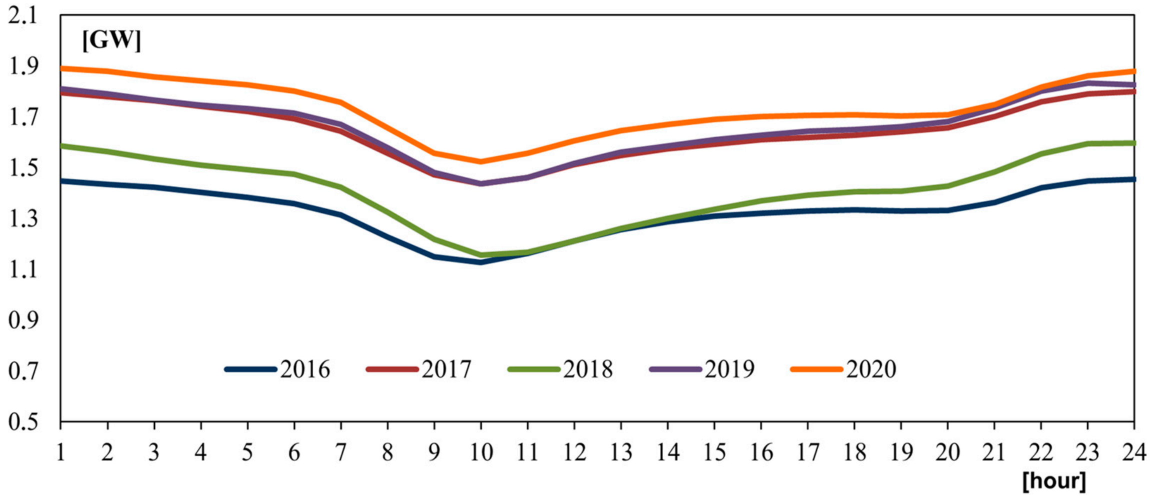

Figure 8. Daily profiles of wind generation in 2016–2020.

Table 6. Results of analysis of daily profiles of Onshore WF generation and power demand, 2020.

Profile	$\bar{x}$ [GW]	σ_{10-21} [GW]	α_{MP} [o]	α_{EP} [o]
Onshore WF generation—winter	1.99	0.10	−2.95	2.04
Onshore WF generation—summer	0.98	0.16	−1.34	−2.78
Demand—winter	19.17	2.17	46.09	12.53
Demand—summer	17.78	2.17	44.25	0.37

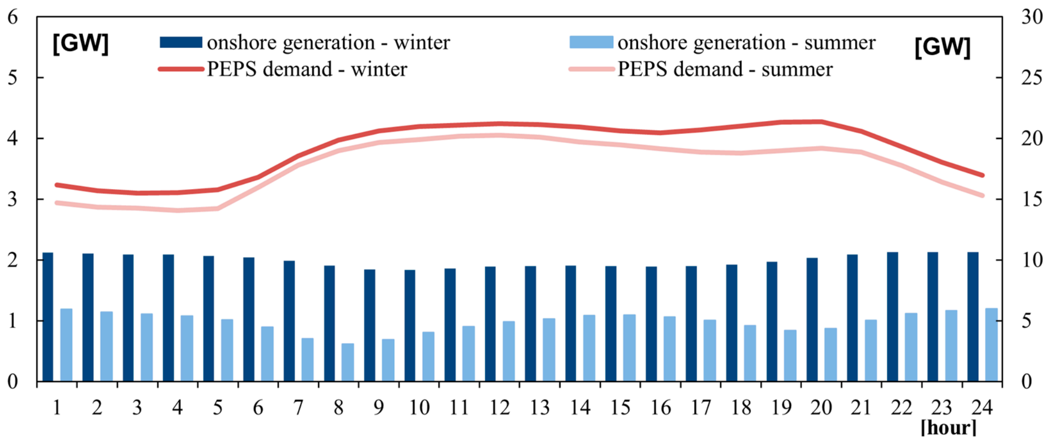

Figure 9. Daily profiles of onshore WF generation and power demand, 2020.

The resulting curves are subjected to statistical analysis conducted using selected indicators. The first one was the average value $\overline{x}$. This indicator allowed us to compare onshore WF generation intensity and demand between the winter and summer months. From Table 5, in winter, both wind generation and power demand were more intensive than in the summer season.

Next, onshore WF generation variability and demand between the morning and evening peaks, i.e., between 10 am and 9 pm, were analyzed. In this case, standard deviation σ_{10-21} was used. The results shown in Table 5 demonstrate that onshore WF generation in winter is less variable than in summer. For power demand, standard deviation for the winter season is larger than for the summer season, which indicates a higher variability of daily demand in the former season.

To assess the increment rate of wind generation and power demand in time, curve slope α_p was determined based on the following relationship:

$$\alpha_p = arctg(a) \quad (3)$$

where α_p represents curve slope for range p of the day and a represents curve slope ratio.

Depending on the phenomenon studied, the time bracket in which the slope α_P was investigated would change. The slope in the daily profile for the value of morning peak α_{MP} was specified between 6 and 10 am. The slope of the daily profile for the evening peak α_{EP} was specified for a time range between 4 and 8 pm.

For power demand, the upslope angle during the morning peak α_{MP} for the summer period is larger than in the winter period. In the winter period α_{EP}, the upslope angle is positive, which means that demand in the evening peak is more than in the morning peak. For the summer period, demand in the morning peak is more than in the evening peak, which makes the upslope angle α_{EP} negative.

For onshore WF generation, upslope angle α_{MP} is negative both in summer and in winter. It means that generation is weaker during growing demand, which needs dispatching additional CDGUs in that period. For the evening peak, slope α_{EP} is negative in summer and positive in winter, as shown in Table 6.

5.5. Correlation between Wind Generation and Demand

The Pearson coefficient of correlation r_{xy} was used to determine the relationship between wind generation and demand. Figure 10 shows the Pearson coefficient of correlation r_{xy} values for the night valley (1 am–5 am), morning peak (6 am–10 am), and evening peak (4 pm–8 pm) for the winter and summer seasons, respectively. The aggregation of data shows a strong correlation between wind generation and power demand during the night valley, both in the summer and winter periods. For the morning and evening peaks, coefficients of correlation are negative, which means an inverse correlation between wind generation and power demand. The correlation analysis reveals potential power system balancing problems in demand peaks both in the summer and winter periods. Weakening onshore WF generation in the morning and winter peaks requires dispatching additional CDGUs. Therefore, the effect of variability of wind generation on CDGU operation is a major topic to be addressed.

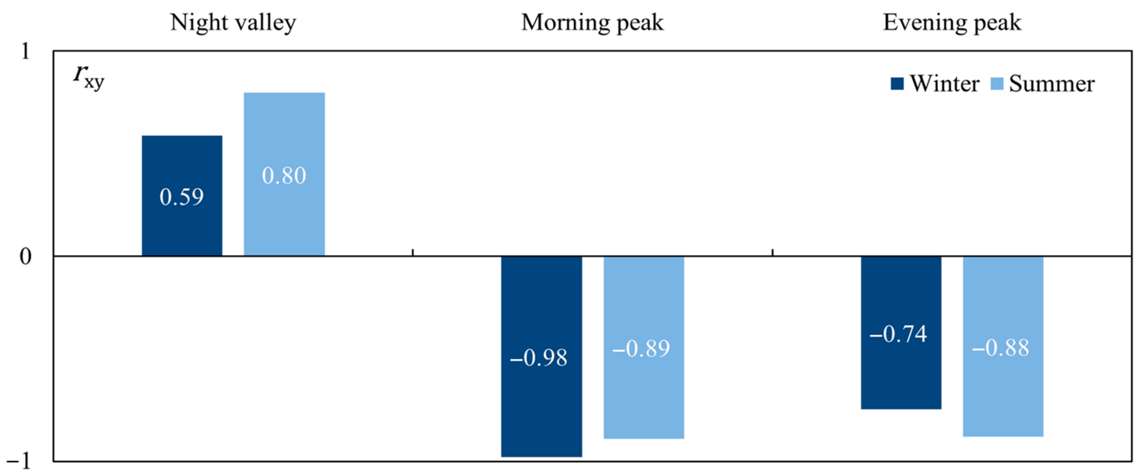

Figure 10. Correlation between onshore WF generation and power demand, 2020.

6. Conclusions

This paper describes the development of wind energy sector in Poland and analyzes electric power from wind. The periods before and after Poland's accession to the European Union were specified. The development of wind generation was noted to have involved onshore wind farm installations only. At the end of 2020, the installed capacity of onshore wind farms was 6.3 GW. Offshore wind farms are at the planning stage, and the first offshore installations are to be completed by 2025. However, 5.9 GW is planned in OWFs by 2030, which indicates a significant expansion. It needs to be highlighted that due to the regulations adopted by Poland, intensive development of OWFs was effectively stopped in 2016. Since that year, the installed capacity of wind sources has remained at a similar level. Therefore, the analysis of the operation of wind farms in 2016–2020 allows for assessing the variability of wind conditions in Poland. This paper provides a detailed analysis of parameters such as power and energy.

The analysis of the average monthly wind generation shows that in the winter months, wind generation is much higher than in the summer months. For the summer months, even 3 GWh was obtained, while for the summer months this value does not exceed 1.5 GWh. Moreover, wind generation shows a strongly variable nature, as evidenced by monthly average values of the capacity factor. Monthly average values of the capacity factor for onshore WFs vary from 0.14 in August to 0.48 in February. Wind generation in winter is less volatile than in summer. Moreover, the results of studies show a lack of correlation between wind generation and demand for power in the Polish Power System. This is indicated by the coefficient of determination R^2 being close to zero. The above disadvantages can be eliminated by using countermeasures in the form of energy storage—both battery storage and pumped storage power plants. In addition, the results of the research of daily profiles showed that the highest wind generation occurred during the night valley (positive correlation $0.59 \div 0.80$). The above contributes to rising difficulties in the operation and management of the power system. They can also be an issue in balancing the power system at peak demand. This also emphasizes the need to develop energy storage systems.

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