Dampening Variations in Wind Power Generation Through Geographical Diversification

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Abstract. Wind power is currently one of the most promising energy sources, both in Europe and across the world. In Poland, a large annual increase in the installed wind turbine capacity has been observed for many years. Power generation from wind turbines is related to wind parameters, which, in turn, result from changes in atmospheric conditions. This is why the observed wind speed has different values depending on time and place (location and altitude). This affects the amount of generated power and the continuity of its production. The authors of this article carried out an analysis of the potential of the diversification of wind energy sources in Poland. The research was conducted with the aim of assessing the variability of the potential production of electrical energy. The analysis concerned the volatility of the wind speed and the variability of available turbine power, as well as its distribution over appropriate points in the location grid – a set of combinations for every point in the location grid, aiming to present the effect of the diversification. For this purpose, the standard deviation in relation to the average power of wind turbines was selected as a comparative measure. The analyses were conducted based on historical wind measurements and data retrieved from the MERRA database. The results indicate that it is more advantageous for both the Polish power system and power plant owners (energy companies) to build smaller wind farms that are distant from each other and to group them in pairs in order to create a virtual power plant. Despite a wind-farm downtime of less than 15% for most of Poland in the analysed period, the existing power differences do not provide the possibility of ensuring continuity of energy supplies.

1. Introduction

The development of our civilization generates a constant need for electricity. Conventional energy power plants are unfriendly to the natural environment and are therefore the reason for growing interest in renewable power sources such as the wind. The radiation of the sun reaching the earth’s surface causes the wind to blow, creating energy. Wind power, however, is not directly correlated with solar energy. Fossil fuels are energy sources originating from the sun hundreds of millions of years ago. The use of fossil fuels is a cause of pollution and poses environmental hazards in proportion to the extent of its use, the degree of technological advancement and
the extent of exhaust treatment.

Wind energy is less damaging to the environment, as it is clean and does not cause air or water pollution. Infrasound and the shadow flicker generated by the huge blades of turbines, have been identified as substantial hazards to the environment, causing an increase of nervousness in nearby human populations [1,2]. Chiropterans and avifauna are both endangered by wind turbines [3]. Wind power generators have an economic impact of local, regional and national significance, generating social costs associated with infrastructure land adoption, real-estate price adjustment, impact on the landscape and inability to build any residential buildings in the near neighbourhood of wind generators [4].

Other barriers limiting the development of wind power stations include the high cost of power generation due to the high value of fixed costs, lack of financing instruments, high investment costs, limited wind measurements and poorly developed survey infrastructure [5].

The main challenge in wind energy development is overcoming the problem of variations in power generation. The variable and uncertain character of wind energy limits its usage in the national power generation system [6,7]. Sudden increases or drops in the power generated may have negative consequences for the power grid, at the same time increasing the costs associated with [7,8]:

- maintaining an adequate system reliability level,
- non-effective device operation in conventional power generation,
- the need to provide additional systematic services to balance the grid.

A higher level of instantaneous power variations raises the cost of power generation, therefore increasing the final long-term price [9].

Finding an effective way of reducing the instantaneous power variations in the wind-energy industry and making it more predictable, may limit the costs associated with the need to compensate for power fluctuations and may indirectly influence and reduce the price of electricity[10]. Geographical diversification (dispersion) of the wind power generators may serve this purpose, as suggested by Holttinen (2005), Sinden (2007), Archer and Jacobson (2007), Giebel (2007), Drake and Hubacek (2007), Milligan (2000), Warren et al. (2010) and Hasche (2010) [11-18]. At low and very high wind speeds, turbines do not generate any electricity. Wind-speed variations are characterized by local conditions potentially endangering the electrical grid via power instabilities generated in a restricted area [13], necessitating the dispersion of power generators to make the network safer and more reliable. The geographical diversification may improve forecasting of energy needs which can be satisfied by wind power stations introduced into the national grid and may therefore limit the use of extraordinary power-balancing reserves from conventional power generators (usually gas-powered generators) [11,15].

The diversification effect is more pronounced when the wind power stations are far away from each other. The distance diminishes the probability of stations failing to generate power at the same time [10]. The greater the geographical area, the more noticeable this fact becomes, leading to the possibility of increasing the power generated by wind power plants scattered across the national power grid [19]. The research undertaken by Holttinen (2005), Sinden (2007) and Giebel(2007) confirms this fact [13,15,17]. The ability to limit power variations decreases as geographical areas become smaller [20].

If we treat all wind power stations as one virtual station, then in accordance with portfolio analysis, an increase in dispersion leading to the reduction of power output variations makes the virtual station similar to units working within the baseload. The portfolio theory states that linking two independent or negatively correlated assets with stochastic characters, limits the portfolio’s variability, ensuring a more predictable outcome. The lower the wind-speed correlation coefficient or the momentary power output factor, the better the diversification effect, bringing stability and reliability to the national electrical grid [10]. Various studies show that as the distance between the power stations increases, the value of the wind speed correlation coefficient for the power stations decreases [13,15,17,21]. Sinden, for example, (2007) [17] discovered that the hourly correlation coefficient value among British wind farms decreases by about 0.1 with a distance increase of more than 100 km. Therefore, portfolio theory can be useful in finding optimal solutions with regard to the geographical diversification of wind farms [19].

Until recently, the subject of geographical diversification of wind farms, was a rare topic in the literature, especially in the area of assessing its influence on the activity of the farm. Kahn (1971) [22] was the first researcher to analyse the effects of the diversification of wind power stations. He observed that the wind farms
might replace a number of conventional power stations in the electrical grid. Holttinen (2005) [15] was the first to prove the positive aspects of geographical wind-farm diversification in the region. He undertook complex research for the Scandinavian countries. Archer and Jacobson (2007) [11] indicate that wind-farm diversification ensures the stability of wind power. They discovered that around 33% (but no more than 47%) of the yearly wind energy might be securely included into the power system grid. Reichenberg et al. (2014) [9] proved that geographical diversification makes it possible to reduce the output variability in wind farms in a given region by about 33%. These authors also testify that to be guided by correlation coefficient alone in choosing locations is inappropriate, as very windy locations will not necessarily be preferred. Milligan (2004) [16] proposes an algorithm based on production costs and the stability of the energy supply in order to find locations ensuring the greatest energy supply from wind farms. Qiao et al. (2014) [23], in their article, describe a probabilistic approach to assessing a company’s profits resulting from the uncertainty of wind speeds and the geographical scattering of wind farms.

The impact of the geographical diversification on reducing the output variability in wind farms in the studied regions, varied considerably. A small region or an island [11, 24], a whole country [12, 25] and the entire area of Europe [13,26] have been considered.

This article examines the prospect of geographical diversification of wind farms in Poland, and its potential effect on the stability and continuity of electricity production.

1.1 Wind Power Engineering in Europe

Table 1 shows the present state of wind power engineering in Europe. It shows the total wind farm power in selected European countries. There are prospects of further development in this field but as the need for expansion rises, so the necessity for reconstruction of the existing power grids on a large scale emerges, as until recently the wind farms constituted merely an addition to the systems, frequently interfering with their performance.

The objective of increasing the usage of renewable energy sources (RES) in power balancing is the goal of cooperation between wind power and solar power generation (concentrated solar power (CSP) and/or photovoltaics) [27,28]. Progress in scientific research on the implementation of renewable energy in power systems is aimed at limiting the negative influence of a discontinuous supply of energy.

Table 1. The aggregate power (MW) of wind turbines installed in selected European Union countries.

| Country          | 2005 | 2010 | 2015 |
|------------------|------|------|------|
| Austria          | 819.0| 1,011.0| 2,411.5|
| Belgium          | 167.4| 911.0| 2,228.7|
| Denmark          | 3,128.0| 3,752.0| 5,063.8|
| Finland          | 82.0| 197.0| 1,000.5|
| France           | 757.0| 5,660.0| 10,358.2|
| Greece           | 573.3| 1,208.0| 2,151.7|
| Spain            | 10,028.0| 20,676.0| 23,025.3|
| Holland          | 1,219.0| 2,237.0| 3,431.0|
| Ireland          | 495.5| 1,428.0| 2,486.3|
| Germany          | 18,414.9| 27,214.0| 44,946.1|
| Poland           | 83.0| 1,107.0| 5,100.0|
| Portugal         | 1,022.0| 3,898.0| 5,079.0|
| Romania          | 1.7| 462.0| 2,975.9|
| Sweden           | 509.5| 2,163.0| 6,024.8|
| Great Britain    | 1,332.0| 5,204.0| 13,602.5|
| Italy            | 1,718.0| 5,797.0| 8,957.8|
| European Union (28) | 40,517.0| 84,367.0| 141,578.8|
| Whole of Europe  | 40,898.0| 86,279.0| 147,772.0|
The potential of wind energy is enormous and encompasses the whole world. Scandinavia and the countries located in the western part of the European continent experience favourable wind conditions. Apart from the wind conditions and the energy needs, some other circumstances are reflected in the power values of the table (Table 1). These are: assistive measures as a stimulus for the implementation of specific projects, tax incentives and state subsidies [32,33].

1.2 Analysed Areas
The turbine location issue is widely discussed in the literature as one of the most important challenges for modern wind-farm energy production. Often, the lack of the right location creates a barrier to expanding wind-farm development. The reason is the high cost of obtaining wind condition measurements (which applies to poor countries). Such surveys are necessary, as the knowledge acquired is the basis for choosing the right wind turbine location [6,34]. Scientific descriptions on the topic of wind turbine locations are helpful in finding the right space. Let us mention here, as an example, an atlas providing wind maps, developed by the International Renewable Energy Agency (IRENA) [35].

The MapaWietrznosci Polski-CzystaEnergia report [36] confirms that the wind conditions in Poland are favourable enough for it to become an efficient source of electrical power. According to this map, the best conditions are in the northern coastal region of the country, the Mazury region, central and south-east Poland and Lubelszczyzna [37]. However, following Duraczyński’s elaboration, wind-speed measurements at a height of 10 m have no practical use [34]. Bearing this in mind, for wind-energy estimation we used wind-speed estimations at a height of 50 m (Figure 1).

![Figure 1](image-url)  
*Figure 1. Hourly average wind speed at a height of 50 m in the territory of Poland in the period 1st January 2014-31st December 2016, [m/s]. Source: own elaboration based on [38].*

The hourly average wind speed for the whole country of Poland is in the range 4-8 m/s at a height of 50 m. The first conclusion is that the most favourable localities (with the highest average wind speed). In addition, as a pre-calculation, standard deviations of the variability of wind speeds in Poland were also determined (Figure 2).
As mentioned before, the range of the analysis covers the territory of Poland. The analysis includes the variability of the wind conditions connected with various geographical locations, influencing the potential for wind farms. Locations and the distances between grid nodes (hypothetical locations of the wind farms) must be taken into consideration, together with the possibility of negative interference in cases where the distance between wind farms is not large enough.

The calculations pertain to either single turbines, farms or groups of wind farms. On the scale of a region or country, this method serves the purpose of specifying the reliability of wind farms working in cooperation with the power grid system, which is important for potential customers and investors.

State energy security and stable and reliable performance of the electrical power grid demands continuity of the energy supplied by wind generators. Energy producers whose generating capabilities include wind farms can then anticipate uninterrupted performance and stable revenue from the energy sold.

For research purposes, the criterion specifying the stability of the continuity of energy production is the energy variation indicator, defined as the correlation between the standard value of the energy produced in a given time frame and its average value [9]. The lower the value of the indicator, the more stable the system and its operating conditions, and hence the greater the prospect of a successful business [29]. The variability indicator makes it possible to compare very different time series (wind fluctuations). The literature does not provide any information about its objectivity when analysing the energy source of systems working discontinuously. However, some other limitations, such as transmission capacity restrictions, are also taken into consideration [9].

An improvement in the variability indicator calculated for the energy value in a given time interval can be achieved by geographical diversification of the system via territorial scattering of the farms. The effect of the dispersion is a result of diverse meteorological conditions prevailing in different regions at a given moment, including wind strength.

2. Data and Calculations
The data to be analysed were taken from the MERRA database [38], between 1st January 2014 and 31st December 2016 for the observation points shown in Figure 3. Data represent the wind speed at a height of 50 m. The MERRA datasets are the output of the Goddard Earth Observing System Model, Version 5 (GEOS-5) and its Atmospheric Data Assimilation System (ADAS), Version 5.2.0. The data streams assimilated by the GEOS-5 ADAS come from radiosondes, wind pilot balloons, wind profiles, wind radar, aircraft reports, dropsondes, spectroradiometer (MODIS water vapour winds), surface land observations and ship observations [39]. For each grid point (Figure 3), the energy potential of the wind speed was calculated assuming...
that the power generated depends on the scheme shown in Figure 4.

Figure 3. The map of Poland and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) measurement points. Source: own elaboration.

Figure 4. Theoretical turbine power scheme, [m/s].

In this work, a general model (Figure 4) was used, which shows a clear dependence of turbine power on wind speed. The figure shows that above a speed of 12 m/s, turbines produce constant power. Based on the analysis of the turbine performance it is assumed that within a wind-speed range of 3-12 m/s the power is proportional to the cube of the wind speed ($v^3$) while between 12 and 25 m/s the value remains constant.

Figure 5 shows the turbine downtime as a percentage of time in the analysed period.
The shortest downtime was observed for potential coastal locations, and the longest for the Carpathian region. Wind conditions in this location seem to indicate that the downtime of the turbines would be the highest and its overall generated power would be the lowest estimated.

3. Analysis and Calculation Results

The results achieved allow the average power value to be calculated for any individual turbine in a particular locality and for a combination of any pair of turbines (pairing of the base location with any other). In this way the location influence on the continuity of energy production can be demonstrated and expressed as a percentage indicator rate of the instantaneous power variation (the indicator is calculated as the standard deviation of the wind power divided by the average wind power). A lower value of the indicator is desired.

It is worth mentioning that the calculation does not include the amount of energy produced. The points on the vertical axis (Figure 6 b-d) represent the standard deviation as a percentage of the average power of the turbines for the base locations of Słupsk, Bełchatów and Krosno. It should be noted initially that the choice of locations indicates, first and foremost, the method of using the research results, although there are specific arguments in favour of the choice of these particular locations. Słupsk was selected as representative of a coastal strip location with an increased potential of available wind energy, Bełchatów was selected due to the near presence of the largest Polish power station, the wind farms already located there and its access to transmission power lines. Krosno was selected as representative of locations close to the transmission line to the south of Europe. The maps (Figure 6 a-d) show the values for the combinations of turbines located at particular observation sites, working in pairs.

It was observed that the coefficient of turbine power increases with a decrease in the average value of the wind speed. The lowest values are observed in the north-west of Poland and the highest in the south of Poland. This determines the value of the diversification effect, which depends not only on the distance between locations but also on the variability of the turbine power coefficient presented in these figures (depending on the location of the measurement point). For the three selected locations (Figure 6 b-d) the value of the coefficient was calculated for a given pair of points for all grid nodes. To illustrate the effect of diversification between two turbine locations, one was selected as the base. For each location, the values of the coefficients were calculated for the hourly average turbine power value determined for a given location and the selected base location. Similarly, the estimation was made for the other base values. Słupsk was chosen as the first base location, followed by Bełchatów and Krosno.
The largest effect of diversification is achieved in the case of locations with the smallest potential of the wind energy and vice versa. This is an optimization problem with the criteria of maximizing both energy production and the diversification effect. This will be the subject of further research. It was also noted that due to the choice of location, the diversification effect is not always in line with existing theory. This anisotropy is particularly evident when comparing the S-N direction with the E-W direction.
For this reason, an analysis was conducted based on an estimation of the Pearson’s coefficient. Evaluations of the coefficients were made for all possible pairs of turbine locations. The results are shown in Figure 7. It is worth mentioning that the correlation coefficient decreases to zero when the distance approaches infinity.

Figure 7. The dependence of the wind speed correlation coefficient (A) and the wind power correlation coefficient (B) on the distance, for the analysed locations. Source: own elaboration.

The results achieved are typical for these types of problems. As measured, the wind speed correlation coefficient decreases with the distance at a rate of about 0.25 for every 300 km. This result does not differ significantly from that of Hasche (2010) [40] or from the work of Gomez-Quiles and Gil (2012) [41]. At the same time, our results indicate that the dynamics of the decrease in the correlation coefficient with distance is lower than in the works mentioned. The obtained coefficient values presented as distance functions (km) of the separated turbines, clearly show that with an increase in distance the correlation coefficient value decreases. This is in line with the Markowitz portfolio theory. The data shown in Figure 8 confirm that the relationship between the two correlation coefficients is very strong.

Figure 8. The relation between the correlation coefficient calculated for the wind speed and the correlation coefficient calculated for the wind power generated, in the locations considered. Source: own elaboration.

Economic aspects play a very important role in decision-making and should be identified and assessed. Further research by the authors will address this issue.
4. Summary

One of the key results of the study is represented by the elaborated maps of average wind speeds in Poland for the period 2014-2016. Wind-speed assessments correspond to windiness at a height of 50 m, taken from the MERRA-2 database. Observations are higher than those measured by weather stations in Poland (at 10m altitudes) and are more useful in estimating the power and economic potential of wind farms. Unfortunately, the determination of wind speeds and standard deviations only partially helps in choosing precise locations. To limit the uncertainty of the decision process, more precise information is needed, with a much denser measurement grid and consideration of local conditions. Despite a wind-farm downtime of less than 15% for most of Poland during the analysed period, the existing power differences do not provide the possibility of ensuring the continuity of energy supplies. Unquestionably, the northern coastal region has the best conditions in terms of wind. However, there are location difficulties and a lack of transmission networks, as well as risks to the energy security of Poland’s energy system and the risk of joint failure or downtime.

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