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Site selection for wind and solar parks based on resources temporal and spatial complementarity – mathematical modelling approach

***Abstract**. The aim of this paper was the assessment of spatial and temporal complementarity of wind and solar resources based on selected locations in Poland. More specifically, we asked the following questions: a) does the spatial distribution of photovoltaic systems and wind farms own the property of smoothing the energy generation curve? b) is it possible as a result of renewable energy sources distribution over several locations to decrease instances of outliers in terms of energy production? c) to what extent depending on time step exists complementarity of sun and wind energy?. Conducted calculations were based on daily measurements of wind speed and insolation for the period 1984-2004 which were acquired from Institute of Meteorology and Water Management (IMGW) and www.soda-is.com. Obtained results are encouraging since the positive impact of spatial distribution on smoothing the energy generation curve was observed. From the power system point of view an expedient correlation between available wind and solar radiation in yearly time scale exists in analyzed locations.*

***Streszczenie.** Celem przeprowadzonych badań było zbadanie czasowej oraz przestrzennej komplementarności energii promieniowania słonecznego oraz wiatru w wybranych lokalizacjach na terenie Polski. W pracy podjęto się odpowiedzi na następujące pytania: a) czy dystrybucja przestrzenna instalacji fotowoltaicznych oraz parków wiatrowych prowadzi do wygładzenia krzywej uzysku energii elektrycznej? b) czy jest możliwym by na skutek rozmieszczenia źródeł energii na kilka lokalizacji zminimalizować występowanie skrajnych wartości uzyskiwanego wolumenu energii c) w zależności od kroku czasowego, jak kształtuje się komplementarność zasobów wiatru oraz energii promieniowania słonecznego. Przeprowadzone analizy operały się na szeregach czasowych średniej dobowej prędkości wiatru oraz sumie nasłonecznienia, które obejmowały lata 1984-2004 i zostały pozyskane z Instytutu Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy oraz platformy www.soda-is.com. Uzyskane wyniki są zachęcające, ponieważ wykazano istnienie pozytywnego wpływu dystrybucji przestrzennej na wygładzenie krzywej uzysku energii. Co więcej zaobserwowano istnienie silnej ujemnej korelacji pomiędzy zasobami energii wiatru i promieniowania słonecznego w ujęciu rocznym. (**Wybór lokalizacji pod elektrownie wiatrowe i fotowoltaiczne w oparciu o czasową i przestrzenną komplementarność zasobów – podejście: modelowanie matematyczne**).*

Keywords: *solar, wind, complementarity, variability*.
Słowa kluczowe: energia wiatru, energia promieniowania słonecznego, komplementarność, zmienność.

Introduction

Sun and wind energy sources are characterized by their unstable nature in terms of availability and forecastability. However, observed in recent years significant reductions in costs per unit of installed capacity of both photovoltaics plants (PV) and wind turbines (WT) suggest that their share in energy mix of individual countries will substantially increase. This will lead to the emergency of new problems such as dealing with intermittent nature of some of the renewable energy sources (RES) and the need of more electrical energy storage facilities. However, in literature one may found many presumptions that wind and solar energy may complement each other, and thereby ensuring more stable power source. Therefore this paper is dedicated to the complementarity of wind and solar energy sources. The concept of complementarity should be understood as a capability of energy sources to operate in such a manner that they guarantee a stable energy yield. Complementarity may be analyzed on a temporal, spatial and both of those dimensions, between energy sources based on the same energy resource or different ones.

Literature overview

In the literature on the subject one of the most commonly suggested ways to deal with significant temporal variability of wind and solar resources is a spatial distribution. This procedure boils down to the division of planned power source capacity among several locations. The spatial distribution as a tool used to lower the risk of sudden drops in term of generated electrical energy has been a subject of many studies. Inter alia, Holttinen [1] has analyzed the variability of wind resources in Nordic countries concluding that spatial distribution leads to a decreasing variance, more predictability and elimination of null energy generation periods. Kempton [2] investigated the possibility of wind farms locations in sites which represent complementing wind resources, at the same time compering suggested deployment and corresponding increase in terms of transmission lines with available but not needed capability. A cooperation of wind farms and concentrated solar thermal (CSP) power plants in Andalusia (Spain) was analyzed by Santos-Alamillos et al. [3] in order to develop on their basis an energy source generating electrical energy in base load. Wiemken et al [4] and Murata et al. [5] claim that the combination of many photovoltaic installations or wind turbines leads to a decrease in variability which otherwise will be encountered in case of a single site power source. This situation results from the fact that the power generated from power sources located close to each other will undergo synchronous changes. Instead when the will be far apart (over 500 km) Perez and Fthenakis [6] calculated that the value of the coefficient of correlation will be close to zero or negative.

In order to assess the temporal complementarity of solar radiation and hydro energy Beluco et al. [7] proposed a dimensionless index and presented their results in form of maps for southern Brazil. Remaining in the area of Brazil (northeaster) Jong et al. [8] have analyzed the variability of wind, sun and hydro resources in the context of the energy demand curve. They have acknowledged that intermittency of solar and wind sources may be eliminated through the available potential of hydro energy. Sales dos Anjos et al. [9] investigated long term correlation and cross correlation of wind speed and solar radiation on Fernado de Noronha island (northwestern Brazil) and obtaining results indicating to a certain extent correlation of those two stochastic processes.

The cooperation of intermittent energy sources with pumped storage power plants (PHES) has been described by Rehman et al. [10] who additionally gave examples of PV-PHES and WT-PHES systems. They have pointed out that: there is a continuously dwindling number of potential sites for new PHES and their crucial role in national power system as where as in secluded areas. An analysis of PV-WT hybrid system application for islands on Mediterranean See has been presented by Notton et al. [11] who has pointed out that a hybrid power system was the best solution for five sites on Corsica but total energy autonomy based on those two sources leads to significant energy surpluses. Those surpluses may be stored in electrical cars (EV), which are mobile energy storage systems, thus leading to a decrease in carbon dioxide emissions as indicated by Nunes et al. [12]. On the other hand Killinger et al. [13] focused on regional optimization of wind and solar energy resources exploitation based on meteorological conditions as an input data. In their model they have focused on the realization of the German energy policy which implies: economic feasibility, environmental friendliness and insurance of demand coverage. They noticed that an attempt to achieve the best value of LCOE (Levelized Cost of Electricity) criterion in case of PV installations is not always beneficial when it comes to the adjustment to the energy demand curve and in some cases eastern and western orientation of PV modules is more justified.

Andersen et al. [14] analyzed the situation on Danish energy market. They investigated different scenarios of energy mix. The best result were achieved for a combination of wind turbines with 20% share of PV installations which in comparison with 100% share of WT led to a significant reduction in energy surpluses and its better utilization. In Canada (Ontario) Hoicka and Rowlands [15] conducted an analysis of wind and solar resources complementarity pointing out locations which are predisposed to the development of specific energy source according to the population density and accessibility to the energy network. This study has been followed by analysis done by Rowlands et al. [16] which purpose was to determine whether spatial distribution of PV systems allows reduction in terms of energy generation variability. Based on the analysis of Pearson correlation coefficient and standard deviation changes they have confirmed their original assumptions on the positive impact of spatial distribution on the energy yield variance reduction.

Jereaz et al. [17] investigated spatial-temporal complementarity of wind and solar resources in the Iberian Peninsula in order to state locations for individual energy sources, which will enable the realization of established goals in terms of efficiency and stability. The conducted research has reviled an existence of complementarity on at least monthly time scale. A similar analysis has been done for Mediterranean See (Italy) by applying Monte Carlo approach and was performed by Monfroti et al. [18]. For testing period of the year 2005 the wind and solar energy resources have shown positive temporal complementarity which enables their integration to the power system. Research on the wind, solar and hydropower energy sources temporal complementarity in selected sites have been conducted by the authors in the following papers [19, 20]. Analysis conducted revealed that a strong negative correlation exists between wind and solar energy on a monthly time scale.

Data

The selection of adequate sites for which wind speed and solar radiation data were acquired was based on the aim to present distinctive and idiosyncratic ones but was also restricted due to the availability of data. For each site data concerning daily mean wind speed and daily sum of solar irradiation for period 1984-2004 have been collected and in some cases missing values were replaced. In Tab. 1 location and choice underlying premises are presented whereas corresponding statistical parameters of wind and solar time series are in Tab. 2.

Table 1. Meteorological stations locations and presuppositions for its selection

Station	Location	Choice motivation
Łeba	Rąbka St. 1a, 84-360	known for excellent wind conditions
Zlelona Góra	Struga St. 1a, 65-331	need for representative western location in Poland
Bielsko-Biała	Cieszyńska St. 3, 43-300	average wind resources, closeness to industrial sites
Wrocław	Skarżyńskiego St. 36, 54-530	fourth most populous city in Poland
Łódź	Gen. Maczka St. 35, 94-328	central Poland, third largest city in Poland
Lublin	Radawiec Duży, 21-030	distinctive solar energy resources
Suwałki	Puławskiego St. 125, 16-400	good wind resources, northeastern Poland

Table 2. Statistical parameters of wind speed (100m hub height) and solar radiation for selected sites, where: ZG – Zielona Góra, BB – Bielsko Biała,Var – variance, STD – standard deviation

Site	Irradiation [Wh/m^2/day]			Wind speed [m/s]		
	Mean	STD	Var	Mean	STD	Var
Łeba	2783	2045	4182969	5.02	2.67	7.15
ZG	2940	2281	5203496	7.26	3.97	15.77
BB	2773	1934	3739574	4.62	1.79	3.19
Wroc.	2885	1941	3767689	5.21	3.17	10.04
Łódź	2857	1975	3902023	4.65	2.24	5.02
Lublin	2845	1956	3824835	4.86	2.33	5.45
Suw.	2908	1970	3880053	4.57	2.32	5.38

Methodology

Research has been divided into six subtasks from which the first four are purely computational and boil down to the calculation of energy generation and coefficients of correlation. Whereas last two are optimization models with given objective function and constraints. The parts are as follows:

- Estimation of energy generation from individual sources for each site;
- Correlation coefficient with different time step;
- Calculation of correlation coefficient separately for wind and sun resources between analysed locations;
- Assessment of spatial distribution effect on energy generation curve;
- Adjustment of energy generation to the energy demand curve on a monthly basis;
- Minimization of day to day fluctuations through spatial distribution and energy source power regulation.

The approach, assumptions, equations and applied software are presented for each subtask separately.

Energy yield estimation

The energy generation from photovoltaics and wind turbines has been estimated based on Eq. 1 and Eq. 2.

(1) $$S^E = \frac{H*P*\eta^{PV}}{H^{STC}}$$

(2) $$W^E = \begin{cases} 0 \; if \; v < v_1 \\ P(v) \; if \; v_1 \le v < v_r \\ P_r \; if \; v_r \le v < v_2 \\ 0 \; if \; v \ge v_2 \end{cases}$$

In Eq. 1 S^E stands for energy yield [kWh] from PV system;H [kWh/m2] denotes the daily sum of incoming solar energy on optimally inclined (30°) surface and H^{STC} [1kW/ m2] stands for the solar radiation at standard conditions at which solar modules are being tested, η^{PV} refers to the overall performance ratio (here taken as 0.8) and P [kW] is the nominal power of installed PV modules. In Eq. 2 W^E denotes power delivered from wind turbine; v_1 stands for cut-in speed (taken as 4 [m/s]; stands for $v_2$cut-off wind speed (25 [m/s]); P(V) – is the polynomial describing power output change typical for commercial turbine, model Vestas V90 which rated power at v_r wind speed is equal to 2 [MW].

Results

Based on the Eq. 1 and 2 energy generation for each source in each location has been calculated. Results which are averaged values from period 1984-2004 have been presented in Tab. 3. There is no significant difference in terms of energy generated from solar radiation. But it is important to note that in all sites the average yearly energy generation from solar radiation is close to 1 [GWh] per 1 [MW] of installed power. Whereas in case of the wind energy the difference between most advantageous site which is Łeba and least abundant in wind resources which is Lublin is three-fold. Other interesting observations are such that wind and solar energy on the monthly time scale tend to complement each other. In other words when the energy generation from wind turbines in June, July and August is plummeting the photovoltaic installations are reaching their highest values.

Table 3. Average daily and annual energy generation per unit of installed capacity, where: WT – wind turbines, PV - photovoltaics

Site	Site specific electrical energy generation from wind and solar energy sources [MWh/MW]													
	Suwałki		Łeba		Zielona Góra		Bielsko Biała		Wrocław		Łódź		Lublin	
Month	WT	PV	WT	PV	WT	PV	WT	PV	WT	PV	WT	PV	WT	PV
Jan	6.92	0.89	11.12	0.78	4.60	1.10	7.17	1.33	4.92	1.12	5.56	1.14	5.46	1.20
Feb	6.41	1.58	11.55	1.36	4.35	1.73	7.10	2.01	5.04	1.76	5.40	1.81	5.24	1.84
Mar	5.12	2.63	9.19	2.62	3.71	2.58	6.29	2.80	4.77	2.68	5.15	2.75	4.63	2.85
Apr	4.09	3.37	7.59	3.73	2.40	3.41	4.13	3.43	3.26	3.55	3.79	3.41	3.47	3.55
May	3.23	4.21	6.85	4.63	1.65	3.91	3.02	3.88	2.11	4.10	2.56	4.14	1.95	4.17
Jun	2.83	4.01	8.17	4.43	1.47	3.72	2.11	3.72	1.84	3.84	2.11	3.80	1.38	3.92
Jul	2.17	3.88	7.69	4.24	1.31	3.79	2.29	3.84	1.45	3.86	1.75	3.89	1.11	3.89
Aug	1.79	3.77	6.44	3.97	1.09	3.80	1.99	3.87	1.26	3.88	1.42	3.84	0.99	3.91
Sep	3.18	2.83	7.90	2.95	1.71	2.81	3.87	2.97	2.01	2.85	2.74	2.85	1.82	2.88
Oct	4.22	1.75	9.04	1.77	2.42	1.94	5.23	2.06	3.10	1.99	3.34	1.93	2.92	1.99
Nov	4.77	0.92	8.77	0.89	2.86	1.10	5.62	1.24	3.70	1.13	4.09	1.10	4.19	1.15
Dec	5.48	0.72	10.37	0.66	4.02	0.87	6.71	1.08	4.94	0.89	5.37	0.87	4.75	0.93
Sum	1523	931	3178	977	958	937	1684	982	1164	965	1313	961	1149	983

A question then arises whether there exists a temporal correlation between solar and wind resources on daily, monthly and yearly basis. The answer to this a matrix containing correlation coefficients presented in Tab. 4 has been delivered. For calculation purposes monthly and yearly average values of wind speed and solar radiation have been estimated. Firstly in case of daily correlation in all locations there is observable relatively small negative correlation this may indicate that daily lower wind energy generation will be to same extent replaced by energy from PV plant. Secondly on a monthly basis the negative correlation coefficient has a meaningful value. This suggests that over each year when energy output per unit of installed power for each source is equal the energy generation curve from both sources will tend to be straight. Finally annual changes of available wind and solar energy in five sites (Łeba. Z. Góra. B. Biała. Wrocław and Lublin) tend to have positive but small correlation value. In case of Łódź those time series does not indicate correlation whereas in Suwałki it is negative but not greater than -0.3.

Table 3. Temporal complementarity – correlation matrix

Time scale	Daily	Monthly	Yearly
Suwałki	-0.168	-0.835	-0.218
Łeba	-0.214	-0.850	0.228
Zielona Góra	-0.270	-0.837	0.366
Bielsko – Biała	-0.237	-0.884	0.333
Wrocław	-0.268	-0.825	0.309
Łódź	-0.278	-0.806	0.032
Lublin	-0.298	-0.831	0.270

The analysed monthly correlation has an impact on the shape of energy generation curve. In Fig. 1 and 2 cumulated energy yield from 2 [MW] wind turbine and 2 [MW] PV plant have been presented. It is clearly visible that wind and solar energy complement each other over the year. In all seven sites a peak of energy generation has been observed from March to April due to still relatively high average wind speed and increasing solar radiation. One must note that by adding additional power to the PV plant the decrease observed in June and July would be eliminated but this would also lead to a greater peak on the break of March and April.

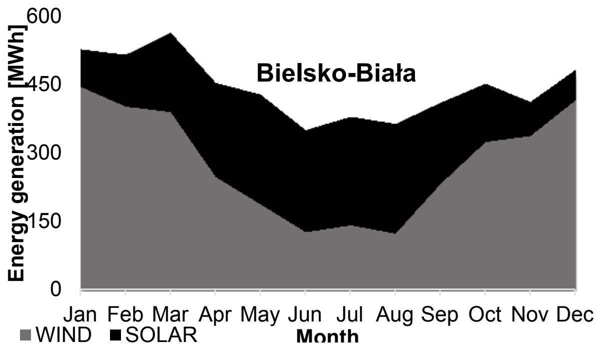

Fig.1. Cumulative energy generation from 2 MW PV installation and wind park in case of Bielsko-Biała

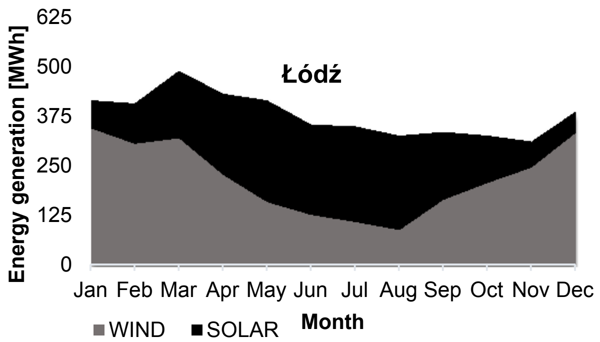

Fig.2. Cumulative energy generation from 2 MW PV installation and wind parks in case of Łódź

Single location vs. spatial distribution – smoothing effect analysis

To assess the impact of spatial distribution on energy generation curve we have proposed the following experiment. Let's assume that there is a possibility of installing a 14 [MW] wind park comprised of seven 2 [MW] wind turbines and a solar power plant of the same rated output power. A decision maker has to decide whether all turbines will be located in the same site or they will be evenly distributed among seven locations – which have been listed formerly in the text. The same is in the case of photovoltaic installation. What is more to show the difference between sun and wind energy variability they will be analysed separately. For calculations as previously data from period 1984-2004 have been used. In order to assess the changes in energy generation time series for each individual location and ensembles of wind turbines as well as photovoltaic systems values of standard deviation (STD) average (MEAN) and a coefficient variation (CV) have been calculated. The obtained results are presented by means of Fig. 4 and 5. Before distribution (for all sites except Łeba) the value of CV was greater than 100%. But the spatial distribution of wind turbines led to a significant drop. It is important to note that Łeba is a very distinctive site which does not only possesses the best wind conditions in terms of mean wind speed value but is also the most stable one in comparison to other locations and their wind resources. On the other hand the value of CV for solar energy is half that for wind and oscillate between 50% to 70%. What is interesting Łeba in terms of solar energy represents the highest values of CV. Spatial distribution of solar energy sources led to a slight drop in CV value. The difference of spatial distribution impact on the coefficient of variation between solar and wind energy may be explained by Fig. 3 in which correlation coefficient decreased faster in case of wind time series.

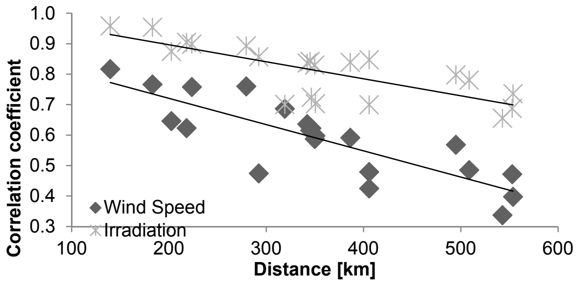

Fig. 3. Correlation coefficient as a function of distance between sites

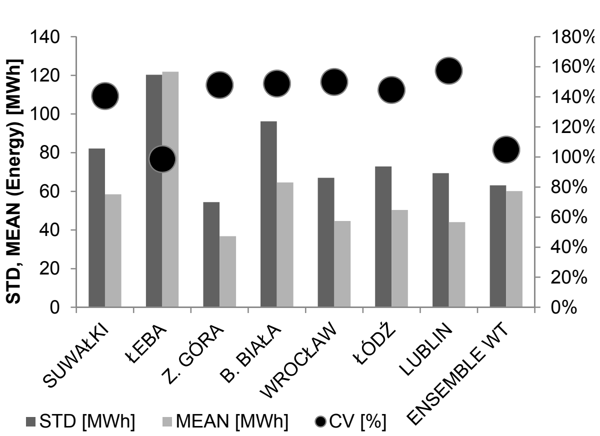

Fig.4. Variability of wind energy generation

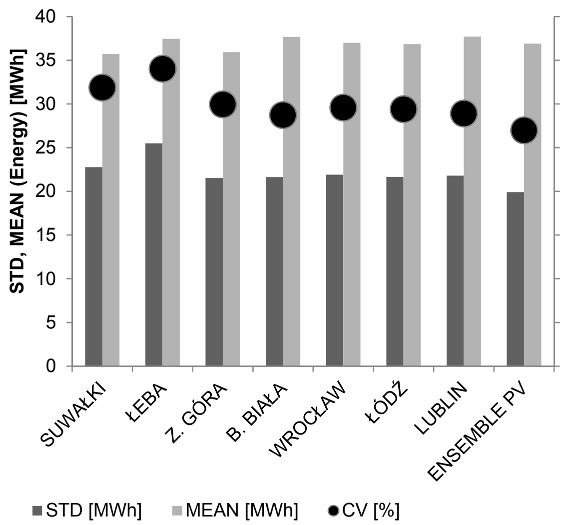

Fig.5. Variability of solar energy generation

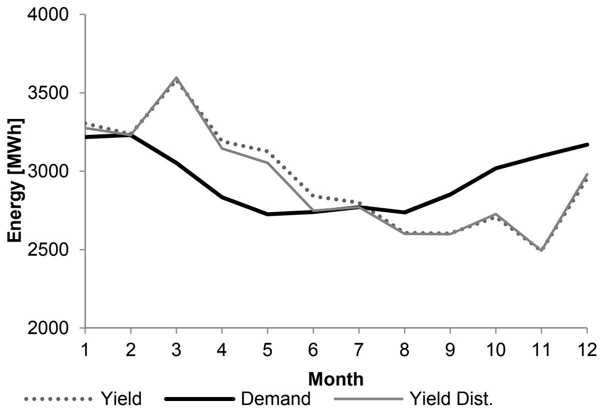

Fig.6. Energy output from a fleet of wind turbines and solar parks with reference to demand curve. Conventions: Yield – energy generation from evenly distributed power sources. Demand – energy demand normalized according to polish energy demand curve. Yield Dist. – energy generation from power sources distributed as presented in Fig. 7

Poland energy demand curve

The wind and solar resources vary along the year and the same is with energy demand curve. The highest energy demand in Poland is observed at the turn of January and February. In order to compare those two varying phenomenon we have collated energy demand with energy generation from PV and wind turbines. But firstly the energy demand curve has been normalized in such a way that the annual energy consumption equals to the energy generation from evenly distributed power sources among seven locations. Conducted analyses in previous sections were a strong indication that there will be periods when energy demand overbalances the energy supply. This situation has been presented in Fig. 6. Over the whole year the energy consumption amounted to 35.4 [GWh]. In case of evenly distributed energy sources the absolute sum of surpluses and shortages accounted to 8.5% of total energy demand. Whereas in case of optimized distribution (which is presented in Fig. 7) this number dropped to 7.5% and there was an observable decrease in surpluses by almost 18%. Further investigation has shown that there is a possibility to avoid energy shortages by deploying energy sources amongst sites which are most abundant in wind resources, namely Łeba.

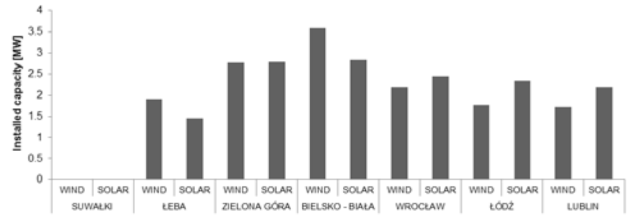

Fig. 7. Suggested distribution of solar and wind parks which allows to minimize the volume of surpluses and shortage

Model for a daily energy yield fluctuation minimization

Due to the intermittent nature of solar and wind energy resources power system has to deal with fluctuations in terms of produced energy volume. As previously mentioned those changes occur on yearly, monthly, daily, hourly and even from second to second basis. However, the observed correlations between energy resources and examined locations allow as to assume that proper spatial distribution of solar and wind energy generation sources will lead to the decrease in an abrupt and meaningful changes in term of produced energy. In order to verify this assumption a mathematical model has been developed in which daily values of average wind speed and solar irradiation have been used. The objective function expressed by Eq. 3 was to minimalize absolute values of energy generation changes from day to day. The model has been implemented and solved with standard MS Excel 2010 Solver using nonlinear GRG method.

(3) $$min\,Z = max\left|E_{i-1}^{S,W} - E_{i}^{S,W}\right|$$

In Eq. 3 $E_i^{S,W}$ – stands for cumulative energy generation from wind turbines and photovoltaics. The objective function is subject to:

(4) $$\sum_{j=1}^{7} IC_j^{PV} = 7$$

(5) $$\sum_{j=1}^{7} IC_j^{WT} = 7$$

(6) $$0 \leq IC_j^{PV} \leq 7 \;\forall j$$

(7) $$0 \leq IC_j^{WT} \leq 7 \;\forall j$$

(8) $$IC_j^{WT};\; IC_j^{PV} - integer$$

Where in Eq. 4 IC_j^{PV} denotes the installed capacity of photovoltaic at location *j* but the value of must be multiplied by 2 [MW] in order to achieve real capacity because that was the assumed rated power of photovoltaic installation (and wind turbine) from which the energy yield has been estimated. The same is with IC_j^{TW} where it stands for installed capacity of wind turbines. We have assumed that the total amount of installed capacity of both solar modules and wind turbines will not exceed 28 [MW] and ought to be evenly distributed amongst both energy sources. The first assumption is assured by Eq. 4 and 5 whereas the second one by Eq. 6 and 7. We have introduced additional constraint (Eq. 7) which will force the model to consider deploying PV and wind farms of installed capacity equal to 2 MW.

Based on developed mathematical model which objective function was to minimize values of day to day fluctuations in terms of generated energy we have proposed an alternative distribution of energy sources installed capacity. In comparison to evenly distributed capacity of wind turbines and photovoltaic modules among all considered sites the deployment presented in Fig. 8 possesses the capability of reducing the occurrence of extreme values. In the case presented in Fig. 8 the mean yearly electrical energy amounts to 44.5 [GWh] whereas theoretical maximum for power source of 24 [MW] rated power with 100% capacity factor would be 245.3 [GWh]. The respective energy generation from evenly distributed energy sources would be 35.4 [GWh] which is lesser than in case of Fig. 7 and this is mainly due to non-utilization of excellent wind resources appearing in Łeba. Based on mentioned optimization model it was possible to reduce the biggest occurring fluctuation from 307 [MWh] to 274 [MWh] although this reduction caused an increase in standard deviation values from 38.2 [MWh] to 49.7 [MWh]. An increase in standard deviation would be normally perceived as a disadvantageous occurrence however, in this case it was accompanied by a significant increase in mean value of daily energy generation from 37 [MWh/day] to 52.7 [MWh/day]. A summative index which tips the balance toward the optimized configuration of sun and wind power sources is the coefficient of variation which value has decreased from 103% to 94%.

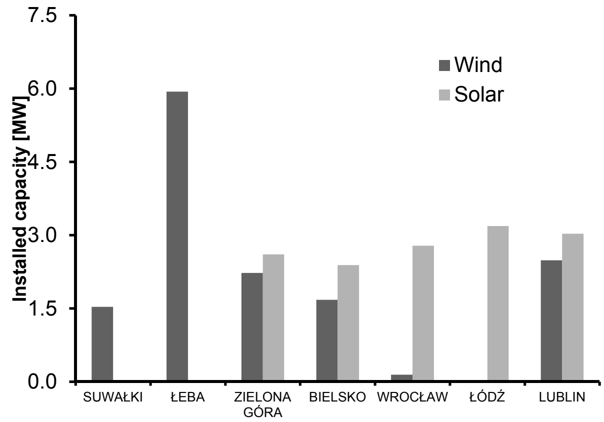

Fig. 8. Power of wind and solar sources distribution among individual sites

Conclusions

In general this study investigated the spatial and temporal complementarity of solar and wind resources among selected locations in Poland. The meaningful values of the correlation coefficient have been observed only on a monthly time scale and in average amounted to -0.84. For a yearly and daily time scales these values were negligible. Additionally it was found that with an increasing distance between sites there is an observable drop in a correlation coefficient between corresponding time series which has a positive impact on the smoothness of an energy generation curve, confirmed especially by a significant decrease in a coefficient of variation in case of the sun energy. Conducted optimization experiments suggest that the identification of an optimal spatial distribution of wind and solar power sources is a way to entrench certain level of energy generation whilst minimizing the inter-daily temporal variations. This study suffers mainly from poor temporal data resolution. However, actions have been undertaken in order to acquire data on wind speed and irradiation with an hourly time step which will enable more precise simulation. Future studies should concentrate on developing proposed approach by coupling variable wind and solar energy sources with energy storage technologies such as pumped-storage hydroelectricity.

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