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Understanding the spatial distribution of renewable power plants for predicting future cumulative impact on the environment: case study of photovoltaic and wind power plants in Poland

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ABSTRACT

This study aims to present the current distribution of photovoltaic and wind power plants in Poland and to determine the relationship between their installed capacity and various factors occurring in the districts where generation units in question are located. The current knowledge of the scope of this investigation is crucial for future environmental impact assessments studies related with evaluating cumulative impact of photovoltaic and wind power plants. Hence, this study contributes to the future assessments, especially authorities obliged to conduct environmental impact procedure can use the findings of this work useful to issue decisions. It was found that due to the non-normal distribution of the analysed variables, the rho-Spearman's correlation coefficient should be determined in similar analyses instead of Pearson's correlation coefficient. The correlation coefficients were determined to describe the spatial dependence of volume of the installed capacity of the renewable power plants analysed and several selected factors.

1. Introduction

1.1. Background of the work

Miscellaneous types of energy have accompanied human since the origins of mankind, and throughout history. Moreover, various energy forms have continuously shaped life on Earth. Among countless energy types, there is energy carrier that plays a crucial role in modern world – electricity [1]. Electricity is obtained using various primary energy resources. These energy sources are, among others: nuclear power, hard coal, natural gas, and solar power. For a long period of time, since the second Industrial Revolution, fossil fuels, especially coal, have been commonly used in order to satisfy the electricity demand [2]. However, despite the global coal reserves are ample and allow for satisfying future energy demand [3], combustion of this energy resource causes air pollution and affects human health [4]. At the same time, the Polish power system strongly relies on lignite and hard coal. Nonetheless, given the fact that fossil fuels have a significant impact on the environment, European countries, as well as Poland, undertook efforts to continuously reduce their use – for instance, the Polish government tries to pursue a policy aimed at introducing nuclear and renewable generation units. These efforts have resulted in the growing share of renewable sources in the electricity system. Photovoltaic and wind power plants and are renewable generation units that both have gained importance in the European energy mix [5]. Considering Polish conditions, the share of energy produced by the mentioned power plants has grown rapidly in recent years [6].

1.2. Literature survey, research gaps and contributions

While an interesting and thought-provoking idea supported by in-depth analysis demonstrated that in order to satisfy the whole Poland's electricity demand, the area of approximately 2584 km^2 should be intended for a photovoltaic power plant [7], solar energy installations as well as wind power plants are rather more spatially dispersed. This is because some development determinants (such as meteorological, environmental, and socioeconomic) shape the possibilities of solar and wind generation units siting [8].

Taking into account the significant level of spatial spread of the renewables in question, it is highly desired to determine the relationship between the presence of photovoltaic and wind power plants throughout the regions and the characteristic of individual regions. While this is an interesting field to investigate since the location and accumulation of power plants within the boundaries of regions may affect the local

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environment, the lack of a proper analysis performed in regional scale is noticeable. Recent studies are focused on the decision-making process for identifying favourable areas for the development of renewables, including photovoltaic and wind power plants. For instance, in one of the recent studies researchers demonstrated the method enabling selection of suitable areas for photovoltaic siting [9]. Overall, it is common that scientists demonstrate analysis for location searching for photovoltaic suitable location based on Geographic Information System [10–12]. As to geospatial analysis for photovoltaic power plants, it is worth noting that the use of geoinformation allows one to properly evaluate the suitability of a given plot for the development of investment in question [13]. Geographic Information Systems also have a broad use for wind power plants site selection [14]. It is worth noting that some Multi-Criteria Decision Making methods could be found useful for searching the most suitable areas for the location of renewables under study [15,16].

It is important to outline the broader literature landscape arising from the studies from other countries in order to place this work in a proper context. In China it appears that the distribution of renewable generation units is dependent on abundance of renewable resources, environmental conditions (which can be understood as resource-dependent characteristics), and supportive policy (policy-based characteristics) [17]. From the perspective of Ecuador, one work shows the spatial distribution of suitable lands for selected renewables siting. The mentioned study indicates areas characterised by the highest potential for renewables development. Interestingly, authors demonstrates that solar technology has the highest development potential in terms of accessible land. However, as it arises from this study, geographical potential is also spatially uneven [18]. Similarly, the renewable energy potential in Turkey is spatially spread, as well as the current installed capacity, what is noticeable in the case of wind energy installed capacity, hydraulic energy, and biomass energy [19]. In Latvia, the installed capacity of renewable generation units is also distributed unevenly in terms of geographical location. Also the spread of suitable terrains is characterised by spatial irregularity [20]. Overall, in light of Europe, it is evident that its area is heterogenous in terms of potential renewable energy production, which arises from various challenges and difficulties which with different regions face [21]. The spatial heterogeneity of renewable power plants distribution is evident not only on European scale, but also in national scale. For instance, the volume of installed capacity of photovoltaic is higher in southern part of Spain and Franc in comparison to northern part of these countries. It arises from the fact that in Europe the space has been a crucial factor in the development process of renewable energy installations [22].

Many recent studies showed the decision-making process for locating photovoltaic and wind power plants. However, there is a research gap regarding the knowledge of relationships between the volume of installed capacity of renewable power plants under study within the borders of the regions and factors occurring there. In addition, the lack of knowledge about the exact spatial distribution of the renewables in question is noticeable. Thus, this study aims to fill both mentioned knowledge gaps by providing an analysis conducted on regional scale for the area of Poland. The purpose of this research is, moreover, to describe the current spatial distribution of the studied generation units. The results obtained demonstrate the correlation between mentioned variable using Spearman's rank correlation coefficient. As a consequence, the results lay the foundations for further works concerning environmental impacts of both photovoltaic and wind power plants, since the impacts of these renewable installations on natural elements can occur as cumulative impacts.

1.3. Necessity of spatial distribution investigation of renewable power plants in question

It should be highlighted that a good understanding of the spatial distribution of the industrial infrastructure under study is essential to determine the future cumulative impact of these investments on the environment. This study lays the foundations for future environmental impact assessments by showing the current distribution of photovoltaic and wind power plants and the determinants of their development. For purposes of environmental impact assessment procedures, the outcomes of this investigation can be found to be highly useful, especially when it comes to indicating the cumulative impact of them on various elements of the environment, such as local communities, different species of fauna and flora, including birds, and a local land use structure.

2. Data used

This research is based on the data shared by Energy Regulatory Office covering information on renewable energy power plants connected to the national power system. The data is current as of June 30, 2024 and available via Office's internet site [23] and is shared as an excel file. Thus, consequently, information included take the form of the table. Renewable power plants are divided into several groups depending on the type of technology. Those groups are as follows: hydroelectric power plants, wind power plants, photovoltaic power plants, biogas power plants, biomass power plants, installations of thermal treatment of waste, co-combustion power plants (combusting conventional fuels and biomass or biogas), installations using renewable hydrogen. Furthermore, the dataset presents the amount of installed capacity of each power plant operating in Poland. The location of individual power plant is there indicated, making it possible to analyse the installed capacity of each type of renewable power plant at the level of localities. Table 1 summarizes the data gathered in the dataset under discussion.

Data of the administrative division of Poland was obtained via WFS shared by Head Office of Geodesy and Cartography [24].

To describe the characteristics of district data from Local Data Bank was used [25]. Data concerning 2023 was used to carry out this study.

3. Method

First, from the data of renewable energy power plants gathered in the dataset used, characteristics concerning the location attribute of photovoltaic and wind power plants was extracted, as well as the information on their installed capacity. Since the aim of this research is to investigate the spatial distribution of photovoltaic and wind power plants, the administrative division of Poland spatial data mentioned in previous section was used. Consecutively, the data was exported to the shapefile so that the further geospatial analysis could be conducted. This research was carried out at the regional scale. Thus, the data of district borders in the form of polygons was used to define the spatial distribution of infrastructure under analyse.

Subsequently, the summation of the installed capacity of power plants in relation to their location at the district level was carried out. At

Table 1
Summary of installed capacity and the number of each type of renewable power plants in Poland - state on June 30, 2024. Own elaboration based on [23].

Type of renewable power plant	Total number of power plants connected to the grid	Total amount of installed capacity [MW]
Hydroelectric power plants	497	984
Wind power plants	1425	9864
Photovoltaic power plants	5410	6621
Biogas power plants	400	301
Biomass power plants	48	1252.08
Installations of thermal treatment of waste	10	171
Co-combustion power plants (combusting conventional fuels and biomass or biogas)	32	13,557
Installations using renewable hydrogen	1	0.999

the end of this step, the values representing installed power in each district were combined with the shapefile layer. Consequently, the spatial distribution of the power plants under discussion could be demonstrated.

There are several districts in Poland that have the same name. In view of this, an additional, manual analysis was conducted which purpose was to eliminate errors resulting from combining excel file and shapefile. For instance, *bielski* district is a name of two different administrative units. Therefore, it was crucial to designate of the one to whom the data of Energy Regulatory Office refers. It was done by comparing the voivodeships in which individual districts are placed.

The indispensable purpose of this study, in addition to determining spatial distribution of photovoltaic and wind power plants in Poland, is to relate intensity of presence of mentioned renewable installations in districts with the characteristics of those administrative units. It allows us to understand the patterns of the development of studied installations as well as designate the determinants of their development. Considered examined factors are gathered in Table 2.

Data for global horizontal irradiation and mean wind speed were obtained as raster files (meaning that the geodata consist of cells containing the assigned values of a given factor) from Global Solar Atlas and Global Wind Atlas, respectively [26,27]. The raster files were first clipped to the inland boundaries of Poland. Then a reclassification was performed to group the values of irradiance and mean wind speed values into several groups. The data prepared in this way were polygonised, and the values of each characteristic were joined by location with centroids of district geometry, which allowed one to define the level of solar irradiation and mean wind speed within individual districts borders. Fig. 1 presents distinguished groups of global horizontal irradiance and averaged wind speed at a height of 100 m above ground.

Global horizontal irradiance essentially consists of the sum of two factors: direct normal irradiance and diffuse horizontal irradiance. The value of this factor used in this study is an annual average that covers the period 1994–2018. For wind speeds, the Global Wind Atlas uses data covering the period 2008–2017.

To relate the volume of installed capacity in districts with their characteristics, in order to specify factors affecting the location of power plants, the correlation analysis was conducted. First, it was planned to use the Pearson correlation coefficient. It is worth noting that the use of Pearson coefficient requires that both variables (in this study: the volume of installed capacity in districts and individual factors $x_1,\ldots x_n$) have a normal distribution. It means that the data must fit a bivariate normal distribution – both variables should be normally distributed [28]. To verify the normality of distribution of analysed variables, Kolmogorov-Smirnov (KS) test was used. The KS test verifies the goodness of fit of empirical data to a theoretical distribution [29]. Therefore, let $F_0(x)$ be the population cumulative distribution function, and $S_n(x)$ be the empirical distribution function. Then, the null hypothesis H_0 states that population under analysis is normally distributed while the alternative hypothesis H_a states that the population is not characterized by normal distribution [30–32]:

Table 2
Factors subjected to correlation study.

General group of factors	Factor	Designation	Factor's unit
Environmental	Forestation	x_1	%
	Coverage of region by environmental conservation forms	x_2	%
	Global Horizontal Irradiation	x_3	$kWh\cdot m^{-2}$
	Mean wind speed at the height of 100 m	x_4	$m\cdot s^{-1}$
Spatial planning and local government	Share of the land covered by local development plans	x_5	%
	Total income of municipalities	x_6	PLN
Local society and economy	Population density	x_7	Persons/ km^2
	Urbanisation index	x_8	%
	Median price of 1 m^2 of sold properties	x_9	PLN
Agriculture characteristics	Percentage of arable farms propertied farmlands of area above 5 ha (data from 2020)	x_{10}	%

$$\begin{aligned} H_0 &: F_0(x) = S_n(x) \\ H_a &: F_0(x) \neq S_n(x) \end{aligned} \tag{1}$$

The KS test characterises itself by a certain statistical level of significance α. For the purposes of this study, 1 % significant level was chosen. Thus, the significance level (α) and a level of confidence (*CI*) can be written as:

$$\begin{aligned} \alpha &= 0.01 \\ CI &= 1 - \alpha = 0.99 \end{aligned} \tag{2}$$

In order to test the null hypothesis, equation (3) is used [32]:

$$d = \sup_x [|F_0(x) - S_n(x)|] \tag{3}$$

The result of equation (3) must be later compared to the critical value $d_\alpha(N)$ and when $d \geq d_\alpha(N)$ it means that null hypothesis must be rejected, which is equivalent to the fact that surveyed sample is not normally distributed. As Massey demonstrates [31], for the sample of $N > 35$ and the level of significance $\alpha = 0.01$, critical value of $d_\alpha(N)$ can be given by the following equation:

$$d_{\alpha=0.01}(N > 35) = \frac{1.63}{\sqrt{N}} \tag{4}$$

Using the aforementioned test, normality of spatial distribution of both installed capacity of photovoltaic and wind power plants was tested first. The mean value and standard deviation for wind power plants installed capacity in districts is 24.326 and 50.091, respectively. For photovoltaic power plants, the values of these descriptive statistics equal 16.798 and 23.94, respectively. Both populations consist of 380 values. With given KS test, it must be claimed that with 0.01 level of significance, null hypothesis must be rejected – analysed datasets are not normally distributed. Calculated KS test statistics for dataset describing installed capacity of photovoltaics is 0.2388, and for wind power plants this coefficient reaches 0.31097. It means it is higher than critical value $d_\alpha(N) = 0.0836$.

Interestingly, even for other, typical values of level of significance, it is required to reject null hypothesis. This is demonstrated in Table 3.

Therefore, considering the above-described procedure for the KS test and its result, it must be said that the Pearson correlation coefficient is not applicable to the study in question. Therefore, another correlation coefficient should be adopted to the analysis. Hence, the Spearman correlation coefficient has been selected in order to perform the correlation analysis. Contrary to Pearson coefficient, selected correlation coefficient does not assume any distribution of variables, including normal distribution [33].

The Spearman's rank correlation coefficient (rho-Spearman coefficient) is a nonparametric correlation measure; this coefficient may be expressed as follows:

$$r_S = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n^3 - n} \tag{5}$$

where d_i is the difference for each pair of ranks:

$$d_i = R(X_i) - R(Y_i) \tag{6}$$

To verify the significance of the rho-Spearman coefficient, the Student's t-test was carried out. The t-statistic is defined as follows:

$$t = r_s\sqrt{\frac{n-2}{1-r_s^2}} \tag{7}$$

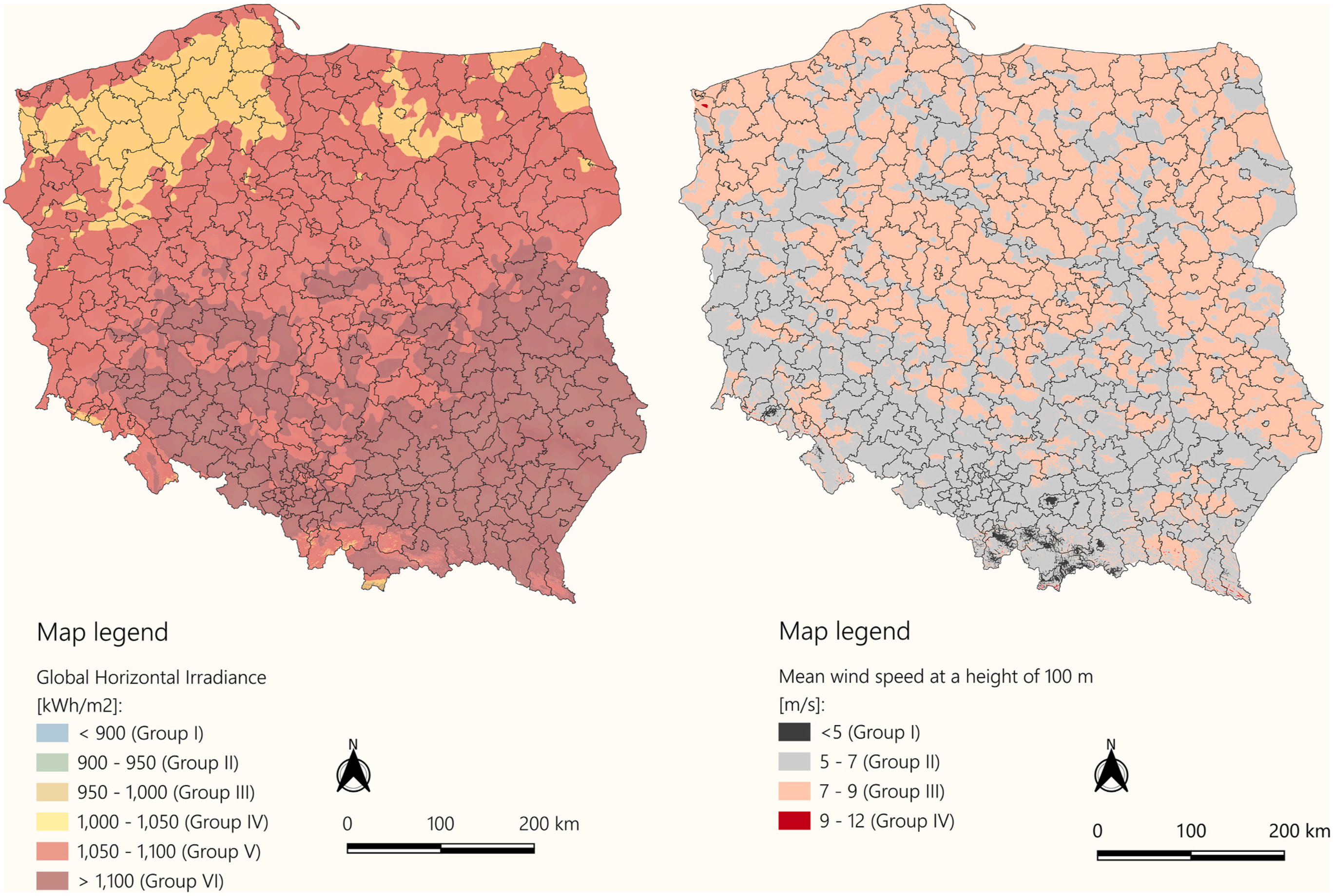

Fig. 1. Irradiance and mean wind speed in Poland – distinguished groups.

Table 3
Results of KS test calculations. Own elaboration based on [31].

KS test – distribution for installed capacity of wind power plants ($N = 380$)		$\mu = 24.326$ $\sigma = 50.091$ $d = 0.31098$
Coefficient of significance	Critical value	Should null hypothesis be rejected?
$\alpha = 0.01$	$d_\alpha = 0.08362$	Yes
$\alpha = 0.05$	$d_\alpha = 0.06977$	Yes
$\alpha = 0.1$	$d_\alpha = 0.06258$	Yes
$\alpha = 0.2$	$d_\alpha = 0.05489$	Yes
KS test – distribution for installed capacity of photovoltaic power plants ($N = 380$)		$\mu = 16.7979$ $\sigma = 23.9398$ $d = 0.2388$
Coefficient of significance	Critical value	Should null hypothesis be rejected?
$\alpha = 0.01$	$d_\alpha = 0.08362$	Yes
$\alpha = 0.05$	$d_\alpha = 0.06977$	Yes
$\alpha = 0.1$	$d_\alpha = 0.06258$	Yes
$\alpha = 0.2$	$d_\alpha = 0.05489$	Yes

where $n - 2$ denotes degrees of freedom.

To verify whether the statistical significance of the correlation exists, the null hypothesis and the alternative hypothesis are posed. The null hypothesis H_0 claims that the correlation between the variables is not statistically significant, while the alternative hypothesis H_a states that the statistical significance between them exists. The null hypothesis should be accepted if the calculated value of *p*-value of Student's t-test is higher than assumed level of significance α. For this study, the level of significance was set at $\alpha = 0.05$.

The strength of correlation between analysed variables was assumed to be interpreted as follows [34]:

- $|0 - 0.1|$ – negligible correlation;
- $|0.1 - 0.39|$ – weak correlation;
- $|0.4 - 0.69|$ – moderate correlation;
- $|0.7 - 0.89|$ – strong correlation;
- $|0.9 - 1|$ – strong correlation.

When the correlation coefficient takes negative values, it means that variables are inversely related. Otherwise, when the positive correlation is observed, it means the increasing magnitude of one variable is associated with an increase of magnitude of the other variable.

It is important to underscore that the correlation means the degree of association between given two variables, and the analysis of correlations grows out of interdependence study [35]. Hence, since the correlation describes association between variables, this term does not refer to causation, because variables can be interrelated, but one may not cause the other. The correlation coefficient, in turn, is a gauge that measures the correlation. This coefficient takes the values between -1 and $+1$, and the sign indicates the direction in which the variables are correlated, i.e., whether they are positively or negatively related. If the correlation coefficient takes a value of zero, it means that there is no correlation between given variables [36].

4. Results and discussion

4.1. Installed capacity of renewable power plants in Poland

As demonstrated in Table 1 placed in the previous section, the number of photovoltaic and wind power plants in Poland has reached 5410 and 1425 in June 2024, appropriately. The number of these power plants translates into installed capacity of, respectively: 6.62 GW and

9.86 GW. It is worth noting that these figures refer to installations other than micro installations, whose installed capacity is up to 50 kW in accordance with binding legal provisions.

Prior to geostatistical analysis, it is crucial to determine the characteristics of power plants in question. This allows to characterize the variability among the studied population of photovoltaic and wind power plants.

In order to conduct statistical analysis, power plants under study have been separated into several groups according to the installed capacity of power plant. Tables 4 and 5 show subsequently identified groups of photovoltaic and wind power plants with the share of each group and its installed capacity among individual types of technology.

When it comes to photovoltaic power plants, we can distinguish three main groups considering their installed power. These groups are, in turn: small scale (of capacity up to 1 MW), large scale (of capacity from 1 MW to 100 MW), and very large scale. The installed capacity of the latter one exceeds 100 MW [37]. Both large scale and very large scale photovoltaic power plants can be considered as utility scale solar energy [38]. Concerning installed capacity of photovoltaic power plants in Poland, it is clearly seen that the largest group in terms of numbers are installations with a capacity of less or equal to 1 – small scale power plants. Interestingly, despite utility scale photovoltaics account for 6.3 % of the installations in question, their contribution to the total installed power reaches nearly 39 %.

Groups of wind power plants can be defined variously depending on the scale of power plant and current national policy or based on the current needs of the research being conducted. Moreover mentioned groups may be even determined by the installed power of individual wind turbine. Considering the possibilities of wind turbine location, social acceptance of these energy projects and their landscape impact, in this study power plants of installed capacity above 5 MW are marked as utility scale once. It is furthermore assumed that power plants above 50 MW of installed power fulfil the criterion of large-scale power plants. It is worth noting that installations of that scale require large acreage to be constructed, since it is essential to deploy wind turbines constituting wind power plant according an appropriate spacing between them. This ensures the optimal performance and energy yield of installations in question.

Table 4
Characteristic of the share of installed capacity among each designated group of photovoltaic power plants in Poland.

Groups by capacity [MW]	Number of power plants in group	Total power of the group [MW]	Percentage of designated power plant group in total number of power plants [%]	Share of the installed power of group in total technology installed power [%]
Less than or equal to 1	5071	4045.06	93.7	61.1
More than 1 and less than or equal to 9.999	314	1133.95	5.8	17.1
More than 9.999 and less or equal to 50	14	461.11	0.3	7.0
More than 50 and less or equal to 100	8	547.83	0.1	8.3
More than 100	3	432.76	0.1	6.5

Table 5
Characteristic of the share of installed capacity among each designated group of wind power plants in Poland.

Groups by capacity [MW]	Number of power plants in group	Total power of the group [MW]	Percentage of designated power plant group in total number of power plants [%]	Share of the installed power of group in total technology installed power [%]
Less than or equal to 1	609	400.93	42.7	4.1
More than 1 and less than or equal to 5	485	1110.432	34.0	11.3
More than 5 and less or equal to 10	140	990.81	9.8	10.0
More than 10 and less or equal to 50	151	4250.679	10.6	43.1
More than 50	40	3110.925	2.8	31.5

4.2. *Spatial distribution of photovoltaic and wind power plants installed capacity and the correlation between the capacity and local conditions*

The first finding of this study is the spatial distribution of discussed power plants at a regional (district) level. The location of the power plants under study is designated by their installed capacity. Figs. 2 and 3 demonstrate the spatial distribution of the considered installations (as installed capacity) of photovoltaic power plants and wind power plants in Poland, respectively. As seen on these figures, spatial distribution of studied renewable energy power plants varies in Poland on a local level. We can observe a concentration of photovoltaic system in the western part of Poland, while wind energy installations dominant in the northern and central part of country. It is clearly evident in Fig. 4, which shows the summary of previous figures on the background of voivodeships boundaries.

Considering the installed capacity of photovoltaic power plants, it should be stated that their presence is strongly marked in western voivodeships, while in central Poland, as well as in its southern part, the amount of installed capacity and, consequently, the area occupied by these installations (being a derivative of the first factor) is much smaller. The northern and central-west parts of the country are dominated by wind power plants. In southern voivodeships, we can observe a notably noteworthy small number of mentioned installations. Interestingly, there are not many districts within which boundaries photovoltaic power plant is not operating, while the lack of wind turbines is evident. However, in many administrative units, the presence of both is less noticeable than in the others. Only in 21 districts (equivalent to 5.5 %) there is no photovoltaic power plant. As for wind energy systems, these are during the operation phase in 218 districts. It means that in 42.6 % of districts wind power plants have not been erected yet. Table 6 presents the percentage of districts belonging to each group of districts in terms of installed capacity within their boundaries.

As it was described in Method section, in this study rho-Spearman's rank correlation coefficient is used in order to determine the interdependence between the installed capacity in districts and the characteristic factors of these administrative units. It is worth to highlight that the Pearson's correlation coefficient can not be used since the distribution of installed capacity of both photovoltaic and wind power plants is not non-normal.

Table 7 shows the determined rho-Spearman's correlation coefficient

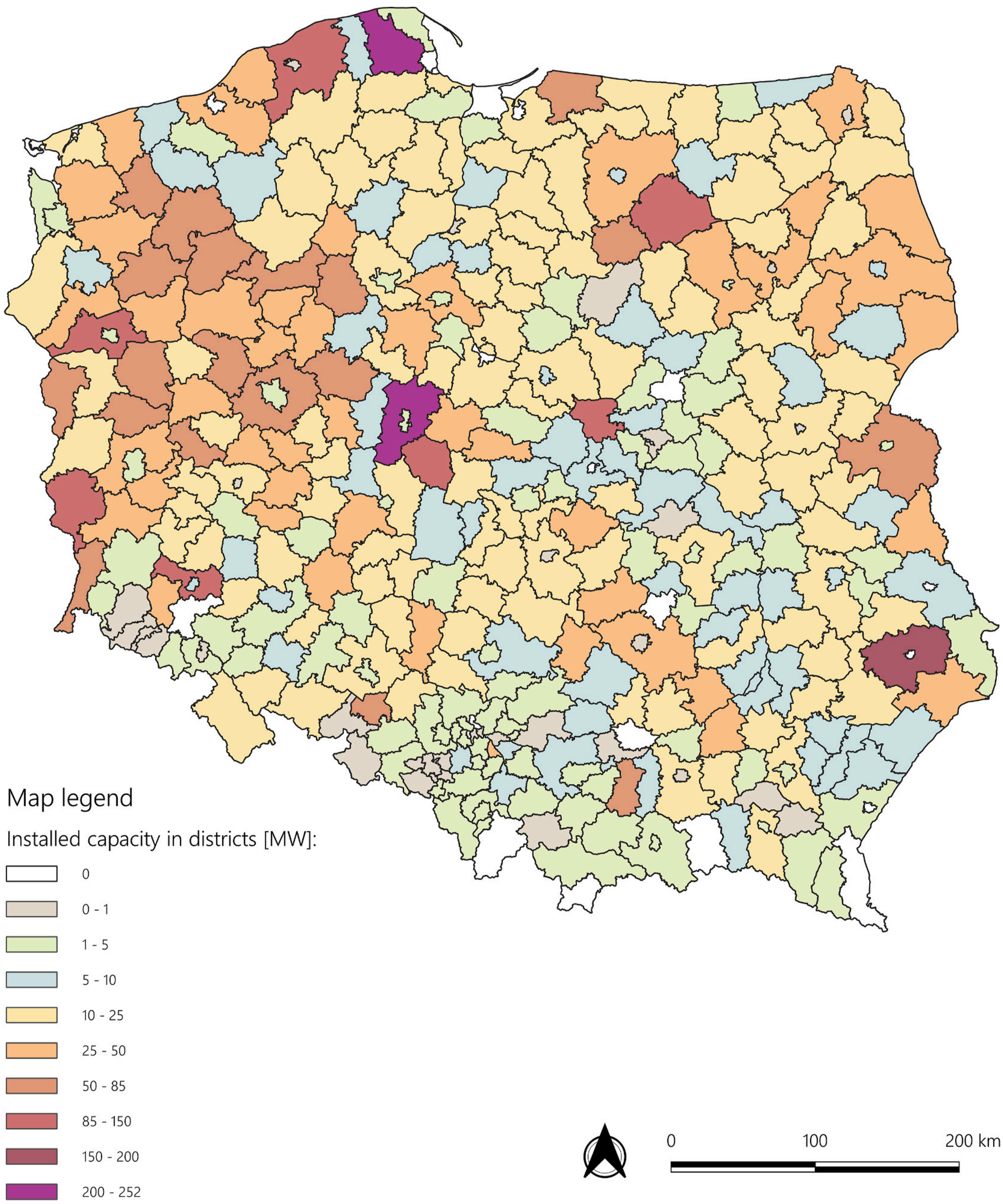

Fig. 2. Spatial distribution of installed capacity of photovoltaic power plants at the regional level of administrative division of Poland. Own elaboration.

for the studied variables with indicated levels of significance α, value of Student's t-statistics p-value and the explanation of statistical significance of the result. Furthermore, it is worth noting that the determined correlation coefficient between photovoltaic and wind power plants' location is statistically significant (with p-value of 0 and $\alpha = 0.05$) and amounts to $r_s = 0.5212$.

As it is seen in Table 7, the determined correlation coefficient is significant statistically for the majority of given variables. However, considering the distribution of wind power plants in terms of the installed power, it turns out that the rho-Spearman coefficient should not be taken into account to identify a relation between their installed capacity in districts and forestation (x_1) and global horizontal irradiation (x_3) since the result of Student's t-statistic proves that there is the lack of statistical significance between these factors. Table 8 presents the level of correlation between analysed variables. The interpretation of determined correlation coefficients is presented in Table 8.

A weak negative correlation is observed between the distribution of installed capacity of wind power plants and, in turn: population density, shared of the land covered by local development plans, urbanisation index, median price of square meter of sold properties in 2023, and finally total income of municipalities. It means that the increase in installed capacity of wind power plants is accompanied by a decrease in the factors mentioned listed. Wind turbines appear to be preferred to be constructed within regions of low population density ($r_s = -0.3931$) and low urbanisation index ($r_s = -0.1963$), in regions where lower properties prices occur (e.g., in rural areas, $r_s = -0.1958$). Higher volume of installed power of discussed power plants is moreover weakly correlated with the income of municipal authorities – wind turbines are constructed in administrative units, where local governments obtain less amounts of income ($r_s = -0.1948$). Interestingly, despite the fact that since 2016 wind power plants are required to be developed on the basis of local development plan, these renewables occur rather in regions where land coverage of local plans is low ($x_5 = -0.3363$). The reasons for this may be two and they are as follows: first, the wind turbines may

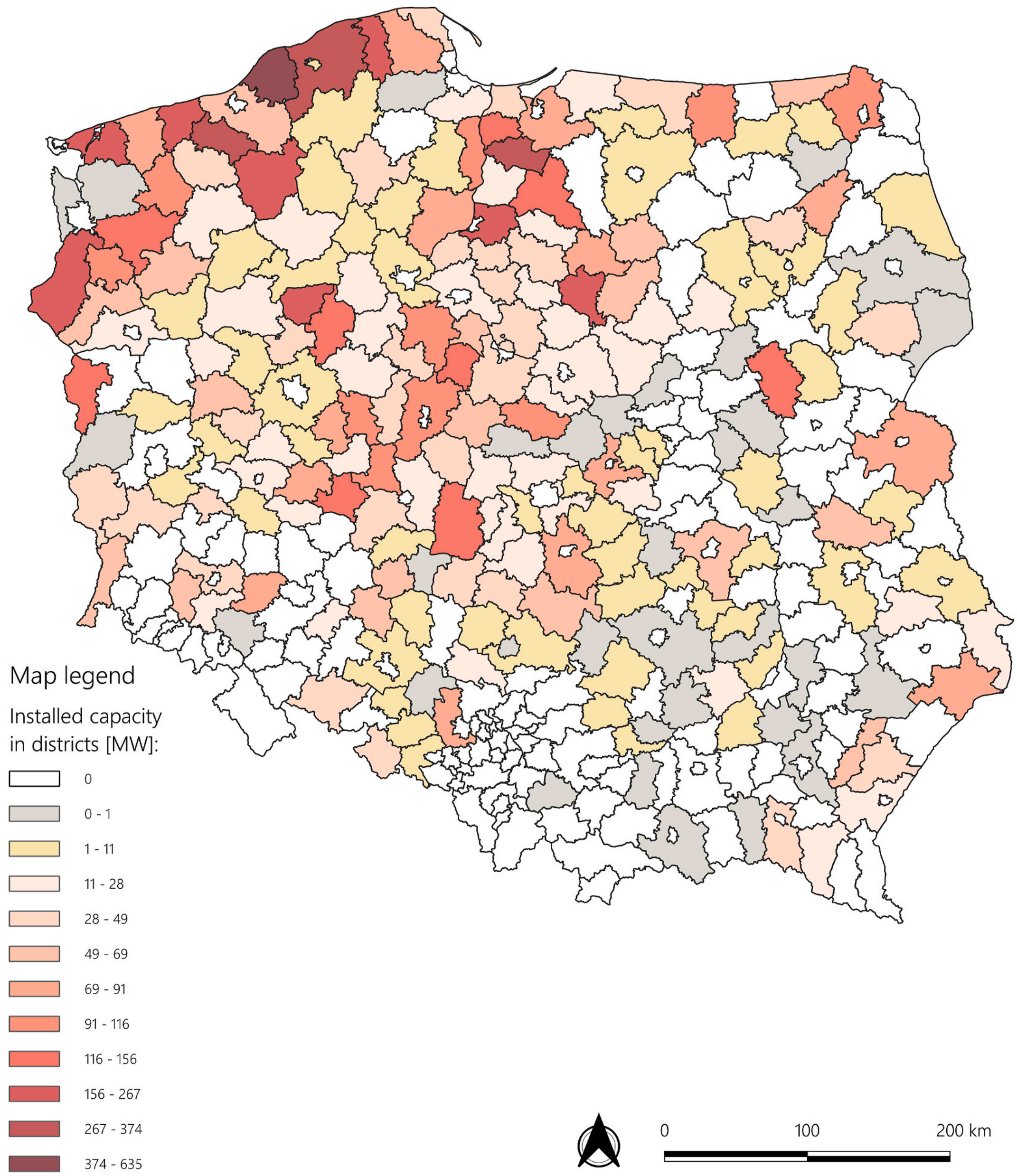

Fig. 3. Spatial distribution of installed capacity of wind power plants at the regional level of administrative division of Poland. Own elaboration.

have been constructed before the provisions of Act on wind power plants investments enforced, and in consequence investors erected currently existing wind turbines on the basis of the so-called zoning decision and a valid building permit; secondly, it may be that there is a large variation within some districts and renewables under discussion were built within the boundaries of municipalities where the land coverage rate of local plans is high, while for the district is lower – this may happen, for example, in a situation where several municipalities forming the district have enacted local plans at a large acreage of land they manage, while other municipalities have not adopted these local legal acts of law. However, despite the fact that the correlation between mentioned factors was proved, it should be emphasized that the values of the rho-Spearman coefficients are low enough to conclude that the correlation is weak.

Surprisingly, a weak positive correlation ($r_s = 0.1315$) is observed between the percentage of land within administrative units in question covered by nature conservation forms and the installed power of wind power plants within their boundaries. This state of affairs can in fact impact negatively on subjects of protection of these formal protected areas. Nonetheless, it is necessary to highlight that the correlation between two mentioned factors is weak, so the impact indicated can be noticeable with different strength in various districts. Moreover, it appears that the share of land covered by terrains under discussion is not a paramount determinant of wind power plants localisation.

A moderate positive correlation exists between wind power plants' installed power and forest cover level ($r_s = 0.5742$). This make it to conclude that within the increase of forestation factor, the presence of wind turbines at regional scale is greater. It is highly interesting taking into consideration negative impact of these installations on birds, especially on a biodiversity of forests-related and migrant birds [39]. Hence, despite the determined level of correlation is moderate, this state should be considered in future when siting options of installations under discussion in this paragraph are considered. However, since the determined correlation is moderate, it appears that the forestation factor does not play a key rule in location-selection process.

Finally, a moderate positive correlation between mean wind speed in

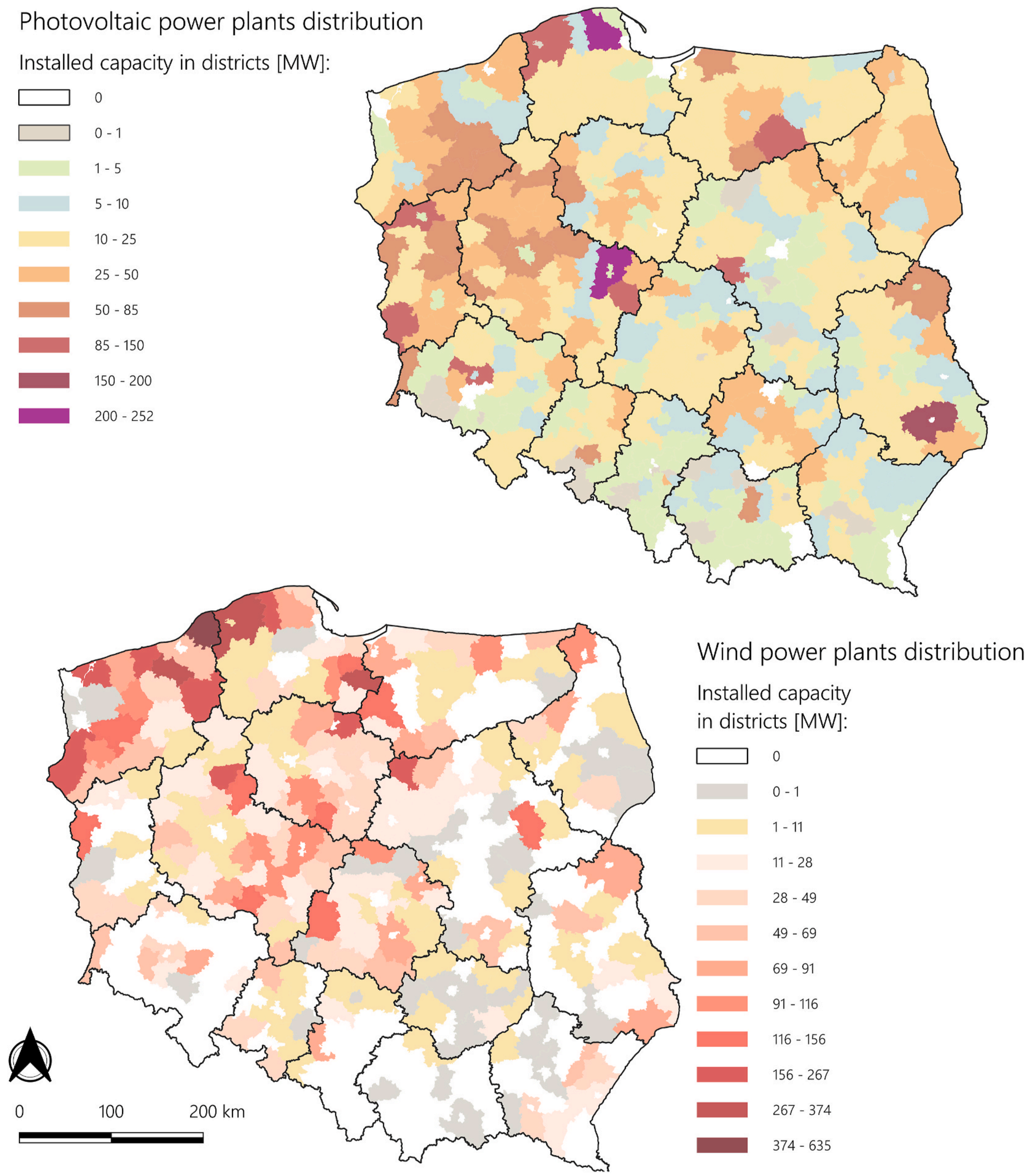

Fig. 4. Spatial distribution of wind and photovoltaic power plants at the background of voivodeships boundaries of Poland. Own elaboration.

selected regions and installed power of wind power plants was captured ($r_s = 0.5443$). Hence, it can be inferred that for investors wind conditions are not essential for wind turbines site selection; however, this factor is made allowance at a certain level for mentioned purposes since moderate correlation was discovered. It can be suggested that in regions where wind conditions (especially wind speed – factor taken into consideration in this study) are favourable, some other factors considered as obstacles in terms of wind energy installations development can be found, including dense or dispersed development, adverse landforms, presence of nature conservation forms or local plans that do not allow to construct wind power plants.

When it comes to the correlation between the installed capacity volume of photovoltaic power plants and analysed factors, the highest rho-Spearman's correlation coefficient can be observed for population density ($r_s = -0.5415$) and percentage of land covered by local development plans ($r_s = -0.4527$). The designated correlation is negatively moderate between total installed power in districts and those two factors. These results prove that photovoltaic power plants are rather developed on the basis of zoning decisions than by virtue of local plans. Furthermore, given the fact that there is a moderate negative correlation between the capacity of installations in question and population density, it can be claimed that these renewables are developed within regions with a smaller population. This expresses the state in which the higher volumes of installed capacity of photovoltaics are observed in regions of smaller population. This is an interesting result that strengthens existing research in this field proving inverse relationship between renewable energy production and population density. It is worth to underscore the variability of population density within Poland. While southern parts of Poland and larger urban centres, as well as central parts of country, have the highest level of population density rate, north-west, and north-east parts of Poland are significantly less populated and this is a long-term observable trend. The correlation between the population density and installed capacity of photovoltaics is well-seen in the map study, as shown in Fig. 5.

The relationship between installed capacity of photovoltaic power plants and the urbanisation index is weakly negative ($r_s = -0.2929$), as well as for median price of sold properties ($r_s = -0.2328$) and total municipal revenue ($r_s = -0.1884$). These results suggest that the

Table 6
Share of districts characterised by the amount of installed capacity of studied renewable energy power plants. Own elaboration.

Installed capacity of photovoltaic power plants in districts						
Group number	1	2	3	4	5	6
Power of photovoltaic power plants in district [MW]:	0	0–10	1–10	10–50	50–100	>100
Percentage of districts in group [%]:	5.53	7.73	39.21	40.26	5.79	1.84
Percentage of districts in group of districts with installed power higher than 0 MW [%]:	–	7.8	41.5	42.62	6.13	1.95
Installed capacity of wind power plants in districts						
Group number	1	2	3	4	5	6
Power of wind power plants in districts [MW]:	0	0–50	50–100	100–200	200–300	>300
Percentage of districts in group [%]:	42.62	41.32	8.98	4.74	1.32	1.05
Percentage of districts in group of districts with installed power higher than 0 MW [%]:	–	72.02	15.6	8.26	2.29	1.83

analysed generation units are rather developed within regions that are less urbanised, where the value of properties is lower than in big urban centres. It appears that agricultural areas attract investors who seek the development of photovoltaic power plant projects more than outskirts of the larger cities. Therefore, it seems that we can expect constant transformation of rural landscape caused by transforming arable lands into industrial form of land use. Hence, local society of rural areas is more affected by energy transition than urban community. However, it is worth to underscore that determined correlation between mentioned variables is weak.

Interestingly, the correlation between installed capacity of photovoltaics and the global horizontal irradiance was found to be negligible since the value of rho-Spearman coefficient is $r_s = -0.0965$. It is highly thought-provoking considering the fact that the efficiency of solar systems is dependent on irradiation level. This result suggests that investors tend to focus on other factors when making their final site selection decision, or do not even do take a factor in question into consideration. It means that alternative spatial factors are under consideration. However, the lack of correlation between the variables discussed will potentially translate into the situation in which expected yield of photovoltaic systems in national scale will be lower than assumed by, among others, policy makers, energy providers and grid operators.

The strongest weak positive correlation was found between volume of installed power and mean wind speed at the height of 100 m (r_s =

Table 8
Interpretation of the results of determined values of rho-Spearman correlation coefficient. Note that for distribution of installed power of wind power plants, factors denoted as x_1 (forestation) and x_3 (global horizontal irradiation) have been left out since there is a lack of statistical significance between them and analysed volume of installed capacity.

Correlation between photovoltaic power plants installed capacity and selected factors			Correlation between photovoltaic power plants installed capacity and selected factors		
X	r_s	Correlation	X	r_s	Correlation
x_7	−0.5415	Negative moderate	x_7	−0.3931	Negative weak
x_5	−0.4527		x_5	−0.3363	
x_8	−0.2929	Negative weak	x_8	−0.1963	
x_9	−0.2328		x_9	−0.1958	
x_6	−0.1884		x_6	−0.1948	
x_3	−0.0965	Negligible	x_2	0.1315	Positive weak
x_2	0.1348	Positive weak	x_4	0.5443	Positive moderate
x_1	0.2672		x_1	0.5742	
x_4	0.3635				
x_{10}	0.524	Positive moderate			
Correlation between installed capacity of wind and photovoltaic power plants	0.5212	Positive moderate			

Table 7
The results of the study. Note, if the statistical population is less than 380 it means that there was a lack of information in dataset.

	X	n	r_s	Student's t-test			
				α	t	p-value	Statistical significance
Distribution of photovoltaic power plants	x_1	380	0.2672	0.05	5.391	0.0000	Yes
	x_2	371	0.1348	0.05	2.6133	0.0093	Yes
	x_3	380	−0.0965	0.05	−1.885	0.0602	Yes
	x_4	380	0.3635	0.05	7.5862	0	Yes
	x_5	380	−0.4527	0.05	−9.8709	0	Yes
	x_6	380	−0.1884	0.05	−3.7297	0.0002	Yes
	x_7	380	−0.5415	0.05	−12.5228	0	Yes
	x_8	380	−0.2929	0.05	−5.9558	0	Yes
	x_9	380	−0.2328	0.05	−4.654	0	Yes
	x_{10}	380	0.524	0.05	11.9614	0	Yes
Distribution of wind power plants	x_1	380	0.0504	0.05	0.9811	0.3272	No
	x_2	371	0.1315	0.05	2.5482	0.0112	Yes
	x_3	380	−0.0726	0.05	−1.4152	0.1578	No
	x_4	380	0.5443	0.05	12.6148	0	Yes
	x_5	380	−0.3363	0.05	−6.9428	0	Yes
	x_6	380	−0.1948	0.05	−3.8613	0.0001	Yes
	x_7	380	−0.3931	0.05	−8.3119	0	Yes
	x_8	380	−0.1963	0.05	−3.8922	0.0001	Yes
	x_9	380	−0.1958	0.05	−3.8819	0.0001	Yes
	x_{10}	380	0.5742	0.05	13.6357	0	Yes

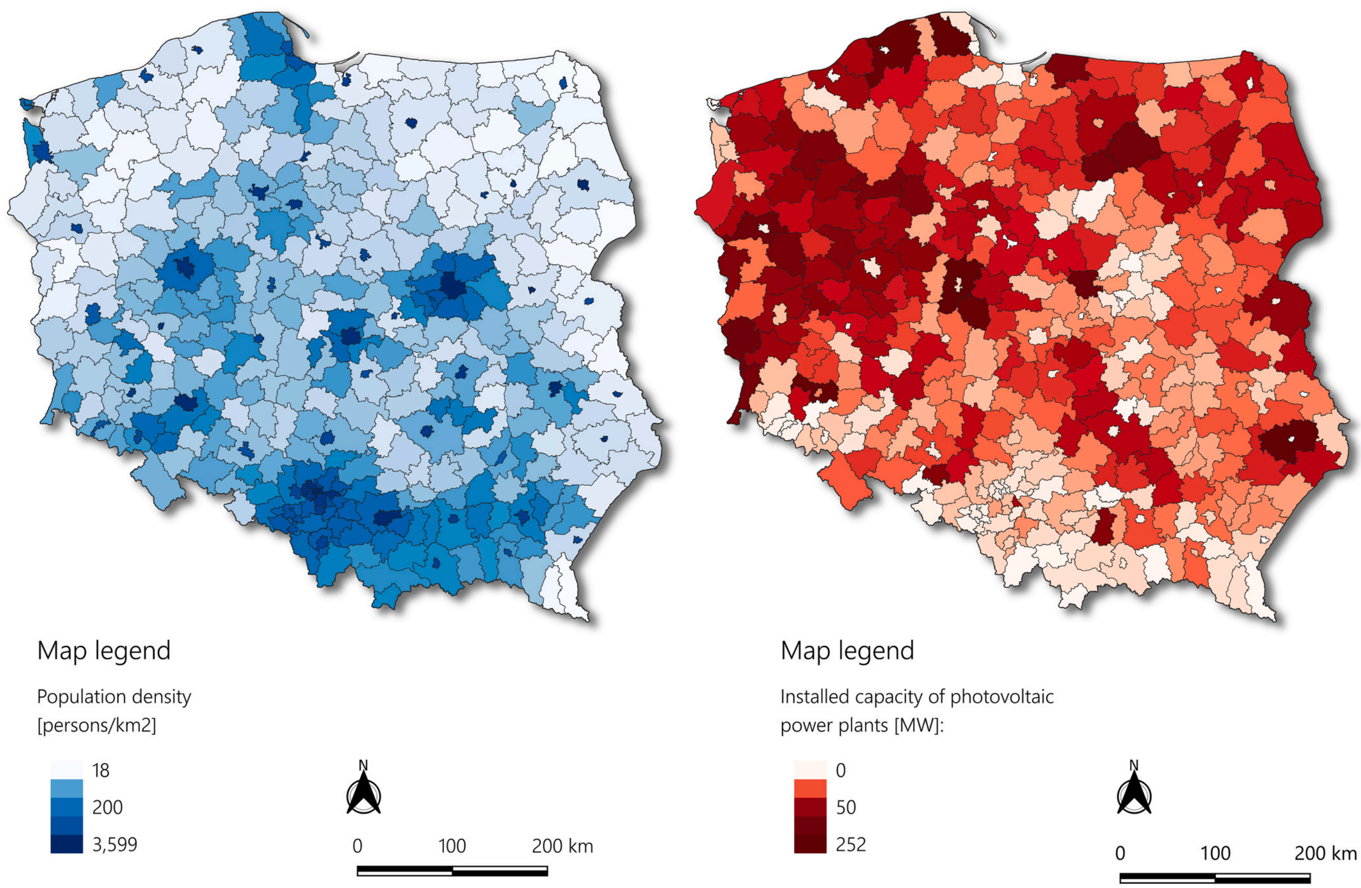

Fig. 5. Graphical presentation of correlation between population density and installed capacity of photovoltaic power plants.

0.3635). This finding is very astonishing; however, it suggests that photovoltaic power plants are sited within regions with a windier climate, that is, in the north and central parts of Poland. However, considering the correlation coefficient between two factors: installed power of wind and photovoltaic power plants, we will notice that there is moderate positive correlation between these variables ($r_s = 0.5212$). Thus, taking into account that the location of two analysed renewable generation units in question is correlated at mentioned level, it can be noted that photovoltaics occur in districts where wind turbines are located. And this can be a reason for the correlation between photovoltaics capacity and higher values of wind speed.

It is also astonishing that the volume of installed capacity of photovoltaic power plants correlates weakly positively with forestation level and the share of land in districts covered by nature conservation forms. Rho-Spearman coefficients reach for these factors, in turn: 0.2672 and 0.1348. This weak correlation means that photovoltaic power plants are more likely to be developed in regions with large areas covered of forest cover than less forested districts. The presence of these generation units is marked stronger within administrative units, where more terrains are enacted as protected once. However, the correlation for the latter one factor is close to negligible. Nonetheless, if a cumulative impact assessment of operating solar systems is carried out, this factor should be considered and, moreover, a detailed analysis of photovoltaic systems location in relation to forests should be conducted. It would allow one to investigate the impact of these industrial facilities on, among others, migration corridors and local mobility of fauna.

One of the most thought-provoking outcomes of the correlation analysis is the result of the correlation of the relationship occurring between the installed capacity of photovoltaic systems and the share of arable farms propertied farmlands of area above 5 ha. Correlation coefficient between mentioned factors is $r_s = 0.524$. Contemplating the fact that photovoltaic power plants require large acreages of land to be developed, it is clear that investors are likely to acquire agricultural properties owned by farmers who have larger plots at their disposal. When it comes to the acquisition process, it is worth noting, parenthetically, that the majority of projects (if not all of them) are rather subject of lease, not purchase of property. Therefore, the result of the analysis proves that photovoltaic power plants are siting in administrative units that are characterised by presence of large plots.

4.3. Summary

This paper provides new insights into the knowledge of the current spatial distribution of photovoltaic and wind power plants. Analysis carried out allowed us also to determine the relationship between installed power of these generation units (and, consequently, their spatial location, since cumulative area covered by them is a derivative of the volume of capacity) and several factors. This analysis was based on regional level correlation representing relationship between factors occurring at the scale of districts.

The first crucial outcome arising from this analysis is that the Pearson correlation coefficient is not a suitable gauge of measuring the relationship between spatial distribution of installed capacity of installations in question and factors analysed. However, the rho-Spearman coefficient was found useful for this purpose. Thus, in the current state of affairs, first mentioned indicator should be avoided and analysis aiming to relate spatial factors with installed capacity of renewables in question should use Spearman correlation analysis.

Overall, the results obtained present the correlation between installed capacity of renewables in question and several factors which represent four general groups of indicators: environmental; spatial planning-related and local government-related factors; local society-related and economic factors; agriculture characteristics.

The correlation analysis performed proved that there is no strong correlation between the variables under study. Regarding photovoltaic power plants, moderate negative correlation was discovered between the volume of their installed power and, in turn: population of districts and urbanisation index. On the other hand, installed power of these renewable installations moderately positively correlates with the presence of larger properties being subject of ownership in districts. It was demonstrated that photovoltaic systems are more likely to be siting in regions where the structure of propertied farmlands is characterised by the presence of properties of larger acreage. Moreover, it should be underscored that the correlation between the main factor in question and global horizontal irradiance is negligible.

Regarding the distribution of installed capacity of photovoltaic power plants, as the result of this study emerges a picture that describes their location and the relationship between it and analysed factors. First, the location of installations under study is spatially uneven. Some regions experience a stronger presence of photovoltaics, while others are less affected by it. The results of correlation analysis shows that photovoltaic power plants are likely to be developed in rural areas with lower population density and relatively small urbanisation index. The prices of properties in those regions are also lower, as photovoltaic systems are not developed in urban centres or in their proximity. Furthermore, the irradiation level is not a key factor that is taken into consideration when the decision of installation location is made.

Moving on to the results concerning the distribution of wind power plants, it is evident that the essential factor affecting the yield of these renewables (mean wind speed) correlates moderately positively with the location of existing objects. Interestingly, performed correlation analysis demonstrated that wind turbines are siting in regions with a lower population density factor. It is also evident that these power plants are located rather in regions of low coverage of nature conservation forms and, what is surprising, in districts with relatively low share of lands covered by enacted, binding local spatial development plans. This outcome suggests that many of wind power plants under operational phase was constructed on the basis of zoning decision, before the provision mandating to locate wind turbines using only local plans. Notably, the lack of statistical significance was found as to correlation of the distribution of wind power plants and, in turn: global horizontal irradiation and forestation.

This study also points out that location of wind power plants and location of photovoltaics is interrelated and the correlation between these to factors is moderately positive. This outcome suggests that the projects of both renewable installations in question are developed in similar regions.

Given the fact that spatial distribution of industrial infrastructure translates into direct and indirect environmental impacts, it should be suggested that further work should be focused on the analysis of cumulative environmental, social, and economic impacts caused by both photovoltaic and wind energy power plants, especially related to influences associated with, among others, the value of properties, communities' well-being, the effect of reducing the migration of fauna, and cost of energy. Thus, with factors constituting the environment. This work creates foundations for research aimed the analysis of mentioned impact.

At the end, it is worth noting that the location of photovoltaic and wind power plants can have long-term impacts on natural environment. These impacts may be related with the location of analysed generation units as, for instance, their presence in the proximity of forests may impact fauna mobility and biodiversity. What is more, siting renewable installations such as solar system within regions of large acreages of agricultural properties is potentially hazardous for agriculture. Therefore, it was essential to indicate relationship between their spatial distribution and the intensity of occurring individual characteristics of Polish districts. It allows one to conduct further works in the subject of matter. Especially, the findings of this study can contribute to the future environmental impact assessments procedures since the cumulative impact of photovoltaic and wind power plants can be investigated, what is important for planned investments.

5. Conclusions

This work demonstrates the current distribution of photovoltaic and wind power plants in Poland and determines their spatial location in relation to selected topographic objects presence. First of all, it was proved that Spearman's rank correlation coefficient should be used to determine the correlation between the spatial distribution of renewable power plants in question and the presence of topographic objects. Therefore, since investigated variables (location of renewable installations) are not described by normal distribution, Pearson's correlation coefficient should be avoided.

Secondly, the correlation between the location of installations for which this investigation was performed and analysed variables is not strong. Interestingly, the spatial distribution of installed capacity of photovoltaic and wind power plants is interrelated since the result of correlation analysis is moderately positive. This investigation shows therefore with presence of which factors location of renewables studied is correlated. Hence, the results of the analysis describe a pattern ruling the development of photovoltaic and wind power plants.

Moreover, the result of this analysis proved that the distribution of photovoltaic and wind power plants is spatially uneven. This state of affairs leads to the situation, in which some regions are more affected by the presence of analysed installations than others. Therefore, considering the environmental impact of photovoltaic and wind power plants that is described in the literature, it is necessary to take into account the spread of those installations (especially large-scale ones) for analysis with the aim of describing the cumulative impact on the environment. As it was already mentioned, since some regions are characterised by greater volume of installed capacity, the local environment can be more affected by the presence of these generation units. When it comes to environmental impact, this study gives the thought-provoking result that some environmental components can be affected by the presence of power plants in question more than others, as for some variables the value of correlation coefficient is higher than for others. Therefore, the result of this study allows to predict the environmental impact of both photovoltaic and wind power plants, as well as cumulative impact of them.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Szymon Pelczar reports a relationship with Valorem Energies Poland that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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