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GIS-based approach for the evaluation of wind energy potential: A case study for the Kujawsko–Pomorskie Voivodeship

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ABSTRACT

The use of renewable energy sources for energy production is increasingly gaining importance in the transition of energy systems based on fossil fuels. In Poland, wind energy is expected to play a mayor role in fulfilling the recent targets set out by the national policy. As the utilisation of wind energy is perceived to be associated with various negative impacts, this kind of energy source should be systematically addressed by related spatial policy instruments to ensure its harmonisation with infrastructural, ecological and socio-economic systems.

The objective of this study is to develop an approach to support the decision making process connected with the site selection for wind energy projects using a geographical information system.

Available locations for wind farm sites were investigated according to defined criteria reflecting the spatial and ecological policy and regulations. The technical and economic potential was estimated to quantify the conditions of the case study region regarding the utilisation of the wind source.

The methodology was applied to the Kujawsko–Pomorskie Voivodeship, since no such study is available for the region. The results from the study should help to build a developmental vision for sustainable energy systems based on locally available resources.

Contents

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1. Introduction

In December 2008, the European Commission approved the mandatory target of 20% of RES share in the EU primary energy consumption, and imposed on each member state individual targets allowing them to decide on their own preferred mix of alternative energy sources. Poland is expected to increase the fraction of renewable sources in its total energy consumption from today's 7% to at least 15% in 2020. Among other alternative resources, the promotion of wind energy is to be the leading measure in achieving the target, as *the Polish Energy Policy until 2030* aims for the very ambitious goal of increasing by ten times the capacity of 666 MW currently gained from installed wind energy plants by 2020 [1].

Moreover, *the Directive 2009/28/EC* calls upon the member states to define and coordinate the administrative responsibilities of the national, regional and local self-governments, integrating the RES technologies into energy portfolios through spatial and energy planning.

Under the current legal framework, the role of the regional authorities in creating the energy policy and planning is rather passive [2]. Therefore, while preparing the implementation of the RES target sought by the Directive 2009/28/EC, the Convent of Heads of the Polish Regional and Local Self-Governments expressed its concern about the lack of consultation of the representatives of regional self-governments. Neither the "production potential" allocation by the Voivodship administrations, nor the share of particular renewable energy sources [3] are known.

According to the Polish Energy Act, the commune as a basic self-governmental entity is responsible for shaping the spatial and energy plans. However, the lack of financial resources and expertise has often been the main barrier to implement municipal land use plans and development strategies,[1] which link the commune mid-term development objectives with energy, environmental and infrastructural issues [4]. A situation like this leads to spatial disorder [5] and slows down the development of renewable energies.

As the wind energy and other RES are perceived to be associated with various negative impacts, they should be systematically and carefully addressed by related spatial policy instruments to ensure a cross-border developmental vision for sustainable energy systems based on locally available resources.

To ensure the land-use as well as socio-economically and ecologically sound wind energy growth, it is therefore necessary to conduct a preliminary regional-scale assessment to bridge the gap between a national-scale and a local or site-specific wind potential assessment.

Moreover, the appliance of regional planning instruments on energy issues would lead to a more sustainable energy policy and to different benefits for self-government authorities as well as for individual developers.

Thus, the objective of the present study carried out at regional level was to contribute to the global assessment of wind energy development potential, and to incentivise municipal authorities to elaborate the communal spatial and energy plans that harmonize wind-power based and other renewable energy projects.

In this paper, a methodology is proposed that can contribute to indentify essential favourable conditions for the installation of wind turbines by taking into consideration regional specific characteristics. The geographical information system (GIS) was chosen as instrument because it provides a logical solution for analyzing a variety of spatially related data in a cost-effective way. Moreover, GIS allows for an integrated assessment of technical and economic potential, resulting in the determination of appropriate zones according to multifaceted and conflicting criteria.

The proposed approach was implemented on the case study of the Kujawsko–Pomorskie Voivodeship.

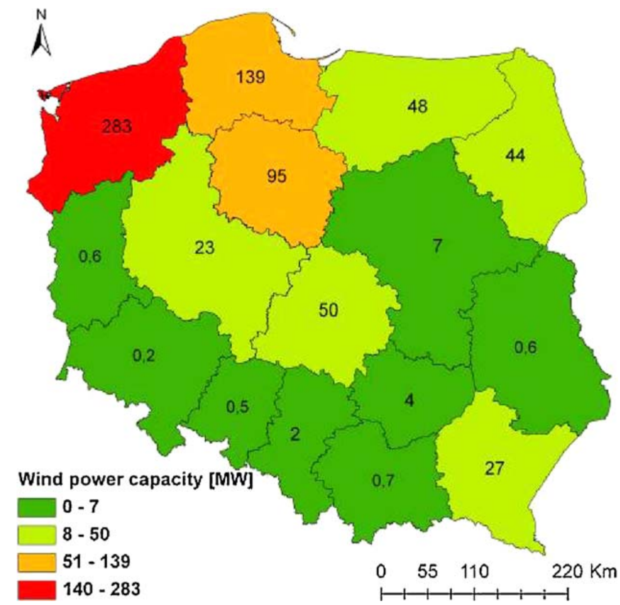

Fig. 1. Installed wind power capacity by the end of the year 2009 [11].

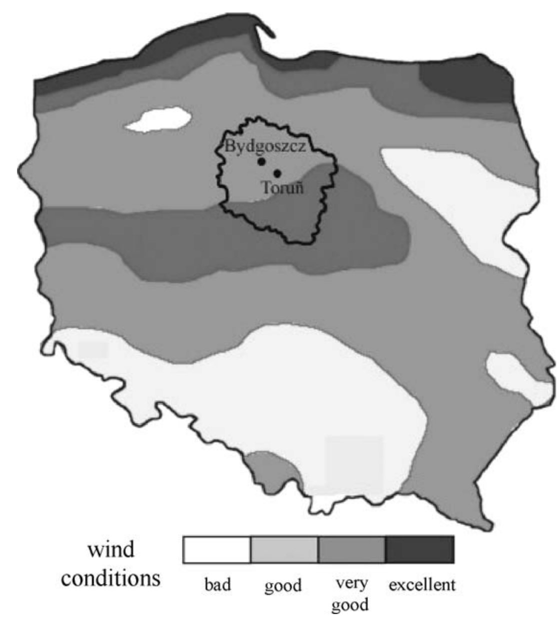

Fig. 2. Wind energy zones in Poland [10].

2. Status quo of wind energy in the region Kujawsko–Pomorskie

The Kujawsko–Pomorskie Voivodeship can be subdivided into good and very good zones according to the amount of wind energy harvested at a height of 30 m above ground, as classified by [10]. It is the third most favourable region with regard to wind regime conditions (compare Figs. 1 and 2). By the end of the year 2009, 120 wind turbines with a total power capacity of 95 MW were operated in the Voivodeship [11]. Most of them (78 wind turbines of 67 MW

[1] Municipal authorities are in charge of preparation of three basic documents: the study of the conditions and directions of the spatial management of a commune, the local land use plan, the assumption for planning and the organisation of heat, electricity and gaseous fuels supply.

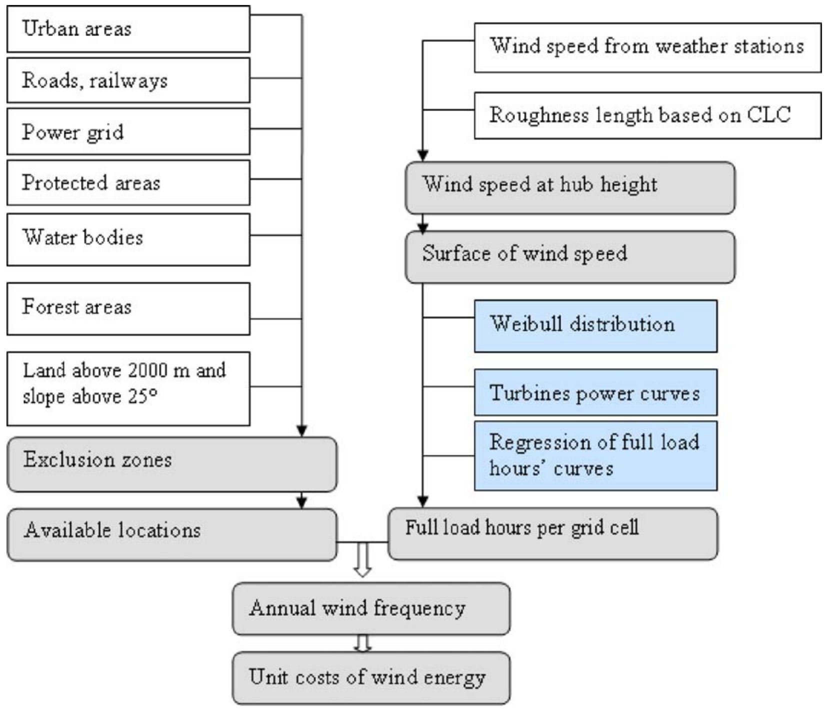

Fig. 3. Overview of the approach to assess the wind energy potentials.

power) are located in four counties: inowroclawki, radziejowski, wlocalawski and aleksandrowski, the area of the latter crossing the "very good zone" in terms of wind regime. The favourable wind and terrain conditions make the region suitable for the development of wind projects. According to [12], the total planned wind power yield is to reach 2540 MW, a quite ambitious plan compared to today's figures.

3. Methodology and scope of the study

The developed methodology for evaluating the wind energy potentials is a set of sequential steps that incorporate the technical and geographical characteristics of the region as well as the restrictions on utilisation of the wind energy. The following actions were performed: first, available locations for wind siting were investigated according to the defined criteria reflecting the spatial and ecological policy. Second, measured wind speed datasets from weather stations were horizontally and vertically interpolated to derive the continuous surface of wind speed at rotor blade heights. Further, the number of full load hours was estimated for three turbines of different powers based on the Rayleigh probability distribution parameters and power curves. Next, the layer of available locations for a wind farm construction was overlaid with the layer of full load hours to determine the technical potential of wind energy in the case study regions. Finally, to evaluate the economic viability, unit costs in the grid cell were estimated. The steps are presented in Fig. 3.

White boxes represent the geographical information derived from vector or raster datasets; whereas blue boxes depict the information calculated from the wind speed regime. Grey boxes describe the results of main phases described above.

3.1. Assessment of suitable areas for wind turbines

The selection of appropriate locations for the construction of wind parks must fulfill certain conditions, since the aim is to enhance environmental benefits and to prevent conflicts related to the wind farm siting. The procedure presented here involves as a first step the investigation of areas unlikely to be available for wind energy development because of their cultural, historical or ecological importance. Siting constraints are most often related to on land use functions which are either mutually exclusive or compatible, like the dual use in the case of agricultural land that can combine the functions of crop cultivation or keeping cattle and energy generation [13].

Generally, one expects wind turbines not to be installed in areas such as wetland, settlements and industrial areas, network infrastructure, nature protection areas, sensitive landscape conservation areas, protection areas, special protection areas according to the EU faun and flora directive, forests, parks and moors, a wide range of different biotopes and cultural heritage.

So far, in Polish spatial and energy policy, there are no specific mandatory recommendations relative to the site assessment for wind farms. The related criteria and constrains were derived from relevant polish legislations, among them the Law on Nature Protection, and from two Polish and German studies [14–16]. Appendix A lists the criteria applied as well as suggested appropriate distances to surfaces of sensitive ecological forms, infrastructure and socio-cultural components. The digital map layers representing the land use and functions was obtained from the Office of Spatial Planning of the Kujawsko–Pomorskie Voivodeship [17].

A proximity to the territory of special protection of birds or other habitats is usually determined on site, thus, in the regional-scale study, this serves only as an example.

Landscape areas are a type of protected areas with less stringent restrictions on development and economic use, as in the case of national parks. Therefore, within such areas, the wind turbine construction may be not strictly excluded. Such exceptions are only permitted if the environmental impact assessment demonstrates that such impact would be tolerable. Table 1 presents the area of potentially suitable locations. It differentiates between sites inside or outside of current and projected landscape parks and landscape protected areas. From almost 12,000 km^2 of agricultural space, only 63% of the original area remains available.

Table 1
Area of sites location in the region of Kujawsko–Pomorskie [km^2].

Total area of Kujawsko–Pomorskie [km^2]	17,971	Share in total area [%]
Site location within current and projected landscape parks and landscape protected areas	7740	43
Site location outside of current landscape parks but inside of projected landscape parks and landscape protected areas	7632	42.5
Site location outside of current and projected landscape parks	7493	41.7

On a regional scale, the precautionary principle should be followed to avoid any detrimental impact on sensitive areas, since the environmental impact assessment is performed on local level.

In this study, the turbine siting is considered to be best within the restricted areas, if the characteristics of the wind regime are significantly more favourable than wind conditions outside of those areas.

Additionally, due to the scale of the digital dataset (1:750,000), small settlements units and sites of scattered rural buildings, individual objective of cultural heritage or smaller forest as well as wetlands were not taken into account in the analysis. For the same reason, the assessment on a regional scale allows only for a preliminary selection of available site locations, but not for the actual wind farm planning.

3.2. *Technical potential*

The accurate determination of annual wind regimes requires the recording of anemometer data at a rotor height of 10 m or higher for at least 12 months, while a site specific decision on specific investments is made. However, for the preliminary decision-making, values of average daily annual wind speed were used, as an indicator for the wind energy potential of certain sites. In the following section, the load hours and energy yield from three exemplary power turbines were calculated on the basis of information derived from the measured wind speed dataset.

3.2.1. *Wind speed data*

In Poland, non-commercial digital information on wind speed that could be used to evaluate the energy potential from wind is not available [18]. In the past, several wind atlases have been prepared [10,19], however, these maps only present the zone of wind speed or wind energy potential at 30 m height above the ground as shown in Fig. 2. As the wind turbine capacity grows rapidly, the wind speed data must be corrected to a hub height 80 or 100 m for the average size of capacity of 2–2.5 MW onshore [13].

For the purpose of preliminary assessment and to draw up the characteristic of wind regime, a dataset was derived from the website of the National Climatic Data Centre [20]. Based on this data, EEA evaluated the wind energy potential for Europe [13]. The dataset for this study included the average daily wind speed collected by 28 meteorological stations over a period of time of four years (2005–2009).

The minimum and maximum distance between the measurement stations is 12 km and 395 km, respectively. The elevation of the considered surface differs between 0 m and 332 m and the highest measurement point is located at 190 m above see level. The average annual wind velocity differs between 2.5 and 4.5 m/s at 10 m above ground in the considered area.

3.2.2. *Wind speed extrapolation*

As the wind speed is related to rotor height, the wind velocity from meteorological stations must be corrected based on the rule that wind speed profiles vary with roughness length of the terrain according to a logarithmic pattern. For the quantitative description of vertical profiles of wind changes, the mathematical formula (Eq. (1)) has often been chosen while considering heights exceeding 60 m above ground [21–23].

$$V_{ZR} = V_z \frac{\ln(Z_R/Z_O)}{\ln(Z/Z_O)} \tag{1}$$

where V_z is the wind data collected at the anemometer height of Z, V_{ZR} is the wind velocity at hub heights Z_R of 50, 80 and 100 m and Z_0 is the roughness length that was derived from the CORINE land cover data (CLC).

The CLC database version 2006 (at 100 m × 100 m resolution) reflects 44 land cover classes [50]. The data was disaggregated to 12 main classes, reflecting similar land use types (see Appendix B).

3.2.3. *Wind speed interpolation*

Once the wind speed had been extrapolated to hub heights, a spatial interpolation technique was used to predict the wind speed in locations where data is not available. A variety of deterministic and geo-statistical methods are available to interpolate the values of meteorological phenomena [24–28]. Among them [29], seven methods were assessed and used to estimate the daily mean wind velocity surface. This appraisal confirmed previous results [27,30] that kriging methods produce most accurate results compared to deterministic techniques.

As the accuracy of results is not only affected by the choice of method, but also by the data sampled, its density and its spatial distribution [31] in the study, the validation of the following methods were tested based on the Inverse Distance Weighting (IDW), Polynomial Interpolation Method (PIM), the ordinary kriging and the ordinary cokriging procedures.

Geo-statistics is effective if data exhibit a Gaussian distribution, otherwise the data must be transformed to adapt it to a normal distribution. Before applying the interpolation methods, the distribution of data was analysed by explanatory data analysis (EDA) in order to look for local trends and to examine outliers and non-homogeneity of the sampled points and spatial correlation.

The common rule of thumb test for normality is the parameter of skewness and kurtosis that suggested in this case deviation from a normal distribution. To check this presumption, the Shapiro–Wilk test was chosen, which deals with a small number of variables. However, the test confirmed the null hypothesis of normality for wind data.

In addition, information derived from explanatory analysis pointed out trend effects. With increasing longitude, a small trend is noticeable and with increasing latitude, the yearly mean speed exhibits a trend in the north–south direction, which is likely to depict differences in elevation between the data points or the roughness length of surface (compare). A Voronoi map was created to checkout possible outliers.

Based on a normally distributed dataset without any outliers, the wind velocity was interpolated at different levels of 50, 80 and 100 m above ground level. The methods of ordinary kriging, ordinary cokriging as well as IDW and PIM procedures were applied trough a Geostatistical analyst extension of the ArcGIS 9.3.

With respect to the trend, which should only be removed if significantly improving results [32] and to satisfy stationarity assumptions [29], the procedures for data with removed trend were performed in the process of the Trend Analysis.

The first step in the kriging procedure was to compute the empirical semivariogram from the set of points to measure the degree of correlation of spatial random variables, after having fitted the suitable mathematical model to the empirical semivariogram and covariance. The fitting of the model into the semivariogram is an fundamental step on the way to determining optimal weights for

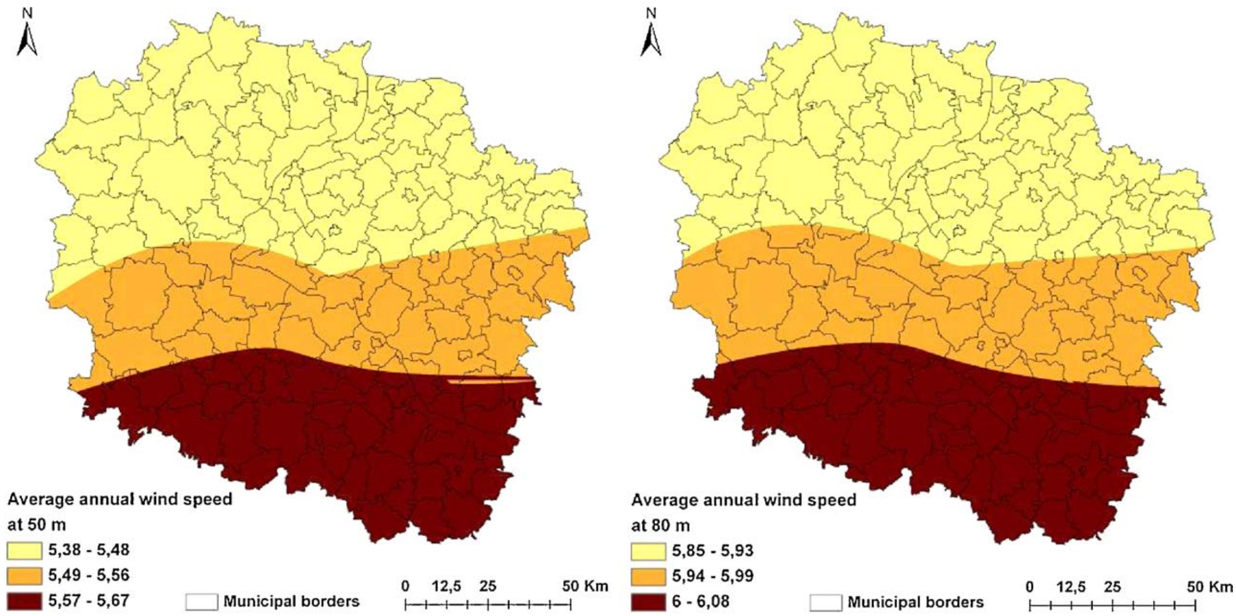

Fig. 4. Interpolated surface of annual wind speed at 50, 80 m above ground.

interpolation [33]. To verify the interpolation accuracy and validity of models before producing the final surface, a cross-validation tool, provided through ArcGIS Geostatistical Analyst, was applied. The spherical model for the ordinary kriging method resulted in most accurate projections, producing the smallest mean standardized error and the mean error closest to zero compared to other models.

Next, the surface for wind speed was interpolated using the cokriging procedure by taking into account the digital elevation model in the subsidiary variable. The cokriging requires an additional estimation of the autocorrelation for each variable and the cross-correlation of both models. The correlation analysis performed for variables, the wind speed and the elevation, suggested a very weak linear correlation ($R = 0.1$), probably due to relatively insignificant elevation differences of the measurements station (between 7 and 190 m a.s.l. see Fig. 6), a fact that conformed the cross-covariance procedure. In this case, the ordinary cokriging technique did not provide any better prediction maps than the ordinary kriging. The IDW and PIM methods have also been rejected as the root mean square and mean error were not as good as in the ordinary kriging.

Once models and the interpolation techniques had been validated, the wind speed surfaces were generated. The wind speed at a height of 50 m, 80 m and 100 m above ground, as presented in Figs. 4 and 5, rises from the north direction, which suggest that the produced data is fairly consistent, while comparing with the zones of in Fig. 2.

3.2.4. Wind energy production

The wind energy harvest is determined by three main parameters, the wind speed, its frequency distribution and the characteristic of power curve of a wind turbine.

Since a range of wind turbine is available in the market, different combinations between swept area, rated power, conversion efficiency, cut-in, cut-off velocity and wind regime are possible, leading to different numbers of load hours and energy yield, three types of turbines were considered. Their technical characteristics are outlined in Table 2. Based on a trade-off between increased power due to the higher turbine power capacity on the one hand and additional cost caused by a larger turbine on the other hand, the energy yield was calculated for different wind turbines with a rated power of 600 kW, 1.65 MW and 2.5 MW, respectively.

The power curves were calculated following the formula:

$$Pn = \frac{1}{2} q A C_{pi} V_{mi}^3 \tag{2}$$

where A is the rotor diameter, C_{pi} is the curve of rotor efficiency for wind speed intervals of 1 m/s, V_{mi} are mean wind speed intervals and q is the air density calculated at anemometer height calculated from Eq. (3). The air density varies significantly with pressure and temperature, thus, for different heights this parameter was corrected by the following equation [36]:

$$q = qo - (1194 \times 10^{-4}\, h_m) \tag{3}$$

where h_m is the site elevation in meters.

For the energy generation assessment, not only wind speed strength but also its probability of occurrence over a certain period

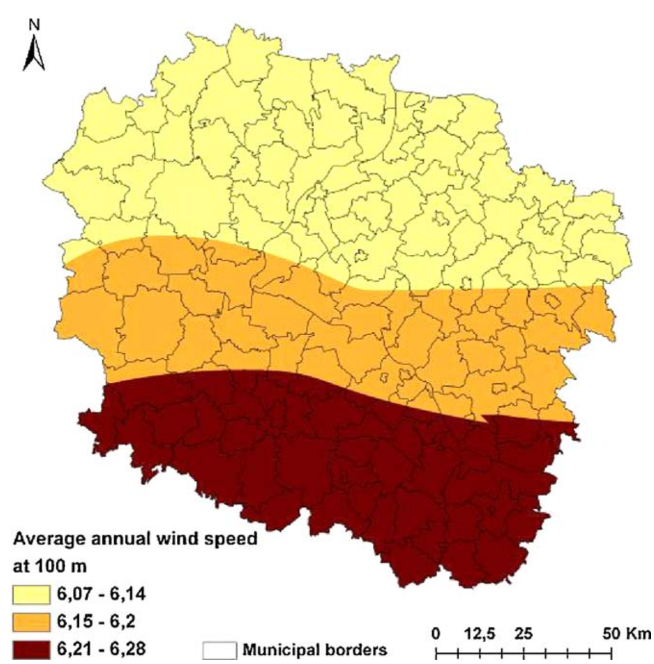

Fig. 5. Interpolated surface of annual wind speed at 100 m above ground.

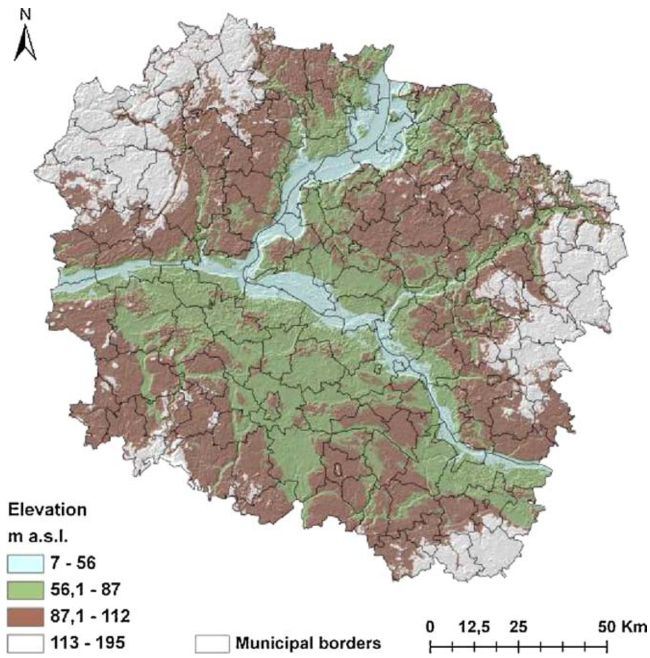

Fig. 6. Elevation above see level.

of time is important. Thus, Weibull and Rayleigh are commonly used functions of statistical distribution for representing wind regime from an average mean value of wind velocity with an acceptable accuracy level [22,37,38]. Rayleigh probability density function is a simplified case of Weibull function with constant shape parameter (k) that ranges from 1.5 to 3.0 for most wind conditions and is given by [39]

$$f(V) = \frac{\pi}{2}\left(\frac{V}{{V_m}^2}\right)\exp\left[-\pi/4\left(\frac{V}{V_m}\right)^k\right] \quad (4)$$

Table 3
Linear regression function for three turbine types and correlation coefficient.

Turbine type	Regression function
Bonus 600	$y = 631.47x - 2018.5$
Vestas 82	$y = 660.74x - 1754.4$
Nordex 80	$y = 648.91x - 1924.1$

where V_m is the average wind speed, k is the shape parameter, V is the wind speed interval.

The Rayleigh distribution for the wind energy analysis has been validated and established to provide reasonable outcomes [40]. The function was used for the purpose of the study.

The annual energy yield (E) was calculated by multiplying the wind turbine power curve (P) with the intervals of frequency distribution of wind speed $f(V)$ calculated with Eq. (4) with the shape factor $k = 2$ as recommended by [41]

$$E = 8760\sum_{t=1}^{t=n} P_n f(V) \quad (5)$$

In the GIS-based approach, the calculation of the energy harvest was automated based on the relation that the energy output is characterised by the rated power and the number of full load hours. In the model, the findings from different studies [42,43] were applied, that full-load hours is a function of a power curve and the average wind speed calculated on the basis of Rayleigh function. To depict a linear relation between the duration of wind speed intervals and the average annual wind velocity, as presented in Fig. 7, the regression functions were plotted for three power curves.

The number of load hours for grid cells over the surface was calculated using a Single Math Algebra tool in ArcGIS 9.3 applying the functions presented in Table 3. The continuous surface of corrected wind speed at hub heights per each grid cell is reflected by the x parameter in the regression functions.

In a practice, a number of full load hours is lower than calculated ones due to two main reasons: the efficiency of wind farms

Table 2
Technical specification of wind turbines.

Producer	Rated power	Hub height	Rotor diameter	Cut-in	Cut-off
Bonus 600	600	50	44	4	25
Vestas 82	1650	80	82	3.5	25
Nordex N80	2500	100	80	3	25

Source: [35].

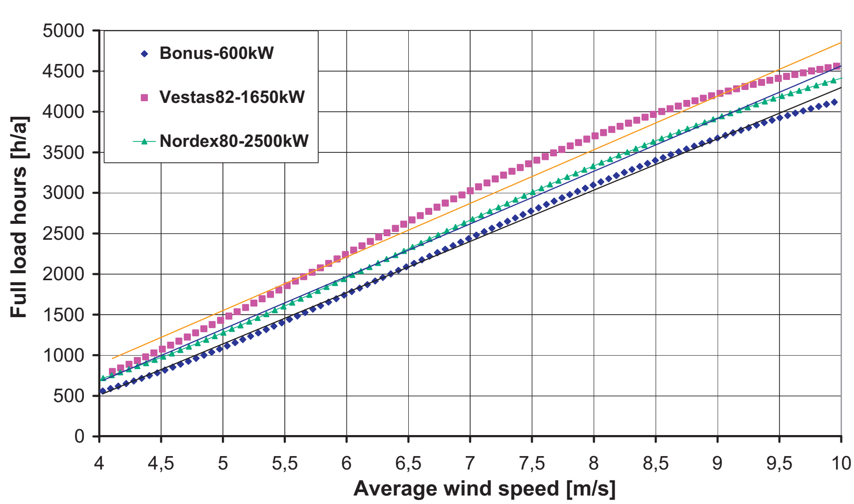

Fig. 7. Linear regression function of the duration of wind velocity within an wind speed interval of 0.5 m/s.

Table 4
Land area occupied by turbine and power density.

Turbine	Power [kW]	Rotor diameter [m]	Area under turbine [ha]	Turbine density per km^2
B44	600	44	7	14
V82	1650	82	24	4
N80	2500	80	23	4

is lower if turbines are sited closer to each other, as well as due to maintenance actions and periods when the turbine is on standby during calms and very height winds [44]. Thus, the full load hours should be multiplied by a parameter ranging from 0.83 to 0.9 for onshore wind parks [13].

Wind slows down as it passes through the blades and reduces the available power to downwind machines. Therefore, the sufficient distance between turbines in form of rectangular array is recommended as follows 3–5 rotor diameters between towers in row and 5–9 diameters between rows [14,21].

In the case study, the land area occupied by a turbine (LAT) is estimated based on the square array of six rotor diameters (D_i) according the following formula:

$$LAT = 6D_i x 6D_i = 36D_i^2 \quad (6)$$

The turbines of either 1650 kW or 2500 kW of power capacity occupied the area of 24 ha, since the size of rotor is similar. A small turbine of the power capacity of 600 kW with a rotor diameter of 44 m takes only 7 ha, as shown in Table 4.

Concerning the landscape protected areas, as outlined above, the intersection of both layers of the number of full load hours and available sites (including landscape surfaces) showed that the technical potential within this protected surface is not higher than outside of those areas. In further steps of analysis, the protected landscape locations were, thus, omitted.

Finally, the wind energy potential in grid cells (of 7 ha or 24 ha) was derived from the multiplication of raster representing the usage time of wind turbines, power rated of turbines and correctness factor as

$$E_i = Pr_j f_i n \quad (7)$$

where Pr_j is the rated power of considered turbines j, f_i is a number of load hours in a grid cell i derived from regression functions and n is a factor (0.89) used to correct load hours.

The spatially spread out time of a working turbine and the annual amount of energy generated by three selected turbines are presented in Figs. 8–10. The annual harvest of wind energy varies most strongly with respect to the working time of a turbine and its power capacity.

The results showed that in the southern part of the study's region, the technical potential is higher with respect to the wind regime conditions. The roughly finding is concordant with the status quo of the wind energy development in the Kujawsko–Pomorskie Voivodeship as shown in Fig. 11 [45].

Assuming the average power density of 1 MW per 1 km^2, Fig. 12 illustrates the area where wind turbines are already being constructed per county (red bar), and the area that would be dedicated to the wind farms (orange bar), as estimated in the previous section.

As simply derived from the comparison, the technical potential remains still untapped. Having compiled a clear picture of the quantity of the wind energy, municipal authorities have considerable influence in deciding on what part of the potential can be utilised without harming social and environmental systems.

The additional, essential factor influencing the projects viability is the willingness of the community to integrate these installations into their energy portfolio.

In the complex process of harmonizing the alternative energy projects with the spatial and energy plans of municipalities, economic factors also play a significant role. The commune will benefit from the investment due to tax incomes, while local communities will do so when leasing the land.

3.3. The economic potential of wind energy

The previous sections dealt with the environmental, infrastructural and technical aspects of the wind energy development. Additional aspects that influence on the growth of wind energy utilisation are market and policy factors which play a significant role in the promoting the development of any renewable energy project [46]. These factors include electricity tariffs, level of subsidies to green electricity and administrative project related policy.

It is of importance to appraise the monetary value of the existing technical potential of the wind energy in order to

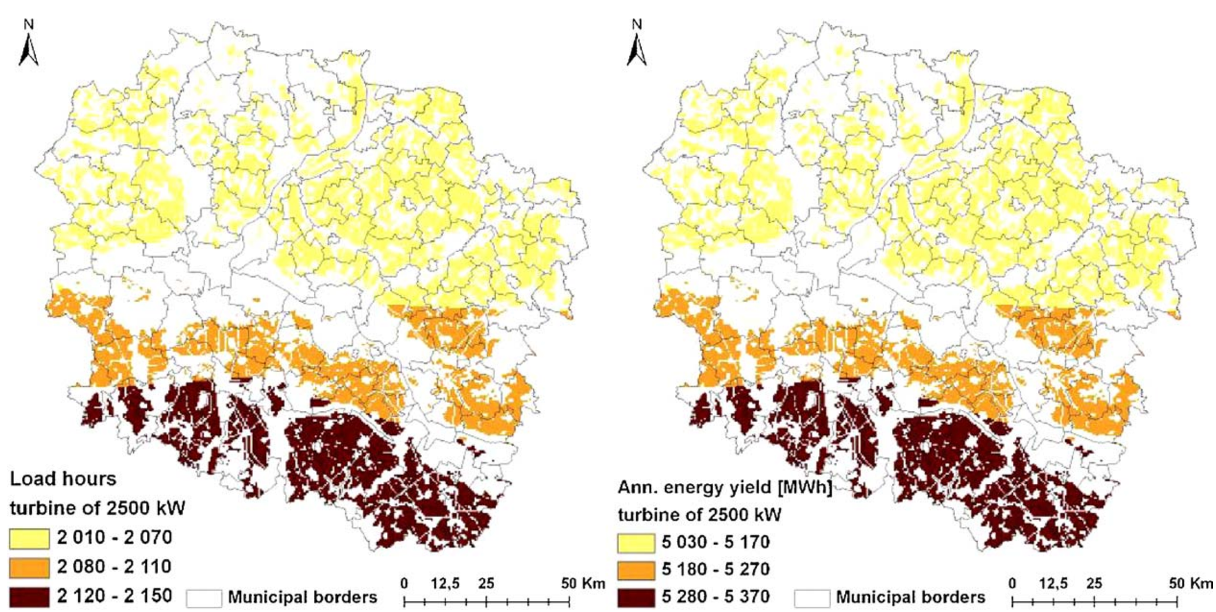

Fig. 8. Average annual number of load hours and energy generated by turbines of 2.5 MW.

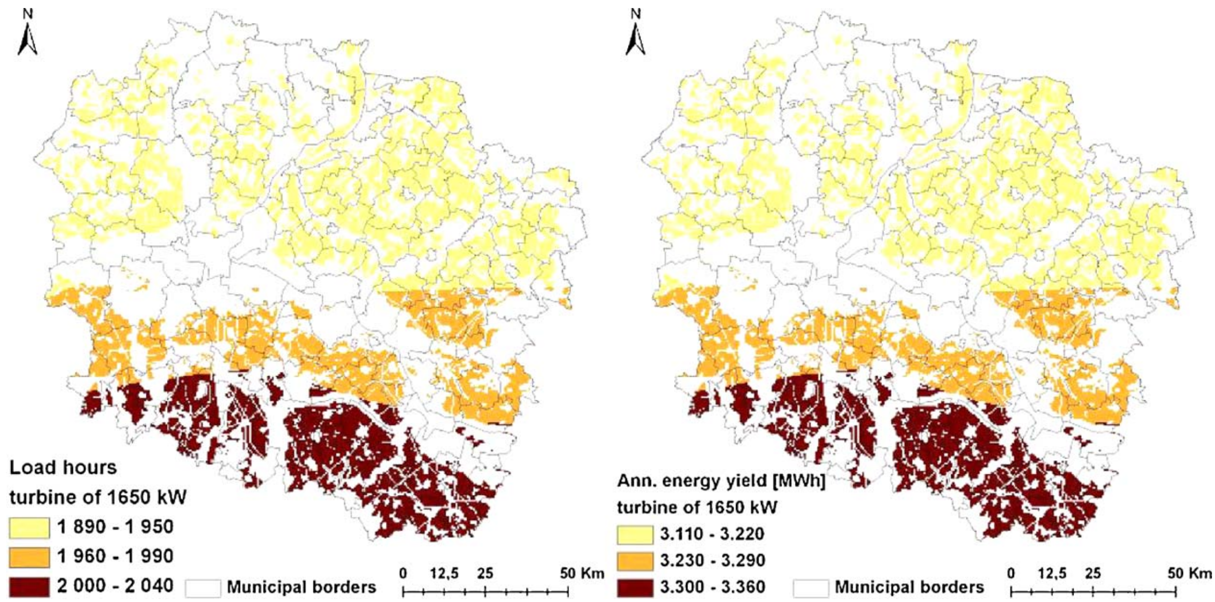

Fig. 9. Average annual number of load hours and energy generated by turbines of 1650 kW.

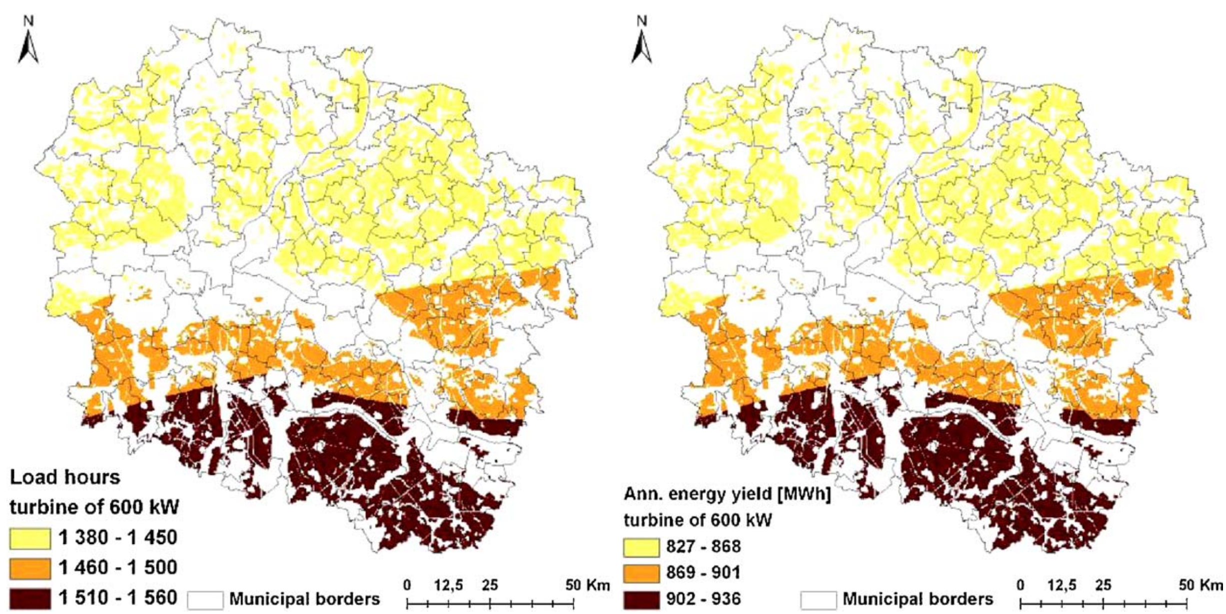

Fig. 10. Average annual number of load hours and energy generated by turbines of 600 kW.

obtain insight into costs and incomes of the energy production.

In Poland, the total price earned by producers of wind energy is composed of the market price of electricity and the price of the tradable green certificates, which fluctuate in the course of time. For instance, in 2009, the minimum sale price guaranteed by the Energy Regulatory Office[2] amounted to 40 € per 1 MWh (155 PLN) and the median price of a "green certificate" was 65 € per 1 MWh (255 PLN).

The average cost of wind energy investment per kW is estimated to be around 1000–1200€, reaching up to 1600€ in extreme cases [13,47–49]. From this price, the expenditure related to the auxiliary and road infrastructure as well as to grid connection may amount up to 15% of the total cost. Annual operation costs include debt service cost, insurance, property tax and lease of land, expenditure on maintenance amount to 3% of the initial capital cost. The additional expenses vary from project to project depending on different site-specific conditions. Nevertheless, for the onshore wind energy, the costs of a generator is still around 75–85% of the total expenses.

In the study, the level of costs was calculated for the range of the total cost per kW (min of 1000 and max of 1600€) to cover the differences of the local-specific expenditures.

[2] The electricity sale price is he equivalent to the median market price during the previous sales year.

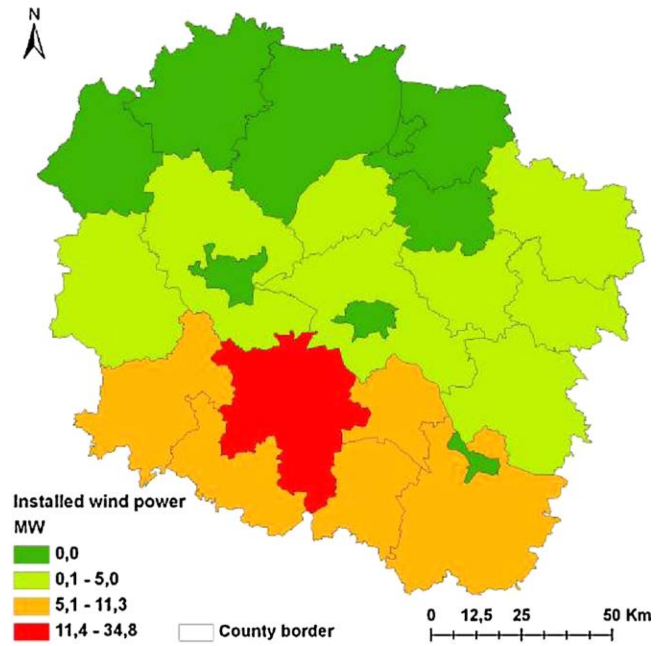

Fig. 11. Installed wind power [MW] per counties in the Kujawsko–Pomorskie Voivodeship, based on data derived from [45].

The average annual cost per kilowatt-hour of electricity generated by a wind turbine was derived from the sum of total annual investment and operating costs and the turbine's annual energy yield. The unit cost of energy was calculated straightforward using the following formula:

$$CE_i = \frac{IPR_{O\&M} + A}{Ei} \quad (8)$$

$$A = IP\frac{r(1+r)^n}{(1+r)^n - 1} \quad (9)$$

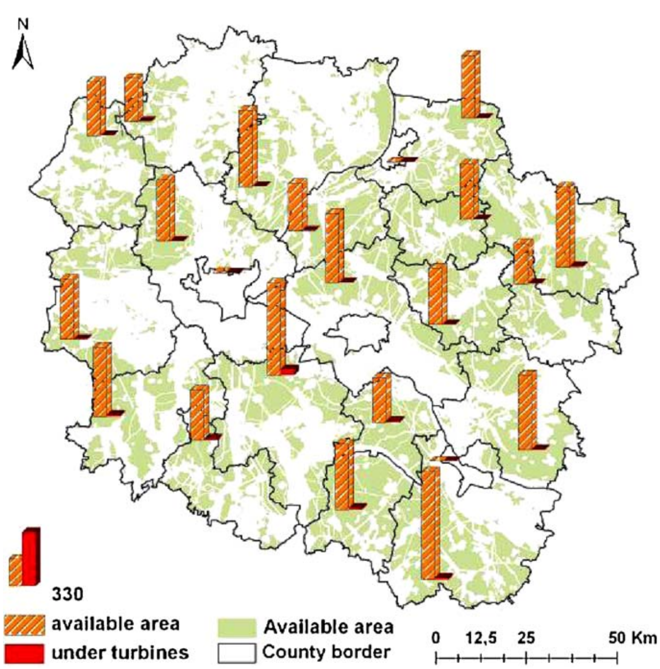

Fig. 12. Available area for wind turbine construction and already occupied by turbines (330 km^2 is an average available area in the case study).

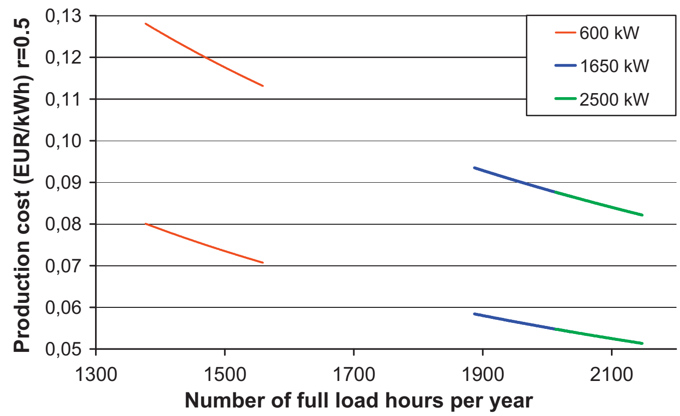

Fig. 13. Electricity generation cost from three turbines as a function of number of load hours.

where CE_i is the cost of 1 kWh of electricity generated in a grid cell i, I is the initial investment cost depending on the turbine size, Ei is the energy yield per grid cells i, n is the life time of the system (20 years), $R_{O\&M}$ is the rate of operation and maintenance costs, r is the interest rate (5%). A is the annual loan payment. The operation and maintenance costs were assumed to be of a constant rate of 0.03 of investment over the life time of installation.

The costs of energy generated for three turbines based on the number of full hours are compared in Fig. 13.

The minimum electricity cost based on the average cost of wind energy investment (1000€/kW) amounts to 51 cents/kWh generated by a turbine of 2500 kW of capacity power, whereas the maximum of 80 cents/kWh produced by a 600 kWh turbine. The technical potential seems to be very attractive from the economical point of view, when comparing the production costs with the sale energy price of 1 €/kWh. At this assumed level of investment cost, all those installations would be considered viable if commissioned by private investors.

With the assumption of the maximum level of an investment cost (1600 €/kW), the energy production costs ranges from 81 cents/kWh to 1.28 €/kWh. Even in the case of the highest investment costs, the wind project of the power capacity of 2.5 MW may still generate some financial benefits. Additionally, due to the scaling up of a wind farm, the costs will fall down by reducing additional expenditures. The results are consistent with the values found in the literature [13].

The calculated economic potential corresponds to the discount rate of 5% and the investment lifetime of 20 years time. A signifi-

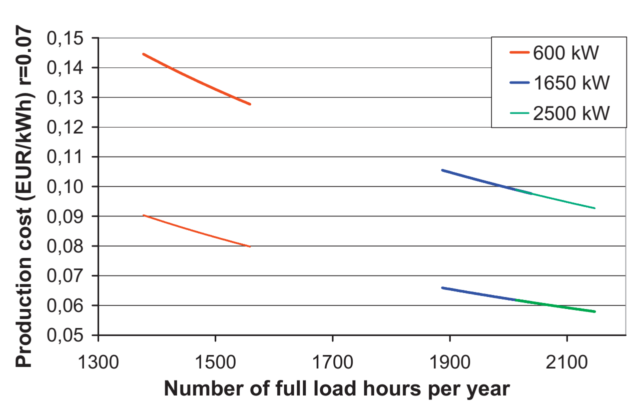

Fig. 14. Electricity generation cost from three turbines calculated with an interest rate of 0.07.

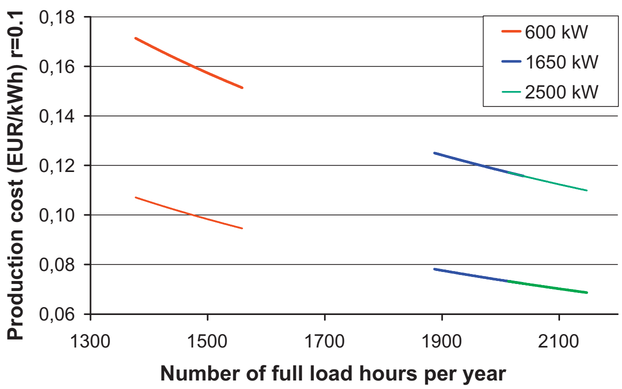

Fig. 15. Electricity generation cost from three turbines calculated with an interest rate of 0.1.

cant factor in estimating project profitability is the capital cost. A sensitivity analysis conducted with the values of interest rate of 0.7 and 0.10 shown in Figs. 14 and 15 the fluctuation of energy production costs. At the highest investment cost of 1600 €/kW and interest rate of 0.7 and 0.1, respectively, the costs exceed the benefits. In the case of the capital cost of 1000 €/kW, the discount rate of 0.7 slightly influenced the rise of the production costs, however still remaining cost-effective (below 1 €/kWh). Paying the highest capital cost ($r = 0.1$), it is still profitable but with a number of load hours higher than 1500 h per year.

The monetarisation of the technical potential showed that the region offers favourable economic conditions for inventors thanks to the current sale prices and the level of subsidies.

4. Conclusion

The proposed method strived to evaluate the geographical distribution of wind energy, by including ecological, technical and economic criteria, and provided the new framework for spatial and energy planning involving the wind energy.

The application of a GIS-based approach showed that the Kujawsko–Pomorskie Voivodeship could be used to a great extent for wind energy production, since the major technical potential remains untapped. By excluding the infrastructural and ecological related barriers, almost 7500 km^2 of the area remains available for wind siting. As the GIS-based appraisal of wind regime showed, the entire available land represents a promising technical and economical potential, the degree of utilisation of this potential will depend on the local-specific sustainability as well as on the willingness of the community to integrate these installations into the commune system.

The designing of policy instruments for promoting renewable energies should be lead by the objective to ensure a certain degree of efficiency. The wind energy development faces various problems, among them the lack of appropriate planning strategies with authorities at lower levels of the planning hierarchy. A better recognition of the feasible wind energy potential, due to a spatially integrated approach, would allow for its sustainable integration into socio-economic and ecological systems.

5. Outlook

This approach is to be further expanded to perform a comprehensive survey including other renewable energy sources. An evaluation of multiple resources of energy would provide policy makers and authorities at different organisational levels with more comprehensive information in order to facilitate a transition of national targets. Different RES utilisation processes are associated with different impacts. As a consequence, the recognition of potential risks in planning processes is essential for building up a development vision for RES energy based on local resources.

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Appendix A. Constrains for wind turbine siting in the region Kujawsko–Pomorskie

	Distance
Settlements	
Residential area	500
Single dwellings	500
Industry and commercial development zone	250
Leisure time and green areas	
Leisure and recreation areas	450
Green land and graveyard, camping	450
Infrastructure facility	
Planned motorways	150
Roads	100
Railway lines	100
Airports	3000
Power network	200
Mine and dump areas	100
Cultural assets	
Castle, cultural relict	1000
Wetlands	
Streams	250
Inland water	200
Flood area	200
Nature protection	
Nature reserves	500
Projected nature reserves	500
Landscape parks	200
Projected landscape parks	200
Protected landscape areas	200
Projected protected landscape areas	200
Protective zone of landscape parks	200
Nature 2000	500
Areas of special protection of birds	1000
Areas of special protection of habitats	500
Ecological areas	500
Documentation sites	500
Nature monuments	100
Landscape-nature complexes	200
Ecological corridors	500
Habitat of migrating birds	5000
Forest and semi-natural areas	
Forest	200
Protected forest	500
Orchards	50
Forest of ecological significance	200
Protected soil	

Source: [15,16,53].

Appendix B. Roughness length based on the CLC data

Roughness	CLC classes
1.200	Continuous urban fabric
0.750	Broad-leaved forest Coniferous forest Mixed forest
0.600	Green urban areas Transitional woodland-shrub Burnt areas
0.500	Discontinuous urban fabric Industrial or commercial units Port areas Construction sites Sport and leisure facilities
0.300	Complex cultivation patterns Land principally occupied by agriculture, with significant areas of natural vegetation Agro-forestry areas
0.100	Vineyards Fruit trees and berry plantations Olive groves Annual crops associated with permanent crops
0.070	Road and rail networks and associated land
0.050	Non-irrigated arable land Permanently irrigated land Rice fields Inland marshes Salt marshes
0.030	Pastures Natural grasslands Moors and heath land
0.005	Airports Mineral extraction sites Dump sites Bare rocks Sparsely vegetated areas
0.001	Glaciers and perpetual snow Peat bogs Salines Intertidal flats
0	Beaches, dunes, sands Water courses Water bodies Coastal lagoons Estuaries Sea and ocean

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