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On-shore wind power potential in Poland: A GIS-Based analysis of distance regulations

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ABSTRACT

In Poland's future decarbonized power system, wind energy is expected to play a dominant role in delivering clean, relatively inexpensive, but still non-dispatchable energy. Over the years, multiple regulations have been proposed, discussed, and implemented when it comes to the criteria under which wind farms can be located. This resulted in a very "chaotic" development pattern of this energy source in the recent decade. Considering the above, this work aims at performing a high-resolution analysis based on the most recent spatial data to reveal the onshore wind power potential (km^2 of land suitable for wind turbines and GW in terms of installed nameplate capacity) across Poland. The analysis was performed based on existing regulations plus additional scenarios concerning the distance between wind turbines and residential buildings, namely 10 h (here 1700 m), 700 m, 500 m, and 200 m (as in some regions across the world). A multicriteria approach was applied, where each spatial constraint was treated in a binary manner meaning that areas were considered suitable only if all criteria were simultaneously satisfied. After estimating the available area, the OpenStreetMap data containing information about existing wind turbines along with their installed capacity was used to derive country-specific power density of wind parks in Poland. Based on a representative sample of 110 clusters, the median and mean power densities were found to be 7.07 MW/km^2 and 8.89 MW/km^2. Leveraging these assumptions, the onshore wind power potential was estimated at 239.5 GW for the most liberal 200-meter distance, 105.1 GW for the currently discussed 500-meter distance, 56.4 GW for the 700-meter distance, and 1.3 GW for the most conservative 10 h distance. Achieving this potential will require addressing spatial mismatches between supply and demand and overcoming regulatory, environmental, and grid infrastructure constraints.

1. Introduction

Wind energy is a crucial element in Poland's transition to renewable energy, yet its development faces multiple challenges, ranging from legislative constraints through technical (e.g., grid saturation or power system flexibility) to spatio-social conflicts [1]. Nevertheless, over the recent years, the landscape of the Polish power system has undergone a significant transformation that, to an extent, has reshaped how the present system operates. Fig. 1 provides a brief insight into the energy mix as for the year 2023, the evolution of installed capacity in solar PV and onshore wind is juxtaposed with the situation on the electricity market for two specific days with relatively very high (53.95 %) and very low (0.98 %) share of solar and wind generation compared to the daily demand.

When it comes to the wind potential, so far, multiple studies have been performed for onshore wind on either a global [3], national (e.g., Germany [4], China [5]) or regional level (e.g., parts of Iran [6]), followed up by off-shore wind potential estimates for example for the USA [7]. This overview below summarizes the findings from various works, presenting a comprehensive picture of wind power potential estimation in Poland and the critical issues surrounding it.

The challenges of wind turbine siting in Poland have been addressed in a work by Kazak et al. [8]. Their study has introduced a multi-criteria spatial decision support system that incorporates 13 location factors, providing a framework for stakeholders to balance competing interests. Tested in the Wrocław agglomeration (southern Poland), this system highlights the utility of spatial tools in facilitating informed decisions and mitigating potential conflicts.

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Despite the observed growth of the wind energy sector, Poland's legislative environment has posed significant barriers. For example, Sokołowski [9] examined the restrictive 2016 'distance act' which mandates extensive buffer zones around wind turbines, effectively blocking most new investments. Such constraints have created stagnation in the sector, despite the critical role of wind energy in meeting national and EU renewable energy targets. Wielewska [10] further emphasizes that these legislative restrictions are among the most stringent in Europe, limiting the country's ability to capitalize on its favorable environmental (wind) conditions.

Several studies highlight the application of GIS tools to assess regional wind energy potential. For instance, in [11] authors used ecological and spatial criteria to identify viable sites for wind farms. The study highlights the need for systematic approaches to utilize local wind resources. On a smaller scale, Amsharuk & Łaska [12] identified 704 plots of land, covering 32.5 km^2, suitable for wind farms in Podlaskie Voivodeship. This approach demonstrated the potential to increase power capacity by 62 %, adding 131.5 MW to the region's energy supply.

On a national scale, Hajto et al., [13] reveal that up to 99.1 % of Poland's land area is unsuitable for wind farms under the current regulations. Settlement areas and landscape values (visual aspects) were identified as primary constraints, necessitating integrated spatial and energy policies to overcome these challenges. At the same time, the offshore wind energy offers a promising alternative, as detailed in [14]. Their work assessed the Polish exclusive economic zone of the Baltic Sea, identifying a highly suitable area of 16,218.67 km2. Depending on turbine placement density, this area could support 9–15 GW of capacity. Including moderately suitable areas raises the potential to 31–50 GW, underlining the strategic importance of offshore wind in Poland's renewable energy plans.

On a much smaller scale, the wind energy solutions in urban areas have been investigated in work by Aydin et al. [15]. The study used Efficient Global Optimization techniques to estimate wind potential for rooftop turbines. The findings indicate that city-type turbines could generate electricity directly for urban buildings, presenting a viable option for local energy needs; however, this requires further economic analysis. Spatial conflicts are another significant hurdle, as highlighted in work by Nowak et al. [16]. Their work identifies critical issues arising from spatial plans and court cases, proposing a framework for addressing these conflicts. By integrating judicial perspectives, this approach contributes to a more comprehensive understanding of the barriers to wind energy development. The dynamic nature of Poland's energy landscape is evident in the work by Talarek et al. [17]. Their work discusses the impact of the Russian energy crisis and EU climate policies, which have revitalized interest in wind energy. According to Talarek et al., the offshore projects and hybrid solutions, such as integrating wind and thermal plants, are highlighted as potential viable and interesting alternatives.

Based on the above conducted literature review, several knowledge gaps have been identified. Which further were formulated as a set of the following research questions:

- What is the potentially available land area (km^2) for wind power plants development in Poland under various regulatory scenarios?
- How does the distance between wind turbines and households impact the wind power potential?
- Across which capacity factor or wind speed regimes can wind turbines physically be installed, considering legal constraints?
- What is the spatial distribution of potential sites for wind parks development compared to demand?
- How does the existing location of wind parks match with the considered scenarios?

2. Data and methods

2.1. GIS and input data

A multi-criteria spatial analysis was conducted within a GIS environment. The input data for the analysis consisted of vector data on land use and land cover (LULC) for the territory of Poland. These data was sourced from the Database of Topographic Objects (BDOT10k) at a reference scale of 1:10,000. BDOT10k is a comprehensive dataset on spatial development, recognized as the most accurate of its kind in the country. It is freely available as open-access data. The database includes information such as the location and extent of forests, surface waters,

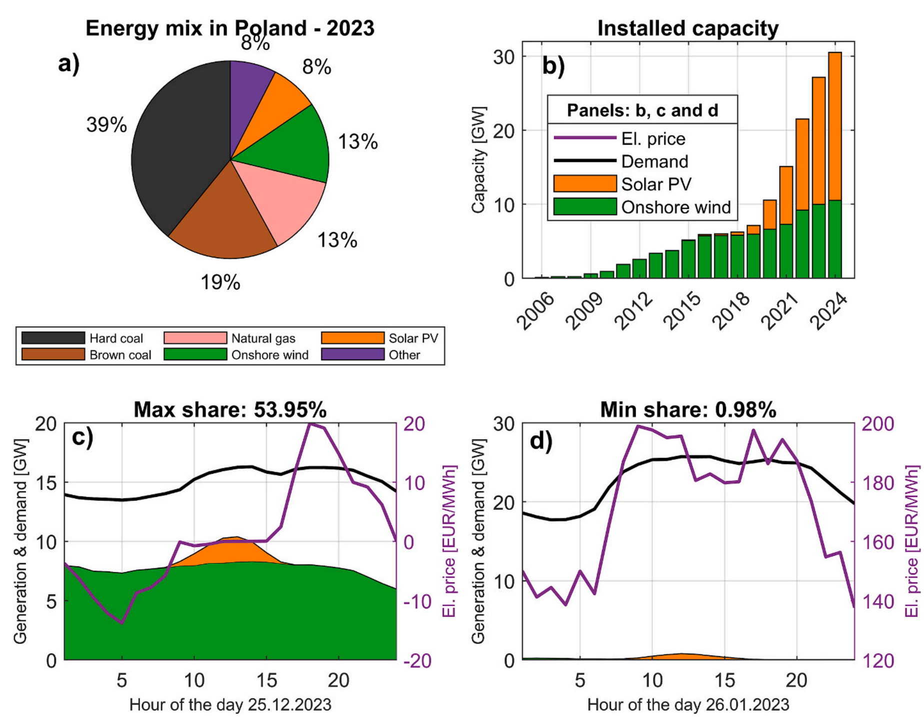

Fig. 1. A brief overview of the energy mix of the Polish power system in 2023. Based on data from EnergyCharts [2].

built-up areas, agricultural lands (including crops and grasslands), as well as ecologically significant and protected areas. It also provides details on the location and classification of buildings, along with the routes and types of linear infrastructure such as roads, power lines, and rivers. BDOT10k is regularly updated and verified by state geodetic services under the authority of local government bodies.

Using these data resources, a multi-criteria spatial analysis was performed to assess the potential availability of land for wind farm development, incorporating relevant legal regulations and specific assumptions (Table 1) for the defined scenarios. The analysis began with the selection of relevant LULC categories essential for further evaluation, such as forest areas, surface waters, and the locations of residential buildings or structures with residential functions. Subsequently, buffer zones were delineated, including areas excluded from wind farm development. For example, a 700-meter exclusion zone was established around every residential building in Poland, along with a 500-meter exclusion zone around nature reserves, among others. The core of the analysis involved identifying and removing from consideration all areas within the country that were deemed unsuitable for wind farm placement. These analyses included scenario-based evaluations, primarily focusing on varying the minimum distance from residential buildings. The analysis was performed using vector data and implemented in ArcGIS Pro 3.2 software. A multicriteria approach was applied, where each spatial constraint was treated in a binary form and areas were considered suitable only if all criteria were simultaneously satisfied. The general procedure concerning pure GIS analysis is visualized schematically in Fig. 2 and archived in the following dashboard [18].

2.2. Scenario definitions

Considering the current state of knowledge in terms of onshore wind potential in Poland, research questions stated, and information provided in Section 2.1 (Table 1), the GIS analysis was performed for the overall four scenarios hereafter referred to as: d_200, d_500, d_700, and d_10h.

Table 1
Criteria for exclusion and distance requirements for wind potential estimation.

No.	Aspect	Value	Ref
1	Built-up areas	excluded	[19]
2	Distance to residential buildings or buildings with a residential function	Scenario dependent: 200, 500, 700, and 1700 *m*	
3	Distance from the highest voltage power grid	≥ 3 x (rotor + blades) ≥ 2 x total height (whichever is greater)	
4	National Parks, Landscape Parks, Nature Reserves, Natura2000 Areas	excluded	[19,20]
5	Distance from National Parks	≥ 10 x total height	
6	Distance from Nature Reserves	≥ 500 *m*	
7	Sea shore	Excluded technical belt of the seashore ≥ 200 m from the cliffs	[20]
8	Forest areas	excluded	[21,22]
9	Agricultural land with I-III quality classes	excluded	[22,23]
10	Standing and flowing surface water areas	excluded	[24]
11	Distance from standing and flowing surface waters	≥ 100 *m*	
12	Areas at particular risk of flooding 1 %	excluded	
13	Distance from public road areas	in undeveloped areas: highways ≥ 50 *m* expressways ≥ 40 *m* national roads ≥ 25 *m* provincial roads ≥ 20 *m* county and municipal roads ≥ 15 *m*	[25]
14	Distance from forests	≥ 300 *m*	[26]

Where d – stands for distance, and following number pertains to criterion number 2 from Table 1, namely the minimal distance between the wind turbine and the residential buildings. The GIS analysis for each scenario resulted in a detailed map of the area available for wind parks. The scenario d_10h refers to the already mentioned regulation where the distance between the wind turbine and residential building should be at least ten times the height (h) of the wind turbine. The wind turbine here is defined as the "tip height", which is the height of the tower plus the blade length. Here, it has been assumed h = 170 m, as for the majority of modern wind turbines with hub heights of approximately 100 m and blade length of 70 m. The analysis performed relied on a *greenfield* approach without considering existing wind turbines.

2.3. GIS results processing

The GIS analysis of land availability constitutes to a foundation of this work. However, sole information about the location of area available for wind parks in given locations is not sufficient to address the research questions stated at the end of the Section 1. Therefore, these data must be further processed, and a simplified schematic of these procedures is shown in Fig. 3. The processing relies on additional sets of spatial data concerning location of existing wind turbines (taken from OpenStreetMaps – OSM), capacity factors of wind turbines in various locations (adopted from GlobalWindAtlas – GWA) and spatial distribution of electricity demand on a county level (extracted from Joint Research Centre – JRC) project results. To enhance clarity, the methods adopted to address each research question are briefly presented in the corresponding subsections of Section 3.

3. Results and discussion

3.1. Area available

Based on the potential estimation method presented above, the area suitable for wind turbines in Poland was calculated to range from 10.9 % to 0.1 % of the country's land area, corresponding to the most liberal (d_200) and most conservative (d_10h) scenarios, respectively. For currently debated amendments to legal regulations, the area available is 4.8 % and 2.6 % respectively for scenarios assuming 500- and 700-meter buffer zones between wind turbines and residential buildings. As shown in Fig. 4, increasing the required buffer zone has a significant impact on the available area for wind parks development. Interpolating the results for scenarios d_200, d_500, and d_700 shows that one additional meter of the buffer zone reduces the availability of potential areas by 52.7 km^2 on a country scale.

Consequently, scenario d_500 with an available area of 2.6 % is comparable to the plans implemented in Germany, where 2 % of the total area of each Bundesland [27] should be dedicated to wind farms to meet the country's onshore wind development goals.

The reported in this article numbers have in general a good match with other studies. As shown in [28], the 700 m and 500 m buffers result in respectively 2 % (this work 2.6 %) and 4 % (4.8 %) of the country's area feasible for onshore wind turbines. Another study [29] shows that the area available under three scenarios, d_10h, d_700, and d_500 is 874 km^2, 18,000 km^2, and 32,500 km^2, respectively. However, more significant discrepancies can be observed as values reported by [29] are 4.8 times higher for scenario d_10h, 2.25 times higher for scenario d_700, and 2.18 times higher for scenario d_500. A report by the Polish Wind Association [30] shows that the theoretical potential of onshore wind for the d_500 scenario is 3.3 % of country's area and 1.7 % for the d_700 scenario. Research conducted by the Instrat foundation [31] shows that the d_10h scenario restricts 99.7 % of the country's area from wind development. Notably, our analysis presents even more conservative results, indicating that 99.94 % of the country's area will not be suitable for wind turbines. According to Instrat, a proposed liberalization (from d_10h to d_500) is estimated to make 7.08 % of the country's land area

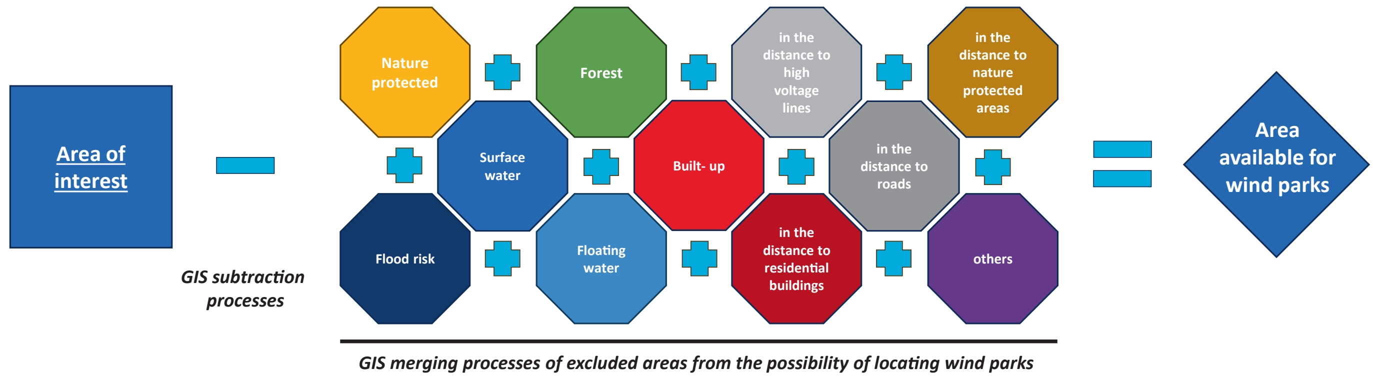

Fig. 2. Flowchart showing the adopted GIS-based analysis.

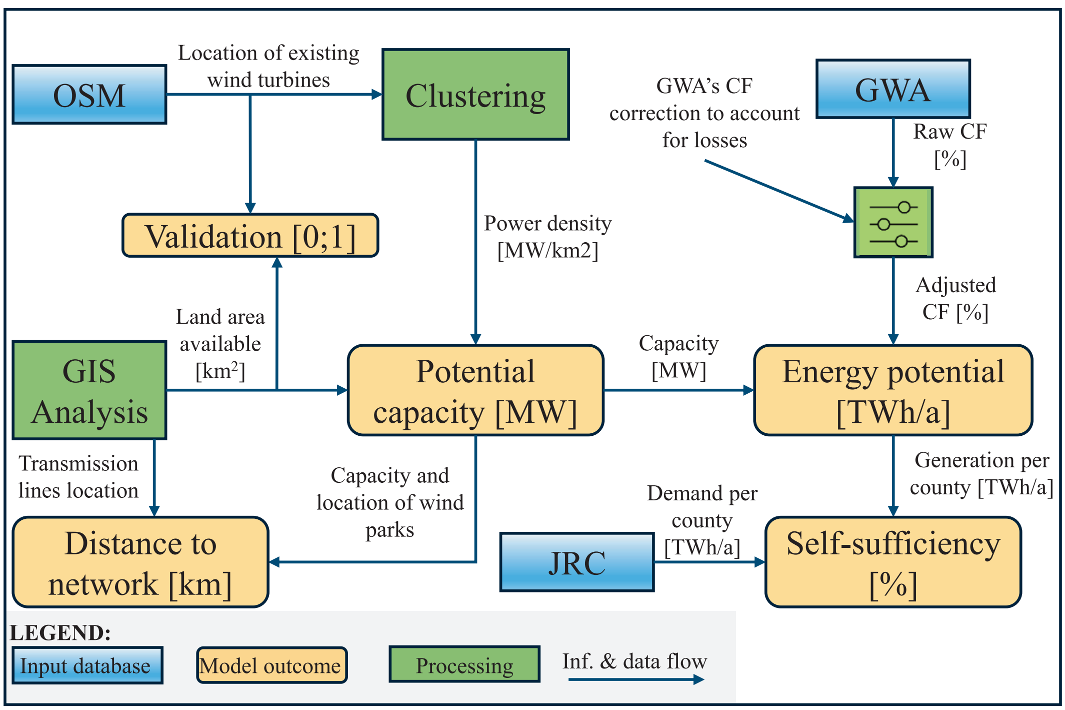

Fig. 3. Overview of the workflow adopted in this research.

suitable for siting wind turbines.

The observed differences in reported values across studies can be largely attributed to differences in underlying data sources, time of data acquisition, and specific methodological assumptions, such as treatment of exclusion zones, land use classification, or population density. While some discrepancies, especially for the most restrictive scenario (d_10h), appear significant in absolute terms, the overall alignment in order of magnitude across most studies provides credibility to the findings. Most importantly, for the d_500 and d_700 scenarios, the results generally converge around a few percent of the country's area, suggesting a relatively consistent assessment of technical wind siting potential, despite methodological differences. For easier comparison, the above-presented values are consequently summarized in Table 2 and visually in Fig. 5.

In terms of land use, it was found that in scenarios d_200, d_500 and d_700 from 87.8 % to 88.5 % of potentially suitable areas are classified as farmland, followed by 8.6 %-8.8 % being categorized as grassland. However, the distribution changes substantially for the 10 h scenario, where 20.8 % is characterized as grassland, 59.1 % as farmland, and the 20.2 % belong to other categories. The observed shift implies that stricter spatial constraints limit the feasibility of wind development on agricultural land, directing potential installations toward less intensively used land such as grasslands and other open areas.

3.2. Capacity potential – power density

In the previous section, the potential area for wind parks has been presented for various scenarios and compared with other studies. Nevertheless, this alone does not provide a clear picture of the theoretical capacity potential. This can be derived based on known capacity density of wind parks. It is important to stress that the power density referred to here is the installed power density (i.e., rated capacity per unit area), not the output power density (i.e., actual energy generated per unit area over time).

The values of installed power density vary significantly between countries and regions due to factors such as local conditions, land availability, or wind farms' layouts, as well as often due to the methodological differences in defining what constitutes a wind farm. A study by Enevoldsen and Jacobson [32] found that the mean power density of onshore wind parks in Europe is 19.8 MW/km^2, whereas some previous works reported (all values in MW/km^2) 6 [33], 9.2 [34], 9 [35], 6.5 [36], 5 [37], 8.3 [38], 3 [39],11.5 [40], 8.9 [3], 8 [41], 2.9 [42],13.6

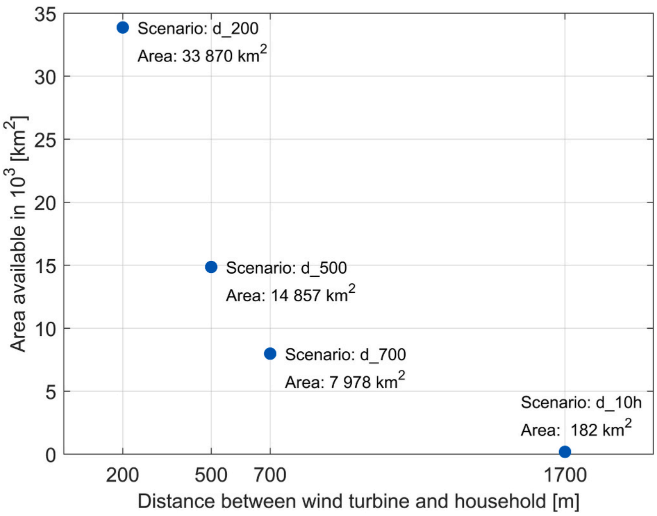

Fig. 4. Area potentially available for wind turbines development for each scenario.

Table 2
Onshore wind potential (% of country's land area) according to various studies.

Scenario	This study	Ref. [28]	Ref. [29]	Ref. [30]	Ref. [31]
d_500	4.8	4	10.4	3.3	7.1
d_700	2.6	2	5.8	1.7	
d_10h	0.06	–	0.3	–	0.3

[43]and 7.1 [44]. The above values show a mean power density of wind parks at 8.48 MW/km^2.

In this work the power density of wind parks in Poland has been estimated using data from OpenStreetMaps [45], which provides information about the exact location of turbines and their installed capacities. A clustering analysis was performed based on the ArcGIS inbuilt clustering algorithm that revealed the existence of 618 potential clusters, each consisting of at least three turbines. After additional screening (e.g., removing clusters with missing information about turbines installed capacity), a subset of 110 clusters, containing a total of 1943 wind turbines (17.6 turbines on average per cluster), were selected for further analysis. The area of the wind park was set as a convex hull (the smallest convex polygon that contains a given set of points – wind turbines) without any additional buffer layers. Consequently, it was calculated that for the considered subset, the median power density is 7.07 MW/km^2 with a mean value of 8.89 MW/km^2. Some representative clusters are shown in Fig. 6. It is important to note that very high-power densities are observed for wind parks located in mountain ranges, where wind park layout has a linear nature. The values potentially derived (based on presented available area and maximal installed capacity) in [30] are 11.46 MW/km^2 and 11.88 MW/km^2, depending on the scenario. In contrast, the Instrat report [31] appears more conservative, estimating a power density of 2 MW/km^2 (44 GW for 7.08 % of country's area).

Considering a fair alignment of the calculations conducted in this study with the literature reported values, a power density of 7.1 MW/km^2 was assumed to consequently derive the maximal installed capacity in each scenario. Taking into account the area available in each scenario, the cumulative capacities are 1.3 GW, 56.6 GW, 105 GW, and 240 GW for the d_10h, d_700, d_500, and d_200 scenarios, respectively.

3.3. Energy potential – capacity factors

The wind conditions for large-scale onshore wind farms in Poland, although favourable, are not uniform. Relying solely on installed capacities does not provide sufficient insight into their energy generation potential. Therefore, we utilize a multi-annual mean capacity factor (CF) metric that measures the ratio between the energy generated in a given period (E_{gen}) and the maximum energy production potential (E_{max}), according to the installed capacity. It is quantified as a percentage and determined using the following Eq. (1):

$$CF = \frac{E_{gen}}{E_{max}} \times 100\% \quad (1)$$

A dataset representing the mean capacity factor for the entire country was sourced from the Global Wind Atlas (GWA) platform [46]. Provided data features a high spatial resolution (250 x 250 m) and simulates wind conditions for the period 2008–2017. To ensure adequate spatial and temporal resolution and coverage, GWA uses downscaling methods and, inter alia, the ERA5 weather reanalysis data as input. From this database, the CF values for the IEC Class III wind turbine type were selected and assigned to areas previously mapped as accessible.

The results for each scenario are presented in Fig. 7. Regardless of the scenario, the observed CFs are relatively high, with the area-weighted values ranging from 44 to 47 %. These figures significantly exceed commonly reported national averages by at least 15–20 percentage points. Interestingly, these values align more closely with the reported CF for offshore wind parks in the UK [47], where mean CFs are approx. 40 % and range from 31 % to 52 %. Concerning onshore wind, Malecha [48] reported that the mean CF for wind parks generally varies from 20 % to 40 %. For instance, the Margonin wind park in Poland (120 MW) operates with a mean CF of 27 %. Similarly, Olczak and Surma [49] indicated that the onshore wind farms in Poland achieved a mean CF of 25.5 % in 2021 and 30.1 % in 2022. Furthermore, the Wind Europe [50] report projects that the future onshore wind parks in Europe will achieve a mean CF of 35 %, compared to previously assumed 27 % by the European Commission.

To complete the above literature analysis, this work relied on reported installed capacities (MW) and generation (TWh) for wind turbines in Poland. To consider the investment process in wind farms and uncertainties resulting from reporting the capacity (GW) for a given year *t*, the installed capacity was calculated as an average of the capacity installed in year *t* and the preceding year (*t-1)*. The mean CF of Polish onshore wind farms, based on the data compiled by IRENA [51] (2010–2022) and supplemented for the year 2023 using [2], ranges from 21 % in 2010 to 30.2 % in 2023, with a mean value of 26.8 %. A statistically significant ($p = 0.00022$) upward trend of CF for the period 2010–2023 is observed. Year-to-year variation in CF can be attributed to multiple factors, ranging from resource variability [52], curtailment [53], phase-out of outdated turbines, repowering of wind parks, and investment in new turbines with higher towers, enabling improved operational efficiency and higher CF.

The above indicates that the operational CFs of existing onshore wind parks are significantly lower than those extracted from GWA. It is important to note, however, that GWA provides the CF estimated for a single wind turbine and does not account for various losses at different levels. These include turbine-level losses (e.g., icing [54] even up to 10 % of annual generation), wind park-level losses (e.g., wake losses [55] on average 10 % for selected wind park) and power system-level losses (e.g. curtailment, which varies depending on the power system and the share of variable renewable energy sources, but was reported to reach as high as 34.3 % from individual wind farms in China [56]). Overall, the Wind Energy – The Facts project, financed by Intelligent Energy – Europe, indicates that the wind farm losses typically would range from 10 % to 20 %. The primary causes of these losses include: wake effects (internal, external and future); availability (at turbine level, balance of plant, and grid availability); electrical efficiency (operational efficiency and self-consumption); turbine performance (generic power curve adjustment, and high wind speed hysteresis); environmental factors (performance degradation, shutdown due to icing/temperature, and tree

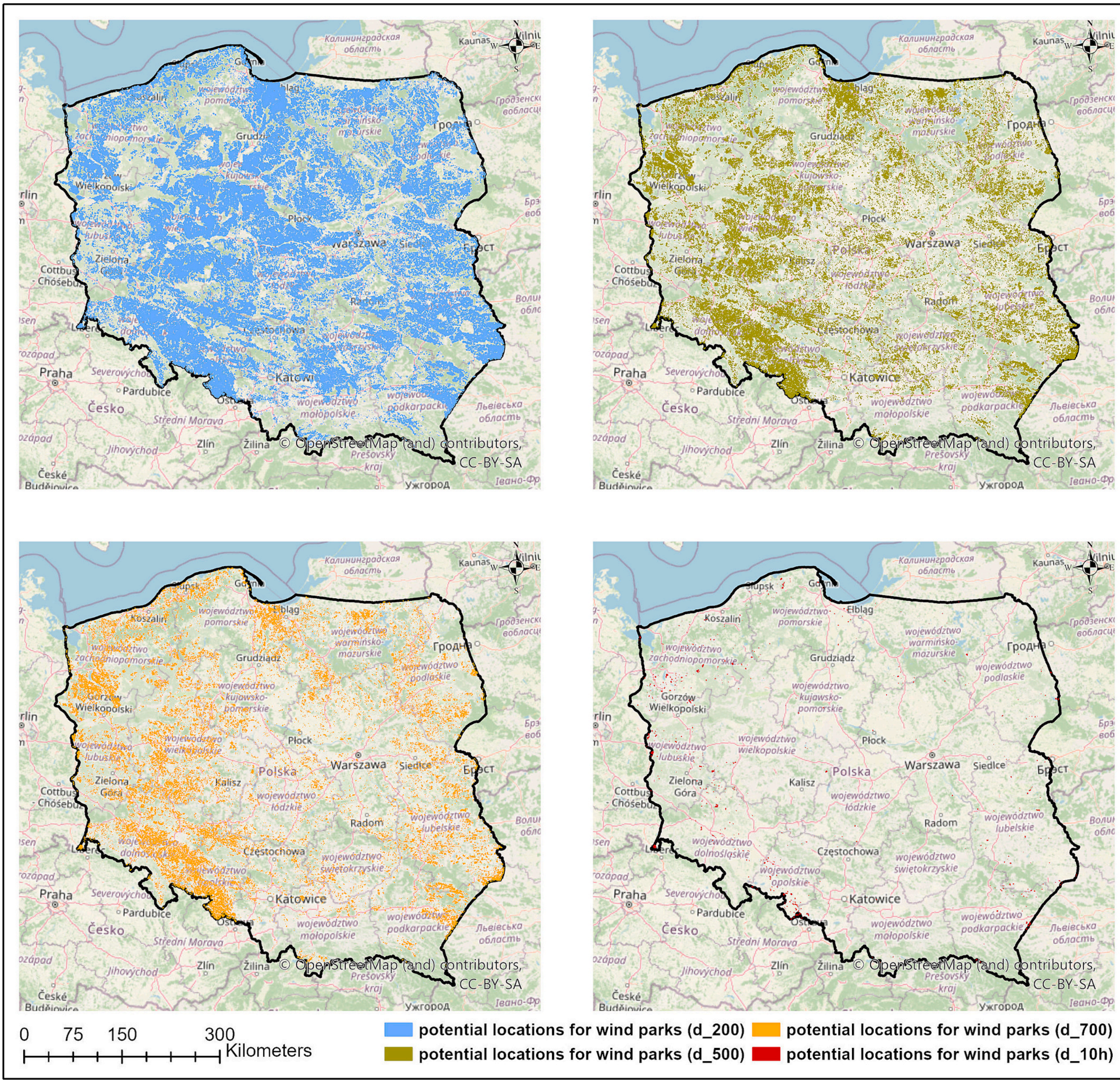

Fig. 5. Potential locations for wind turbines for the considered scenarios.

growth) as well as curtailment (wind sector management, grid curtailment and noise). The values presented by PSEW [30] indicate that 118 GW and 63 GW of installed wind capacity have the potential to deliver 360 TWh and 195 TWh of electricity, respectively. This corresponds to CFs of 34.83 % and 35.53 %, which consequently matches the projections made by WindEurope [50] for future wind parks.

Considering the above, for further energy-related calculations, it is decided to adjust the CFs derived from the GWA by accounting for 25 % of potential additional losses on all levels (wind turbine, wind farm, and power system). Consequently, the corrected CFs for scenarios d_10h, d_700, d_500, and d_200 are 32.7 %, 34.5 %, 34.8 % and 35.1 %, respectively. These numbers closely align with the projections made by the transmission system operator (TSO) [53], which assumes that 18 GW of onshore wind installed capacity will deliver 55 TWh of electricity annually, corresponding to a CF of 34.88 %. The energy generation potential, combined with additional parameters, is summarized in Table 3.

According to a recent report published by Forum Energii [57], electricity consumption in Poland in 2023 totalled 170.2 TWh, of which 14.3 % was attributed to electricity self-consumption in power plants or losses in transmission and distribution networks. Due to the intermittent nature of the wind as an energy source and constraints of the power system, national electricity demand cannot be solely met by a single technology. Various reports and studies conducted recently show different demand for onshore wind installed capacities. Clean Air Task Force [58] projected a need for 74 GW of onshore wind capacity, depending on the scenario. The Instrat foundation [59] indicates values ranging from 13.8 GW to 34.9 GW for a not fully decarbonized power system. Whereas, the Polish Energy Policy is more conservative and indicates greater expansion of offshore wind [60]. Additionally, studies referenced by EMBER [61] demonstrate that achieving the EU’s 2030 climate goals will require at least 17 to 27 GW of installed onshore wind

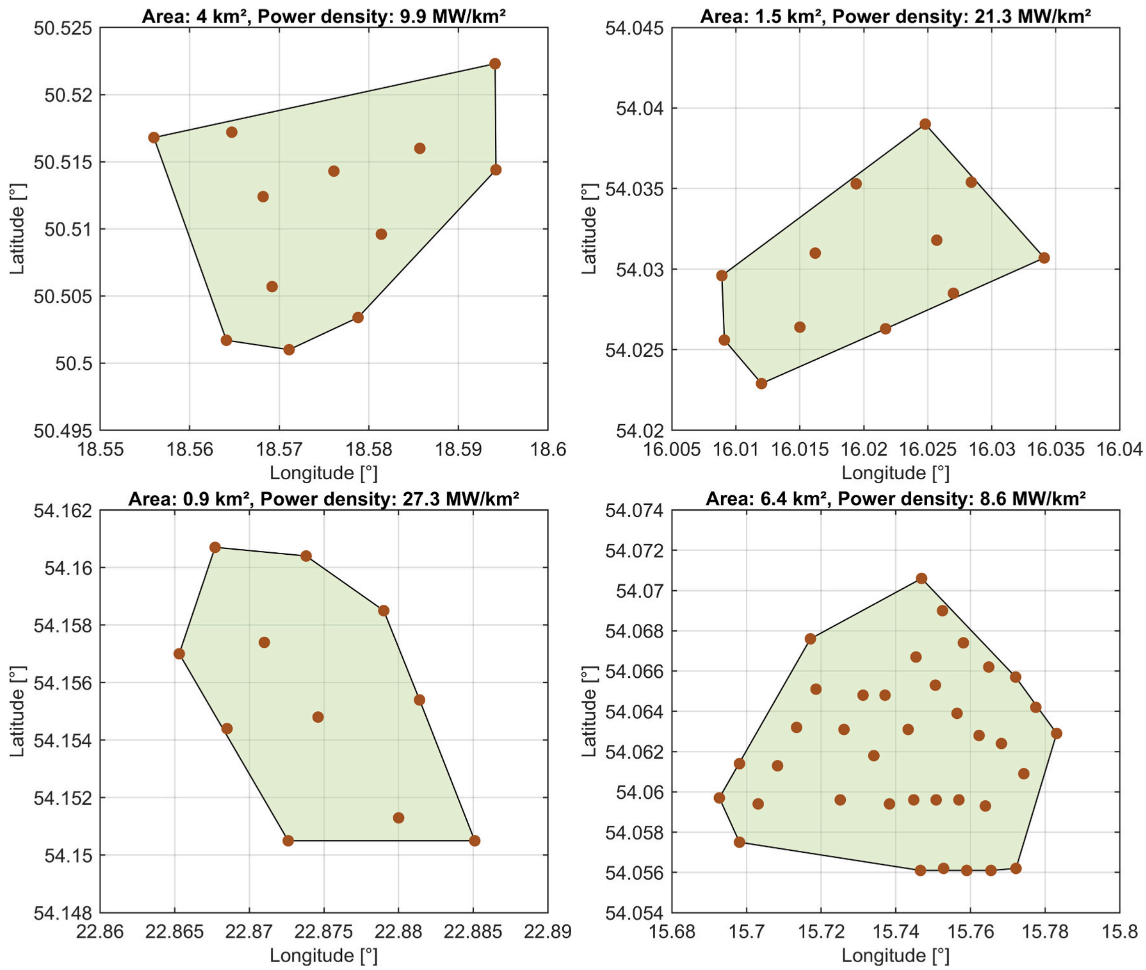

Fig. 6. Layout, area and power density of four representative clusters selected from OSM.

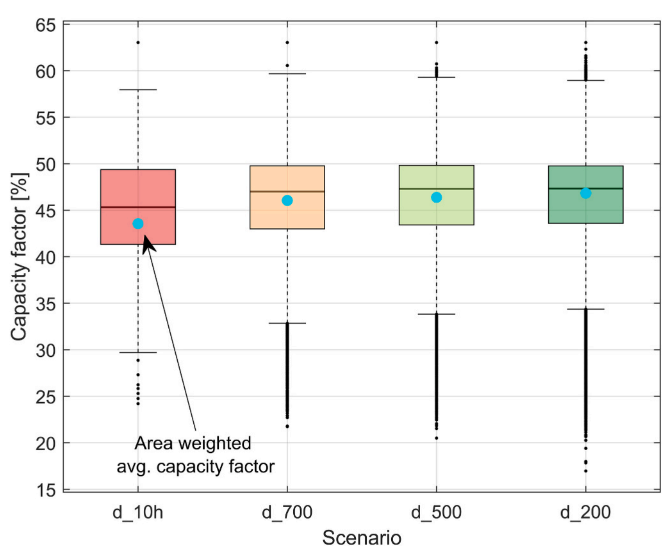

Fig. 7. A box plot of capacity factors in potential locations for wind parks. Original CFs are derived from GWA for ICE3. For comparison, the dots indicate the average scenario capacity factor calculated as area-weighted mean.

capacity.

The corrected estimates in the table suggest that, even under the most ambitious scenario, the energy output (~259 TWh/year) far exceeds Poland's current annual electricity consumption of 170.2 TWh.

Table 3
Summary of main parameters for onshore wind potential per scenario.

Parameters	Scenario			
	d_10h	d_700	d_500	d_200
Area available [km^2]	182.5	7978.3	14,858	33,870
Max capacity [GW]	1.3	56.6	105.5	240.5
Installed power density [MW/km^2]	7.12	7.09	7.10	7.10
Average CF [%]	32.7	34.5	34.8	35.1
Output power density [MW/km^2]	2.33	2.45	2.47	2.49
Energy [TWh/year] *	3.7	171.4	321.4	739.9
Energy** [TWh/year]	1.3	60	112.5	259

*based on the respective values of the capacity factor. **assuming, as per PSEW [30], that the economic and environmental potential is further reduced by 65%. Values placed in single rows which are comparable to each other are provided with two decimal places.

However, practical deployment will be limited by realistic installed capacity targets, which range from ~ 13.8 GW to ~ 74 GW, as highlighted in various studies. Meeting the EU climate targets specifically requires 17–27 GW of onshore wind capacity by 2030. This indicates that, while the resources are abundant, the actual expansion must be carefully planned to address systemic, environmental, and economic barriers.

3.4. Distance from transmission lines – wind parks clustering

The existing transmission and distribution infrastructure, as reported regularly by the TSOs and DSOs, is largely saturated when it comes to connecting new generators. Nevertheless, for future reference, it remains relevant how far the areas suitable for wind development are placed from the transmission lines. For the scenario d_700, such results are presented in Fig. 8. It was found that 90 % of potential sites are within 700 m of the closest medium voltage line (not transformer but just the line itself), whereas more than 98 % of sites are closer than 1 km. In case of high voltage lines, 20 % of sites are located further than 6 km, and potentially 25.7 GW of capacity is in less than 2 km. This analysis is complemented by a clustering analysis, which considered the hosting capacity (MW) of each polygon and its distance to the medium-voltage transmission lines as attributes characterizing each polygon. Based on the “elbow curve” [62] method, it was found that the optimal number of clusters is four. The results are shown graphically in Fig. 9 and Fig. 10. As can be observed, the largest cluster (37.2 GW) is characterized by areas of a mean hosting capacity of 3.1 MW and, on average, located very close to the transmission lines. It should be emphasized that individual areas (polygons) can be aggregated into larger clusters. For all clusters, the average capacity factors remain relatively similar and range from 33.7 % to 34.7 %.

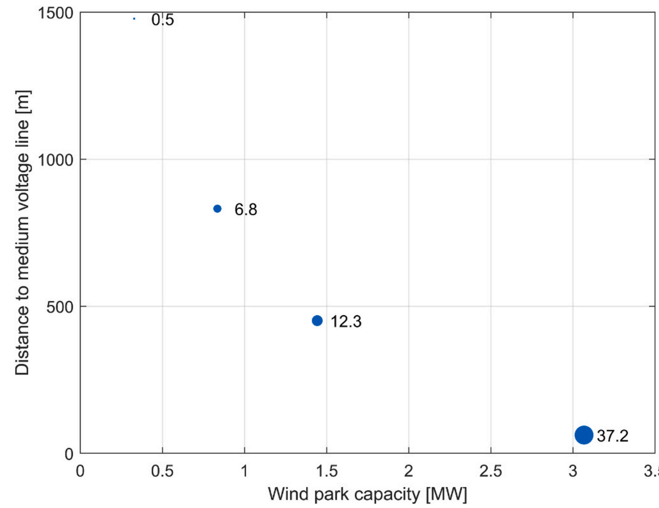

Fig. 9. Distinguished centroids of four clusters, for scenario d_700.

3.5. Regulations vs reality

Already existing wind turbines have been located in line with various legally binding regulations and based on local permissions. However, over time, many of the currently operating wind turbines will approach the end of their technical lifespan. One of the commonly applied practices is to repower the operating or decommissioned wind park with new wind turbines [63]. However, as the regulations change, repowering might not be an option. An analysis combining the locations of existing wind turbines with areas designated as suitable under the four scenarios revealed significant differences. Currently, only 53.6 %, 37.9 %, 20.5 %, and 0.3 % of turbines are situated in areas deemed appropriate for wind development under scenarios d_200, d_500, d_700, and d_10h, respectively, as illustrated in Fig. 11. This indicates that many of the currently operational turbines might not be eligible for repowering. Moreover, implementing more stringent regulations in the future could potentially lead to a significant decrease in installed wind capacity in Poland.

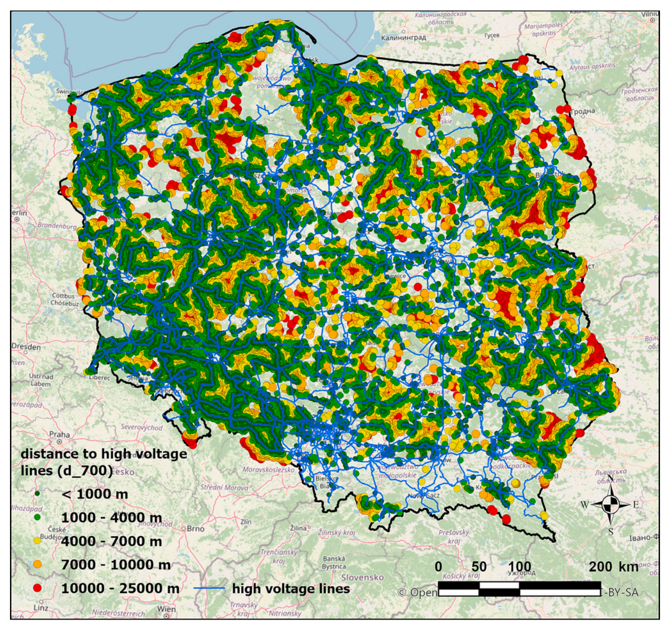

Fig. 10. Distance from high-voltage transmission lines.

3.6. Supply-demand matching

To complete the discussion, a supply–demand matching analysis was performed on a county (pol. powiat) level. A JRC 2019 [64] dataset was used to attribute electricity demand to each county. This dataset contains TIFF maps of the EU energy demand in tons of oil equivalent (toe) for 2019, broken down by economic activity categories and aligned with EUROSTAT’s 1x1 km reference grid. The wind potential generation in each county was estimated based on available area (four scenarios), power density of 7.1 MW/km^2 (see Section 3.2), and corrected capacity factors from GWA (see Section 3.3). The supply–demand matching was performed on an annual basis. The results obtained for representative scenario d_700 are shown in Fig. 12. Due to the distribution of the calculated values, the potential generation and energy demand were rescaled through $atan(x_i)/atan(\max(x))$. The maximal observed demand is 12.92 TWh/year (in the capital city county), whereas the maximal generation is 3.85 TWh/year (county in north-western Poland with very low population density). The mean values are 0.43 TWh/year and 0.45 TWh/year for the demand and generation, respectively. Notably, both the demand and supply exhibit high spatial variability. Generation potential is primarily located on the coastal and peripheral areas of the country (apart from the southern east), while demand is concentrated in the central regions and the major urban areas. The capability to cover the demand, as illustrated in Fig. 12 (bottom left), ranges from 0 %

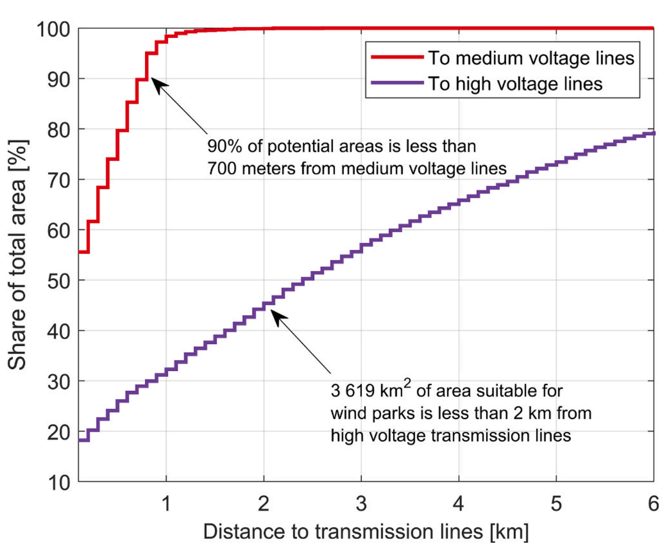

Fig. 8. Cumulative area available for wind parks development as a function of distance to the transmission infrastructure, for scenario d_700.

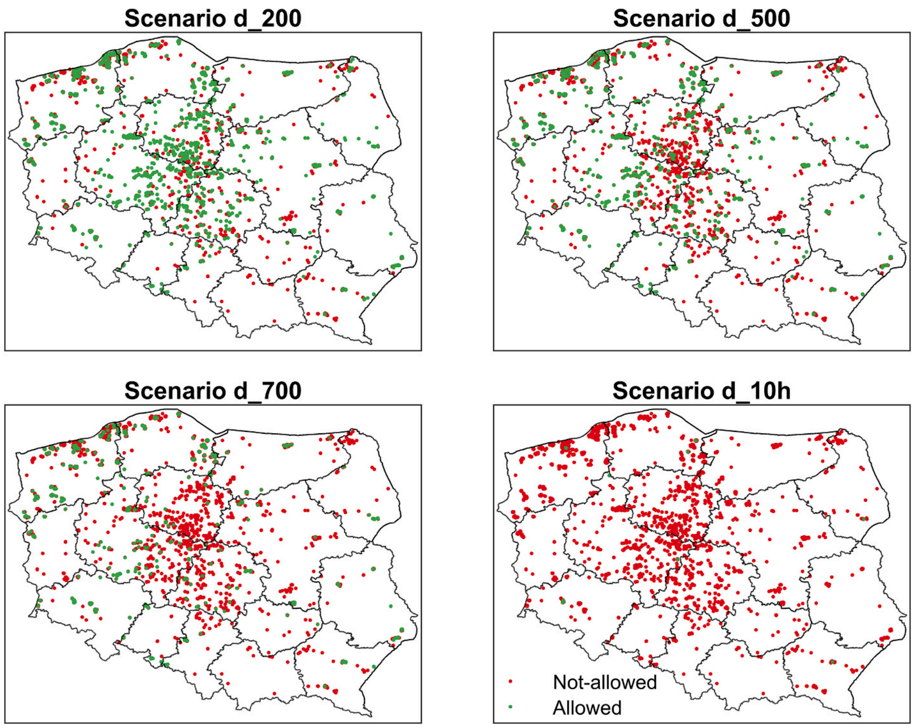

Fig. 11. Are existing wind turbines placed in line with current regulations and proposed scenarios? Green dots represent the existing wind farm locations that meet distance requirements under the assumed scenario; Red dots represent sites that do not satisfy the criteria. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

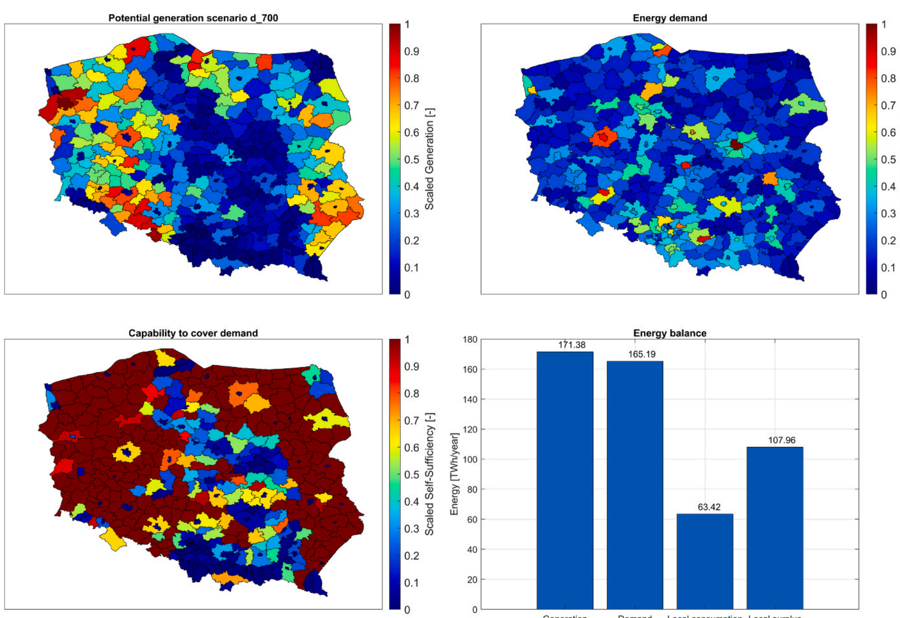

Fig. 12. Spatial distribution of annual electricity demand and wind generation potential in Poland at the county (pol. powiat) level for the d_700 scenario. The maps illustrate the estimated annual generation potential (top left), electricity demand (top right), the ratio of potential generation to demand (bottom left). The bar chart (bottom right) presents wind power generation potential and electricity demand at national scale demand. Bottom left: areas with a scaled self-sufficiency ratio of 1 represent potential energy surpluses, whereas a value of 0 indicates no wind energy potential in the given county.

(counties where investment in wind energy in scenario d_700 is not feasible) to 100 %. The 100 % was set as a maximum for visualization purposes, while according to the data, generation exceeds demand by an average factor of 2.2, with some counties showing generation potential up to 47.4 times greater than the demand. Overall, in 170 of 380 counties (45 %), the generation potential is at least equal to the demand.

As further noted, (Fig. 12 bottom right) for the scenario d_700, the maximal generation potential very closely matches the demand. However, this analysis is limited to an annual scale, as the hourly or sub-hourly supply–demand matching lies beyond the scope of this work. A more detailed evaluation indicates that only 37 % of the generated electricity (63.4 TWh) is consumed "locally", whereas the remaining 63 % constitutes local overgeneration/surplus compared to the demand. This disparity underscores a significant spatial mismatch between the electricity demand and supply.

4. Conclusions

The analysis conducted in this work contributes to a better understanding of the theoretical onshore wind potential in Poland, but also establishes a foundation for ongoing research aimed at developing a method to quantify the prolonged energy scarcity periods from renewable sources, known as renewable energy droughts. Based on the performed calculations, the following key conclusions can be derived:

- The size of the buffer zone significantly impacts the available land for wind turbine deployment. For Poland, the available area ranges from 10.9 % (most liberal scenario, d_200) to 0.1 % (most conservative scenario, d_10h) of the country's land area.
- A stricter buffer zone policy drastically reduces land availability, with each additional meter of buffer decreasing potential wind development areas by 52.7 km^2 at the national level.
- The available land area for scenarios d_500 (4.8 %) and d_700 (2.6 %) aligns with international benchmarks, such as Germany's goal to dedicate 2 % of its territory for wind energy development.
- Corrected capacity factors (accounting for losses) range from 32.7 % to 35.1 %, resulting in an annual energy generation potential from 3.7 TWh (d_10h) to 739.9 TWh (d_200). Under the most ambitious scenarios, these values far exceed Poland's current annual electricity consumption (170.2 TWh in 2023).
- Wind energy potential is unevenly distributed, with high-generation counties often located in sparsely populated regions, leading to spatial mismatches between supply and demand.
- Under scenario d_700, only 37 % of generated electricity is consumed locally, while the remaining 63 % represents overgeneration relative to local demand. This highlights the need for improved grid infrastructure or storage solutions to balance the system.
- While 170 counties could meet or exceed their local demand, overgeneration in others underscores the challenges of integrating wind energy efficiently across the country.

These findings underscore the necessity of adopting a comprehensive and well-coordinated strategy for onshore wind energy development in Poland. Such a strategy must balance the ambition of national deployment targets with the realities of spatial planning, legal frameworks, and infrastructure limitations. The strong influence of buffer zone regulations on land availability, combined with the spatial mismatch between high-generation regions and centers of electricity demand, reveals that technical potential alone is insufficient to guide policy and investment decisions.

To fully harness the substantial wind energy potential identified in this study, it is essential to integrate land use planning with grid modernization efforts, regional energy balancing mechanisms, and supportive legal instruments. Moreover, aligning national spatial planning with international benchmarks could provide a more pragmatic foundation for wind energy deployment. Addressing these multidimensional challenges will be critical not only for expanding renewable generation capacity but also for ensuring the resilience, stability, and sustainability of Poland's future energy system in the context of decarbonization and climate goals.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 4o (https://chatgpt.com/) in order to refine the language quality of the already written by the authors' text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Jakub Jurasz: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Paweł B. Dąbek:** Data curation, Formal analysis, Methodology, Resources, Software, Visualization, Writing – original draft. **Bogdan Bochenek:** Writing – review & editing, Data curation. **Mikołaj Ostraszewski:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors 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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Data availability

Data will be made available on request.

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