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Optimization of wind power generation in Kosovo based on GIS modelling and terrain data (GWA, SRTM, CORINE)

ABSTRACT: The purpose of the study is to analyze the wind energy potential in Kosovo using geographic information systems, considering environmental and infrastructural factors. The research methodology is based on a comprehensive analysis using geographic information systems, which includes modeling wind speeds based on data from the Global Wind Atlas, assessing terrain characteristics through the Shuttle Radar Topography Mission digital elevation model, filtering suitable areas according to land cover types and infrastructural constraints, and conducting a techno-economic analysis to optimize locations and estimate annual electricity generation. Standardized land-use indicators (0.5 km²/MW) were applied to ensure accuracy. The results demonstrate that the wind energy potential of Kosovo offers opportunities for the development of renewable energy capable of substantially reducing the region's dependence on coal-fired power plants and supporting decarbonization objectives. The technical potential was estimated at 6,248 MW across an area of 3,124 km² suitable for wind turbine installation. However, after accounting for environmental constraints, topographical characteristics, and infrastructural factors, the most probable technical

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potential amounted to 1,774 MW, distributed across the following regions: Pristina (646 MW, 36%), Mitrovica (497 MW, 28%), Gnjilane (220 MW, 12%), Peja (120 MW, 7%), Prizren (119 MW, 7%), Gjakova (98 MW, 6%), and Ferizaj (62 MW, 4%). The practically realizable potential, considering logistical and regulatory constraints, is estimated at 1,100–1,200 MW. The projected annual electricity generation, at a capacity factor of 0.3, reaches 4.66 million MWh/year, reducing CO₂ emissions by ~4.20 million tonnes per year. Flat and low-mountainous areas of Pristina and Mitrovica with slopes of less than 15 degrees and firm soils (agricultural land, implementation probability coefficient 0.9–1.0) were identified as optimal, as they ensure minimal costs. The findings contribute to the implementation of the objectives of the European Green Deal and the Energy Community, providing a foundation for the transition to sustainable energy through strategic planning of wind energy projects.

KEYWORDS: technical potential, annual generation, emission reduction, energy system, infrastructural constraints, techno-economic analysis

Introduction

In the context of the global pursuit of a sustainable energy future, wind energy stands out as one of the most efficient renewable sources, capable of reducing greenhouse gas emissions and ensuring a reliable energy supply. Between 2014 and 2024, global wind power capacity has grown significantly: according to the International Renewable Energy Agency (IRENA), by 2024, the worldwide installed wind capacity reached 900 GW, representing a 10% increase compared with 2023 (Renewable capacity statistics 2024 2024). This growth has been driven by technological advancements, reductions in turbine costs, and government support through subsidies and tax incentives. In Kosovo, where coal-fired power plants provide the majority of electricity generation, the development of wind energy could contribute to a substantial reduction in CO₂ emissions while supporting the objectives of the European Green Deal (The European Green Deal... n.d.) However, limited research on wind resources, outdated grid infrastructure, and the region's complex topography create barriers to unlocking this potential. Within this context, studies employing geographic information systems (GIS) and wind flow modeling offer precise assessments of suitable locations, enable optimization of turbine placement, and facilitate the development of integration strategies for the energy system, thus reducing reliance on fossil fuels, improving energy security, and supporting Kosovo's climate objectives.

The assessment of wind energy potential in Kosovo builds upon the analysis of existing research exploring various aspects of renewable energy deployment in the region, including technical and infrastructural challenges. In the study by Gjukaj et al. (2024), the integration of renewable sources, including wind energy, into the energy system of Kosovo was examined with an emphasis on distributed generation. The authors highlighted the need for grid modernization and the implementation of intelligent management systems to improve energy quality and

address limitations associated with variable generation. In the study conducted by Hoxha and Dragusha (2020), the WAsP11 software was applied to forecast wind potential using turbines rated at 3,200–3,600 kW. The findings demonstrated that regions with moderate wind speeds have considerable potential but require accurate modeling to optimize turbine placement. The study by Krasniqi et al. (2022) focused on the assessment of wind energy potential within the urban environment of Pristina using local meteorological data and GIS analysis. The results demonstrated a limited yet viable potential for small-scale wind installations, emphasizing the necessity of incorporating urban factors such as building structures and turbulence into the planning process.

In the study by Manske et al. (2022), geodetic data, random forest methods, and image recognition techniques were applied to create a dataset of geolocations of wind, solar, bioenergy, and hydropower installations in Germany based on open-source information. The developed data correction and localization methods produced highly accurate datasets suitable for use in GIS applications, facilitating the analysis of spatial, social, and environmental impacts of renewable energy deployment (Brych et al. 2023; Pstrowska et al. 2024). The study conducted by Khodakarami et al. (2025) employed innovative GIS techniques and remote sensing to identify hidden areas with high wind potential in regions with limited meteorological data. The findings demonstrated that a combined approach incorporating satellite data improves the accuracy of site identification, thereby enhancing the energy efficiency of wind farms. In the study by Gaugl et al. (2021), a GIS-oriented methodology was developed to optimize the placement of wind turbines in Austria while considering ecological and technical constraints. The results showed that multilayer GIS analysis enables the achievement of Austria's wind energy targets for 2030, ensuring a balance between maximizing productivity and minimizing integration costs within the energy system.

Attention should also be given to the analysis of international studies that demonstrate advanced approaches to optimizing wind farms through the use of geospatial and analytical methods. Abdelmassih et al. (2021) developed a model for selecting wind turbine sites based on fuzzy logic, integrating data on wind speed, topography, and infrastructure in the United States. The results indicated that the application of fuzzy logic allows for highly accurate ranking of potential locations, reducing subjective errors and improving the overall energy efficiency of wind farms. In the study by Zubir et al. (2022), GIS analysis was used to determine optimal locations for wind farm placement in the state of Selangor, Malaysia, considering population density, land use, and wind conditions. It was demonstrated that multilayer spatial analysis effectively identifies areas with high wind potential while reducing conflicts with urban development and agricultural land. The study by Ifkirne et al. (2022) applied multicriteria GIS analysis to map suitable sites for wind farms in the south-eastern regions of France, considering ecological, topographical, and social factors. The findings indicated that a multicriteria approach ensures a balance between technical feasibility and environmental sustainability, supporting the selection of locations with minimal ecological impact.

Notably, the studies mentioned are mostly focused on specific aspects, such as GIS analysis, wind flow modeling, or placement optimization, but they do not provide a comprehensive

assessment integrating techno-economic analysis with the consideration of topographical, ecological, and infrastructural constraints specific to Kosovo. Furthermore, these studies do not devote sufficient attention to environmental and economic factors, nor do they examine the detailed costs associated with the modernization of the existing energy system.

The purpose of this study is to conduct a comprehensive assessment of the wind energy potential of Kosovo using geographic information systems to identify technically and economically optimal locations for wind turbine placement, thereby contributing to the reduction of dependence on coal-fired power plants and supporting the objectives of the European Green Deal. The following objectives are set to achieve this purpose: to analyze the spatial distribution of wind speed and topographical characteristics using data from the Global Wind Atlas and the Shuttle Radar Topography Mission digital model to identify suitable areas while considering ecological and infrastructural constraints; to calculate the annual electricity generation based on technical potential and evaluate the efficiency of integrating wind energy into the energy system of Kosovo, including the costs of grid modernization and the implementation of energy storage systems; and to assess the environmental benefits of wind energy by estimating CO₂ emission reductions resulting from the substitution of coal-based generation, thereby supporting the region's climate objectives.

1. Materials and methods

The wind energy potential of Kosovo was assessed using an integrated approach that combined spatial data analysis, wind condition modeling, topographical evaluation, techno-economic analysis, and GIS-based filtering. The analysis was conducted at the level of the main administrative regions, Gjakova, Peja, Prizren, Mitrovica, Pristina, Ferizaj, and Gnjilane, which enabled the consideration of regional differences in potential. The methodology comprised four main stages: analysis of wind speed distribution, evaluation of topographical and terrain constraints, filtering of technically suitable areas based on land cover types and infrastructure, and techno-economic analysis with optimization of zones according to annual electricity generation. Each stage involved specialized tools and datasets to ensure the accuracy and reliability of the results.

For the analysis of wind speed and its spatial distribution, data from the Global Wind Atlas (GWA) (2025) were used, providing high-resolution wind mapping with a spatial resolution of 250 meters at a height of 100 meters above ground level. These data represent ten-year averaged values for the period 2014–2024, offering a robust basis for long-term planning. Wind speeds were classified into suitability zones with a minimum threshold of 5 m/s, which corresponds to the lower limit for economically viable wind turbine operation (Li et al. 2025). GIS tools (ArcGIS Pro) (2025) were employed for data processing, enabling the creation of wind potential maps that highlighted areas of varying energy intensity.

In addition, wind power density (WPD) was calculated using Equation (1):

$$WPD = 1/2 \cdot \rho \cdot v^3 \quad (1)$$

where:

- ρ – air density (1.225 kg/m³ at sea level),
- v – wind speed [m/s].

This parameter enabled the assessment of the energy efficiency of zones with identical average wind speeds but different cubic intensities, which is critical for identifying optimal turbine placement sites.

The evaluation of topographical and terrain constraints was performed using a digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) dataset (2000) with a spatial resolution of 30 m. These data provided information on elevation, which in Kosovo ranges from 275 to 2,670 meters above sea level, and surface slope. Areas above 1,750 meters were excluded from the analysis due to technical constraints, including turbine icing risks, difficulties of maintenance access, and an increased probability of equipment failure under low-temperature conditions. Surface slope analysis identified territories with gradients exceeding 20 degrees as unsuitable for turbine installation, since such conditions complicate foundation construction and increase the risk of soil erosion. GIS-based algorithms were applied to calculate surface gradients, allowing the precise identification of suitable areas with slopes below 15 degrees, primarily flat and low-mountain terrains.

Filtering of technically suitable areas was conducted using a multi-layer GIS analysis that integrated wind speed data, terrain features, land cover types, and infrastructural constraints. Based on land-use data obtained from European sources, such as CORINE Land Cover (2025), zones unsuitable for wind energy deployment were excluded, including urban areas, water bodies, wetlands, forests with a low implementation feasibility coefficient (0.25), and protected territories, such as the Bjeshkët e Nemuna National Park and the Sharr Mountains. CORINE Land Cover (CLC) uses a minimum mapping unit of 25 hectares for areal features and a minimum mapping width of 100 meters for linear ones, available in both vector and 100 m raster formats. Position accuracy meets or exceeds 100 meters. Suitability coefficients ranging from 0.25 to 1.0 were assigned to each land cover category according to technical feasibility and ecological restrictions. For example, agricultural lands and pastures were assigned coefficients of 0.9–1.0 due to stable soil conditions, whereas forested territories were assigned 0.25 because of the need for deforestation. A standard land requirement of 0.5 km² per MW, recommended by European guidelines, was used to estimate the theoretical installed capacity.

The technical potential under spatial constraints was determined using the installed capacity Formula (2):

$$P_{installed} = A_{suitable} / A_{perMW} \quad (2)$$

where:

- $P_{installed}$ – installed capacity [MW],
- $A_{suitable}$ – suitable area [km²],
- A_{perMW} – land requirement per MW (0.5 km²/MW).

The techno-economic analysis encompassed the assessment of costs associated with construction, grid connection, transportation, and turbine operation, alongside the evaluation of energy efficiency. Foundation and equipment transportation costs were estimated with reference to terrain characteristics and proximity to road infrastructure. Grid integration feasibility was examined by analyzing distances from 110 kV transmission lines and substations, incorporating transmission losses (3–5% per 100 km) and construction costs for new lines (50,000–100,000 EUR per kilometer). Economic viability was evaluated based on the annual electricity generation, calculated using Equation (3):

$$AEG = P_{installed} \cdot CF \cdot 8,760 \quad (3)$$

where:

- CF – capacity factor (0.3),
- 8,760 – number of operating hours per year.

The annual electricity output of wind power plants was determined according to Equation (4):

$$\begin{aligned} \text{Annual electricity generation} = \\ \text{installed capacity} \cdot \text{coefficient electricity usage} \cdot \text{hours per year} \end{aligned} \quad (4)$$

Based on the calculated annual electricity generation by wind farms, the volume of avoided CO₂ emissions was derived using Equation (5):

$$\text{Reduction of CO}_2 \text{ emissions} = \text{annual electricity generation} \cdot \text{coefficient emissions} \quad (5)$$

Optimization of suitable zones based on annual generation potential was conducted by ranking sites according to combined criteria, including wind speed, terrain, land cover, and infrastructural accessibility. Priority was assigned to flat and low-mountain areas with slopes below 15 degrees and stable soil conditions (agricultural land and pastures), where construction costs are minimal, and energy production remains stable. GIS algorithms were employed to overlay multi-layer datasets, enabling the exclusion of zones with elevated ecological risks or complex terrain. Seismic stability of turbine foundations was also analyzed, particularly within mountainous regions, to ensure structural reliability under the geotechnical conditions of Kosovo. This methodology provides a comprehensive framework for assessing wind energy potential, integrating high-resolution spatial datasets, advanced modeling techniques, and standardized

criteria, thereby establishing a reproducible foundation for the strategic planning of wind energy projects in Kosovo.

2. Results

Wind turbines are capable of operating efficiently at wind speeds ranging from 4 to 12 m/s, measured at hub height, which typically varies between 80 and 160 m and, in some cases, reaches up to 200 m. Achieving maximum performance and ensuring the structural stability of wind power plants requires a careful selection of locations based on detailed topographic analysis. Sites with slopes exceeding 15–20° are excluded, as steep gradients cause air turbulence that reduces turbine efficiency and present significant challenges for constructing stable foundations and establishing access roads. In addition to slope-related constraints, areas with special status or increased vulnerability are also classified as unsuitable for wind farm installations. These include national parks, urban areas, wetlands, nature conservation zones, and sites of critical infrastructure. Such territories are excluded from consideration for wind turbine placement, even in cases where high wind potential is present, due to ecological, social, or technical limitations (Wind energy in Europe...2025).

Kosovo's primary environmental protection law is the Law on Environmental Protection (2008), which mandates responsibilities for public and private entities to manage pollution, waste, and natural resources while ensuring economic activities do not harm the environment. This law requires Environmental Impact Assessments (EIAs) for projects, including those in renewable energy, to minimize ecological impacts. The Law on the Promotion of the Use of Renewable Energy Sources (BRE) (2024), approved by Kosovo's Assembly, establishes policies for promoting clean energy like solar, wind, and hydropower, aligning with EU directives and the Energy Strategy 2022–2031. It sets a national target of 35% renewable energy in gross final consumption by 2031, includes support schemes such as feed-in tariffs and auctions, and emphasizes grid integration and sustainability criteria for biofuels and biomass.

Figure 1 illustrates the territory of Kosovo, highlighting the main protected natural areas. The map shows the distribution of national parks, nature reserves, and other conservation zones.

The largest protected area is Bjeshkët e Nemuna (Prokletije), occupying the western part of the country and highlighted in green along the borders with Montenegro and Albania. Another major conservation zone, the Sharri/Sharr Mountains, is located in the south and stretches across the border with North Macedonia and Albania. Several smaller protected sites are situated in the central and northern regions of the country.

Figure 2 presents the territories of Kosovo classified as unsuitable for the construction of wind power plants. The spatial distribution of such zones clearly demonstrates that the most significant restrictions arise from urbanized areas, transportation corridors, and water bodies.



Fig. 1. Protected natural areas in Kosovo

Note: light green indicates the country's general forest-covered area; dark green denotes large national parks; grey represents other protected natural territories; brown dashed areas indicate smaller reservations; green patches correspond to minor natural zones of local importance; and red dots mark individual protected objects.

Source: compiled based on Geoportal Republic of Kosovo (2025).

Rys. 1. Obszary chronionej przyrody w Kosowie

In the central and southern parts of the country, a considerable concentration of continuous and fragmented urban development forms extensive clusters of unsuitable land. Additional barriers include industrial and commercial zones, quarries, landfills, and recreational complexes, which are primarily located around major settlements. Water bodies and river valleys also represent spatial constraints, as they cross multiple regions of the country and hinder turbine placement in floodplains and ecologically sensitive zones. Fruit orchards, vineyards, and urban green spaces, although smaller in scale, further reduce the availability of land for energy infrastructure.

Figure 3 presents a combined exclusion map based on wind speed and topographic constraints.

The application of exclusion criteria that consider both technical and environmental constraints resulted in approximately 4,800 km², representing about 44% of the total area of Kosovo, being classified as unsuitable for the installation of wind power plants.

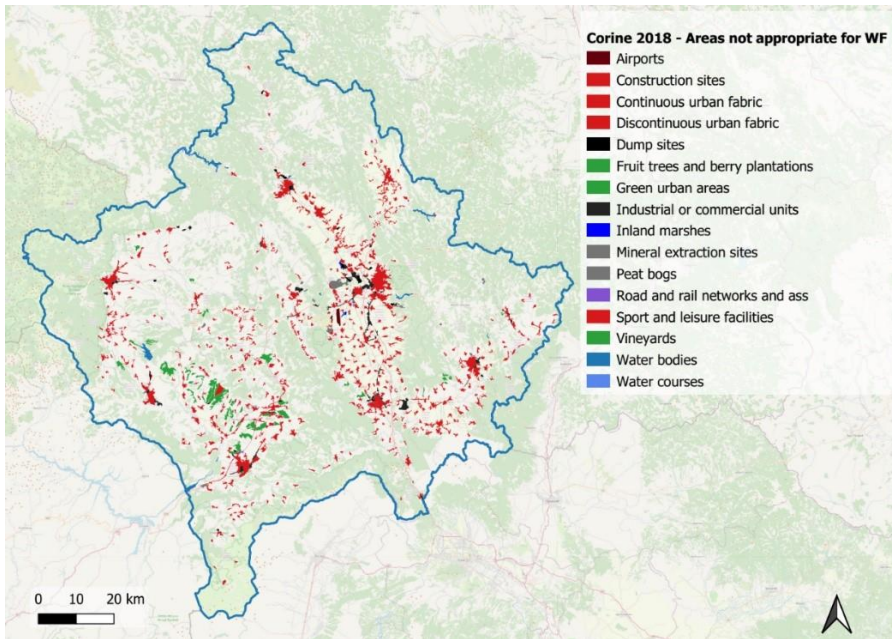


Fig. 2. Unsuitable areas of Kosovo for the construction of wind power plants
Source: developed based on CORINE Land Cover (2025)

Rys. 2. Tereny Kosowa nieodpowiednie do budowy elektrowni wiatrowych

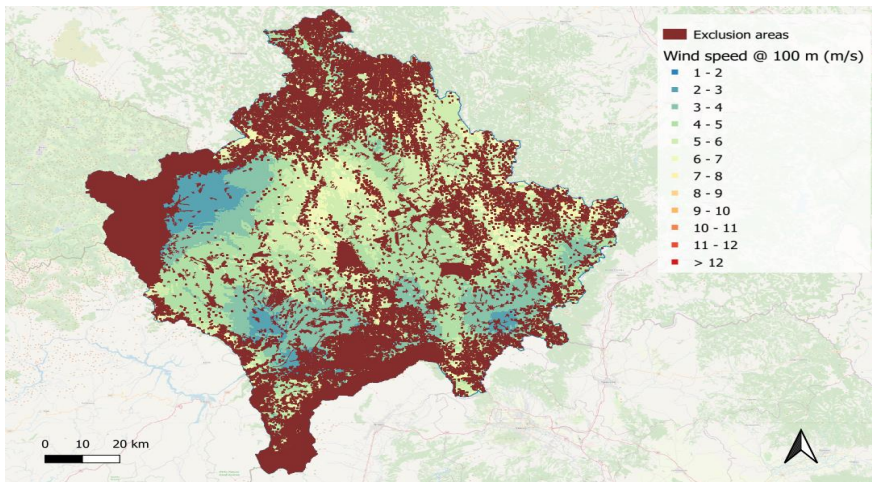


Fig. 3. Combined exclusion map based on wind speed and topographic constraints – unsuitable areas for the construction of wind power plants
Source: developed based on CORINE Land Cover (2025)

Rys. 3. Połączona mapa wykluczeń oparta na prędkości wiatru i ograniczeniach topograficznych – obszary nieodpowiednie do budowy elektrowni wiatrowych

Given the limited capacity for conducting detailed wind speed measurements across the entire territory of Kosovo, caused by logistical and technical challenges, this study relied on verified datasets characterizing the medium-term wind potential of the region. These spatial datasets, processed using geoinformation analysis methods, enabled precise identification of areas where the average wind speed exceeds the threshold value of 5 m/s, required for the efficient operation of wind turbines. The assessment incorporated factors such as terrain elevation, slope gradients, and land-use categories (Wind energy in Europe... 2025). Figure 4 provides a detailed spatial representation of the areas identified as technically suitable for the construction of wind power plants, with wind speed ranges between 5 and 11 m/s, ensuring optimal turbine performance.

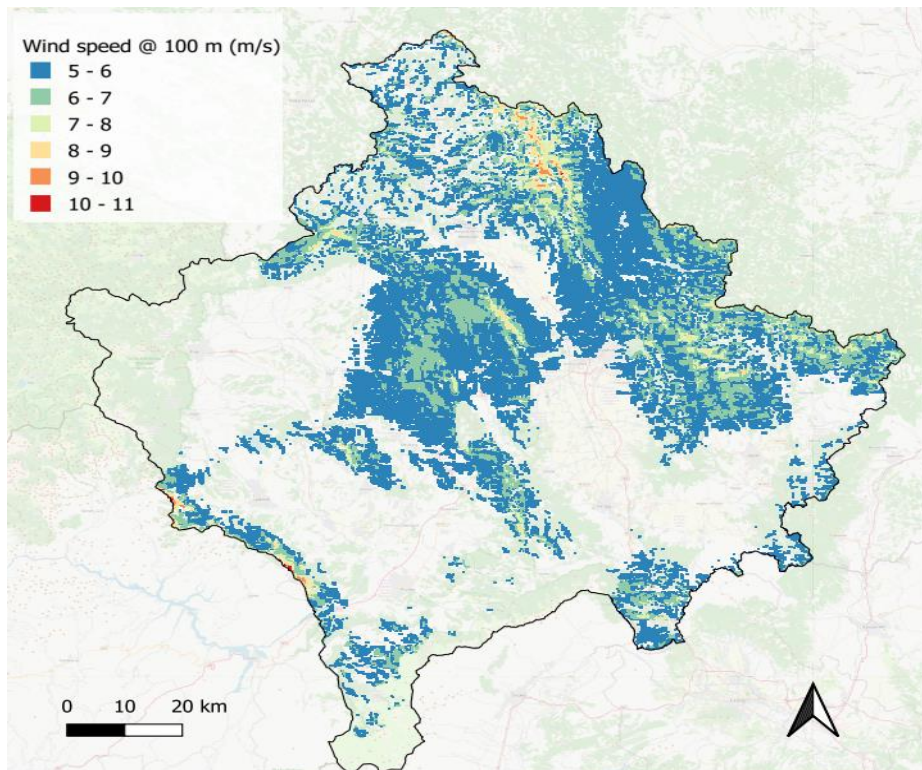


Fig. 4. Map of wind speed ranges across suitable areas of Kosovo for wind power plant construction
Source: developed based on Global Wind Atlas (2025)

Rys. 4. Mapa zakresów prędkości wiatru w obszarach Kosowa odpowiednich pod budowę elektrowni wiatrowych

Detailed assessments of these areas are presented in Table 1, which serves as the basis for further calculations. These data were essential for determining the theoretical installed capacity of wind energy facilities under conditions of optimal spatial allocation and full compliance with all identified constraints.

TABLE 1. Distribution of suitable areas by wind speed

TABELA 1. Podział odpowiednich obszarów według prędkości wiatru

Wind speed range at 100 m height [m/s]	Area [km ²]
5–6	2,150
6–7	790
7–8	145
8–9	28
9–10	9
10–11	2
Total	3,124

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

According to the data presented in Table 1 and Figure 4, the largest share of technically suitable areas for wind power plant installation is characterized by an average wind speed of 5–6 m/s. This range covers a significant portion of land, highlighting the prevalence of zones with moderate wind potential that remain suitable for efficient turbine operation.

As demonstrated in Figure 5, adopting a stricter technical threshold that includes only areas with wind speeds between 6 and 10 m/s would considerably reduce the size of suitable territories. Such a limitation decreases the available land for wind energy development and necessitates more careful site selection for optimal turbine placement.

Based on Table 1, an area of 3,124 km² is optimal for wind turbine installation. Calculating the potential installed capacity for these zones requires consideration of several technical aspects. Wind turbines with higher nominal capacities typically require less land per megawatt, enabling more efficient use of available space. Topographic characteristics significantly influence turbine placement strategies: turbines may be aligned along mountain ridges to capture stable airflows, distributed across hilly areas to minimize turbulence, or clustered on flat plains to simplify construction and operation (Kerimkhulle et al. 2022; Deryaev 2023). The direction and stability of prevailing winds play a decisive role in determining the optimal turbine orientation for maximum energy generation. Preventing aerodynamic interference that reduces operational efficiency requires maintaining adequate spacing between individual turbines, which necessitates precise spatial planning.

Given the spatial and aerodynamic constraints associated with turbine placement, a widely adopted approach allocates approximately 0.5 km² of land per megawatt of installed wind energy capacity. This coefficient accounts for the required spacing between turbines to minimize wake effects and ensures efficient use of available land. Based on this ratio, the theoretical potential of wind energy was calculated for the identified areas with a total surface of 3,124 km² suitable for the placement of wind installations.

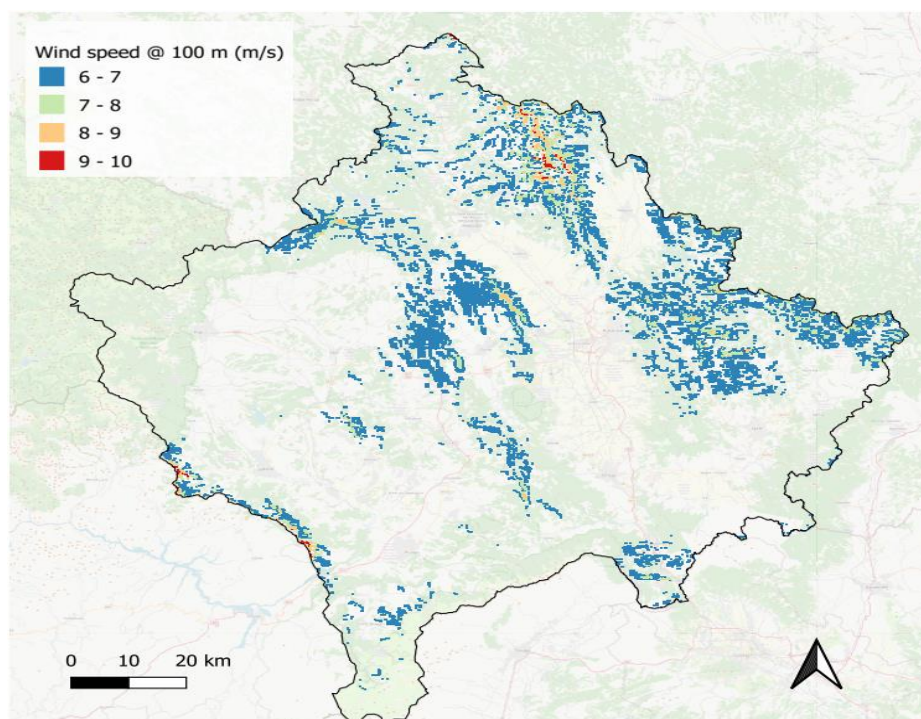


Fig. 5. Map of wind speed ranges (above 6 m/s) across suitable areas of Kosovo for wind power plant construction
 Source: developed based on Global Wind Atlas (2025)

Rys. 5. Mapa zakresów prędkości wiatru (powyżej 6 m/s) w obszarach Kosowa nadających się do budowy elektrowni wiatrowych

According to Formula (2), the theoretical potential of wind energy amounts to:

$$P_{installed} = 3,124/0.5 = 6,248 \text{ MW}$$

This result assumes maximum land-use efficiency with minimal restrictions related to infrastructure or environmental constraints, such as protected zones or complex terrain. For an accurate assessment of technical potential, several critical factors were considered, including terrain relief, land cover types (with open grasslands preferred over dense forests), stability of wind flows, and proximity to electrical and transportation networks, which directly affect infrastructure costs. Environmental and cultural constraints were also evaluated, as they preclude the utilization of certain areas for energy purposes.

Table 2 presents the probability coefficients for utilizing different wind speed ranges in the implementation of wind power facilities.

The area suitable for the placement of wind power plants is distributed according to different types of land cover and wind speed, as presented in Table 3. These data reflect the characteristics

TABLE 2. Probability coefficient for the utilisation of wind speed ranges in Kosovo

TABELA 2. Współczynnik prawdopodobieństwa wykorzystania zakresów prędkości wiatru w Kosowie

Wind speed range [m/s]	Area [km ²]	Probability coefficient
5–6	2,150	0.4
6–7	790	0.7
7–8	145	1.0
8–9	28	1.0
9–10	9	1.0
10–11	2	1.0
Total area	3,124	

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

of the landscape and environmental factors that determine the feasibility of constructing wind farms across various regions of Kosovo.

TABLE 3. Types of land cover and probability coefficient of land use for wind power plants in the Republic of Kosovo

TABELA 3. Rodzaje pokrycia terenu i współczynnik prawdopodobieństwa użytkowania gruntów pod elektrownie wiatrowe w Republice Kosowa

Land cover type	Total area [km ²]	Suitable area for wind power plants	Probability coefficient
Broadleaf forests	4,020	1,370	0.25
Coniferous forest areas	210	20	0.25
Mixed forest areas	120	17	0.25
Shrubland	95	280	0.50
Complex agricultural lands	1,450	320	0.80
Non-irrigated arable land	1,295	365	0.90
Agricultural areas	1,165	440	0.90
Natural pasturelands	710	190	1.0
Areas with sparse vegetation	180	60	1.0
Pasture areas	165	45	1.0
Uncultivated lands	50	2	1.0
Burnt areas	30	10	1.0
Rocky terrains	5	0	1.0
Total	9,495	3,119	

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

The distribution of wind speed ranges across the Republic of Kosovo, depending on land cover, for the implementation of wind power plants, is shown in Table 4.

TABLE 4. Wind speed in the territory of the Republic of Kosovo, depending on land cover

TABELA 4. Prędkość wiatru na terytorium Republiki Kosowa w zależności od pokrycia terenu

Wind speed range [m/s]/ Land cover type	5–6	6–7	7–8	8–9	9–10	10–11	Total area [km ²]
Broadleaf forests	860	422	80	8	0	0	1,370
Coniferous forest areas	11	6	3	0	0	0	20
Mixed forest areas	11	5	1	0	0	0	17
Shrubland	185	78	14	2	1	0	280
Complex agricultural lands	265	55	0	0	0	0	320
Agricultural areas	320	108	12	0	0	0	440
Non-irrigated arable land	345	20	0	0	0	0	365
Rocky terrains	0	0	0	0	0	0	0
Burnt areas	8	2	0	0	0	0	10
Uncultivated lands	1	1	0	0	0	0	2
Natural pasturelands	85	65	25	10	4	1	190
Pasture areas	38	6	1	0	0	0	45
Areas with sparse vegetation	41	12	4	2	1	0	60
Total area [km ²]	2,170	780	140	22	6	1	3,119

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

The theoretical energy potential in megawatts (MW) under ideal conditions in Kosovo, assuming the absence of ecological, topographical, and infrastructural constraints, and considering optimal wind conditions with speeds from 5 m/s and above at a height of 100 meters above ground level, depending on land cover types for the implementation of wind power plants, is presented in Table 5.

The majority of the ideal technical potential of wind energy is concentrated in the wind speed range of 5–6 m/s, representing approximately 70% of the total capacity, while 95% of the potential falls within the range of 5–7 m/s. Full achievement of this ideal potential appears unlikely due to various constraints.

Figure 6 presents the geographical distribution of potential zones for the installation of wind power plants, considering wind speeds in the range of 5–11 m/s and excluding areas restricted for ecological or infrastructural reasons.

TABLE 5. Energy potential [MW] under ideal conditions in the territory of Kosovo, depending on land cover type and wind speed range

TABELA 5. Potencjał energetyczny [MW] w idealnych warunkach na terytorium Kosowa w zależności od rodzaju pokrycia terenu i zakresu prędkości wiatru

Wind speed range [m/s]/ Land cover type	5–6	6–7	7–8	8–9	9–10	10–11	Total area [km ²]
Broadleaf forests	1,720	844	160	16	0	0	2,740
Coniferous forest areas	22	12	6	0	0	0	40
Mixed forest areas	22	10	2	0	0	0	34
Shrubland	370	156	28	4	2	0	560
Complex agricultural lands	530	110	0	0	0	0	640
Agricultural areas	640	216	24	0	0	0	880
Non-irrigated arable land	690	40	0	0	0	0	730
Rocky terrains	0	0	0	0	0	0	0
Burnt areas	16	4	0	0	0	0	20
Uncultivated lands	2	2	0	0	0	0	4
Natural pasturelands	170	130	50	20	8	2	380
Pasture areas	76	12	2	2	0	0	92
Areas with sparse vegetation	82	24	8	4	2	0	120
Total area [km ²]	4,340	1,560	280	46	14	4	6,240

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

Table 6 provides the most probable technical potential of wind energy, considering land cover types and wind speed.

Analysis of Table 6 indicates that the most probable technical potential of wind energy in Kosovo amounts to 1,774 MW, with the largest share concentrated in zones with wind speeds of 5–6 m/s (1,037 MW, 58%) and 6–7 m/s (546 MW, 31%). This confirms the suitability of the region for turbines adapted to moderate wind conditions. The greatest contributions are provided by agricultural areas (388 MW, probability coefficient 0.9), non-irrigated arable land (274 MW, 0.9), and natural pasturelands (239 MW, 1.0), owing to their flat terrain and high accessibility for construction. Forested areas (broadleaf, coniferous, and mixed) have a lower potential (total 373 MW) due to the low probability coefficient (0.25), reflecting difficulties associated with clearance and site preparation. Zones with higher wind speeds (7–11 m/s) contribute only 9% of the potential (184 MW), indicating the limited number of such areas, mainly located on shrubland and pasture terrains.

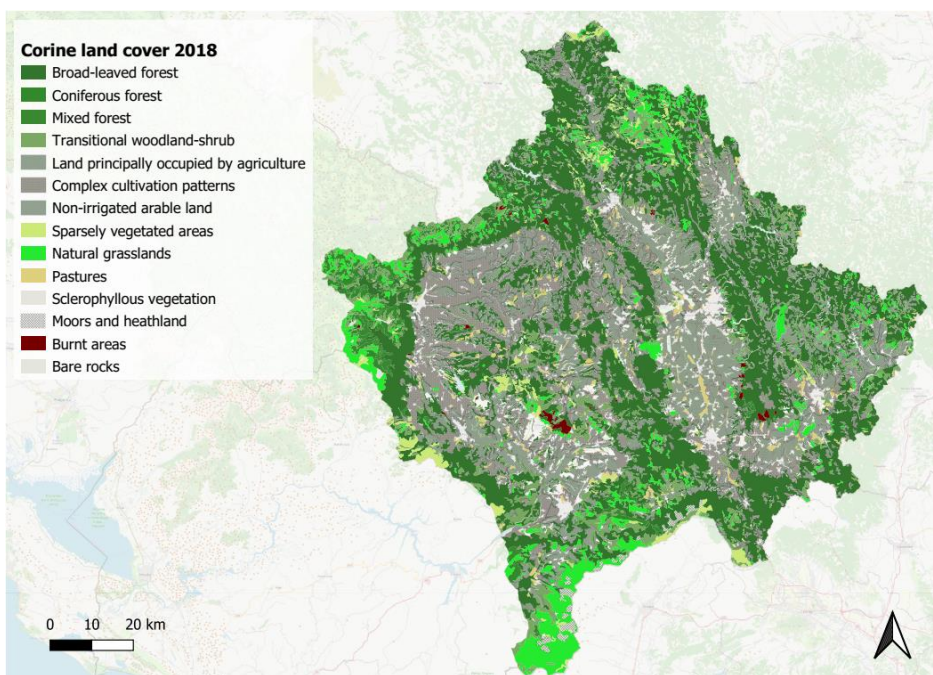


Fig. 6. Distribution of potential zones for the installation of wind power plants in Kosovo, considering wind speeds of 5–11 m/s, excluding areas restricted for ecological or infrastructural reasons

Source: developed based on CORINE Land Cover (2025)

Rys. 6. Rozkład potencjalnych stref instalacji elektrowni wiatrowych w Kosowie, biorąc pod uwagę prędkość wiatru 5–11 m/s, z wyłączeniem obszarów objętych ograniczeniami ze względu na ekologiczne lub infrastrukturalne

Table 7 presents the ideal technical potential of wind energy by regions of Kosovo and wind speed ranges, providing insight into the spatial distribution of potential opportunities for wind energy development in the territory.

Analysis of Table 7 demonstrates that, under ideal conditions, the technical potential of wind energy in Kosovo reaches 6,248 MW, with the greatest contributions from Pristina and Mitrovica due to extensive areas with moderate wind speeds of 5–7 m/s (5,880 MW, 94% of total potential). The majority of this potential is concentrated in the 5–6 m/s range (4,300 MW, 69%), indicating the suitability of the regions for turbines adapted to moderate wind conditions. Areas with higher wind speeds (7–11 m/s) provide only 368 MW (6%), reflecting the limited extent of such zones, predominantly in Mitrovica and Pristina.

Table 8 presents the adjusted technical potential of wind energy, reflecting all spatial, infrastructural, and environmental constraints, which allows for the assessment of a realistic distribution of potential across the regions of Kosovo.

Data from Table 8 indicate that the most probable technical potential of wind energy in Kosovo is 1,774 MW, with Pristina and Mitrovica leading due to extensive areas with wind

TABLE 6. The most likely technical potential of wind power [MW] by land cover types and wind speed

TABELA 6. Najbardziej prawdopodobny potencjał techniczny energii wiatru [MW] według rodzajów pokrycia terenu i prędkości wiatru

Land cover type	Probability coefficient	5–6 m/s	6–7 m/s	7–8 m/s	8–9 m/s	9–10 m/s	10–11 m/s	Total [MW]
Broadleaf forests	0.25	172	147	39	5	0	0	363
Coniferous forest areas	0.25	2	3	1	0	0	0	6
Mixed forest areas	0.25	2	2	0	0	0	0	4
Shrubland	0.50	73	58	15	2	0	0	148
Complex agricultural lands	0.80	169	59	0	0	0	0	228
Agricultural areas	0.90	231	135	22	0	0	0	388
Non-irrigated arable land	0.90	251	23	0	0	0	0	274
Rocky terrains	1.0	0	0	0	0	0	0	0
Burnt areas	1.0	6	2	0	0	0	0	8
Uncultivated lands	1.0	0	0	0	0	0	0	0
Natural pasturelands	1.0	67	92	50	20	8	2	239
Pasture areas	1.0	30	10	2	0	0	0	42
Areas with sparse vegetation	1.0	34	17	8	4	1	0	64
Total		1,037	548	137	31	9	2	1,764

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

TABLE 7. Distribution of ideal technical potential of wind energy [MW] by regions of Kosovo and wind speed

TABELA 7. Rozkład idealnego potencjału technicznego energii wiatrowej [MW] według regionów Kosowa i prędkości wiatru

Wind speed range [m/s]	Gjakova	Peja	Prizren	Mitrovica	Pristina	Ferizaj	Gnjilane	Total [MW]
5–6	258	360	330	1,078	1,648	192	482	4,348
6–7	62	83	85	462	524	75	264	1,555
7–8	21	9	13	75	109	8	45	280
8–9	7	1	3	29	14	1	1	56
9–10	3	0	2	9	2	0	0	16
10–11	2	0	1	0	0	0	0	3
Total	353	453	434	1,653	2,297	276	792	6,258

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

TABLE 8. Technical potential of wind energy [MW] in Kosovo, considering wind speed, land cover type, and probability coefficients

TABELA 8. Potencjał techniczny energii wiatrowej [MW] w Kosowie, uwzględniający prędkość wiatru, rodzaj pokrycia terenu i współczynniki prawdopodobieństwa

Wind speed range [m/s]	Gjakova	Peja	Prizren	Mitrovica	Pristina	Ferizaj	Gnjilane	Total [MW]
5–6	58	88	75	257	420	38	97	1,033
6–7	22	27	34	174	167	21	98	543
7–8	11	4	6	41	50	3	25	140
8–9	4	1	2	19	8	0	0	34
9–10	2	0	1	6	0	0	0	9
10–11	1	0	1	0	0	0	0	2
Total	98	120	119	497	645	62	220	1,761

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

speeds of 5–7 m/s (1,583 MW, 89% of total potential) and favorable land cover types, such as agricultural lands with high probability coefficients (0.9–1.0). The majority of potential lies in the 5–6 m/s range, confirming the efficiency of turbines designed for moderate wind conditions. Other regions, including Gjakova, Peja, Prizren, Gnjilane, and Ferizaj, have lower potential owing to topographical constraints and smaller areas of suitable land. Zones with high wind speeds (7–11 m/s) contribute only 184 MW (10%), reflecting their limited availability.

The most probable technical potential of 1,774 MW may be substantially reduced during project implementation due to practical limitations, such as considerable distances from existing energy infrastructure, which increase costs and complicate integration of wind farms into the grid, rendering some areas economically unviable. Remoteness from existing roads presents logistical challenges for the transport of large-scale equipment and materials, affecting project feasibility (Iskandarov 2024; Peleshenko et al. 2017). Moreover, areas critical for biodiversity conservation, including habitats of migratory birds or bats, may be excluded to minimize ecological impacts, while sites near archaeological or culturally significant landmarks are subject to restrictions to protect Kosovo’s heritage. Disputes over land ownership and local community objections represent further constraints that may complicate project implementation (Babak et al. 2021; Mukhamediyarova et al. 2025). Such limitations could reduce the achievable installed capacity of wind energy to approximately 1,100–1,200 MW, representing a more realistic estimate for practical implementation.

In most parts of Kosovo, wind speeds do not exceed 7 m/s, while areas with the highest wind speeds are typically located in environmentally sensitive regions, such as nature reserves or zones with dense high-altitude forests. Despite their high wind potential, these regions are unsuitable for the installation of wind turbines due to environmental and regulatory restrictions.

Consequently, such areas must be excluded from wind energy development plans within the framework of the strategic expansion of energy capacities. The most realistic wind energy potential, estimated at 1,774 MW, may be further adjusted to approximately 1,700–1,750 MW overall, reflecting reductions in key regions, including Mitrovica and Pristina. The analysis indicates that around 57% of the total potential is concentrated within the wind speed range of 5–6 m/s, while approximately 88% falls within the range of 5–7 m/s, highlighting the predominance of moderate wind speeds across suitable territories. The assessment of wind power generation potential is based on a comprehensive analysis of multiple data sources, including wind speed measurements, land cover characteristics, and spatial constraints.

The most accurate scenario for estimating wind potential is presented in Table 8, which specifies installed capacity in MW by land cover type and wind speed range. These findings emphasize the importance of a holistic consideration of spatial, environmental, and technical factors for optimizing the placement of wind power plants, enabling the maximization of energy production while minimizing the impact on the natural and cultural environment of Kosovo.

An engineering analysis was conducted to assess the performance of wind turbines in Kosovo, aiming to calculate the annual electricity generation by region (Gjakova, Peja, Prizren, Mitrovica, Pristina, Ferizaj, and Gjilan) based on the most probable technical potential of wind energy. The calculations incorporate key parameters, including installed capacity, the capacity utilization factor, and integration characteristics within the energy network of Kosovo. Table 9 presents the estimated annual electricity output by region, using a conservative capacity utilization factor of 0.3, which corresponds to the typical efficiency of wind turbine operation under moderate wind speed conditions.

TABLE 9. Annual electricity generation by region in Kosovo based on the most probable technical potential of wind energy

TABELA 9. Roczna produkcja energii elektrycznej w Kosowie według regionów na podstawie najbardziej prawdopodobnego potencjału technicznego energii wiatrowej

Region	Installed capacity [MW]	Annual electricity output [MWh/year]
Gjakova	98	257,544
Peja	120	315,360
Prizren	119	312,732
Mitrovica	497	1,305,276
Pristina	645	1,697,928
Ferizaj	62	162,936
Gnjilane	220	577,920
Total	1,761	≈ 4,662,000

Source: compiled based on Global Wind Atlas (2025), CORINE Land Cover (2025).

The efficiency of integrating wind energy, estimated at approximately 4.60 million MWh per year with an installed capacity of 1,774 MW, into the energy system of Kosovo largely depends on the ability of the existing infrastructure to adapt to the variable nature of wind generation. The largest share of production is concentrated in the regions of Pristina (≈ 1.70 million MWh/year) and Mitrovica (≈ 1.31 million MWh/year), which possess relatively well-developed grid infrastructure that facilitates the connection of wind farms. However, achieving the full utilization of the 1,774 MW potential will require the modernization of existing transmission lines and the construction of new substations, particularly in less developed areas such as Ferizaj and Gjakova. The remoteness of some prospective sites from grid infrastructure may lead to transmission losses, which in turn increase project implementation costs and reduce the overall efficiency of integration.

The primary challenge for integrating wind energy in Kosovo lies in the current structure of the energy system, which relies heavily on coal-fired power plants that provide stable but environmentally harmful generation (Tagybayev et al. 2023; Akbarova et al. 2024). Wind energy, by contrast, is characterized by variability caused by fluctuations in wind speed, which complicates maintaining grid balance (Nakashydzhe et al. 2021). Addressing this instability requires balancing systems, such as battery energy storage solutions, that can store surplus energy during periods of strong wind and release it back into the grid when production decreases. For example, the deployment of lithium-ion batteries, similar to those used in electric vehicles, could smooth peak loads and ensure a stable energy supply for wind power plants in Kosovo. The implementation of smart grids would further enhance integration by dynamically regulating electricity flows and optimizing the connection of wind farms, particularly in Pristina and Mitrovica, where over 60% of the potential is concentrated. Nevertheless, the current infrastructure of Kosovo, designed around coal-based generation, demands substantial investments to accommodate renewable sources, including the upgrading of transformers and network management systems.

The selection of optimal sites for wind turbine deployment in Kosovo represents a crucial step towards achieving efficient electricity generation based on the technical potential of 1,774 MW. According to the data presented above, 60% of the potential is concentrated within wind speeds of 5–6 m/s, and 90% within the 5–7 m/s range, which highlights the prioritization of areas with moderate wind conditions. The subsequent techno-economic analysis focuses on identifying locations that combine high turbine performance with minimal financial costs, thereby ensuring maximum project profitability.

The terrain of Kosovo, comprising plains, hills, and mountain ranges, has a considerable influence on the technical suitability of sites for wind turbines (Fig. 7).

Lowland and low-hill areas, such as those in Pristina and Mitrovica, are technically optimal due to their moderate surface inclination (up to 10–15 degrees), which facilitates the construction of turbine foundations. These regions, which concentrate 64% of the potential, are predominantly covered by agricultural land and pastures (implementation probability coefficient 0.9–1.0), providing a stable base for foundations and minimizing ground preparation costs (\sim EUR 50,000–70,000 per turbine). Mountainous zones, for example, in Peja and Prizren, experience higher wind speeds (7–11 m/s); however, steep slopes (exceeding 20 degrees) complicate installation

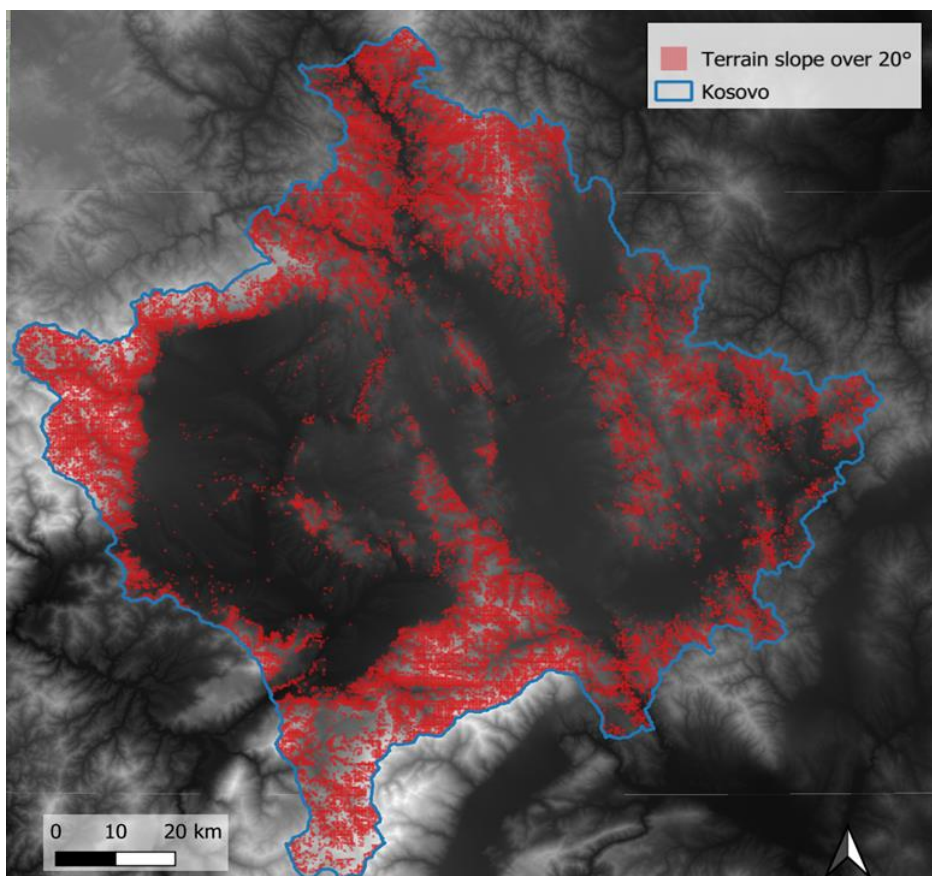


Fig. 7. Areas of Kosovo with slopes exceeding 20 degrees
 Source: compiled based on Shuttle Radar Topography Mission (SRTM) (2000)

Rys. 7. Obszary Kosowa o nachyleniu przekraczającym 20 stopni

and significantly increase earthwork costs (up to ~EUR 100,000 per turbine due to leveling requirements). Wind turbine foundations in seismic zones typically account for soil-structure interaction (SSI), peak ground acceleration, and combined loads via response spectra, as seen in offshore and onshore studies. The more technically challenging terrain also raises the risk of erosion, necessitating additional soil stabilization measures, such as geotextiles or drainage systems, which add approximately 10–15% to construction expenses. Elevation plays an equally important role in the technical efficiency of turbines. Most suitable sites in Kosovo are situated at altitudes between 500 and 1,000 meters above sea level (Figs 8 and 9), typical for the plains and hills of Pristina, Mitrovica, and Gjakova.

Figure 8 presents a digital elevation model of the terrain of Kosovo, illustrating the contrast between the low-lying central regions and the elevated mountain ranges along the periphery.

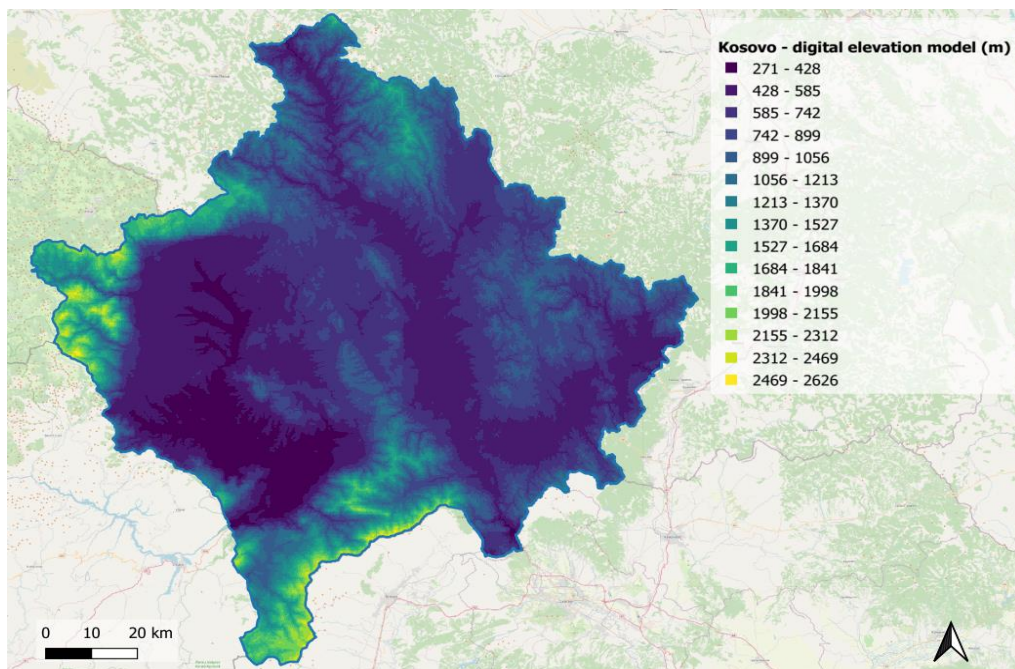


Fig. 8. Relief of the territory of Kosovo
 Source: compiled based on Shuttle Radar Topography Mission (SRTM) (2000)

Rys. 8. Rzeźba terenu Kosowa

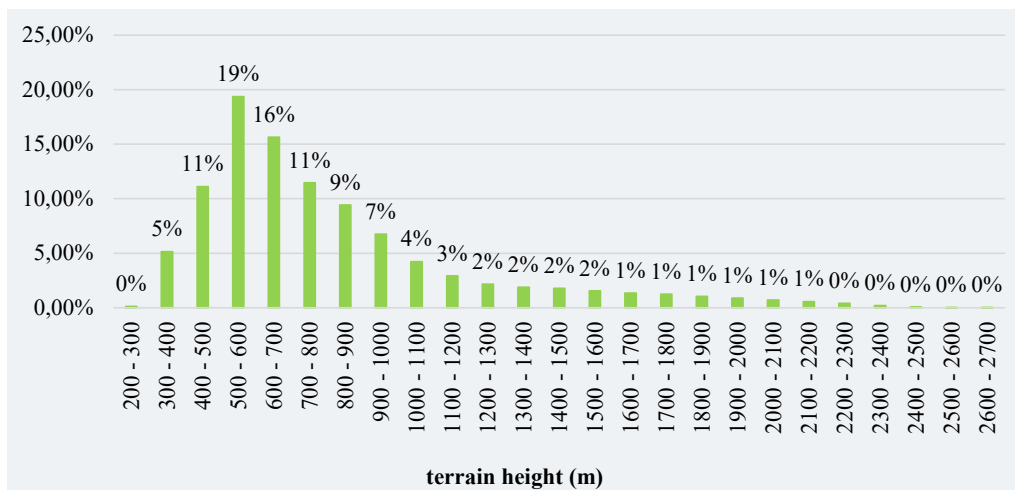


Fig. 9. Distribution of elevations in Kosovo
 Source: compiled based on Shuttle Radar Topography Mission (SRTM) (2000)

Rys. 9. Rozkład wysokości w Kosowie

The lowest areas (271–585 m, dark violet) dominate the central part of the country, forming a broad lowland basin. Medium-altitude ridges (742–1,370 m) are visible in the north-east, east, and south, gradually transitioning into high mountain areas. The highest zones are located in the west and south-west, represented by mountain systems where elevations exceed 2,000 meters and, in some places, reach beyond 2,500 meters. The terrain of Kosovo is thus characterized by a combination of a lowland central core surrounded by mountain ranges, which determines both climatic conditions and the possibilities for land use and infrastructure placement.

The diagram in Figure 9 illustrates the distribution of Kosovo's territory by elevation ranges. The largest share of the area is concentrated between 400–500 m (19%) and 500–600 m (16%), indicating the dominance of low-hill and foothill landscapes. Substantial areas are also located at 300–400 m and 600–700 m (11% each), while above 1,000 m the share gradually decreases: from 7% at 900–1,000 m to 12% within the 1,200–1,800 m range. Elevations above 2,000 m occupy less than 1% of the territory, while those exceeding 2,400 m are virtually absent. Overall, the terrain of Kosovo is characterized by a predominance of mid-low elevations with a gradual increase towards mountainous regions at the periphery, while high-altitude areas remain limited in extent.

Lower air density directly lowers the kinetic energy extractable from wind, potentially cutting power output by 10–30% at sites above 1,000 m compared to sea level. Wind speeds may increase with altitude due to reduced surface friction, sometimes boosting generation despite density losses. Turbine designs for high-altitude sites often feature larger blades or adjusted pitch to compensate. These territorial features provide stable wind flows at heights of 100–150 meters, corresponding to the hub height of wind turbines. According to Figure 10, most of the country experiences wind speeds of 4–6 m/s, indicating moderate wind potential. The lowest values (1–3 m/s) are observed in the central lowland regions, where the terrain restricts air circulation.

In contrast, in the mountainous areas of the west and south, as well as in certain elevated zones in the east, wind speeds reach 6–8 m/s and above, making these regions the most promising for the placement of wind energy facilities. Locally, on ridges and high-altitude plateaus, speeds exceeding 9–10 m/s are possible, indicating zones with significant energy potential. The map confirms the dependence of wind intensity on elevation and topographic barriers, outlining the areas most suitable for wind energy development along the peripheries of Kosovo.

Analysis of Figure 11 shows that the most frequent wind speeds fall within the 4–5 m/s range (30.4%) and the 5–6 m/s range (28.36%), together accounting for more than half of all observations. Wind speeds of 3–4 m/s (18.29%) and 6–7 m/s (11.69%) are also relatively common, while higher speeds become progressively less frequent: 7–8 m/s (3.47%) and above 8 m/s in fewer than 2% of cases.

Extremely low values (below 2 m/s) occur only sporadically, representing less than 0.2%. The wind regime of Kosovo at an altitude of 100 meters is therefore predominantly concentrated within the medium range of 4–6 m/s, indicating a stable but moderate potential for wind energy utilization, with localized opportunities in areas experiencing speeds above 7 m/s.

The use of tall turbines enables access to stronger winds, increasing the capacity factor, yet it requires additional expenditure on towers (approximately EUR 200,000 per turbine)

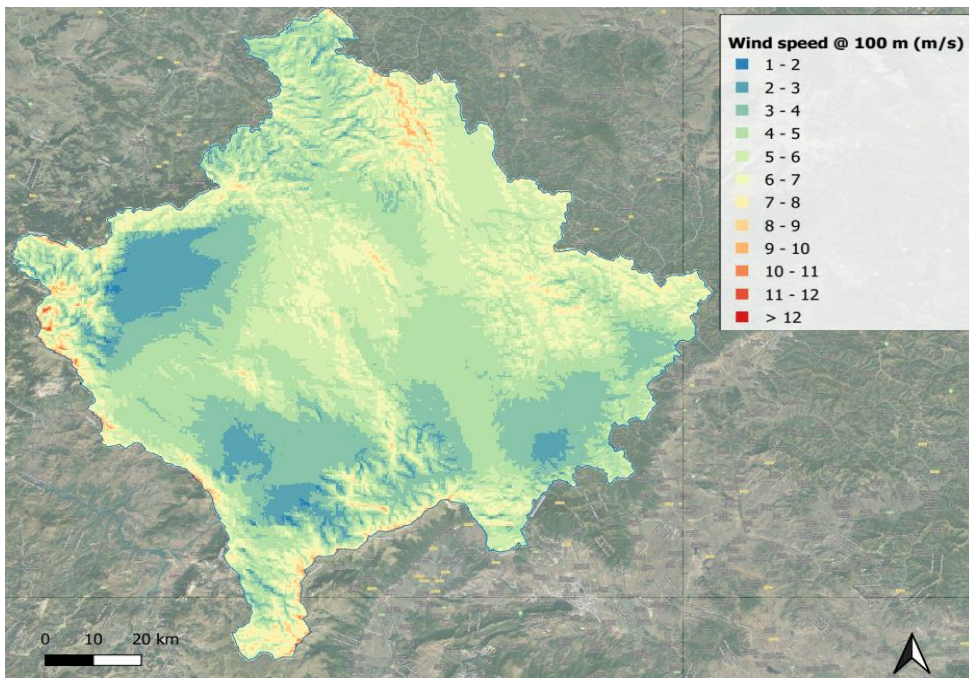


Fig. 10. Wind speed map (100 m)
 Source: developed based on Global Wind Atlas (2025)

Rys. 10. Mapa prędkości wiatru (100 m)

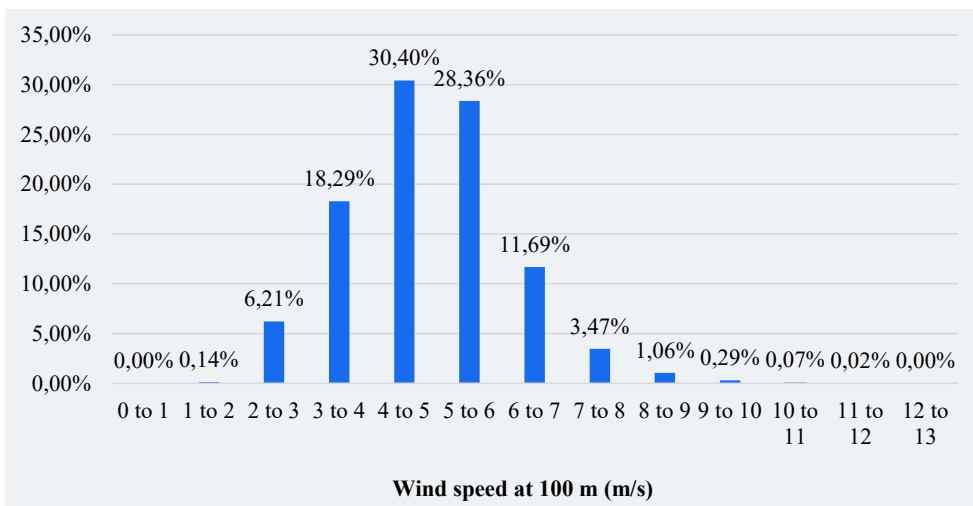


Fig. 11. Wind speed distribution chart
 Source: developed based on Global Wind Atlas (2025)

Rys. 11. Wykres rozkładu prędkości wiatru

and reinforced foundations to ensure seismic stability, which is relevant for Kosovo given its geological characteristics. High-altitude areas (above 1,000 m), such as those in Peja, although offering better wind conditions, often coincide with protected natural zones or forested regions with a low implementation probability coefficient (0.25). This complicates their utilization due to environmental restrictions and elevated deforestation costs (up to ~EUR 20,000 per hectare) (Renewable power generation costs in 2022 2022).

The type of land cover, as indicated in Table 6, further affects both the technical and economic feasibility of site selection. Agricultural land and pastures, which dominate in Pristina and Mitrovica, are characterized by solid soils that provide a reliable base for foundations without substantial preparation costs (approximately 5–10% of total construction expenses). Forested areas in Gnjilane and Peja, by contrast, require clearance and levelling, potentially costing up to ~EUR 50,000 per hectare, while also increasing the risk of environmental impacts, such as disruptions to bird migration routes. Rocky terrains, despite having a high implementation probability coefficient (1.0), are technically challenging due to drilling requirements, which raise foundation costs to approximately EUR 100,000–150,000 per turbine, making them less economically attractive compared with lowland zones. Access to transport and electrical infrastructure is critical for ensuring the techno-economic viability of projects. In Pristina and Mitrovica, a well-developed road network facilitates the transport of large components, such as blades (up to 67 meters in length) and towers, reducing logistics costs to approximately EUR 50,000 per turbine. In more remote regions, such as Ferizaj and Peja, the construction of temporary roads may add up to EUR 100,000 per site. Similarly, proximity to grid connection points is crucial: in Selacë (Mitrovica), a 20-kilometer 110 kV line provides efficient connectivity, whereas in Gjakova and Ferizaj, the construction of new lines may be required, costing EUR 50,000–100,000 per kilometer. Transmission losses of 3–5% per 100 km also affect economic performance, particularly for remote sites, where profitability decreases due to higher capital expenditures (Renewable power generation costs in 2022 2022).

Thus, the optimal locations for wind turbines in Kosovo are lowland and foothill areas in Pristina and Mitrovica, where moderate terrain, suitable soil cover, and developed infrastructure ensure both technical efficiency and economic feasibility. Mountainous regions, despite offering better wind conditions, are less suitable due to high construction costs and environmental constraints. The use of tall turbines, precise modeling of wind flows, and optimization of grid connectivity maximize energy generation while reducing expenses, thereby ensuring the profitability of projects (Kharlamov et al. 2014; Goolak et al. 2025).

Wind energy development in Kosovo also offers significant opportunities for reducing carbon dioxide (CO₂) emissions by displacing electricity generated from fossil fuel sources such as coal and oil. An analysis of the potential reduction of CO₂ emissions associated with the implementation of wind power plants was conducted based on the technically achievable capacity of wind energy identified in this study.

With an adjusted technically achievable installed capacity of approximately 1,774 MW and applying a capacity factor of 0.3, the annual electricity generation of wind power plants was calculated using Formula (4):

$$\text{Annual electricity generation} = 1,774 \text{ MW} \cdot 0.3 \cdot 8,760 \text{ hours} \approx 4,662,000 \text{ MWh/year}$$

This calculation assumes the stable operation of wind turbines throughout the year (8,760 hours) and recognizes that actual generation may vary depending on weather conditions, technical maintenance, and other factors. The resulting volume of electricity demonstrates the potential of wind energy to replace conventional energy sources, contributing to a reduction in the carbon footprint and supporting environmental sustainability objectives in Kosovo.

For the estimation of CO₂ emission reductions resulting from the use of wind energy in Kosovo, an emission factor characteristic of the current regional energy balance was applied, which predominantly relies on coal-fired power plants. According to the recommendations of the Intergovernmental Panel on Climate Change (IPCC), the average CO₂ emission factor for electricity generated from coal-fired power stations is approximately 0.9 kg CO₂ per kWh, or 900 kg CO₂ per MWh. Based on the calculated annual electricity generation of wind power plants (4,662,000 MWh/year; see previous calculation), the volume of avoided CO₂ emissions was determined using Formula (5):

$$\text{CO}_2 \text{ emissions reduction} = 4,662,000 \text{ MWh/year} \cdot 900 \text{ kg CO}_2/\text{MWh} \approx 4,196,000,000 \text{ kg CO}_2/\text{year}$$

This volume of emissions reduction highlights the importance of wind energy deployment in Kosovo as an effective instrument for lowering the carbon footprint. The transition to renewable energy sources such as wind contributes not only to decreasing dependence on fossil fuels but also to promoting environmentally sustainable development across the region. The achieved reduction in emissions aligns with the strategic priorities outlined in the European Green Deal and with the commitments of Kosovo under the Energy Community Treaty, aimed at mitigating the impacts of climate change and meeting the targets for decarbonizing the energy sector.

3. Discussion

The study established that the wind energy potential of Kosovo, which is ideally estimated at 6,248 MW over an area of 3,124 km², is reduced to a more probable technical potential of 1,774 MW and a practically achievable range of 1,100–1,200 MW after considering environmental, topographical, and infrastructural constraints, thereby requiring strategic planning for effective implementation. A comparison with international studies indicates both similarities and differences in approaches and outcomes. In the study by Albraheem and AlAwlaqi (2023) on Saudi Arabia, a substantial wind potential of the region was identified using GIS and the Analytic Hierarchy Process (AHP). However, the constraints of desert topography and low population density resulted in a smaller reduction of suitable land compared with Kosovo, where

environmental restrictions substantially limit the available area. Similarly, in the study by Rezik and El Alimi (2024) on southern Tunisia, GIS and multi-criteria analysis were used to identify optimal zones, but unlike Kosovo, the focus was on desert areas with minimal ecological barriers, which simplifies implementation. In the study conducted by Rehman et al. (2020), a heuristic approach was applied to optimize the layout of wind farms in Saudi Arabia, emphasizing the importance of wind power density (WPD). This aligns with the methodology of the current study, yet it does not account for seismic risks, which are significant for the mountainous areas of Kosovo. In the study by Xu et al. (2020) in China, suitable areas for wind farm installation were determined using GIS and multi-criteria analysis, although this approach was more oriented towards social factors, such as the distance from settlements, whereas in Kosovo, environmental constraints also play a critical role.

The study by Dehkordi et al. (2022) integrated economic and ecological considerations, highlighting the importance of CO₂ reduction, which corresponds to the results and direction of the present research, but it does not address infrastructural limitations, which are essential in the context of Kosovo. Mokarram et al. (2022) applied the OWA-ANP method to minimize environmental impacts, which is consistent with the inclusion of biodiversity considerations for Kosovo, although the analysis provided less detail regarding network integration costs. Furthermore, in the study by K. Aghaloo et al. (2023) on Bangladesh, GIS and the BWM method were employed for hybrid systems, demonstrating that a combined approach enhances the accuracy of site selection. However, unlike Kosovo, this paper focused on regions with an already developed renewable energy sector. Thus, the current findings for Kosovo confirm the broader trend in applying GIS and multi-criteria methods to narrow down wind energy potential from ideal to realistic estimates, while emphasizing the necessity of integrating local factors into strategic planning.

The study also established that the most promising regions for wind energy development in Kosovo are Pristina (646 MW, 36% of the total potential) and Mitrovica (497 MW, 28%), distinguished by optimal wind conditions (90% of the potential within the wind speed range of 5–7 m/s, with 60% concentrated in the 5–6 m/s interval), lowland and low-altitude areas with slopes of less than 15 degrees, and the predominance of agricultural land (implementation probability coefficient of 0.9–1.0), which together enable an annual generation of approximately 4.66 million MWh/year, including 1.70 million MWh/year in Pristina and 1.31 million MWh/year in Mitrovica at a capacity factor of 0.3. In the study by Gil-García et al. (2023), a two-level GIS-MCDM approach was applied to optimize offshore wind farms in Spain, emphasizing turbulence minimization and proximity to ports, which is only partially relevant for the inland lowland zones of Pristina, where transport accessibility plays a comparable but less maritime role; unlike Kosovo, where agricultural land facilitates construction, the offshore context requires consideration of marine currents, which is not pertinent to the present research. In the study by Yousefi et al. (2024), AHP and GIS were used to identify lowland territories with wind speeds of 5–7 m/s as the most cost-effective, which aligns with the selection of Pristina and Mitrovica; however, the focus on economic optimization through market mechanisms is less applicable to Kosovo due to limited grid infrastructure, necessitating further investment. The

study by Kahatapitiya et al. (2023) developed a weighted GIS model for Sri Lanka, focusing on agricultural plains with low foundation costs (similar to Pristina), but this study highlights the importance of microclimatic analysis, which in Kosovo remains constrained by seasonal datasets and requires further investigation. Gharaibeh et al. (2021) optimized the use of low-altitude land in Jordan, where a well-developed road network reduces logistical costs, consistent with the advantages of Mitrovica (access to 110 kV lines), although this approach does not account for seismic risks, which are critical for Kosovo. In the study by Bertsiou et al. (2021), MCDM and GIS were applied on a Greek island, confirming the importance of slopes of less than 15 degrees, as in Pristina and Mitrovica; however, the focus on the limited area of the island contrasts with the more extensive plains of Kosovo, which allow for greater scalability. In the study by Wang et al. (2022), lowland zones were identified as economically advantageous in China due to low construction costs, which is consistent with the agricultural land of Kosovo; however, large-scale projects employing high-capacity turbines are less applicable to Kosovo, where medium-capacity turbines are predominant. Spyridonidou and Vagiona (2020) optimized the offshore wind farm placement in Greece, focusing on proximity to power grids, which partially reflects the advantages of the Mitrovica region; however, the analysis of marine conditions does not consider land-based constraints, such as the need for reinforced foundations. The research on the wind energy potential of Kosovo, therefore, confirms the global trend of selecting flat areas with moderate wind resources and accessible infrastructure but stands out due to its emphasis on addressing local challenges, including the modernization of the existing energy system, which requires a unique approach to harnessing wind potential.

Spacing balances turbine density for land use against wake losses, using models like genetic algorithms that incorporate site-specific wind data, terrain, and rotor size. Larger farms benefit from wider spacing as more turbines experience wakes. Software simulates thousands of layouts to maximize annual energy production. Optimal turbine spacing in wind farms typically ranges from 3–5 rotor diameters (D) perpendicular to the prevailing wind direction and 5–9D in the direction of prevailing winds to minimize wake effects and maximize efficiency. Wake effects occur when upstream turbines create turbulent, slower wind that reduces power output for downstream turbines, potentially causing 10–20% average power loss in dense farms (Cao et al. 2022). These wakes can extend several kilometers, with deficits persisting 5–20 km downstream under certain conditions, though they recover partially after 5–10D. Stable atmospheric conditions can prolong wakes up to 70–100 km (Ahmed et al. 2024).

The findings of this study also demonstrate that the implementation of wind energy in Kosovo, with an annual generation of 4.66 million MWh, ensures a reduction of CO₂ emissions by approximately 4.2 million tonnes per year at an emission factor of 900 kg CO₂/MWh, highlighting the role of wind power for regional decarbonization. In the study by Zalhaf et al. (2021), a GIS-based fuzzy AHP approach was applied to select wind farm locations in Sudan, emphasizing the potential reduction of CO₂ emissions through the replacement of diesel generation, which aligns with the outcomes of the present research but places less emphasis on the quantitative assessment of emissions. The study by Benti et al. (2023) employed an AHP-GIS model in Ethiopia, showing that wind farms located in flat areas can reduce CO₂ emissions by

substituting coal-based energy sources, although this analysis does not provide precise calculations of emission reductions, unlike the case of Kosovo. Elhosiny et al. (2021) adopted a neutrosophic GIS-MCDM approach to identify suitable locations for wind farms in Egypt, highlighting environmental benefits through emission reductions, but researchers primarily focused on minimizing the impact on desert ecosystems, in contrast to the predominantly agricultural landscapes of Kosovo. In the study by Liu et al. (2023), the reduction of CO₂ emissions in China was evaluated as a result of wind turbine deployment, demonstrating environmental advantages consistent with the present study, although the emphasis on technological innovations is less applicable to the existing infrastructure. In the study by Peri and Tal (2020), a comprehensive GIS-based analysis in Israel demonstrated that wind farms contribute to lowering CO₂ emissions, yet the paper concentrated on landscape impacts rather than on quantitative indicators. In the study by Bilal et al. (2024), conducted in Qatar, a GIS-MCDM framework was used to assess both wind and solar energy potential, showing a possible reduction of emissions by 25% by 2030 and underlining the importance of replacing coal-based generation. Otsuki et al. (2022) analyzed the pathway to achieving net-zero emissions in Japan by 2050, emphasizing the role of wind power in CO₂ mitigation, although the focus on offshore farms and strict land-use constraints contrasts with the terrestrial agricultural zones of Kosovo. The research on Kosovo provides a precise quantitative assessment of CO₂ reduction, demonstrating the role of wind energy in a coal-dependent region and indicating the need for further evaluation of impacts on diverse ecosystems, as partially addressed in other studies.

Studies aimed at evaluating wind energy potential play a pivotal role in the global transition towards sustainable energy sources, providing scientifically grounded solutions for decarbonization, reducing dependence on fossil fuels, and achieving climate objectives. The use of advanced methodologies, including geographic information systems, multi-criteria analysis, and wind flow modeling, facilitates the accurate identification of optimal locations for wind farms, minimizes construction and integration costs, and accounts for ecological and infrastructural constraints (Prokopov et al. 1989; Babak and Kulyk 2023). Such research not only contributes to the development of national energy strategies but also supports international initiatives, including the European Green Deal, by providing data for investment planning and policy reforms. In the context of increasing global installed wind capacity, these studies become an essential tool for ensuring energy security and environmental sustainability across regions with diverse geographical and economic conditions.

Conclusions

The study established that wind energy in Kosovo has substantial potential, which can serve as a foundation for transitioning to renewable energy sources, reducing dependence on coal-fired power plants, and achieving environmental objectives. Using geographic information systems

(GIS) and multifactor analysis, which included an assessment of terrain, soil cover types, and infrastructural constraints, the ideal technical potential of wind energy was estimated at 6,248 MW across a total suitable land area of 3,124 km². However, after considering ecological constraints (such as biodiversity protection, including bird migration routes), the availability of transport and grid infrastructure, and terrain-related challenges, the most probable technical potential was adjusted to 1,774 MW. The practically achievable potential, when evaluated against additional factors such as distance to grid connection points, logistical costs, and regulatory limitations, is estimated to range between 1,100 and 1,200 MW. These findings highlight the necessity of a strategic approach to wind energy project planning to maximize potential while minimizing ecological and economic impacts.

The most promising regions for wind energy development were identified as Pristina (646 MW, 36% of total potential) and Mitrovica (497 MW, 28%), which concentrate the majority of generation capacity due to favorable wind conditions and terrain. Approximately 90% of the potential falls within the wind speed range of 5–7 m/s, with around 60% corresponding to 5–6 m/s, making these regions optimal for installing turbines designed for moderate wind conditions. The estimated annual electricity generation, based on a capacity factor of 0.3, amounts to approximately 4.60 million MWh/year, of which around 1.70 million MWh/year is provided by Pristina and about 1.30 million MWh/year by Mitrovica. This generation enables a reduction of approximately 4.20 million tonnes of CO₂ emissions per year, based on an emission coefficient of 900 kg CO₂/MWh. The flat and low-hill terrains of these regions, with slopes below 15 degrees and a predominance of agricultural lands and pastures (implementation probability coefficient 0.9–1.0), facilitate foundation construction and minimize land preparation costs.

The study also noted that the integration efficiency of wind energy into the energy system of Kosovo, where most electricity is produced by coal-fired power plants, is complicated by the variable nature of wind generation. Processing 4.60 million MWh/year requires modernization of the grid infrastructure, including 110 kV transmission lines and substations, particularly in Pristina and Mitrovica. In less developed areas, such as Ferizaj (62 MW) and Gjakova (98 MW), the distance from the grid requires the construction of new transmission lines, which may cost between 50,000 and 100,000 EUR per kilometer. The implementation of smart grids and energy storage systems enables the smoothing of generation fluctuations, thereby ensuring grid stability. The techno-economic analysis emphasized that flat areas in Pristina and Mitrovica are optimal due to their low slopes, solid soils, and proximity to infrastructure, which reduces foundation and transportation costs. Mountainous regions, such as Peja and Prizren, despite having higher wind speeds (7–11 m/s), are less suitable due to steep slopes exceeding 20 degrees, ecological constraints, and significant costs associated with land leveling and deforestation. The use of high-hub turbines (up to 178.5 m) increases energy output on flat terrains but requires reinforced foundations, which add up to 15% to overall costs.

Notably, this study is limited by insufficient detail on seasonal variations in wind speed, which may affect the accuracy of annual electricity generation forecasts. Further research should involve an in-depth analysis of microclimatic conditions in Pristina and Mitrovica

using data from local meteorological stations to improve the precision of wind potential assessments.

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Ines BULA BUNJAKU, Edin BULA, Alush MEXHUANI

Optymalizacja wytwarzania energii wiatrowej w Kosowie w oparciu o modelowanie GIS oraz dane topograficzne (GWA, SRTM, CORINE)

Streszczenie

Celem badania jest analiza potencjału energetyki wiatrowej w Kosowie z wykorzystaniem systemów informacji geograficznej, z uwzględnieniem czynników środowiskowych i infrastrukturalnych. Metodologia badań opiera się na kompleksowej analizie z wykorzystaniem systemów informacji geograficznej, która obejmuje modelowanie prędkości wiatru w oparciu o dane z Globalnego Atlasu Wiatrów, ocenę charakterystyki terenu za pomocą cyfrowego modelu wysokościowego misji Shuttle Radar Topography Mission, filtrowanie odpowiednich obszarów zgodnie z typami pokrycia terenu i ograniczeniami infrastrukturalnymi oraz przeprowadzenie analizy techniczno-ekonomicznej w celu optymalizacji lokalizacji i oszacowania rocznej produkcji energii elektrycznej. W celu zapewnienia dokładności zastosowano znormalizowane wskaźniki użytkowania gruntów ($0,5 \text{ km}^2/\text{MW}$). Wyniki pokazują, że potencjał energii wiatrowej w Kosowie stwarza możliwości rozwoju energii odnawialnej, która może znacznie zmniejszyć zależność regionu od elektrowni węglowych i wspierać cele dekarbonizacji. Potencjał techniczny oszacowano na 6248 MW na obszarze 3124 km^2 nadającym się do instalacji turbin wiatrowych. Jednak po uwzględnieniu ograniczeń środowiskowych, cech topograficznych i czynników infrastrukturalnych najbardziej prawdopodobny potencjał techniczny wyniósł 1774 MW, rozłożony na następujące regiony: Prisztina (646 MW, 36%), Mitrowica (497 MW, 28%), Gnjilane (220 MW, 12%), Peja (120 MW, 7%), Prizren (119 MW, 7%), Gjakova (98 MW, 6%) oraz Ferizaj (62 MW, 4%). Potencjał możliwy do zrealizowania w praktyce, z uwzględnieniem ograniczeń logistycznych i regulacyjnych, szacuje się na 1100–1200 MW. Prognozowana roczna produkcja energii elektrycznej, przy współczynniku wykorzystania mocy wynoszącym 0,3, wynosi 4,66 mln MWh/rok, co pozwala ograniczyć emisję CO_2 o około 4,20 mln ton rocznie. Jako optymalne zidentyfikowano płaskie i nizinne obszary Prisztiny i Mitrowicy o nachyleniu poniżej 15 stopni i twardych glebach (grunty rolne, współczynnik prawdopodobieństwa realizacji 0,9–1,0), ponieważ zapewniają one minimalne koszty. Wyniki badań przyczyniają się do realizacji celów Europejskiego Zielonego Ładu i Wspólnoty Energetycznej, stanowiąc podstawę przejścia na zrównoważoną energię poprzez strategiczne planowanie projektów związanych z energią wiatrową.

SŁOWA KLUCZOWE: potencjał techniczny, roczna produkcja energii, redukcja emisji, system energetyczny, ograniczenia infrastrukturalne, analiza techniczno-ekonomiczna

