International Journal of Innovative Technology and Interdisciplinary Sciences
https://journals.tultech.eu/index.php/ijitis
ISSN: 2613-7305
Volume 9, Issue 3
DOI: https://doi.org/10.15157/IJITIS.2026.9.3.1600-1624
Received: 13.05.2026; Revised: 29.06.2026; Accepted: 28.07.2026

Research Article

Comparative Techno-Economic Feasibility Assessment of Onshore Wind Energy Deployment: A Multi-Site Analysis

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Abstract

Given Albania's high dependence on hydropower and its sensitivity to hydrological fluctuations, identifying alternative renewable energy sources has become increasingly important. This study presents a comparative techno-economic feasibility assessment of onshore wind farm development in ten selected areas in Albania. Since studies simultaneously evaluating the technical and economic feasibility of multiple potential wind energy sites remain limited in Albania, this work provides a broader assessment of wind energy development feasibility. Wind resource assessment was performed using long-term wind atlas-based data where available complemented by on site measurements. WAsP software was used to assess the wind energy resources and to simulate the wind farm energy output. Weibull methodology was used for probabilistic assessment of wind speeds. Five wind turbine models were simulated. The Vestas V163 4.5 MW turbine at 126 m hub demonstrated the best technological and economic overall performance and was selected as the reference wind turbine for the economic assessment. The economic assessment was performed using RETScreen Expert software while sensitivity analyses were performed with respect to variations in installation cost, electricity price and discount rate. Wide range of values of the technical wind farm indicators and economic indicators was reported across the studied sites. Vau i Dejës, Mali i Rencit and Pukë can be considered to have the most favourable technical and economic indicators due to their high wind farm capacity factor and low LCoE value, combined with high NPV and IRR values. The LCoE varied from approximately 49 to 63 €/MWh. Notably, Mali i Rencit emerged as one of the best-performing sites despite not belonging to the highest wind power classes, indicating that feasibility also depends on other site-specific factors beyond wind potential. Furthermore, the comparison between WAsP and RETScreen highlighted the importance of a detailed and representative wind resource assessment for improving the reliability of wind farm evaluations. Overall, the findings provide a useful basis for identifying priority areas and supporting future investment decisions in Albania's wind energy sector.

Keywords: Wind Energy; Wind Resource Assessment; Weibull Distribution; Wind Farm Feasibility; Techno-Economic Analysis; WAsP.

INTRODUCTION

Over the past decade, there has been a significant shift in the worldwide energy industry toward Renewable Energy, to meet the dual challenge of cutting down emissions of the Green House Gases and assuring long-term energy security [1-5]. The significance of increasing the deployment of renewable energy capacities in Europe became even more prominent in the light of the energy crisis that occurred in 2021-2022, fuelled by the geopolitical instability, which triggered soaring electricity prices and supply uncertainties. During periods of high demand, prices in the European electricity market exceeded 300 €/MWh, while gas supply disruptions uncovered the structural deficiencies of the European energy system [6-8]. Consequently, there has been considerable attention in boosting the exploitation of renewable energy capacities in Europe, mostly in countries with abundant natural resources. Windpower is among the most advanced and competitive renewable energy technologies in Europe today, with the installed wind power reaching approximately 304 GW in 2025 and producing 17% of the total EU electricity production, which, together with solar energy has exceeded the EU electricity production from fossil fuels for the first time ever [9, 10].

Albania's electricity system is characterized by a high reliance on hydropower. Diversification of the electricity sector with a renewable-based power system, though, increases the country's exposure to hydrological annual variability (especially in dry years, when the electricity import rises substantially). This situation increases the exposure of the Albanian electricity sector to international electricity price fluctuations and higher energy prices. The electricity import has increased by approximately 26,5% in 2025 compared to 2024 in respect to the national electricity balance [11]. Possible exploitation of other renewable sources of energy, wind energy in particular, is thus an important step to advance in the diversification of the Albanian energy supply.

Recent studies have demonstrated that wind energy development can not only contribute to the diversification of electricity production but also decrease the operating costs of energy system in industrial and regional energy systems [12]. However, prior studies in Albania have usually studied only one or a few locations and they cannot depict the country's characteristics of diverse climatic and geographical conditions. Therefore, comparative studies evaluating the wind energy potential and economic feasibility of multiple sites across Albania remain limited, highlighting the need for further research.

Although Albania has significant wind energy potential, it is still underdeveloped regarding utility scale wind power projects in comparison with other neighbouring Balkan countries, i.e., at the end of 2025 Greece had established some 5706 MW capacities of wind power, North Macedonia, Kosovo and Montenegro presented some 103 MW, 137 MW and 118 MW respectively [9], while in Albania there are currently no operational land-based wind farms. Therefore, higher resolution technical and economic assessments are needed for upcoming investments and energy planning.

Although interest in wind energy development in Albania and the Western Balkans region has increased in recent years, several research gaps in the existing literature are still evident. First, most studies conducted in Albania have focused on individual sites or on limited regional assessments, limiting the possibility of comparing wind energy potential under different geographical and climatic conditions. Second, studies that combine wind resource assessment, turbine selection and techno-economic analysis within a common methodological framework remain limited. Finally, the compatibility between detailed wind resource assessment tools, such as WAsP, and more simplified pre-feasibility tools, such as RETScreen, has not been sufficiently studied in several sites simultaneously. Addressing these gaps is important for supporting evidence-based renewable energy planning and identifying priority areas for future wind energy investments in Albania.

In addition, limited attention has been given in the literature to how differences between detailed microscale wind resource modelling and simplified pre-feasibility assessment approaches can affect the technical and economic evaluation of wind energy projects in areas with different terrain characteristics. This issue is particularly important in countries such as Albania, where significant topographic variability can affect both wind resource assessment and project performance. Therefore, a systematic comparison of these approaches within a common assessment framework can provide useful insights for future wind energy planning and project development.

To address these gaps, this study investigates wind energy development opportunities across ten representative sites in Albania (Vau i Dejës, Pukë, Mali i Rencit, Velipojë, Vajkal, Tragjas, Mamaj, Dropull, Tren and Vernik), through a comparative techno-economic assessment and a probabilistic wind resource evaluation based on Weibull parameterisation. The study sites are situated in various geographical settings and climatic conditions, having been selected, not solely on the basis of wind resource potential, but also taking account of aspects which are likely to be encountered when developing new wind energy sites in the future (e.g. site accessibility, location relative to the national 110 kV grid infrastructure). This approach provides the opportunity for evaluating wind energy resources over a broad range of terrain types yet presenting a realistic overview of wind farm deployment prospects.

Based on the identified research gaps and the study objectives, this paper examines the following hypotheses:

- H1: Areas characterized by higher wind resource potential are expected to present more favorable indicators of technical and economic performance.
- H2: Turbines with larger rotor diameters and higher tower heights are expected to achieve higher wind farm capacity factors in most of the studied areas.
- H3: Detailed wind resource assessment and power generation modelling through WAsP are expected to provide more representative estimates of wind farm performance compared to simplified pre-feasibility assessments conducted with RETScreen.

The focus of this study is the application of a common assessment framework for the whole analysis which combines wind resource estimation, selected turbine parameters, performance analysis and techno-economic assessment of wind farms with ten out of the most representative locations in Albania. With this methodology, it is possible to compare technical and economic parameters for all ten areas based on national assessment criteria and to have an overall view of the wind energy potential development in this country.

This paper presents the following investigation on utility-scale wind power projects: wind resource evaluation based on measured and wind atlas data; Wind farm layout optimisation and energy simulations in WAsP; Economic assessment and feasibility analysis with RETScreen Expert. The performance of five modern utility scale wind turbine models is compared at the same site location and under same farm layout scenarios. The economic feasibility of the selected wind farm configurations is analysed through a sensitivity analysis study for a set of key financial parameters. Techno-economic and financial indices are used for the wind farm configurations evaluation, e.g., capacity factor, levelized cost of energy (LCoE), net present value (NPV), internal rate of return (IRR) and payback period.

METHODOLOGY

Selection of Areas

The study areas were identified using a pragmatic screening methodology whereby sites with feasible potential for the future development of wind farms were sought. Selection criteria considered not only the wind resource, but also geographical conditions, ease of access, location in relation to the existing 110 kV transmission system and possible constraints, such as protected areas. In the first stage, the wind atlas database was utilized to select sites having promising wind conditions. Then, for the second stage of the selection process, the sites obtained in the first stage were filtered out by analysing the influence of terrain, accessibility to road networks, distance to electrical grid, and the site information provided by Ministry of Infrastructure and Energy along with locations of interest for prospective wind energy investors.

Figure 1 shows the locations of the study areas in Albania, covering coastal, mountainous and inland settings that allow the evaluation of wind farm performance under a wide range of topographical and climatic conditions.

In accordance with the spatial presentation illustrated in Figure 1; Table 1 depicts a summary of the parameter's characteristic of the chosen areas. The table lists the fundamental physical, geographic, infrastructural and wind parameters of each site, including terrain type, elevation, distance to the electrical network and most common wind parameter. This information gives a comparison of the sites and is used as input for the technical and economic evaluation in the next section.

The suitability classification presented in Table 1 is consistent with previous wind resource investigations based on multiannual datasets from BWA and NEWA databases, complemented by field measurements where available [13-15]. Coastal and mountainous areas generally exhibited higher wind potential, whereas inland areas were characterized by more moderate and stable wind conditions. In addition, the comparison between atlas-derived data and real measurements, particularly for the Mamaj and Pukë sites, showed good agreement and supported the reliability of atlas-based datasets for preliminary wind resource assessment [13, 14]. Based on these validated datasets, the WAsP software was then used for wind farm layout design and energy production estimation. The characterization of the selected areas in terms of wind resource potential is further examined through wind resource modelling, as discussed in the following section.

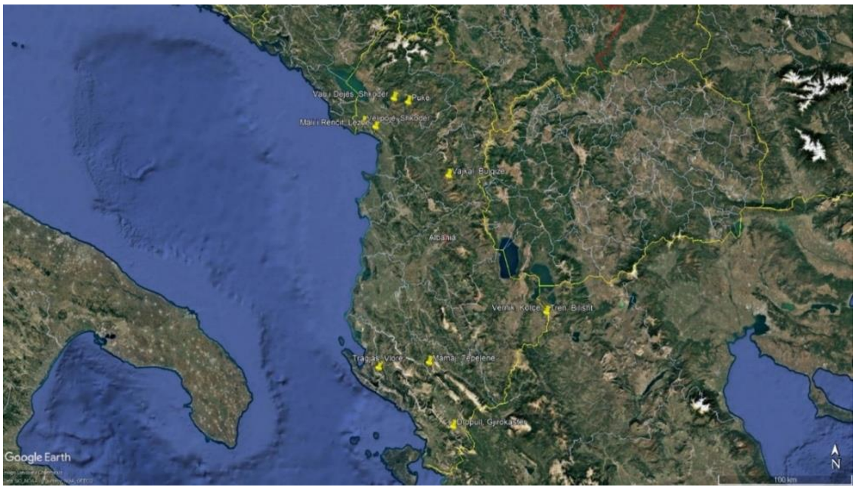


Figure 1. Geographic Distribution of the Selected Study Areas for Wind Energy Assessment in Albania

Table 1. Main Characteristics of the Selected Study Areas for Wind Energy Assessment in Albania

Area	Region of Albania	Terrain	Elev.(m)	Grid	Wind Regime	Suitability
Dropull	SW	Mountain slope	≈900	Road/grid access	Valley winds	Suitable
Mali i Rencit	N coastal	Coastal ridge	≈400	≈12 km to grid	Marine winds	Highly suitable
Mamaj	S	Valley/hills	≈150-300	≈1 km to grid	Stable winds	Highly suitable
Pukë	N	Mountainous	≈670	≈13 km to grid	High wind potential	Highly suitable
Tragjas	SW	Coastal hills	≈1300	Close to grid	Sea-driven winds	Highly suitable
Tren	SE	Hilly terrain	≈1080	≈12 km to grid	Moderate winds	Suitable
Vajkal	NE	Mountain	≈1700	Close to grid	Topography-driven	Suitable
Vau i Dejës	NW	Mountain ridge	≈450	≈6.5 km to grid	Strong winds	Highly suitable
Velipojë	NW coastal	Flat coastal plain	≈30	Close to grid	Sea-driven winds	Highly suitable
Vernik	SE	Hilly terrain	≈1100	≈12 km to grid	Stable winds	Suitable

Wind Resource Modelling

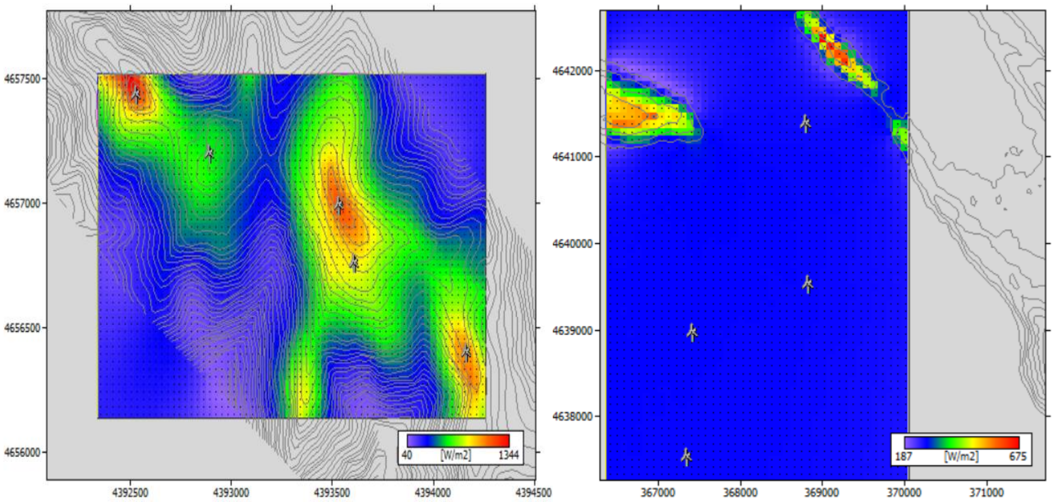
Wind resource assessment in this study is based on long-term wind data derived from the Balkan Wind Atlas (BWA) and the New European Wind Atlas (NEWA), using the

Weibull distribution for probabilistic modelling of wind speed. The available datasets cover long-term periods exceeding ten years and provide a representative description of wind conditions in the analysed areas. Specifically, the BWA datasets used in this study cover the period 2000-2013, while the NEWA datasets correspond to the period 2005-2014.

Field measurements available for the Mamaj and Pukë sites were used to complement the atlas-based datasets employed in this study. The Mamaj dataset covered the period from March 19, 2013 to June 14, 2014, while the Pukë dataset covered the period from October 1, 2020 to November 22, 2021. Detailed descriptions of the mast configurations, and sensor types have been reported in [13, 15].

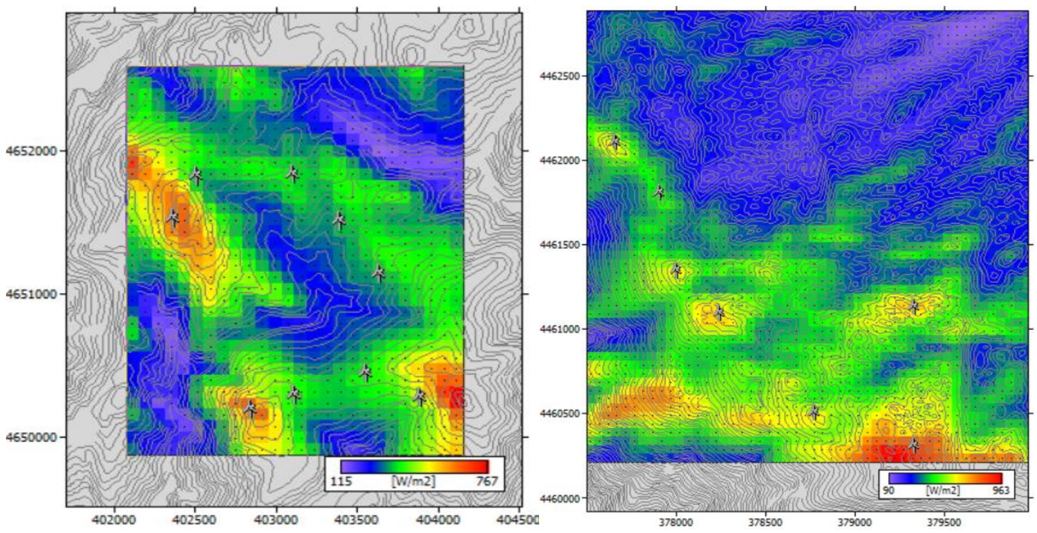
For the study areas where field measurements were available (Mamaj and Pukë), vertical wind shear characteristics were estimated using Windographer. The power-law exponent values resulted in α=0.112 for Mamaj and α=0.175 for Pukë. The corresponding surface roughness lengths, determined using the logaritmic wind profile approach, were z_0=0.00692 m for Mamaj, corresponding to terrain with short grass and cultivated land, and z_0=0.142 m for Pukë, corresponding to terrain characterized by the presence of few scattered trees. For the other study areas, the surface roughness characteristics were defined within WAsP based on terrain observations during site visits and the corresponding land cover characteristics.

The geographic coordinates of the anemometric towers used as input for the WAsP simulations are reported in the authors' previous studies [13-15]. However, since these towers are not always located within the areas of highest wind potential, the wind resource assessment was performed at representative locations within the proposed wind farm sites, based on WAsP-generated wind speed and power density distribution maps. Figure 2 and 3 present representative WAsP-generated wind power density maps and wind farm layouts for the Vau i Dejës, Velipojë, Pukë, and Tragjas study areas selected to illustrate different terrain and wind conditions.



(a) (b)

Figure 2. WAsP-Generated Wind Power Density Distribution Maps and Wind Farm Layouts for the (a) - Vau i Dejës and (b)- Velipojë Sites.



(a) (b)

Figure 3. WAsP-Generated Wind Power Density Distribution Maps and Wind Farm Layouts for the (a) - Pukë and (b)- Tragjas Sites.

Table 2 summarizes the data sources and reference coordinates used for the wind resource assessment of the selected areas.

Table 2. Wind data sources and reference coordinates used for the wind resource assessment.

Area	Data Source	Coordinates
Dropull	BWA	39.911⁰N, 20.223⁰E
Mali i Rencit	BWA	41.853⁰N, 19.538⁰E
Mamaj	Field measurements + WAsP	40.309⁰N, 20.009⁰E
Pukë (Kçirë)	Field measurements + WAsP	42.018⁰N, 19.824⁰E
Tragjas	BWA	40.288⁰N, 19.587⁰E
Tren	NEWA	40.647⁰N, 21.023⁰E
Vajkal	NEWA	41.536⁰N, 20.182⁰E
Vau i Dejës	BWA	42.043⁰N, 19.718⁰E
Velipojë	BWA	41.880⁰N, 19.429⁰E
Vernik	NEWA	40.647⁰N, 21.023⁰E

Furthermore, the Weibull probability density function has been used to describe wind speed distribution. The Weibull distribution function is given by equation (1) which is in the two-parameter form and can be described by the scale parameter, which is related to the mean wind speed, and the shape parameter, which characterizes the shape of the distribution function or the standard deviation of wind speeds. These parameters are very useful in the description of wind regimes and enable a reliable estimate of wind resources.

$$f(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} exp\left[-\left(\frac{v}{A}\right)^{k}\right] \quad (1)$$

where v represents the wind speed, A is the scale parameter, and k is the shape parameter. This function describes the probability of occurrence of different wind speed values and is widely applied in wind energy studies. The scale parameter A is closely related to the average wind speed, while the shape parameter k reflects the spread and stability of wind speed distribution. Higher values of *k* indicate more stable wind conditions, whereas lower values correspond to higher variability. The Weibull parameters used in this research work were derived from WAsP-processed wind climate data, ensuring consistency between wind resource assessment, wind farm layout design, and energy production modelling.

Additionally, the Weibull parameters were obtained from the wind climate data generated in WAsP and then used to characterize and compare the wind regime in each of the study areas uniformly.

The results show clear spatial differences in wind resource potential across the selected areas, as summarized in Table 3, while the corresponding Weibull parameters derived from WAsP modelling at 50 m above ground level, are presented in Table 4.

Table 3. Wind Resource Characteristics of the Selected Areas at 50 m Above Ground Level Derived from Wasp Modelling using Wind Atlas Data and Field Measurements Where Available.

Area	Mean Wind Speed (m/s)	Wind Power Density (W/m²)	Wind Power Class
Dropull	6.17 - 7.70	347 - 697	III-V
Mali i Rencit	6.40 - 7.23	379 - 558	III-IV
Mamaj	5.15 - 6.67	233 - 519	II-IV
Pukë (Kçirë)	6.25 – 7.95	391 - 821	IV-V
Tragjas	6.60 - 7.90	447 - 960	IV-VI
Tren	5.08 – 6.68	227 - 440	III
Vajkal	5.51 – 7.93	300 - 775	III-VI
Vau i Dejës	8.35 - 9.34	570 - 1200	V-VII
Velipojë	5.72 - 5.74	280 - 287	II
Vernik	6.09 – 6.61	316 - 434	III-IV

Wind resource characteristics of the selected areas at 50 m above ground level, derived from WAsP modelling using wind atlas data and field measurements where available. Wind power classes were assigned according to the estimated wind power density values.

Table 4. Weibull Parameters of the Selected Areas at 50 m a.g.l..

Area	Data Source	Weibull A (m/s)	Weibull K
Dropull	WAsP (atlas-based, site-adjusted)	5.8 - 7.8	1.57 - 1.72
Mali i Rencit	WAsP (atlas-based, site-adjusted)	7.1 – 7.8	1.61 – 1.67
Mamaj	Measurements + WAsP (site-adjusted)	5.8 - 7.3	1.47 - 1.48
Pukë (Kçirë)	Measurements + WAsP (site-adjusted)	7.0 - 8.8	1.56 – 1.58
Tragjas	WAsP (atlas-based, site-adjusted)	7.3 – 8.8	1.5 – 1.58
Tren	WAsP (atlas-based, site-adjusted)	6 - 7.1	1.61 - 1.68
Vajkal	WAsP (atlas-based, site-adjusted)	6.2 - 9	1.48 – 1.72
Vau i Dejës	WAsP (atlas-based, site-adjusted)	7.6 – 9.4	1.48 – 1.71
Velipojë	WAsP (atlas-based, site-adjusted)	6.4	1.62 - 1.63
Vernik	WAsP (atlas-based, site-adjusted)	6.7 – 7.4	1.62 – 1.67

Weibull scale parameter (A) and shape parameter (k) obtained from WAsP Observed Wind Climate (OWC) files at 50 m above ground level. The parameters were derived from wind atlas dataset and field measurements and evaluated at representative locations within the proposed wind farm areas.

Wind Turbine Selection

Based on the wind resource characteristics presented in Table 3 and the corresponding Weibull parameters in Table 4, a comparative analysis of wind turbine models was performed to determine the most suitable technology for each study area.

Five utility-scale wind turbines were selected based on their rated power, rotor diameter and hub height, and suitability for the wind regimes identified in the study areas. The selected turbine models are representative of current commercial onshore wind technology and reflect the range of rotor diameters and hub heights currently adopted in utility-scale projects [10, 16].

All selected turbine models correspond to IEC (International Electrotechnical Commission) Class III. While some of the analysed sites exhibited relatively high wind potential, these turbines were considered particularly suitable given that several of the investigated areas were characterized by low to moderate wind speed conditions.

The main technical characteristics of the selected turbine models are summarized in Table 5 including rotor diameter, hub height, rated power, and the characteristic operating wind speeds (cut-in, rated, and cut-out speeds). These parameters are most relevant to turbine efficiency in different wind speed situations.

Table 5. Technical Specifications of the Selected Wind Turbine Models Used in the Analysis

Turbine Model	Rotor Diameter (m)	Hub Height (m)	Rated Power (MW)	Cut-in Speed (m/s)	Rated Speed (m/s)	Cut-out Speed (m/s)
Vestas V126-3.3	126	128	3.3	3	12	22.5
Nordex N163-5.5	163	120	5.5	3	12.5	26
Nordex N149-5.5	149	105	5.5	3	13	24
Vestas V163-4.5 (98 m)	163	98	4.5	3	11	24
Vestas V163-4.5 (126 m)	163	126	4.5	3	11	24

The turbine models' performance was evaluated using WAsP, which makes use of a site-specific wind climate, local terrain features, and turbine power-curves. All turbines were evaluated identically on each study area, and their performance was compared using wind farm capacity factor.

Wind farm simulations were performed using the standard WAsP modelling framework, which takes into account terrain relief, surface roughness, and obstruction effects in calculating the site-specific wind climate. The parameters of the vertical wind shear and surface roughness determined from field measurements or from terrain assessment for each study area, were then used in the WAsP simulations. Wake losses were estimated using modelling routines implemented in WAsP and were included in all power generation calculations. The same modelling assumptions were applied uniformly across all study areas to ensure comparability of results.

For each study area, the same wind farm layout was used so that the comparison among the turbine models could be carried out under identical conditions and the effect of the turbine characteristics on the capacity factor could be better highlighted. During the layout design process in WAsP, turbine positions were selected with the aim of minimizing wake losses resulting from the interaction between turbines, while at the same time following common practices of spacing turbines according to the prevailing wind direction. Although a specific layout optimization for each turbine model could slightly affect the resulting capacity factors, the adopted approach provides a reliable basis for comparing turbine performance by isolating the influence of turbine characteristics from site-specific layout effects.

Table 6 shows the wind farm capacity factors resulting from the WAsP simulations, and Figure 4 depicts the effect of the turbine design variables on wind farm performance in the different study areas.

Table 6. Wind Farm Capacity Factor (%) of the Selected Wind Turbine Models for Each Study Area Based on Wasp Simulations Performed Under the Same Layout Conditions for all Turbine Types

Area	**Vestas V126 3.3**	**Nordex N 163 5.5**	**Nordex N149 5.5**	**Vestas V163 4.5 (98 m)**	**Vestas V163 4.5 (126 m)**
Dropull	45.5	45.5	40.8	47.7	49
Mali i Rencit	42.7	42	37	44.5	46.7
Mamaj	38.4	37.2	32.9	38.3	40
Pukë (Kçirë)	45	43.8	39.3	44.6	47.4
Tragjas	42.6	42.3	37.9	44.1	45.9
Tren	37.5	36	31.6	37.9	40.8
Vajkal	37.9	37	33.7	40.7	41.6
Vau i Dejës	50	50.7	47	51.7	52.8
Velipojë	43.6	42.4	36.5	43.1	47
Vernik	41	40	35	41	44

The consistency among the wind resource parameters (Table 3), the Weibull parameters (Table 4), and the wind farm performance results (Table 6) further confirms the reliability of our approach.

As shown in figure 4, turbines with larger rotor diameters and tower heights generally achieved higher capacity factors in most of the studied areas. This advantage was particularly evident in areas with more moderate wind regimes, such as Mamaj, Tren and Vajkal, where the larger rotor surface area enabled better energy capture at lower wind speed conditions.

The overall highest capacity factors were experienced by the Vestas V163 4.5 MW turbine with a hub height of 126 m. In the locations with the higher wind potential, like

Vau i Dejes, Pukë and Tragjas the power curve for each type of wind turbines was high. The capacity factor for each wind power plant was above 45% indicating that the location had good wind potential. The power curve of Vau i Dejes was higher, Pukë was the following one and Tragjasi was the last.

The variation of the capacity factor among the study sites illustrates the different wind regimes of Albania. Vau i Dejes, Puke and Tragjas have the best technical potential, whereas Mamaj, Tren, Vajkal and Vernik are characterized by a less favorable wind regime. The rest of the study sites have mixed properties.

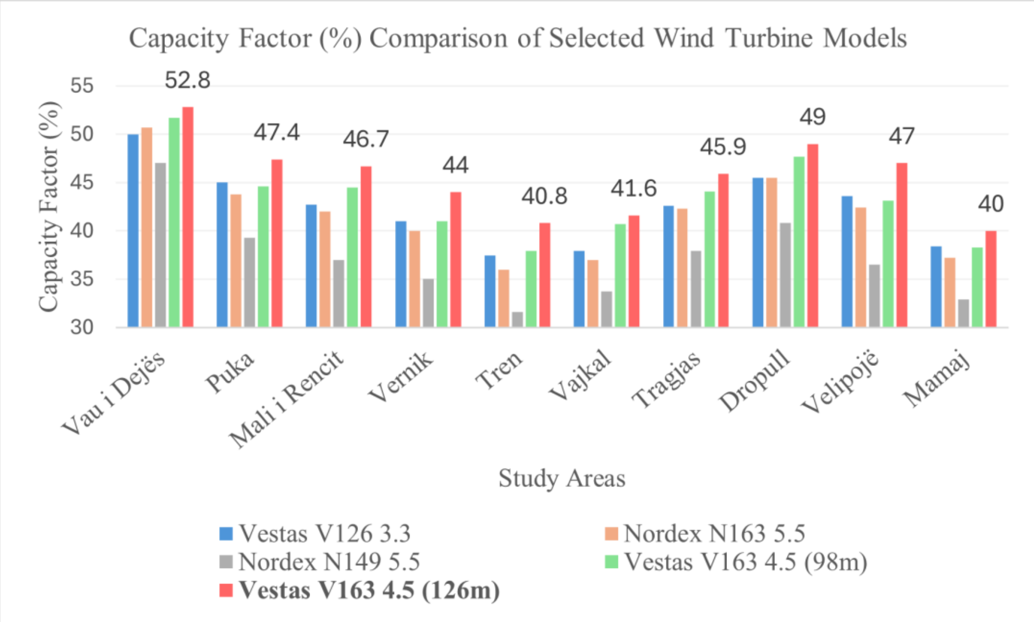


Figure 4. Comparison of Capacity Factor (%) for the Selected Wind Turbine Models Across the Study Areas.

TECHNO-ECONOMIC ANALYSIS (RETScreen)

Energy Production Estimation

Based on the comparative analysis of turbine performance presented in the "Wind Turbine Selection" section, the Vestas V163 4.5 MW turbine with a hub height of 126 m was selected as the most suitable configuration for all study areas, as it consistently achieved the highest wind farm capacity factor (Table 6). Accordingly, this turbine model was used for the subsequent energy production analysis.

The annual energy production (AEP) of the proposed wind farm configurations was estimated using the WAsP software, based on the wind resource characterization presented in the "Wind Resource Modelling" section and the turbine performance analysis described in "Wind Turbine Selection". The simulations incorporate site-specific wind climate data, terrain characteristics, turbine power curves, and wake effects associated with the wind farm layouts.

For each study area all wind farm layouts were compared under the same conditions, with the same layout configuration for all turbines models. This allows the wind farm performance of the different turbines to be compared without modifications in the wind farm performance due to the local wind and terrain conditions.

The calculated wind farm AEP values are therefore more representative of the actual operation of a wind farm, as the interaction between turbines and the corresponding wake losses in the wind farm layout are considered. Then in simplified methods based on single turbine calculations, this is a more representative method for the scale of a project.

It should be noted that the energy production figures calculated with WAsP are higher than those by RETScreen. This is to be expected and is indicative of the way in which each program models the wind farm and the Wind data that each program is using. In WAsP extensive modelling of the wind farm is carried out by simulating the effects of the terrain, turbulence, the effects of wake and the placement of the turbines within the wind farm, to enable the turbines to be sited in the most suitable locations with the best wind conditions [17]. RETScreen, however, uses the reference wind data from measurement sites based on anemometer towers or on wind atlases which are not necessarily based in areas with high wind potential [18]. The cases of Mamaj and Puka clearly illustrate this effect. In Mamaj, the measurement tower was located in the valley, while the most favourable wind conditions were identified in the surrounding hilly terrain, resulting in an approximately 21% lower estimate of annual energy production in RETScreen compared to WAsP. In Puka, where the measurement tower was located closer to the area with the highest wind potential, this difference was reduced to approximately 15% and can be mainly explained by the placement of turbines in WAsP in the most favourable parts of the area, with the aim of maximizing energy production while minimizing wake losses. The differences observed between WAsP and RETScreen are consistent with the findings of previous studies, according to which pre-feasibility approaches, based on a more general description of the wind resource, can lead to lower estimates of energy production compared to more detailed assessment of wind farm performance [19]. These results indicate that the location of wind measurements can affect the estimation of energy production and, therefore, should be carefully considered when comparing results obtained with different estimation methods.

The results also show that sites with higher wind resource potential, such as Vau i Dejës, Pukë, and Tragjas, achieve comparatively high annual energy production. Simultaneously, the sites with the ideal wind conditions together with higher installed capacities like Puk, Mal i Rencit, and Dropull deliver the maximum overall energy production. These results can be correlated with the differences in terms of wind speed and power density exemplified in the Table 3 and also can be observed in the summarized wind farm capacity factors included in the Table 6.

The energy production and performance results of the optimized wind farm configurations are summarised in Table 7. The table includes installed capacity, net annual energy production (AEP), wind farm capacity factor, and wake losses for each study area.

Table 7. Energy Production and Performance of the Optimized Wind Farm Configurations Using the Selected Vestas V163 4.5 MW Turbine (126 m Hub Height)

Area	Number of turbines	Installed Capacity (MW)	AEP (GWh/year)	Capacity Factor (%)	Wake Losses (%)
Dropull	8	36.0	155.75	49	2.23
Mali i Rencit	9	40.5	165.88	46.7	2.42
Mamaj	7	31.5	113.72	40	4.89
Pukë (Kçirë)	9	40.5	168.43	47.4	5.03
Tragjas	7	31.5	126.92	45.9	4.84
Tren	8	36.0	128.77	40.8	5.74
Vajkal	5	22.5	82.02	41.6	3.84
Vau i Dejës	5	22.5	104.13	52.8	1.71
Velipojë	4	18.0	74.93	47	1.08
Vernik	6	27.0	106.41	44	5.18

From a technical perspective, wind farm sites with higher capacity factors may generally be considered more favourable, as they indicate more efficient utilization of the available wind resource and higher energy production efficiency. However, a comprehensive evaluation of site suitability should also consider economic indicators such as the Levelized Cost of Energy (LCoE), Net Present Value (NPV), and Internal Rate of Return (IRR), which are discussed in the following section.

Economic Analysis (RETScreen)

The economic performance of the proposed wind farm projects was evaluated using the RETScreen Expert software, which is widely used in the technical-economic assessments of renewable energy projects, including wind power projects [20]. The analysis was performed using the Vestas V163 4.5 MW turbine with a hub height of 126 m as the reference turbine configuration for all study areas, together with the corresponding installed capacities derived from the WAsP analysis (Table 7). Wind resource inputs were based on real field measurements for Pukë and Mamaj, while atlas-derived anemometric tower data were used for the remaining sites. RETScreen was then used to estimate the corresponding economic indicators based on its internal energy production calculations using the same wind resource inputs, turbine characteristics, installed capacities and wake loss assumptions adopted for each study area.

A reference case scenario was defined using representative mid-range values of the principal economic parameters, including a capital cost of 1200 €/kW, an electricity price of 70 €/MWh, and a discount rate of 7%. These assumptions are consistent with values commonly reported for onshore wind projects in Europe and provide a balanced basis for economic evaluation, without representing either highly optimistic or highly conservative scenarios [21]. These assumptions were used in all the studied sites to give a common comparison basis. The wind resource variability was modelled with the Weibull distribution applied to the results described above.

The economic results were also analyzed with sensitivity tests to different parameters rather than using fixed assumptions, to assess the economic sensitivity to several parameters such as installation cost, electricity price and discount rate.

The main economic parameters used in this study are the Levelized Cost of Energy (LCoE), the Net Present Value (NPV) and the internal rate of return (IRR).

They were used to compare the wind farm project economics for the studied sites. The economic results of the studied wind farm projects in the reference case scenario are summarized in the table 8

Table 8. Economic Performance Indicators of the Proposed Wind Farm Projects Under the Reference Case Scenario (1200 €/kW, 70 €/MWh, 7% Discount Rate)

Area	Installed Capacity (MW)	AEP (GWh/year)	LCoE (€/MWh)	IRR (%)	NPV (M€)
Dropull	36	114.10	53.36	29.72	36.14
Mali i Rencit	40.5	147.85	49.21	36.59	52.98
Mamaj	31.5	90.11	56.36	25.33	25.47
Pukë (Kçirë)	40.5	143.90	49.92	35.20	50.48
Tragjas	31.5	99.06	53.37	29.37	31.12
Tren	36	87.20	62.34	19.12	19.12
Vajkal	22.5	70.50	53.48	29.21	22.07
Vau i Dejës	22.5	82.63	49.06	36.91	29.74
Velipojë	18	59.97	51.69	32.03	19.92
Vernik	27	64.09	63.13	18.44	13.51

The results reveal noticeable differences in the economic performance among the analyzed sites, mainly driven by variations in wind resource potential, wind farm capacity factor, and installed capacity. Sites such as Vau i Dejës, Mali i Rencit, and Pukë demonstrate the most favourable economic results, characterized by relatively low LCoE values, high IRR and NPV. In contrast, Tren and Vernik show less favorable economic indicators, reflected in higher LCoE values and lower financial returns.

The findings ultimately define a relationship between the wind farm CF (Capacity Factor) and the overall economic performance of the wind farm. It can be observed that wind farm sites with higher CF values achieve lower LCoE values and better financial indicators, emphasizing the role of accurate wind characterization at the initial stages of a wind farm.

Contrarily, despite delivering lower amount of annual energy generation than other larger wind farm formats like Pukë and Mali i Rencit, Vau i Dejës achieves higher CAPF and one of the lowest LCoE values than the previously mentioned wind farm formats, revealing an efficient use of the local wind.

Figure 5 illustrates the variation of LCoE among the analyzed wind farm projects under the reference case scenario.

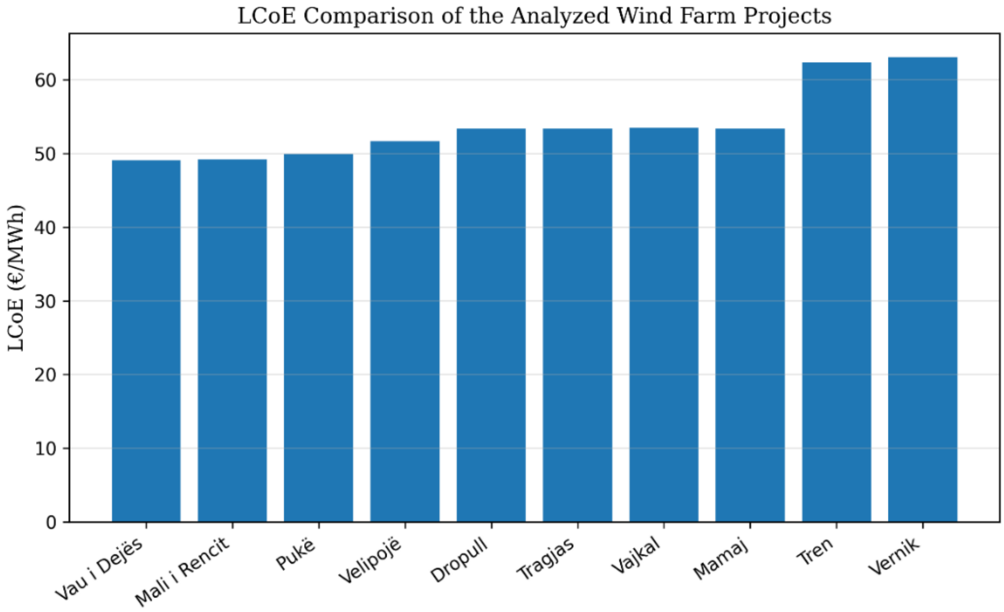


Figure 5. Comparison of Levelized Cost of Energy (LCoE) Values for the Analyzed Wind Farm Projects Under the Reference Case Scenario.

Figure 6 shows that projects with lower LCoE values generally have higher internal rates of return (IRR), indicating that areas with more favourable wind conditions also present better economic performance.

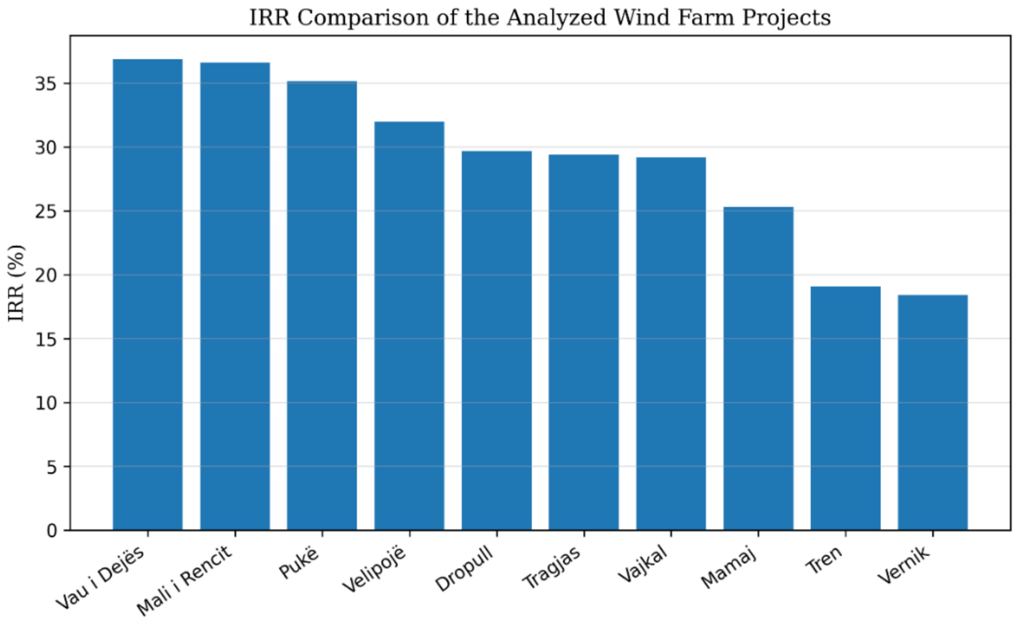


Figure 6. Comparison of Internal Rate of Return (IRR) Values for the Analyzed Wind Farm Projects Under the Reference Case Scenario.

Figure 7 presents representative sensitivity scenarios for selected wind farm projects corresponding to sites with different economic performance levels. The selected cases illustrate the influence of installation cost on project payback period under varying wind resource and economic conditions.

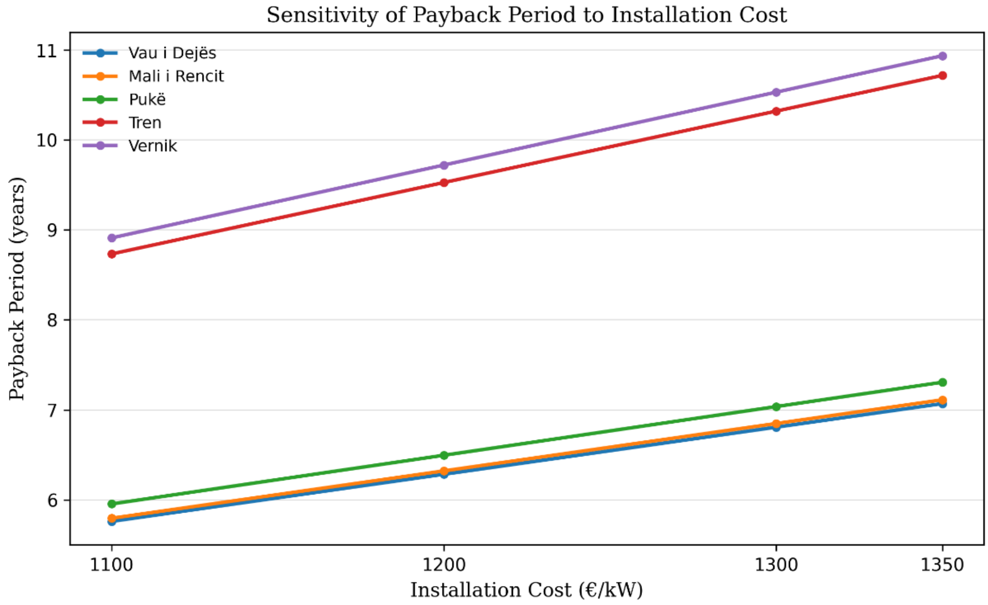


Figure 7. Sensitivity of payback period to variations in installation cost for selected wind farm projects under the reference case scenario (70 €/MWh, 7% discount rate).

Figure 8 depicts the influence of changes in electricity price on the project's profitability. As expected, NPV increases with increasing energy price for all projects. The relative rankings of areas remain nearly the same in all cases of energy prices. Area with cost disadvantages like Vernik and Tren exhibit a maximum sensitivity to falling electricity prices.

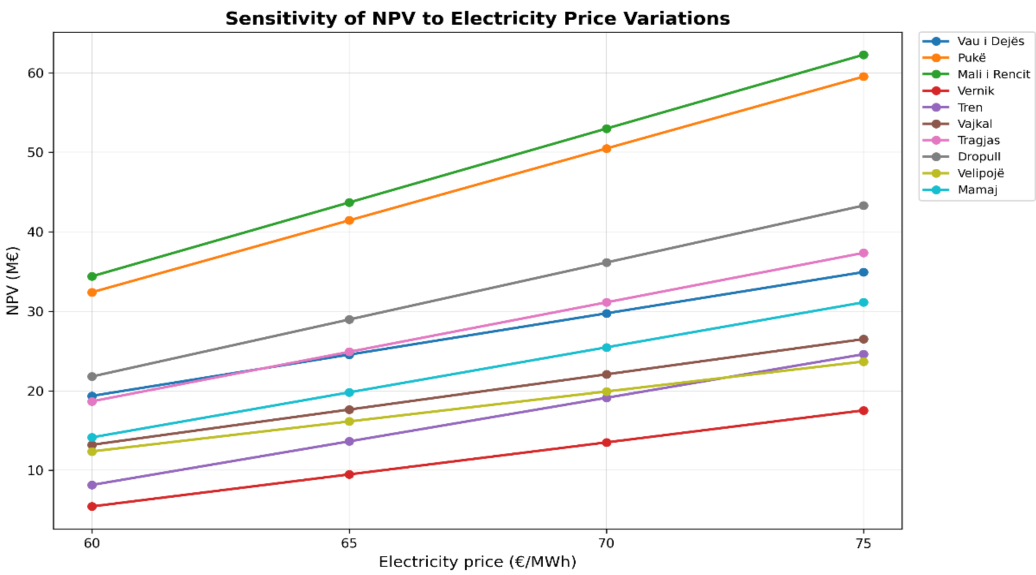


Figure 8. Sensitivity of Net Present Value (NPV) to Electricity Price Variations for the Analyzed Wind Farm Projects Under the Reference Economic Assumptions

While Figures 7 and 8 show the impact of installation cost and electricity price, the economic performance of projects is also affected by changes in the discount rate. In general, increasing the discount rate leads to decreasing NPV and IRR values.

In addition, the sensitivity analysis reveals that weaker wind resource sites, such as Tren and Vernik, are more sensitive to rising discount rate than sites with stronger wind resource conditions. At higher discount rates, these sites saw a sharp decline in both NPV and IRR, emphasizing the market related uncertainties and the adverse effect of financial conditions in the long run. Such an impact is considerable in the case of Albania, where economic conditions and exchange rate fluctuations are thought to have major effects on project performance at longer time horizons.

Applying the same economic assumptions to all study areas was an intentional step to generate a common basis of comparison and to underscore the impact of variations in wind resource potential. In future studies, the analysis could be enriched by considering area-specific costs, such as investment, infrastructure and grid connection costs, to further improve the economic assessment and ranking of the analysed areas.

Additionally, the economic analysis indicates that a handful of the sites evaluated offer potentially favourable wind energy projects under current market assumptions. The combined technical and economic assessment also provides a useful framework for identifying priority areas for future wind energy investment in Albania.

DISCUSSION

The technical analysis conducted in this work revealed a high variability among the studied sites in terms of wind resource potential. The best wind conditions in terms of wind speeds, wind power densities and wind farm capacity factors were observed in the coastal and mountain areas of Vau i Dejës, Pukë and Tragjas. Moderate wind resource conditions were observed in inland areas such as Mamaj, Tren and Vajkal.

The performance comparison of the selected wind turbine models indicated that turbines with larger rotor diameters and modern aerodynamic designs generally achieved higher energy production and capacity factors in the majority of study areas. The consistent trend observed is in line with previous studies, which suggest the use of larger rotor diameters and higher tower heights as effective means to enhance energy capture and improve wind farm performance, thereby improving project economic performance [22-24].

The observed results are largely attributable to differences in rotor swept area, turbine power curves, rated wind speed and turbine-site interactions. The superior performance of the Vestas V163 4.5 MW model turbine with a 126 m hub height further supports H2, highlighting the advantages of larger rotor diameters and higher hub heights for maximizing wind farm capacity factors across different wind regimes. Additionally, the performance of Albanian sites was compared with selected wind energy projects and with published studies in the Balkan region, which analyse the performance of wind farms developed in areas with similar wind conditions [13-15]. The comparison revealed that the performance of the best Albanian sites falls within the range reported for other wind farms in the Balkan region.

For example, the Bogdanci wind farm in North Macedonia (with an installed capacity of 36.8 MW) produced around 110.5 GWh of electricity in 2017, corresponding to a capacity factor of approximately 34%. Similarly, the Kitka wind farm in Kosovo (with an installed capacity of 32.4 MW) reported an annual net production of around 95.6 GWh, resulting in a capacity factor of approximately 34% [25, 26]. The best performing Albanian sites analyzed in this study, including Vau i Dejës, Mali i Rencit, Pukë, Dropull, and Velipojë, achieved capacity factors above 46%, indicating a competitive level of technical performance for the selected turbine configuration.

For Greece, which is a more mature wind energy market, the reported capacity factors of onshore wind farms operating in the most suitable regions (sea coasts and island locations) typically range from 30% to 40% [27].

Other European studies and energy sector reports show that the LCoE of European onshore wind projects typically varies in the range of around 35-70 €/MWh, with weighted average values around 45-60 €/MWh depending on the wind resource, financing conditions and project characteristics [28, 29]. In this context, the most favourable Albanian areas identified in this study (Vau i Dejës, Mali i Rencit and Pukë) achieved LCoE values of approximately 49-50 €/MWh, indicating good economic competitiveness in the analyzed market conditions.

These comparisons between studies should be interpreted with caution, as the resulting performance indicators could depend on the turbine technology, hub height, the method of the wind resource estimation, the design of the wind farm layout and the representativeness of the data considered. For this reason, the capacity factor values obtained in this study should be considered within the context of the selected turbine configuration, the wind resource assessment methodology and wind farm layout design.

From an economic perspective, the results indicate that wind farm profitability is strongly influenced by wind resource quality and wind farm capacity factor. Sites such as Vau i Dejës, Mali i Rencit, and Pukë achieved the most favorable economic indicators, including low LCoE values and high IRR and NPV values. These findings support H1, indicating that areas characterized by stronger wind resources generally achieved higher capacity factors, lower LCoE values, and more favorable economic indicators such as IRR and NPV. In particular, Vau i Dejës demonstrated one of the strongest economic performances despite its lower installed capacity compared to larger wind farm configurations. The case of Vau i Dejës clearly shows that the economic performance of a project does not only depend on the installed capacity, but also on the quality of the wind resource. The high-capacity factor of this project made it possible to achieve one of the most favourable economic performances among the studied areas. This result highlights the importance of high wind resource quality and efficient wind energy utilization in improving project economics. The favourable economic performance of Mali i Rencit is particularly important, as it shows that optimal project economics do not depend only on the highest wind speeds. The combination of a favourable wind resource, high energy production and an efficient wind farm configuration led to one of the highest financial return indicators among the studied areas.

The sensitivity analyses further showed that economically stronger sites remain comparatively stable under varying installation cost scenarios, whereas projects characterized by lower wind resource potential exhibit higher sensitivity to unfavourable economic conditions. In addition to installation cost, the economic performance of the analyzed projects is also affected by electricity price and discount rate variations. Higher electricity prices tend to improve the financial indicators of the projects, while increasing discount rates generally lead to lower NPV and IRR values.

The sensitivity analysis also indicates that economically weaker sites, such as Tren and Vernik, are more affected by increases in discount rate compared to sites with stronger wind resource conditions. Under higher discount rate scenarios, these projects show noticeable reductions in NPV and IRR, reflecting their higher sensitivity to financing conditions and market-related uncertainties. This effect is particularly important in the Albanian context, where economic conditions and exchange rate fluctuations may influence long-term investment performance.

The results obtained in this study further indicate that high wind resource potential alone does not necessarily guarantee the best overall economic performance of a wind farm project. In addition to mean wind speed and wind power density, factors such as wind farm layout efficiency, wake losses, terrain complexity and installed capacity play an important role in determining both net energy production and project profitability. For example, although Tragjas and Dropull showed strong wind characteristics, and relatively high-capacity factors, Mali i Rencit achieved comparatively more favourable economic indicators under the analysed conditions. This result shows that project performance depends not only on wind potential, but also on factors related to wind farm layout and site conditions.

These findings highlight the importance of integrated wind farm design approaches that combine detailed wind resource assessment with microscale flow modelling, layout optimization, and careful turbine selection. Consequently, future wind energy development in Albania should not rely solely on areas with the highest wind speeds, but also consider the broader interaction between terrain conditions, wake effects, infrastructure accessibility, and economic performance in order to achieve more efficient and economically sustainable wind farm projects.

The results also show that detailed wind resource assessment is important for more reliable evaluation of wind farm projects, especially in countries such as Albania where terrain conditions are often complex. The comparison between WAsP and RETScreen results showed that simplified pre-feasibility approaches, such as RETScreen, generally tend to produce more conservative estimates of energy production and capacity factor compared with the more detailed assessments performed using WAsP.

A similar difference between WAsP and RETScreen estimates was also observed for Velipojë, despite its relatively flat coastal terrain conditions. For this site, the annual energy production estimated by WAsP amounted to about 74.9 GWh, while RETScreen estimated about 60.0 GWh, corresponding to a difference of nearly 20%. In Mamaj, the corresponding difference was about 21%, while in Pukë it was smaller, at about 15%. In the case of Mamaj, the measurement tower was located in the valley, while the most favourable wind conditions were identified in the surrounding hilly terrain. In contrast, in Pukë the measurement tower was located closer to the area with the highest wind potential. These results suggest that the differences between the two approaches are not only related to the complexity of the terrain, but are also influenced by the representativeness of the available wind data, the wind farm layout, and the wake effects considered in the WAsP simulations. These findings support hypothesis H3 and suggest that simplified pre-feasibility tools should be used with caution in areas with complex terrain characteristics or where measurement antenna locations do not sufficiently represent wind conditions at the planned turbine locations.

Overall, the results of this study are consistent with the hypotheses formulated in the introduction. Areas characterized by higher wind resource potential generally achieved more favourable technical and economic indicators, supporting H1. Similarly, turbine designs with larger rotor diameters and higher tower heights achieved higher capacity factors in most of the studied areas, supporting H2. Finally, the differences observed between WAsP and RETScreen results support H3 and highlight the importance of a detailed wind resource assessment for improving the reliability of wind farm evaluations.

Despite the encouraging results obtained in this study, several limitations should be considered. For some of the analysed areas, the wind resource assessment relied primarily on long-term atlas-derived datasets due to limited availability of site-specific field measurements. Although the comparison between atlas data and available measurements showed good agreement, additional site-specific long-term measurement campaigns could further improve the accuracy of wind resource characterization and energy production estimates. This consideration is particularly relevant in the present study, where most of the analyzed sites relied on atlas-derived wind data.

Furthermore, although WAsP is widely used for wind resource assessment and wind farm design, its linearized flow approach may be less accurate in highly complex terrain, where phenomena such as flow separation and other nonlinear aerodynamic effects may occur. For this reason, the results obtained for these areas should be interpreted with caution, while future studies may complement WAsP analyses with more advanced wind flow simulation models.

In addition, although this study analysed different economic scenarios, future studies could extend the analysis to take into account additional financial, regulatory, and energy market uncertainties. Furthermore, this study focused on a comparative techno-economic assessment and did not include formal statistical hypothesis testing or stochastic uncertainty analysis. The inclusion of such methods could provide additional insights into the robustness of the results obtained and may be considered in future research. The findings of this study also highlight the importance of conducting long-term wind measurement campaigns in areas identified as suitable for wind farm development. However, the results obtained for Mamaj and Puka show that the availability of site-specific field measurements does not necessarily eliminate all uncertainties in the estimation of energy production. Of particular importance is the representativeness of the measurement location in relation to the area where the turbines are planned to be located. For this reason, future studies should pay attention not only to conducting long-term measurements, but also to selecting measurement locations that best represent the wind conditions at the planned turbine locations.

SUMMARY AND CONCLUSION

This study investigated the opportunities for wind energy development in ten representative areas of Albania through an integrated framework that combines wind resource assessment, turbine performance analysis, and techno-economic assessment. Using wind resource characterization based on Weibull parameters, simulations in WAsP, and economic analysis in RETScreen, the study provided a comparative assessment of the technical and economic feasibility of wind farm projects under different geographical and climatic conditions. The analysis also included sensitivity analyses to evaluate the impact of key economic parameters on the financial viability of the projects.

The results revealed significant variation of wind resource potential among the study areas. Wind speeds, wind power densities and wind farm capacity factors were highest coastal and mountain areas, such as the Vau i Dejës, Pukë and Tragjas areas. Among the selected turbine configurations, Vestas V163 4.5 MW (126 m hub height) generally had the best performance, hence it was used as the reference wind turbine model for energy production and economics analysis.

The economic analysis shows that several areas in Albania offer favorable conditions for future wind energy development. Vau i Dejës, Mali i Rencit and Pukë achieved the most favourable economic performance, combining relatively low LCoE values with high IRR and NPV values in the reference scenario. Sensitivity analyses showed that projects located in areas with more favourable wind resources were generally less affected by changes in economic parameters, while projects located in areas with more limited wind resources were more sensitive to changes in installation costs and discount rates.

The study also highlighted the importance of detailed and representative wind resource assessment in improving the reliability of wind farm evaluation. The comparison between WAsP and RETScreen supported H3 and indicated that simplified pre-feasibility approaches generally produce more conservative estimates of energy production and capacity factor than more detailed WAsP-based assessments. Moreover, the results showed that the availability of field measurements alone does not necessarily eliminate uncertainties, as the representativeness of the measurement location relative to the planned wind farm area also plays an important role.

Overall, the results support all three hypotheses formulated in this study. Areas characterized by higher wind resource potential generally achieved more favorable technical and economic performance, supporting H1. The superior performance of the Vestas V163 4.5 MW turbine with a hub height of 126 m supports H2, highlighting the benefits of larger rotor diameters and greater hub heights in increasing the capacity factors of wind farms. Furthermore, the comparison of WAsP and RETScreen results supports H3 and demonstrates that detailed wind resource assessment, combined with wind farm layout analyses, can provide more representative estimates of wind farm performance than simplified pre-feasibility approaches.

The findings of this study indicate that Albania has several areas that are technically feasible and economically viable for the development of large-scale wind energy development. At the same time, the results show that successful wind farm planning should not be based solely on the potential of the wind resource, but should also take into account terrain characteristics, wake effects, turbine selection, wind farm layout, representativeness of wind measurements and economic conditions. By assessing several areas under a common methodological framework, this study provides a broader understanding of the opportunities and challenges associated with wind energy development in Albania and supports decision-making for future investments and energy planning.

NOMENCLATURE

AEP	Annual Energy Production
CF	Capacity Factor
BWA	Balkan Wind Atlas
NEWA	New European Wind Atlas
OWC	Observed Wind Climate
WAsP	Wind Atlas Analysis and Application Program
RETScreen	Renewable Energy Technology Screening Expert
IEC	International Electrotechnical Commission
LCoE	Levelized Cost of Energy
NPV	Net Present Value
IRR	Internal Rate of Return

ACKNOWLEDGMENT

This study was carried out within the framework of the project entitled “The Study of the Potential of Wind Energy in Areas of Interest in Albania and Its Contribution to the Reduction of Electricity Imports and Environmental Pollution”, supported under Decision No. 5, dated 10.06.2024, on the approval of winning projects of the National Research and

Development Program for the period 2024-2025. The authors gratefully acknowledge the financial support provided by the National Agency for Scientific Research and Innovation of Albania.

CONFLICT OF INTERESTS

The authors confirm that there is no conflict of interest associated with this publication.

AUTHOR CONTRIBUTIONS

"Conceptualization, E.B. and M.A.; Methodology, E.B.; Validation, E.B., and M.A.; Investigation, E.B.; Resources, M.A.; Data Curation, E.B., and A.G.; Writing – Original Draft Preparation, E.B.; Writing – Review & Editing, E.B., and M.A.; Visualization, A.D., and T.S.; Supervision, M.A.; Project Administration, M.A.

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