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Economic and Energy Assessment of the Use of Wind Microturbines in Selected Areas of Poland – A Case Study

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Abstract:

Purpose: *A presentation of the economic assessment and actual performance of low-voltage small-scale wind power installations with a total height not exceeding 3 meters.*
Design/Methodology/Approach: *An assessment of the technical and economic feasibility of implementing residential micro-wind installations up to 3 meters in height in national prosumer systems using horizontal-axis (HAWT) and vertical-axis (VAWT) turbines designed for microscale electrical installations. The analysis examined the impact of the near-surface wind layer on the energy and economic performance of mini wind turbines. An economic analysis of the investment costs of mini wind turbines for two locations in Poland was presented.*
Findings: *It has been shown that vertical-axis wind turbines (VAWTs) are more practical in densely built-up areas than their horizontal-axis counterparts (HAWTs). Although VAWTs have a slightly lower theoretical energy conversion efficiency, their ability to operate in variable and turbulent wind conditions without the need for constant directional adjustment ensures more stable energy production throughout the year. This is particularly important in near-surface conditions, where wind speeds are limited and the turbine can start operating even at low wind speeds. Local atmospheric and terrain conditions have a decisive impact on the actual performance of the analysed installations. Simulations conducted for two different regions of Poland indicate that in areas with higher wind speeds, such as the coast, annual energy production can reach levels that enable a rapid return on investment—even within about 5 years with the support of subsidy programs. In contrast, in the central parts of the country, where average wind speeds are lower, mini-turbines serve as a supplement to other energy sources rather than a standalone solution, due to the reduction in wind speed caused by the ruggedness of the terrain.*

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Practical Implications: *The results presented here can be used during the planning phase of small wind turbine projects to assess their economic and energy-related viability.*
Originality/Value: *It has been demonstrated that mini wind turbines can complement photovoltaic systems, creating hybrid systems with greater stability. Their peak production occurs during the fall and winter months, when photovoltaic panels generate the least amount of energy, which improves the overall energy balance and supports sustainable development goals. Low-voltage mini wind turbines with limited height represent a promising option for the decentralization of energy production in Poland. Along with rising costs of traditional energy sources and regulatory support, they can contribute to increasing the energy self-sufficiency of individual users, thereby supporting the development of sustainable local energy structures.*

Keywords: *Mini wind turbines, economic efficiency of mini wind turbines, energy efficiency of mini wind turbines, return on investment for mini wind turbines depending on geographical location.*

JEL codes: *D2, G2, O3.*

Paper type: *Case study.*

1. Introduction

The contemporary transformation of the energy sector is determined by the requirements of climate policy and the pursuit of decentralization of generation sources (Ministry of Climate and Environment, 2021). In Poland, the development of prosumer energy has so far been based almost exclusively on photovoltaic (PV) systems (Lewandowski, 2021; Zabinska, Matuszak, 2019; Żabińska, 2017) and solar collectors (Matuszak and Matuszak, 2024).

This technology significantly affects the energy balance of households, but its disadvantage is the strong seasonality and daily variability of the generation profile resulting from the physical conditions of solar energy conversion (Hau, 2013; Matuszak and Matuszak, 2024). This leads to a mismatch between energy production and actual consumer demand.

These limitations justify the diversification of renewable energy micro-sources, in which residential wind micro-installations can play a special role (Boczar, 2022). Wind energy is characterized by a different temporal availability profile compared to photovoltaics – in Polish climatic conditions, increased wind activity occurs mainly in the autumn and winter months and at night (Boczar, 2022; Burton and Jenkins, 2011).

Therefore, wind micro-turbines can be a natural complement to PV systems (Burton and Jenkins 2011). The amount of energy that can be extracted from wind is nonlinearly dependent on local airflow parameters – in particular, airflow velocity, density, and stream characteristics (Hau, 2013).

The subject of this paper is the technical and economic characteristics, as well as an assessment of the actual performance of low-voltage wind turbines with a total height not exceeding 3 meters. The choice of this geometric parameter (3 m) stems from the amendment to the Construction Law in early 2026, which exempted wind turbines with such a limited height from the requirement to obtain a building permit and notification (Construction Law, 1994).

This change lowered administrative barriers, opening the possibility of widespread use of microturbines in single- and multi-family housing (Construction Law, 1994). Limiting the installation height to 3 m fundamentally affects the aerodynamic conditions of turbine operation. In the ground-level atmosphere (2-3 m above ground level), airflow is characterized by significant turbulence, high directional variability, and a significant decrease in average wind speed relative to higher layers (Burton and Jenkins, 2011; Firoozi and Hejazi, 2024; Lipian and Czapski, 2020; Manwel and McGowan, 2020; Pellegrini and Guzzini, 2021; Siddiqui and Khalid 2021; Zagubien and Wolniewicz, 2022).

The power available in a wind stream is proportional to the third power of the flow velocity, therefore even a small reduction in speed drastically reduces the energy potential of the microturbine (Hau, 2013; Burton and Jenkins, 2011). The main research problem is to verify the energy efficiency of such small units in real, unfavourable ground-level wind conditions.

The basic physical laws describing wind energy and the generation of aerodynamic forces on rotor blades, the theoretical limitations of Stream Energy utilization (Betz limit), and the specificity of losses in microscale wind systems were analysed (Burton and Jenkins, 2011; González-Hernández and Salas-Cabrera, 2021; Hau, 2013).

The aim of this work is to conduct a comparative analysis of design solutions for horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) dedicated to microscale applications and to assess the technical and economic feasibility of implementing residential wind micro-installations up to 3 meters high in domestic prosumer systems (Boczar, 2022; Guminski and Radkowski, 2020; Ministry of Climate and Environment, 2021).

2. Betz's Limit and Micro-Scale Loss Specificity

According to the laws of aerodynamics, completely extracting energy from an air stream is physically impossible, as this would require the air masses to be trapped

and the flow blocked behind the rotor. The maximum theoretical wind energy utilization factor (C_p), defined by Albert Betz, is 16/27 (approximately 59.3%) (Hau, 2013). However, it should be noted that for microturbines (up to 3 m high), the actual C_p is drastically lower than for large-scale turbines. This is due to the constraints imposed by miniaturization, which determine the types of losses:

- aerodynamic, resulting from phenomena occurring at low Reynolds numbers on small blade profiles, as well as from the significant contribution of boundary vortices (Burton, Jenkins, 2011; Hau, 2013);
- mechanical, resulting from friction generation in the bearings, which, combined with the low torque of the small rotor, consumes a significant portion of the useful mechanical work (Manwell and McGowan, 2020);
- electrical, caused by lower efficiency of small generators (usually low-voltage generators with permanent magnets) and resistance in rectifier systems and inverters (Manwell and McGowan, 2020).

3. The Influence of Terrain Roughness on Installation Performance

Limiting the total installation height to 3 meters creates problems with the ground boundary layer, where wind speed is most significantly inhibited by terrain roughness (development, terrain, vegetation). This relationship is illustrated in Table 1, which is based on the power law of wind profile.

Table 1. *The effect of terrain roughness on wind speed reduction*

Terrain class	Description	Roughness exponent (α)	Speed reduction at 3m vs 10m
0	Sea, open space	0.10	approx. 15%
I	Arable fields, few trees	0.15	approx. 22%
II	Suburban area, low-rise buildings	0.25	approx. 35%
III	City, high-rise buildings	0.40	approx. 50%

Source: *Own authors.*

The data in Table 1 form the basis for the assessment of microturbines (The Act on Renewable Energy Sources, 2015). Standard wind maps and data from the Institute of Meteorology and Water Management (IMGW) provide wind speeds measured at a height of 10 meters.

Implementing a turbine up to a height of 3 meters, especially in suburban or urban areas (Class II and III), results in a reduction of actual wind speed by 35% to even 50%.

Combined with the cubic relationship (v^3), this presents the greatest engineering challenge in the design and selection of this type of prosumer systems (Gasch and Twele, 2011).

4. Legal, Environmental and Installation Conditions for Wind Micro-Installations

4.1 Analysis of the Legal Status in Poland in the Light of the Amendment of 2026

In recent years, the development of micro-wind energy in Poland has been limited by restrictive regulations, including the so-called Distance Act (Rule 10H). A legislative breakthrough occurred with the entry into force of the amendment to the Building Law and the Act on Renewable Energy Sources at the beginning of 2026.

This study is based on the amended Article 29, Section 4 of the Building Law, which introduced a complete exemption from the requirement to obtain a building permit and notify works for wind installations with a total height not exceeding 3 meters (Construction Law, 1994).

The key to proper installation design is a precise definition of the method for measuring the total height:

- roof installation, meaning that the height of 3 meters is measured from the highest fixed point of the roof structure (ridge) to the highest point of the rotor blade in its extreme vertical position (Consrtuction Law, 1994);
- ground installation, meaning that the height is measured from the natural ground level to the highest point of the device (Construction Law, 1994).

The liberalization of regulations does not exempt the investor from complying with construction safety standards and protecting the interests of third parties, especially in the field of noise emission (The Act on Renewable Energy Sources, 1994, Regulation of the Minister of the Environment, 2007).

Devices of the described size (with an actual power of 0.3–1.5 kW) always fall within the definition of a prosumer micro-installation, which simplifies the procedure of connecting to the home low-voltage network (The Act on Renewable Energy Sources, 1994).

4.2 Vibroacoustic Characteristics and Noise Emission Standards

In micro-wind installations installed in the immediate vicinity of residential buildings, sound emission is a critical parameter. Noise generated by turbines is divided into two main components (Guminski and Radkowski, 2020):

- mechanical noise, resulting from the operation of generator bearings and friction of moving parts;
- aerodynamic noise, resulting from turbulence and airflow cutting by rotor blades.

According to Polish environmental standards, the permissible sound level (LAeq) for single-family residential areas is 50 dB during the day and 40 dB at night (Regulation of the Minister of the Environment, 2007).

Technical analysis shows that vertical axis wind turbines (VAWTs), such as Savonius models, generate significantly lower sound pressure levels due to the lower peripheral blade tip speed compared to HAWTs (Guminski and Radkowski, 2020). Under operating conditions (wind of approximately 8 m/s), VAWTs are often almost inaudible, as their acoustic emission does not exceed the background noise generated by wind blowing through treetops (Guminski and Radkowski, 2020). Table 2 shows a comparison of the acoustic emission of different types of microturbines, illustrating the noise advantage of VAWTs.

Table 2. *Comparison of acoustic emission of microturbine types (height < 3m)*

Turbine type	Noise level at 5 m/s	Noise level at 10 m/s	Noise characteristics
HAWT (3-blade)	35 dB	55 dB	Audible whistling sound, high frequency
VAWT Savonius	25 dB	38 dB	Almost silent operation
VAWT Darrieus	28 dB	42 dB	Low vibration, muffled sound

Source: *Authors.*

4.3 Assembly Technologies and Structural Stability

The choice of mounting method for a microturbine up to 3 meters high impacts its energy efficiency and the durability of the building. Three dominant solutions are distinguished (Guminski and Radkowski, 2020):

- roof-mounted systems, the most effective due to utilizing the building's natural height, which allows the rotor to be exposed to laminar airflow. The use of elastomeric vibration isolators is essential, as they dampen low-frequency vibrations, preventing their transfer to the building's supporting structure;
- façade mounting, primarily intended for lightweight VAWT structures. This requires the use of chemical anchors that ensure high mounting stiffness under dynamic loads;
- freestanding masts, with a total height limited to 3 meters from ground level (this solution has the lowest efficiency). In the near-ground atmosphere, wind speed is most significantly reduced by the roughness of the ground (Boczar, 2022).

5. Technical Characterization of Low-Voltage Wind Micro-Installations

For wind turbines up to 3 m in height, the orientation of the rotor's rotation axis determines not only efficiency but, above all, their ability to operate in dispersed

development conditions (Burton and Jenkins, 2011; Guminski and Radkowski, 2020).

Micro-scale HAWT (Horizontal Axis Wind Turbine) designs are characterized by the highest aerodynamic efficiency (C_p within 0.35–0.45), but their efficiency drops dramatically in urban conditions. Advantages include high take-off dynamics in laminar flow and lower blade mass.

Disadvantages include the need for guidance systems (tail control) and high sensitivity to sudden changes in wind direction, which generates significant energy losses due to the inertia of the directional system at heights up to 3 m above the roof (Burton, Jenkins, 2011). Table 3 compares selected turbines up to 3 m in height.

Table 3. *Comparison of selected turbines up to 3 m high*

Feature	**Mini HAWT 300W**	**Savonius 400W**	**Darrieus H-Rotor 1kW**
Rotor diameter	1,2 m	0,6 m (szer.)	0,8 m (szer.)
Rotor height	-	1,5 m	2,0 m
Starting speed	2,8 m/s	1,5 m/s	2,2 m/s
Weight	12 kg	35 kg	55 kg
Noise level (at 8 m/s)	50	25	32
Application	Campers, yachts, open spaces	Roofs of houses, balconies, cities	Hybrid home systems

Source: *Authors.*

For wind turbines up to 3 m in height, VAWT (Vertical Axis Wind Turbine) designs offer functional advantages over horizontal models. Savonius (drag-based) and Darrieus (lift-based) designs dominate. Advantages include the absence of wind orientation requirements, the ability to capture turbulent winds, and a significantly lower noise emission threshold. Disadvantages include a lower theoretical power factor ($C_p \approx 0.15–0.25$) and higher fatigue loads on the lower bearings (Guminski, Radkowski, 2020).

Installations with a power output of up to 1 kW use low-voltage systems (12V, 24V, or 48V DC), which facilitates battery operation (Hau, 2018):

- permanent Magnet Synchronous Generator (PMSG) using neodymium permanent magnets. It allows for low-speed power generation without the need for mechanical gears (Direct Drive system), which increases reliability and reduces noise (Guminski and Radkowski, 2020);
- MPPT charge controller, an intelligent device that adjusts the generator load to the current wind speed to achieve the maximum possible power. It has a built-in rectifier (converting AC from the turbine to DC for the battery) (Kulkarni, 2020; Swamy and Rakshith, 2020; Watil and Magri, 2022);

- Dump Load resistor, which converts excess energy into heat when the batteries are fully charged or the wind is too strong, allowing for electrical braking of the turbine and protecting it from running away (Jiang and Xu, 2022; Rizki and Sulistiawati, 2024; Sebastián and Peña-Alzola, 2020).

6. Summary and Comparison of Selected Mini Wind Turbines

To comprehensive, reliable assess the energy efficiency of low-voltage mini wind turbines, the following section presents an analysis of ten selected turbines with a maximum installation height of up to 3 meters (Table 4), including rotors with a diameter not exceeding this value. The selection of models was based on catalogue data, technical specifications, and technical descriptions, taking into account their application in micro-wind installations (Catalogue, 2016; Moska and Piechowski, 2025; Rosato and Perrotta, 2024).

The analysis took into account basic technical parameters such as turbine type, rotor diameter, nominal power, wind speeds (starting, nominal, and survival), construction materials, and estimated annual energy production (AEP) at an average wind speed of 5.5 m/s, which corresponds to typical conditions in Poland (Boczar, 2022).

Efficiency was assessed based on the power coefficient (C_p) and power density, drawing from theoretical wind turbine models (Hau, 2018; Manwell and McGowan, 2020). Data were obtained from reports and catalogues, including compilations of small wind turbines (Catalogue, 2016), studies on efficient direct drives (Kishore, Marin, 2014), and reviews of microscale technologies (Calautit and Johnstone, 2023; Bianchini and Bangga, 2022).

Table 4. *A list of selected models of low-voltage mini wind turbines with an installation height of up to 3 m*

Model/Manufacturer	Type	Rotor diameter/Height [m]	Rated power [W]	Starting velocity [m/s]	Nominal velocity [m/s]	Survival velocity [m/s]	Materials	Estimated AEP (kWh/year at 5.5 m/s)
HY-400 / Guangzhou HY Energy	HAWT	1,55	400	2,5	12	50	Reinforced nylon fiberglass	800-1000
EXTRACTOR / Alternate Power	HAWT	1,52	300	2.7	10	>39	Aluminum alloy 6063 T6	600-800
Primus Air 40 / Primus Windpower	HAWT	~1,17 (area 1,07 m²)	400	3.1	12,5	40	Glass fiber composites	500-700
Tumo-Int 1000W / Tumo-Int	HAWT	~1.78 (area ~2.5 m²)	1000	2.5	9	40	Anti-corrosion coating (enamel)	1500-2000
Automaxx 1500W / Automaxx	HAWT	~2,0	1500	2.5	13.9	50	Nylon composites	2000-2500
HY-600W / Guangzhou HY Energy	HAWT	1,75	600	2.5	12	50	Reinforced nylon fiberglass	1000-1200

Liam F1 / The Archimedes	HAWT (spiral)	1,5	750 (mean)	2	10	45	Lightweight composites	1500
LXYIUTRW 400W / LXYIUTRW	VAWT	~1,2	400	2	11	40	Fiberglass reinforced	700-900
HY-1000 / Guangzhou HY Energy	HAWT	1,96	1000	2.5	12	50	Reinforced nylon fiberglass	1500-1800
SWEPT / Virginia Tech (prototyp)	HAWT	0,4	1 (demo)	1.7	4	10	Lightweight composites	100-200 (scaled)

Source: *Authors.*

Comparing the parameters in Table 4, variations in wind energy conversion efficiency can be observed. Models with a low start-up speed (below 2.5 m/s), such as the Liam F1 or LXYIUTRW, demonstrate greater suitability for Polish conditions, where average ground-level wind speeds are approximately 5-6 m/s (Boczar, 2022; Manwell, and McGowan, 2020). Their Cp coefficient exceeds 0.4, bringing them closer to the theoretical Betz limit described in the literature (Burton and Jenkins, 2011; Gasch and Twelw, 2011).

In turn, models with higher nominal power, such as the Automaxx 1500W (power density above 200 W/m²), offer better performance in dense installations, although they require more stable wind conditions, as emphasized by research on small turbines (Calautit and Johnstone, 2023). VAWTs, represented by the LXYIUTRW, perform better in turbulent environments, e.g., urban environments, thanks to their omnidirectionality, as indicated in technology reviews (Bianchini and Bangga, 2022).

The assessment of overall energy efficiency is based on estimated AEP, which for most models ranges from 1000 to 1500 kWh/year under assumed conditions, which can cover 10-20% of the energy demand of a typical household, in accordance with Poland's energy policy (Ministry of Climate and Environment, 2021). The most efficient models are the HY series (e.g., HY-1000) and Liam F1, combining high C_p (~0.42) with low aerodynamic losses and resistance to survival speeds above 40 m/s (Catalogue, 2016; Kishore and Marin, 2014).

Prototype models, such as SWEPT, although low in power, indicate the potential for innovation in ultra-low wind speeds (Chertok and Hablanian, 2004). It is recommended to choose HAWT turbines for open areas and VAWT for built-up areas, considering noise standards (Regulation of the Minister of the Environment, 2007) and material durability (Hau, 2018).

7. Methodology for Analysis and Assessment of Energy Efficiency

Due to the low rotor height, a key aspect of the methodology is the transformation of the vertical wind profile from the anemometric height to the turbine's operating height.

Three indicators were defined for the comparative assessment of units up to 3 m high:

- Capacity Factor (*CF*): Determines the degree to which the unit's potential is utilized under specific site conditions:

$$CF = \frac{E_{real}}{P_n \bullet 8760} \tag{1}$$

where:
CF - *Capacity Factor* (nominal power utilization factor) [%],
E_{real} - actual energy produced during the year [kWh/year],
P_n - nominal power of the wind turbine [kW],
8760 - number of working hours per year [h/year];

- system efficiency (η_{sys}): A basic parameter for low-voltage systems (12/24V), considering losses in the AC/DC rectifier, MPPT charge controller, and losses in the cables resulting from high current at low voltage (Hau, 2018);
- self-consumption factor (ϕ_{sc}): It defines the ratio of energy consumed directly by household loads or stored in a local energy storage system to that produced.

The following resources and technical assumptions were used in the analysis:

- meteorological data: Historical time series from the NASA POWER database and the Institute of Meteorology and Water Management (IMGW-PIB), extrapolated down to a 3-meter level using a terrain roughness model;
- power characteristics: Catalog curves *P(v)* for selected microturbines with a rotor diameter not exceeding 1.5 m (in accordance with the total height limit);
- Installation loss model: The transmission loss model for copper conductors with a cross-section of 6-10mm^2, assuming a voltage drop in the DC line of no more than 3.

8. Performance and Profitability Analysis – Case Study

8.1 Assumptions of the Analysis and Characteristics of the Objects

To assess the actual energy potential of low voltage microturbines, a comparative analysis was conducted for two extreme wind scenarios in Poland. A vertical axis wind turbine (VAWT) of the H-Darrieus type was used for the calculations. This choice is dictated by the stringent limit on the total installation height (up to 3 m), which in the case of vertical structures allows for maximizing the rotor swept area while maintaining compact mast dimensions (Guminski and Radkowski, 2020). Table 5 presents the technical parameters of the turbine used for the analysis.

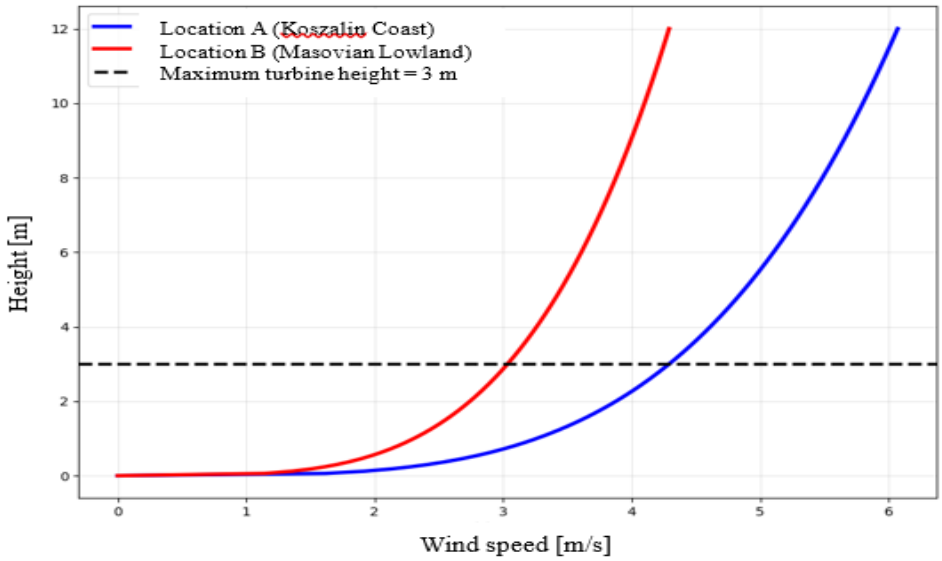
Table 5. *Technical parameters of the turbine accepted for analysis*

Parameter	Unit	Value
Nominal power (Pn)	W	1000
System voltage (DC)	V	48
Rotor diameter	m	1.2
Rotor height	m	1.8
Starting velocity (vstart)	m/s	2
Nominal velocity (vn)	m/s	11

Source: *Authors.*

According to the 2026 installation (Construction Law, 1994), the installation height was set at 3 m above the ground. The air impact from the reference height (10 m) to the rotor axis level (2.1 m) was performed using a roughness exponent of α=0.25 (suburban terrain) (Boczar, 2022). As observed in Fig. 1, such a speed reduction is particularly significant in ground-level layers, which directly affect the operation of the micro-energy turbine. (suburban terrain) (Boczar, 2022). As observed in Figure 1, such a speed reduction is particularly significant in ground-level layers, which directly affect the operation of the micro-energy turbine.

Figure 1. *Change in average wind speed as a function of height for the suburban area (α = 0,25).*

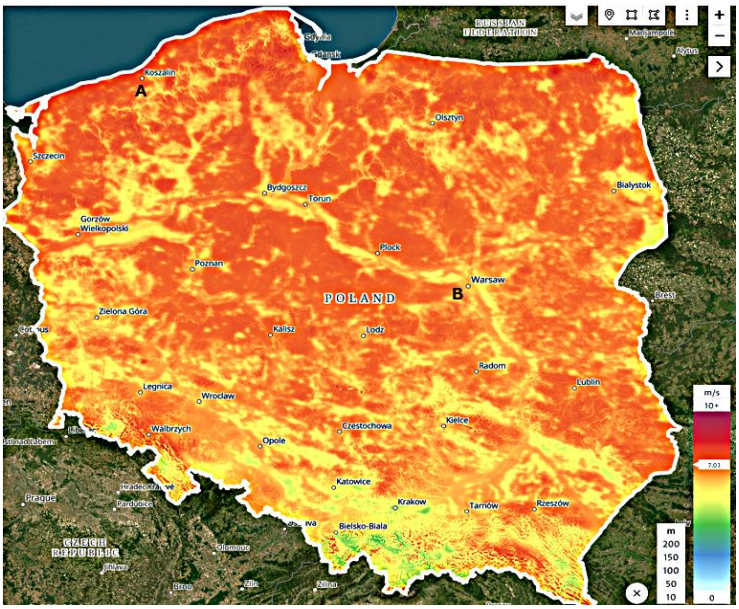


Source: *Authors.*

Selected locations for analysis:
- location A (Koszalin Coast): average.
- location B (Masovian Lowland): average.

Figure 2 illustrates the geographical location of the analyzed locations with extreme wind conditions in Poland.

***Figure 2**. Geographical location of the analysed locations with extreme wind conditions in Poland.*



***Source:** https://globalwindatlas.info/en/*

8.2 Simulation of Annual Energy Production (AEP)

Table 6 presents the forecasted monthly net energy yield [kWh] assuming system losses (rectifier, cabling, storage efficiency) at 15% (Hau, 2018).

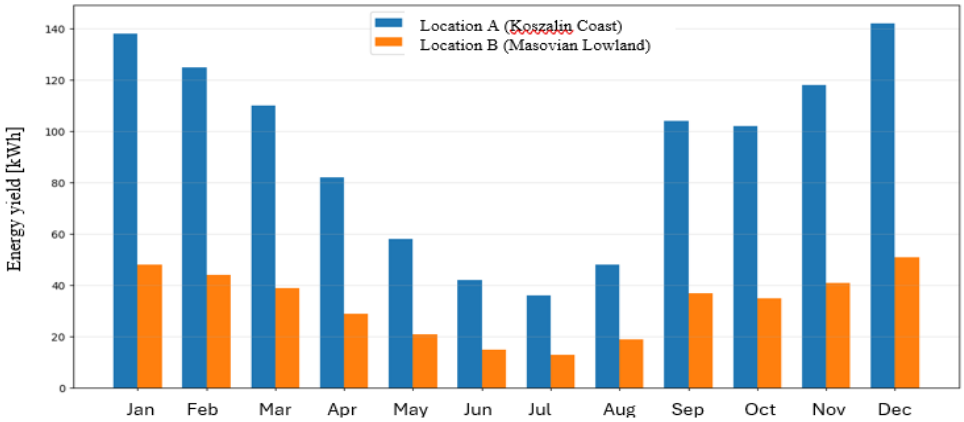
***Table 6.** Estimated monthly net energy yield [kWh]*

Month	Location A (Coast)	Location B (Center)
January	138	48
February	125	44
March	110	39
October	102	35
November	118	41
December	142	51
ANNUAL TOTAL	1105 kWh	392 kWh

***Source:** Authors.*

Figure 3 compares the monthly net energy yield of the VAWT microturbine for the two analysed locations.

Figure 3. *Comparison of monthly net energy yield of the VAWT microturbine for the two analysed locations.*

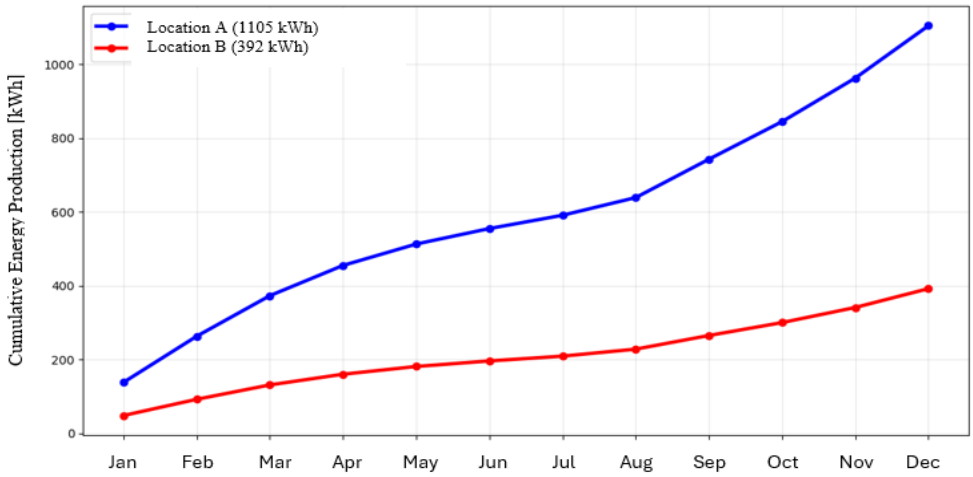


Source: *Authors.*

Applying a 3-meter height limit results in reduced production compared to tall-mast turbines. However, at Site A, the device still generates enough energy to cover a significant portion of the household appliance base's demand during the winter (Lewandowski, 2021). Figure 4 shows the cumulative annual energy production (AEP) for Sites A and B.

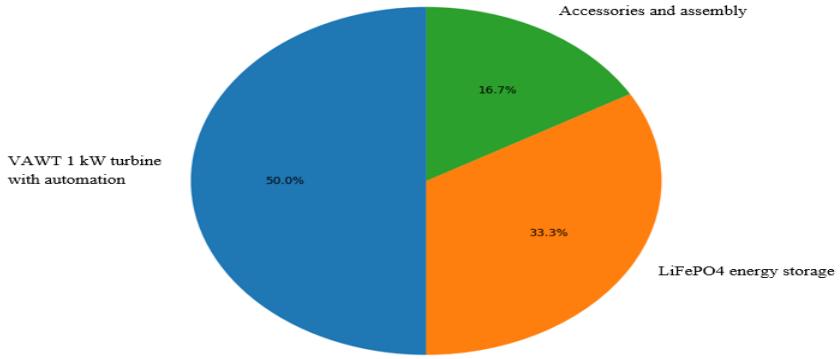
The analysis assumed the market energy prices in Poland forecast for 2026 (PLN 1.25/kWh) and the "Moja Elektrownia Wiatrowa" (My Wind Power Plant) prosumer support system (The Act of Renewable Energy Sources, 2015). Figure 5 illustrates the investment cost structure of a 1 kW micro-wind turbine installation.

Figure 4. *Cumulative Annual Energy Production (AEP) for Sites A and B.*



Source: *Authors.*

***Figure 5**. Investment cost structure of a 1 kW micro wind turbine installation.*



***Source:** Authors.*

Investment costs (CAPEX) included: VAWT 1 kW turbine set with automation - PLN 7,500; LiFePO4 energy storage (dedicated to 48V) - PLN 5,000; accessories and assembly (in accordance with Article 29(4) of the Public Procurement Law) - PLN 2,500. The total costs are PLN 15,000 (PLN 7,500 after considering the 50% subsidy). General economic data are presented in Table 7.

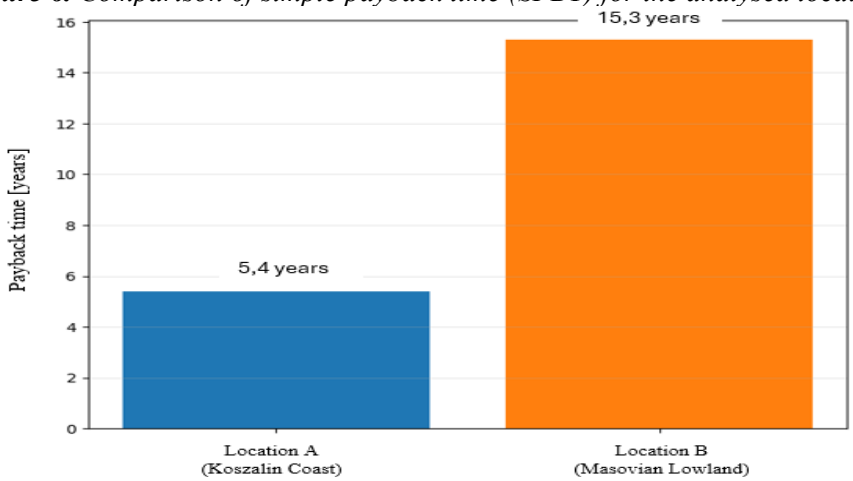
***Table 7.** Economic data*

Indicator	Location A (Coast)	Location B (Center)
Annual savings	1 381,25 PLN	490,00 PLN
Payback time (SPBT)	5,4 years	15,3 years
LCOE (Cost of 1 kWh)	0,34 PLN	0,95 PLN

***Source:** Authors.*

Figure 6 shows the simple payback time (SPBT) for the analysed locations.

***Figure 6.** Comparison of simple payback time (SPBT) for the analysed locations.*



***Source:** Authors.*

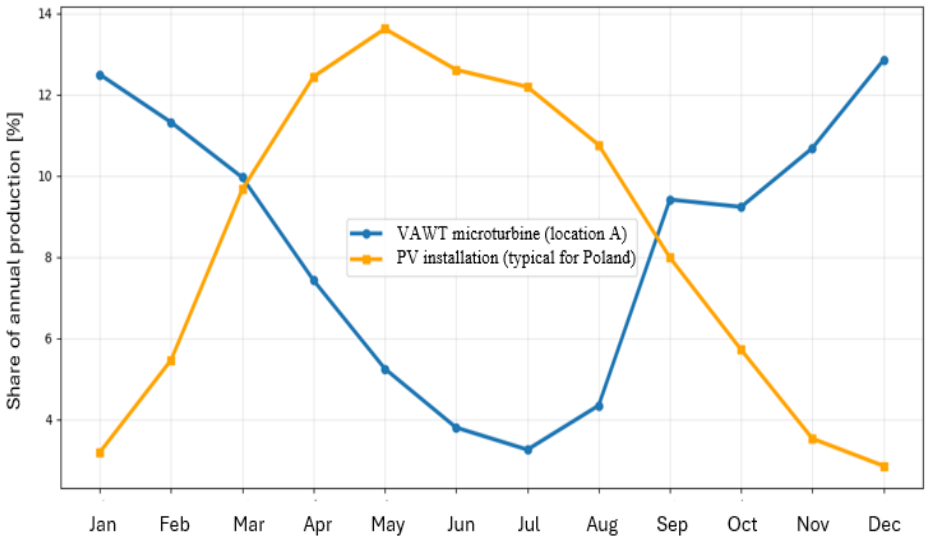
The analysis shows that with current financial support mechanisms (The Act of Renewable Energy Sources, 2015), a coastal installation achieves full payback in less than the warranty period of most components (typically 10 years).

8.3 Complementarity in Hybrid Systems

The main conclusion is the high negative correlation between wind production and photovoltaics. In Location A, a microturbine up to 3 meters tall generates over 60% of its annual energy between October and March (Boczar, 2022). Figure 7 shows the seasonal complementarity of energy production from a wind microturbine and a photovoltaic installation in Poland.

Analysis of the characteristics in Figure 7 indicates that, at the same time, the efficiency of PV systems in Poland drops below 15% of their nominal power. The hybrid system allows for stabilization of the energy storage operation by reducing the depth of discharge of the batteries at night and on cloudy days, which extends their service life (Gumiński and Radkowski, 2020).

Figure 7. *Seasonality of energy production from a wind microturbine and a photovoltaic installation in Polish conditions.*



Source: *Authors.*

9. Conclusions

In the context of miniature wind facilities, vertical axis (VAWT) designs prove to be more practical in dense environments than their horizontal axis (HAWT) counterparts. Although VAWTs have slightly lower theoretical energy conversion efficiency, their ability to operate in variable and turbulent wind conditions, without

the need to constantly adjust direction, ensures more stable energy production throughout the year. This is particularly important in ground conditions, where wind speeds are limited and the turbine can be started at low speeds, which is emphasized by the analysis of aerodynamic parameters (Guminski and Radkowski, 2020).

Local weather and terrain conditions have a decisive impact on the real performance of such installations. Simulations for various regions of Poland indicate that in areas with higher windiness, such as the coast, annual energy production can reach levels enabling a quick return on investment - even within about 5 years with the support of subsidy programs. However, in the central parts of the country, where average wind speeds are lower, these turbines work better as a support for other sources, rather than as a stand-alone solution, due to the reduction in speed caused by the roughness of the terrain (Boczar, 2022).

Legal changes introduced in 2026 significantly facilitated the implementation of wind micro-installations. The exemption from construction formalities for devices less than 3 meters high has removed administrative obstacles, promoting their use in households and small businesses. This allows for wider dissemination of the technology, provided that sound emission and safety standards are met (Construction Law, 1994).

There is a need to combine wind turbines with energy storage systems, such as lithium-iron-phosphate batteries. Without such integration, the utilization rate of the generated energy drops significantly, which reduces the economic benefits. In low-voltage systems, losses on cables and converters additionally emphasize the importance of optimal component selection (The Act on Renewable Energy Sources, 2015).

Mini wind turbines perfectly complement photovoltaic installations, creating hybrid systems with higher stability. Their peak production occurs in the autumn and winter periods, when PV panels generate the least energy, which improves the overall energy balance and supports sustainable development goals (Lewandowski, 2021).

Turbines with a low starting speed (below 2.5 m/s), such as Liam F1 or LXYIUTRW, are more useful in typical Polish conditions, where average wind speeds at the ground level are approximately 5-6 m/s. Their power factor (Cp) exceeding 0.4 approaches the theoretical Betz limit, making them effective in variable wind environments.

Turbines with higher power ratings, such as the Automaxx 1500W (with a power density above 200 W/m²), offer better performance in dense installations, although they require more stable wind conditions. VAWT turbines, represented by LXYIUTRW, perform better in turbulent environments, such as urban ones, thanks to their omnidirection, which suggests their preferential choice in built-up areas.

The estimated annual energy production (AEP) for most models is in the range of 1000-1500 kWh/year at an average wind speed of 5.5 m/s, which can cover 10-20% of the energy needs of a typical household. The most efficient models, such as the HY-1000 or Liam F1, combine high C_p (~0.42) with low aerodynamic losses and endurance at survival speeds above 40 m/s.

Prototype models like SWEPT, although low power, demonstrate capabilities in ultra-low wind speeds, allowing for the development of microscale technologies. It is recommended to choose HAWT turbines for open areas and VAWT for built-up areas, considering noise standards and material durability.

Low-voltage mini wind turbines with limited height represent a promising option for decentralizing energy production in Poland. Together with the rising costs of traditional energy carriers and regulatory support, they can contribute to increasing the energy independence of individual users, supporting the construction of sustainable local structures. Further research should focus on material innovations and control algorithms to further improve their effectiveness in real conditions.

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