

Experimental Investigation of Operational Parameters Affecting Micro-Wind Turbine Performance in a Simulated Urban Environment

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Abstract:

Urban areas play a key role in the global transition toward low-carbon energy systems. While photovoltaic technologies dominate urban renewable energy deployment, small wind turbines are increasingly considered a complementary solution for decentralized electricity generation. However, the complex and highly turbulent airflow conditions typical of urban environments make the optimal placement and operation of wind turbines challenging. This study presents an experimental investigation of the influence of disturbed airflow conditions on the performance of a micro-scale wind turbine. A dedicated laboratory test rig consisting of a modular fan array was developed to simulate non-uniform inflow conditions representative of urban environments. Multiple operational scenarios were analyzed to assess how airflow disturbances across different regions of the rotor-swept area affect turbine performance. The results demonstrate that minor disturbances near the rotor's lateral edges have only a limited effect on turbine performance, reducing power output by less than 7%. In contrast, disturbances affecting the central region of the rotor can lead to substantial performance losses, with power reductions exceeding 80% in extreme cases. The findings highlight the strong sensitivity of micro wind turbines to asymmetric inflow conditions and emphasize the importance of careful turbine placement in urban environments. The experimental results provide a basis for future field investigations to develop installation guidelines and mitigation strategies to improve the performance of building-integrated wind turbines under complex urban airflow conditions.

Keywords:

Renewable energy, wind energy, wind turbines, urban wind, building-integrated wind turbines.

1. Introduction

Improving energy efficiency and increasing the share of renewable energy sources (RES) are widely recognized as essential strategies for achieving global climate targets [1]. Urban areas have become key actors in this transition, as urbanization is associated with growing energy-related pressures, and energy demand is fundamental to the functioning of modern cities. Moreover, cities are not only major centers of energy consumption and greenhouse gas (GHG) emissions, but also important drivers of the transition toward low-carbon energy systems. Currently, cities account for approximately 78% of global primary energy consumption and more than 60% of total GHG emissions [2]. Consequently, sustainable urban development requires the establishment of efficient and environmentally sustainable urban energy infrastructure, since cities concentrate the largest share of final energy consumption [3]. Sustainable energy systems generally rely on renewable natural resources, such as wind and solar energy. Although photovoltaic systems and geothermal heat pumps currently represent the most widely adopted renewable technologies in urban environments, urban wind energy is increasingly being explored as a complementary and still largely underutilized resource. Micro- and small-scale wind turbines can contribute to decentralized electricity generation and help balance the temporal fluctuations associated with solar power production [4,5].

Wind energy technology has advanced significantly over the past decades and has become one of the fastest-growing renewable energy technologies worldwide. Nevertheless, wind farm performance is strongly influenced by several factors, including turbine layout, inflow conditions, wake interactions between turbines, and blade dimensions and structural durability [6,7]. Large-scale wind farms are typically located in remote rural or offshore areas with more favorable wind resources. In contrast, electricity demand is mainly concentrated in densely populated urban areas. This spatial mismatch between energy generation and consumption introduces several technical challenges, including long-distance power transmission, the need

for energy storage systems, and the management of grid stability, frequency control, and peak loads [8]. To address these challenges, the integration of wind turbines directly within urban environments has increasingly been explored. Urban wind turbines can be deployed in several ways, such as mounting them on existing buildings, installing them in nearby urban spaces, or incorporating them into the design of new architectural developments [9]. Among these approaches, Building-Integrated Wind Turbines (BIWTs) have emerged as a promising architectural solution for on-site electricity generation. By embedding wind energy systems within building structures, BIWTs can support the decarbonization of dense urban areas and improve the overall energy performance of building envelopes [10]. Another important advantage of urban wind generation is that the electricity produced can be used close to the point of consumption, thereby reducing transmission losses and lowering infrastructure and storage requirements [11]. Despite these advantages, urban wind energy faces significant challenges. In cities, wind flows are strongly influenced by the presence of buildings, street canyons, and other obstacles, which results in highly complex aerodynamic conditions characterized by lower average wind speeds and higher turbulence intensity. These conditions can significantly affect the aerodynamic performance and reliability of small wind turbines. Turbulence, flow separation, and wake interactions in urban environments may reduce power output and increase mechanical loads on turbine components [12,13]. Consequently, understanding the interaction between turbine operation and urban wind characteristics is essential for improving the feasibility of urban wind energy systems.

Consequently, the deployment of wind turbines in urban areas requires a systematic approach that considers the characteristics of the built environment, local wind conditions, and the technical properties of the turbines. This process typically involves several key stages, as illustrated in Figure 1. First, relevant information on buildings and potential installation sites within a given area must be identified and collected to determine locations suitable for urban wind energy applications. In this context, it is necessary to conduct research that determines the influence of building structural elements and the immediate surroundings on the potential performance of a wind turbine. The next stage involves evaluating wind conditions, including the analysis of annual average wind speeds for different urban sub-areas, considering the representative heights associated with various building groups. Due to the complexity of urban structures, assessing wind conditions is a significant challenge. This assessment is carried out using a range of methods, including wind-tunnel experiments [14], mapping urban wind resources with Geographic Information Systems (GIS) [15], and analyzing wind behavior using Computational Fluid Dynamics (CFD) [16]. Subsequently, the technical parameters and performance characteristics of candidate wind turbines are assessed to determine their suitability for the identified conditions. Among the various turbine technologies, two primary types commonly employed in urban settings are horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs) [17]. Finally, the selected turbines are integrated into the urban setting through careful design, ensuring compatibility with building structures, electrical infrastructure, and other site-specific constraints.

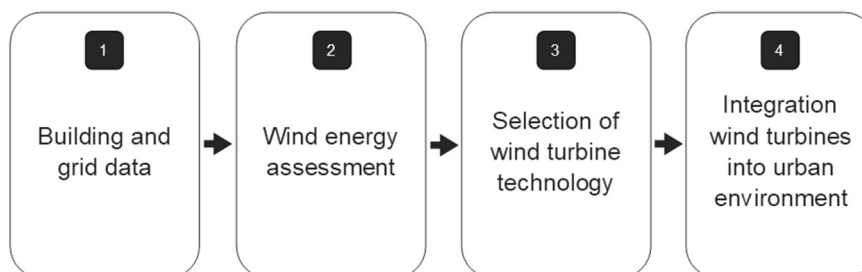


Figure 1. The framework for the implementation of wind turbines in the urban environment [18].

Electricity generated by wind turbines can be used directly by buildings, stored in energy storage systems, or exported to the grid. Moreover, urban wind turbines can be integrated with power-to-heat (P2H) technologies and seasonal thermal energy storage (STES) to improve the efficiency and flexibility of urban energy systems. Wind turbines can complement solar generation by producing electricity during periods of low solar irradiance, thereby contributing to a more balanced renewable energy supply. When surplus renewable electricity is converted into heat through P2H technologies, it can be used in district heating networks or stored in seasonal thermal storage systems for later use. Such integrated solutions enable more efficient use of locally generated renewable energy, reduce dependence on fossil fuels, and support the development of flexible, low-carbon urban energy infrastructure [19]. The general idea of urban wind energy with other RES, STES, and P2H solutions into the district network is shown in Figure 2.

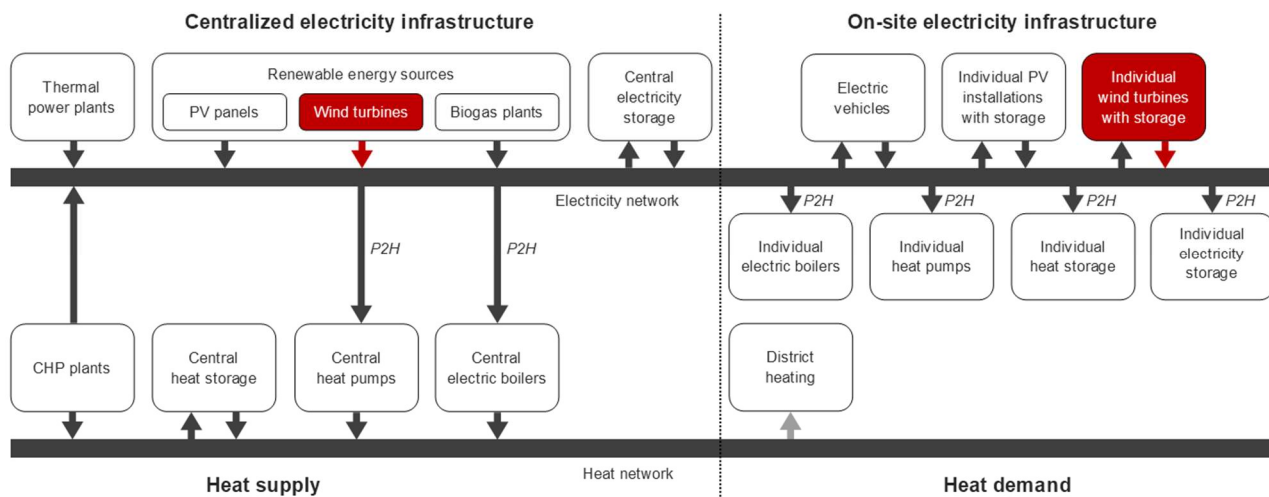


Figure 2. The concept of integrating urban wind energy with other RES, STES, and P2H solutions into the district network (adopted from Ref. [20]).

The performance of small wind turbines installed on rooftops or integrated into buildings is strongly influenced by local flow conditions and installation parameters. Factors such as turbine height above the roof, distance from building edges, inflow turbulence, and rotor orientation can significantly modify the velocity distribution across the rotor plane and ultimately affect power generation. For example, Wang et al. [21] demonstrated that rooftop flow acceleration and vortex formation around building edges can strongly influence turbine efficiency. Similarly, Fan et al. [22] showed that surrounding structures and vegetation can alter wind flow patterns and turbulence levels, thereby affecting the operational performance of rooftop wind turbines. Although numerical modeling approaches such as computational fluid dynamics (CFD) are widely used to assess urban wind resources, experimental investigations remain essential for validating models and understanding real operational conditions. Field measurements and laboratory experiments provide valuable insights into turbine performance under realistic turbulent inflow conditions typical of urban environments. Experimental studies have shown that micro-wind turbines operating in cities often experience significant fluctuations in wind velocity and direction, which can strongly influence their electrical output and overall efficiency [23,24]. However, there is still limited experimental evidence addressing how specific operational parameters influence turbine performance under controlled disturbed-flow conditions.

In this context, the present study discusses the key factors influencing the operation of wind turbines in urban environments and examines the performance of a tested micro-wind turbine under simulated disturbed-flow conditions. A dedicated experimental setup was designed and constructed to simulate different levels of flow non-uniformity and turbulence. The analysis focuses on how variations in inflow conditions affect turbine efficiency and operational stability. The results aim to provide insights into the development of further testing procedures to optimize installation and operating conditions for micro-wind turbines in complex urban airflow environments, thereby supporting the improved integration of urban wind energy systems.

2. Materials and methods

This section presents descriptions of the experimental setup used to validate mathematical models and the research procedure.

2.1. Experimental rig

A dedicated experimental test rig was developed to investigate the performance of a micro wind turbine under controlled airflow conditions representative of urban environments. The experimental system consisted of an array of 36 axial fans (AF) arranged into nine independent segments, each composed of four fans configured in a 2×2 layout. The fan array served as a controllable airflow generator, enabling the simulation of non-uniform wind fields. Each fan segment was controlled independently using a separate regulator, allowing different airflow intensities to be generated across the test section. This configuration enabled the reproduction of various disturbed-flow scenarios, including velocity gradients and spatial variations in wind speed that commonly occur in the urban canopy layer. A micro wind turbine (WT) was positioned downstream of the fan array at a predefined distance (10 cm) to ensure the formation of a representative flow field before interacting with the rotor. The airflow velocity was measured using a manual anemometer (AV) at selected points within the rotor plane in order to characterize the velocity distribution across the swept area of the turbine. Additional measurements included the rotational speed of the turbine rotor, monitored with a tachometer (TACH), and

the electrical voltage and current generated by the turbine under different operating conditions performed using an electronic load (EL). Measurements were conducted for different airflow configurations corresponding to varying levels of flow non-uniformity and turbulence intensity. During each experimental run, wind velocity at the rotor plane, turbine rotational speed, output voltage, and current were observed. A schematic representation of the experimental setup, along with a real view of the test rig, is shown in Figure 3.

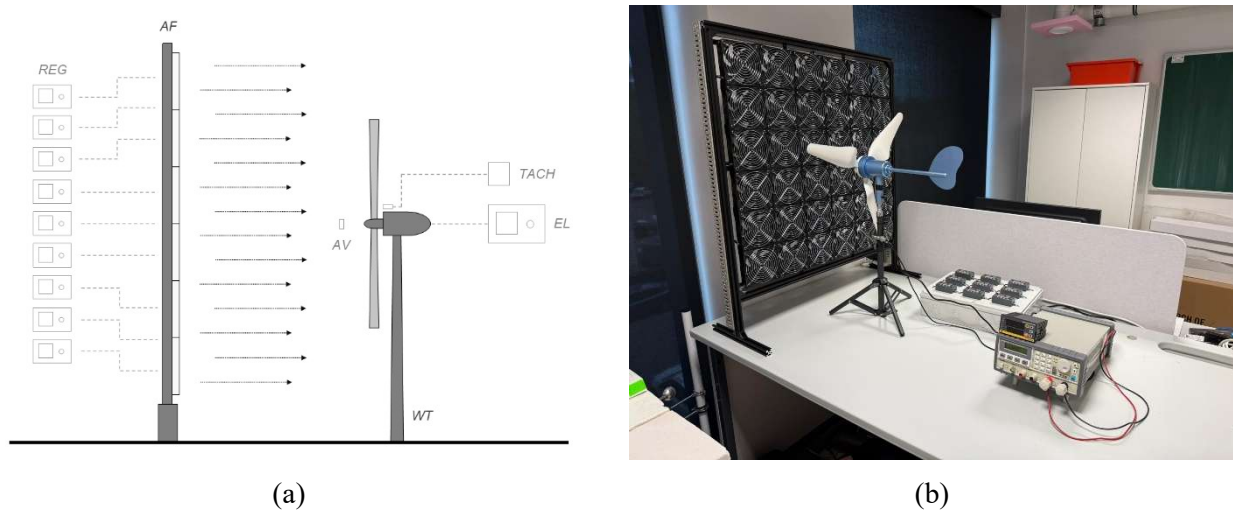


Figure 3. Scheme (a) and real view (b) of the experimental rig.

During the experiments discussed in this paper, the equipment characterized by the following parameters was used:

- Wishcolor micro wind turbine characterized by a theoretical maximum power of 50W, a voltage range of 1-24 V, a rotational speed of 200-1500 rpm, a starting wind speed of 2m/s, and a blade diameter of 500mm.
- Testo 417 anemometer with vane characterized by a velocity range of 0.3-20 m/s, resolution of 0.01 m/s, and accuracy of $\pm(0.1 \text{ m/s} + 1.5\% \text{ of the reading})$.
- T18 digital tachometer characterized by a measurement range of 0.1-10,000 Hz, sampling rate of 0.5-20 s, and accuracy of $\pm(0.1\% + 3 \text{ digits})$.
- Array 3721A programmable DC electronic load characterized by a maximum load of 400 W, an input voltage range of 0-80V, an input current range of 0-40A, voltage accuracy of $\pm 0.1\% + 10\text{mV}$, and current accuracy of $\pm 0.1\% + 5\text{mA}$ (in a range of 0-4 A).
- Deek-Robots DMC-331 PWM regulators for controlling the rotational speed of air fans.

2.2. Research procedure

The work presented in this paper was structured into three main stages. The first stage consisted of a literature review to identify key urban wind-flow characteristics relevant to wind-energy applications. The second stage involved designing and constructing a dedicated experimental setup to enable simplified simulation of operating conditions representative of urban wind turbine installations. The third stage comprised experimental measurements conducted using a micro wind turbine under various operational conditions reproduced within the laboratory test rig. Although the turbulence in the experimental setup was generated by the fan array, it reproduced stochastic aerodynamic fluctuations similar to those observed in urban environments, particularly near building edges and rooflines. The outcomes of these activities provided the basis for defining the assumptions and guidelines required to develop an outdoor experimental setup and to conduct future research under real field conditions.

3. Identification of Urban Wind Flow Characteristics Relevant to Wind Energy Applications

Analysis of the factors influencing wind energy potential in urban areas should start by assessing how urban structures affect wind speed distribution. Wind speed distribution in urban environments is strongly influenced by local topography and the spatial configuration of the built environment. Buildings, vegetation, and other urban structures increase surface roughness and significantly modify atmospheric flow patterns compared with open terrain. As a result, wind velocities within cities are generally lower than those observed in rural or coastal areas, while turbulence intensity is considerably higher. When airflow transitions from open terrain into an urbanized area, it encounters numerous obstacles that introduce aerodynamic drag and friction, leading to the

formation of complex flow structures characterized by reduced mean wind speeds and increased turbulence levels. These processes strongly depend on urban morphology, including building height, spacing, and orientation, which influence the development of recirculation zones, vortex structures, and localized flow acceleration around buildings, as was discussed in Ref. [25].

The airflow around buildings results from the interaction between atmospheric boundary layer (ABL) dynamics and the geometry of urban structures. The ABL represents the lowest part of the atmosphere and typically extends from the Earth's surface to heights ranging from approximately 100 m to 3 km, depending on meteorological conditions, terrain characteristics, and surface properties. This layer is directly influenced by interactions with the Earth's surface, where turbulent processes play a key role in transporting heat, moisture, and atmospheric pollutants [26]. Buildings disrupt the incoming airflow and generate complex aerodynamic phenomena, such as flow separation, wake formation, and vortex shedding, particularly near building edges and rooftops. These processes create highly heterogeneous wind conditions that can vary significantly over short distances. Understanding these flow characteristics is therefore essential for evaluating urban wind resources and identifying suitable locations for wind turbine installations. Numerous studies have investigated the complexity of airflow in urban environments. For instance, Britter and Hanna [27] provided a comprehensive review of wind flow and dispersion processes in urban areas, highlighting the influence of urban geometry on turbulence and pollutant transport. Similarly, Barlow and Coceal [28] analyzed turbulence structures within urban roughness layers and emphasized the importance of accurately representing urban morphology when assessing airflow patterns.

A commonly used framework in urban meteorology distinguishes between two main atmospheric layers that influence wind conditions in cities. The first is the Urban Canopy Layer (UCL), which extends from ground level to approximately the average rooftop height and is directly influenced by buildings, street canyons, and other urban obstacles. Within this layer, wind flow is highly irregular and characterized by strong turbulence and recirculating flows. Above the canopy lies the Urban Boundary Layer (UBL), which develops over the city and reflects the cumulative aerodynamic effects of the urban surface. Wind conditions in the UBL tend to be more uniform than those in the canopy layer, but remain significantly modified relative to rural atmospheric boundary layers [29,30]. Because urban wind conditions are strongly influenced by building geometry and atmospheric processes occurring across these layers, accurate characterization of airflow around buildings is essential for the effective design and placement of urban wind turbines. The structure of the urban wind profile, including the UCL and UBL, is illustrated in Figure 4.

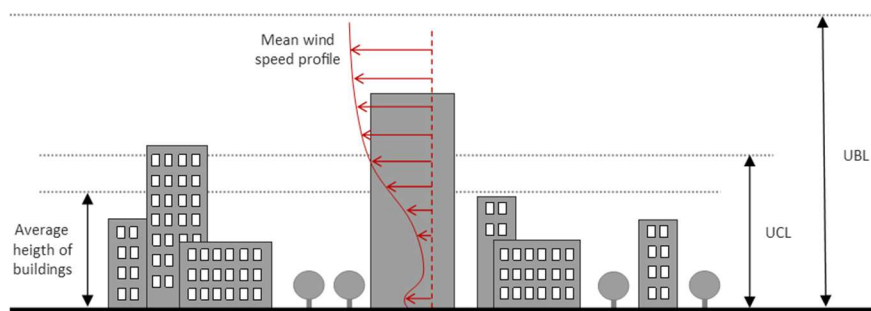


Figure 4. The structure of the urban wind profile, including the Urban Canopy Layer (UCL) and Urban Boundary Layer (UBL) (adopted from Ref. [31]).

Both individual buildings and clusters of structures can substantially modify the surrounding airflow in urban environments. Wind behavior within cities is highly variable and depends on factors such as wind direction, building geometry, and prevailing atmospheric conditions. The interaction between the incoming atmospheric flow and urban structures generates complex aerodynamic phenomena, including localized acceleration regions, recirculation zones, and turbulent wakes, which together shape the overall wind dynamics within the built environment. These include vortex formation near building edges, sheltered areas with reduced wind speeds, flow acceleration caused by the Venturi effect between closely spaced buildings, and channeling of airflow along street corridors [32].

In realistic urban settings, however, small wind turbines operate in environments influenced not only by buildings but also by vegetation, particularly mature street trees. While buildings may enhance wind turbine performance by locally increasing wind speed and turbulence – especially near rooftops where flow acceleration may occur – vegetation typically has the opposite effect. Trees extract kinetic energy from the airflow through drag and canopy interactions, thereby reducing the available wind resource. Despite this, most existing research has focused primarily on the aerodynamic effects induced by buildings, while the influence of urban vegetation on wind conditions has received comparatively less attention [33].

Wind conditions in cities are also closely linked to the quality of the urban microclimate and the comfort of urban residents. Wind plays an important role in natural ventilation, pollutant dispersion, and convective heat

transfer between the atmosphere and building surfaces. At the pedestrian level, excessive wind speeds may cause discomfort or even safety concerns, particularly during colder seasons when strong winds intensify perceived thermal stress. Consequently, urban planning strategies often aim to mitigate high wind speeds in public spaces in order to improve pedestrian comfort and reduce wind-related hazards. However, these design measures may also reduce the available wind resource for energy generation, thereby limiting the potential for urban wind energy applications [34].

Given the complexity of airflow within urban environments, accurately estimating the available wind resource remains a significant challenge. The strong spatial variability of wind speed and turbulence caused by buildings, street canyons, and vegetation makes conventional wind assessment approaches less reliable in cities. As a result, specialized methods are required to evaluate urban wind potential and identify suitable locations for small wind turbine deployment. These methods typically combine long-term measurements, numerical simulations, and urban-scale wind-mapping techniques to capture the influence of local morphology on airflow patterns.

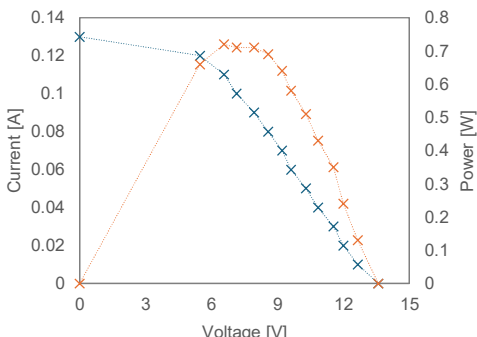
4. Experimental analysis of micro-wind turbine performance under simulated disturbed airflow

Based on the factors identified above that influence wind speed distribution in urban environments, several representative operational scenarios were defined. These scenarios account for the possibility of non-uniform airflow entering the rotor-swept area of the wind turbine. It should be emphasized that building-integrated wind turbines typically lack yaw control or pitch control. Consequently, their aerodynamic performance is highly sensitive to the characteristics of the incoming airflow. The measurement series presented below demonstrates how turbine performance varies with inflow non-uniformity across the rotor plane.

4.1. Reference case (all fans set to 100%)

In the first measurement series, all fan segments operated at 100% capacity, resulting in an average airflow velocity of 3.8 m/s across the rotor-swept area. This configuration simulated turbulent urban airflow conditions without the influence of additional nearby obstacles such as roof edges, chimneys, or other structural elements. Under these conditions, the turbine reached a rotational speed of approximately 570 RPM (about 38% of the maximum rotational speed specified by the manufacturer), resulting in an electrical power output of 0.72 W in the laboratory setup. Although this power level is relatively low, its absolute value is not of primary importance, as it serves mainly as a reference point for comparison with results from the subsequent measurement series. The main results obtained during series 1 are presented in Table 1.

Table 1. Results obtained in case 1, with all air-fan sections set to 100%.

Case	Air fans set [%]	Rotational speed [RPM]	Maximum power [W]	I-U and P-U characteristics									
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100	100	100											
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4.2. Cases 2-5 (reduced airflow in the bottom sections)

In cases 2–5, disturbed inflow conditions were simulated in which the airflow entering the lower portion of the rotor-swept area was partially obstructed. Such situations may occur in urban environments due to nearby obstacles, such as roof edges, chimneys, or other structural elements near the turbine. The results indicate that a relatively small disturbance to the airflow (case 2) has only a minor effect on turbine performance, reducing power output by less than 3%. However, as the degree of disturbance increases, the obstacle's location becomes a critical factor affecting turbine performance, as demonstrated in cases 3 and 4. In case 3, where the airflow disturbance occurred near the rotor's lateral edges, the turbine power output decreased by approximately 7%. In contrast, in case 4, where the disturbance was located in the central region of the lower part of the rotor-swept area, the power output decreased by about 31%. This behavior highlights the turbine's

high sensitivity to asymmetric inflow conditions across the rotor plane. A similar effect was observed in case 5, where the airflow in the lower portion of the rotor-swept area was almost completely obstructed. Under these conditions, the turbine generated only 0.45 W, corresponding to 62.5% of the power in the reference case (case 1), representing a 37.5% reduction in power output. The results obtained for cases 2–5, characterized by reduced airflow in the lower part of the rotor-swept area, are summarized in Table 2.

Table 2. Results obtained in cases 2-5, with reduced airflow in the bottom sections.

Case	Air fans set [%]	Rotational speed [RPM]	Maximum power [W]	I-U and P-U characteristics									
2	<table border="1"> <tr><td>100</td><td>100</td><td>100</td></tr> <tr><td>100</td><td>100</td><td>100</td></tr> <tr><td>100</td><td>100</td><td>0</td></tr> </table>	100	100	100	100	100	100	100	100	0	560	0.70	
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4.3. Cases 6-8 (reduced airflow in the middle and bottom sections)

An even more unfavorable situation occurs when the airflow disturbance affects a larger portion of the wind turbine rotor. In cases 6–8, scenarios were analyzed in which the lower part of the rotor-swept area was obstructed, while additional disturbances occurred within the rotor's central horizontal band. In case 6, the disturbance was located on the lateral side of the central band, resulting in a reduction of turbine power output of approximately 65% compared with the reference scenario. When the disturbance was positioned directly in front of the rotor's central region (case 7), the power output decreased by approximately 83%. Finally, when the disturbance covered both the frontal and lateral parts of the rotor's central band (case 8), the turbine produced no electrical power. Results obtained in cases 6-8, with reduced airflow in the middle and bottom sections, are summarized in Table 3.

Table 3. Results obtained in cases 6-8, with reduced airflow in the middle and bottom sections.

Case	Air fans set [%]	Rotational speed [RPM]	Maximum power [W]	I-U and P-U characteristics		
6	100	420	0.25			
	100				100	
	0				100	100
	0				0	0
7	100	340	0.12	N/A		
	100				0	100
	0				0	0
	0				0	0
8	100	110	0	N/A		
	100				0	0
	0				0	0
	0				0	0

4.4. Discussion of the results and further plans

The results presented above are consistent with the expected effects of airflow disturbances on the operation of wind turbines in urban environments or other locations where upstream obstacles affect the wind flow. It can be observed that relatively small disturbances caused by minor obstacles located near the lateral edges of the rotor-swept area do not significantly affect turbine performance. In contrast, similar disturbances occurring in the central region of the lower rotor section or across the entire lower section lead to a substantial reduction in turbine power. When the disturbance also directly affects the central band in front of the turbine rotor, the generated power decreases dramatically. When the rotor speed falls below 200 RPM, the turbine ceases to operate. At the same time, non-uniform airflow entering the turbine influences the rotor speed (Figure 5a) and, consequently, the electrical power output (Figure 5b). It should also be noted that the reported wind velocity values represent averages calculated from eight measurement points located along the circumference of the rotor-swept area. The analyzed effect may occur in practice when airflow passes around building edges or around the boundaries of structures in which wind turbines are integrated. Another possible scenario involves lateral shielding from chimneys or other vertical obstacles near the turbine. Given the significant impact of such disturbances, it is necessary to explore appropriate mitigation strategies. One potential solution to consider is implementing a rotor tilt control system, which could help reduce the negative effects of airflow vortices and localized wind acceleration near building edges.

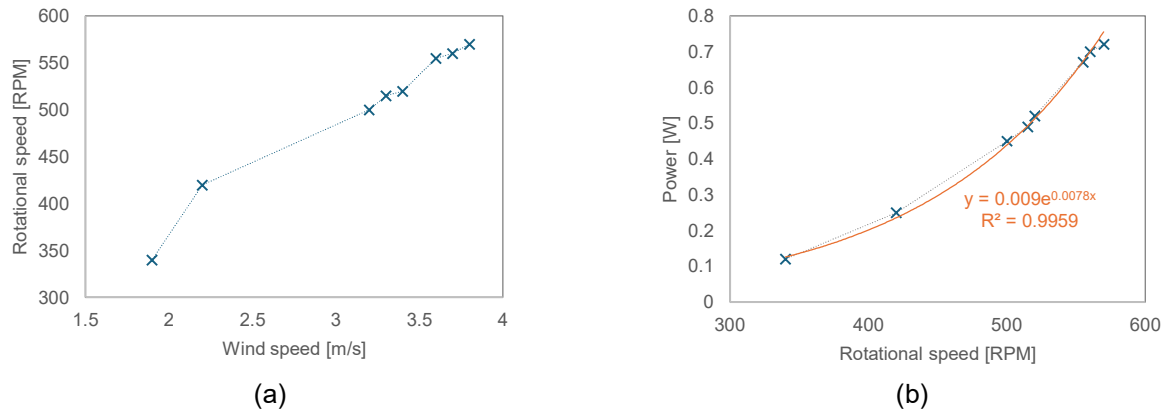


Figure 5. Rotational speed of wind turbine rotor resulted from average wind speed (a) and power generated by wind turbine resulted from rotational speed (b).

The developed laboratory test rig, despite its relatively simple design, enabled preliminary laboratory-scale investigations of the influence of airflow disturbances on the performance of a micro-scale wind turbine. In addition, the practical verification of the measurement procedures enabled further development of the experimental setup, allowing more accurate simulation of real airflow conditions encountered in urban environments. Moreover, the obtained results provided a preliminary basis for planning further research, including field experiments. The field studies will focus on identifying potential solutions to mitigate the negative effects of airflow disturbances on wind turbine performance in urban environments. Given that disturbances affecting the lower portion of the rotor-swept area can result in power reductions of nearly 40%, one of the main research directions will be to test different approaches to mitigate this adverse effect. For this purpose, the wind turbine will be installed near the edge of a building roof, and several installation parameters will be systematically varied, including the height of the rotor above the roof level, the distance between the turbine and the roof edge, and the inclination angle of the turbine rotor. Identifying an appropriate combination of these parameters will enable the development of practical guidelines for the design and installation of wind turbines in urban environments. In the subsequent stages of the research, the experimental studies will be complemented by numerical simulations, which will allow the findings obtained from local measurements to be extended to broader analyses of the feasibility and optimal placement of wind turbines in urban areas.

5. Conclusions

This study presented an experimental investigation of the influence of disturbed airflow conditions on the performance of a micro-scale wind turbine operating in conditions representative of urban environments. A dedicated laboratory test rig equipped with a modular fan array was developed to simulate non-uniform inflow conditions across the rotor-swept area. The experimental results demonstrated that the performance of micro wind turbines is highly sensitive to asymmetric inflow conditions. Minor airflow disturbances near the rotor's lateral edges resulted in relatively small performance losses, typically below 7%. In contrast, disturbances affecting the rotor's central region significantly reduced turbine performance. When the disturbance covered a substantial portion of the rotor-swept area, power losses reached up to 83%, and in extreme cases, the turbine ceased to operate. The results highlight the critical importance of proper turbine placement in urban environments, where nearby obstacles such as building edges, chimneys, and other structural elements may significantly alter local airflow conditions. The findings indicate that disturbances in the lower and central regions of the rotor-swept area are particularly detrimental to turbine performance. The developed experimental setup proved useful for preliminary laboratory-scale investigations of disturbed inflow conditions. The results obtained in this study provide a basis for future research, including field experiments to identify mitigation strategies to reduce the negative effects of airflow disturbances. Future work will focus on analyzing the influence of turbine placement relative to building edges, rotor height above the roof surface, and rotor tilt angle. These studies will support the development of practical guidelines for installing micro wind turbines in urban environments.

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