NÖHÜ Müh. Bilim. Derg. / NOHU J. Eng. Sci., 2025; 14(4), 1211-1221

Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi
Niğde Ömer Halisdemir University Journal of Engineering Sciences

Araştırma makalesi / Research article

www.dergipark.org.tr/tr/pub/ngumuh / www.dergipark.org.tr/en/pub/ngumuh

The impact of a wind concentrator system on the efficiency of roof-mounted wind turbines in rural areas

Rüzgâr yoğunlaştırıcı sisteminin kırsal alanlardaki çatıya monte rüzgâr türbinlerinin verimliliğine etkisi

Zeynep İlkılıç Aytaç[1,*], Halis Deviren[2]

[1] Ondokuz Mayıs University, Yeşilyurt Demir Çelik Vocational School, Department of Machine and Metal Technologies, Mechatronics Program, Samsun, 55300, Türkiye

[2] Dicle University, Diyarbakır Vocational School of Technical Sciences, Department of Motor Vehicles and Transportation Technologies, Automotive Program, Diyarbakır, 21280, Türkiye

Abstract

Wind energy is a crucial pathway for sustainable electricity generation. Nevertheless, the performance of small-scale wind turbines-particularly in urban and rural environments-remains constrained by low and highly variable wind speeds. This study presents a novel wind concentrator system specifically developed to improve the performance of roof-mounted wind turbines by optimizing airflow characteristics. The system utilizes concave concentrator blades positioned circumferentially around the rotor to accelerate the incoming airflow and generate a controlled vortex, thereby increasing the wind velocity incident on the turbine. Experimental and theoretical analyses indicate that the concentrator increases the turbine rotational speed by approximately 39%, thereby enabling the turbine to operate at lower wind speeds that would otherwise result in stalling. Power coefficient measurements indicate an increase from 0.15 without the concentrator to 0.20 with the concentrator, representing approximately a one-third enhancement in power output at a wind speed of 9.5 m/s. Moreover, the concentrator facilitates comparable energy capture using only one-sixth of the rotor area required by a conventional wind turbine. These findings underscore the potential of the system to enhance the feasibility of small-scale wind energy, especially for decentralized and off-grid applications, thereby contributing to the development of distributed renewable energy solutions.

Anahtar kelimeler: Wind energy, Wind turbine efficiency, Wind concentrator system, Vortex dynamics, Wind energy conversion systems (WECS)

Öz

Rüzgâr enerjisi, sürdürülebilir elektrik üretimi için temel bir yol olarak öne çıkmaktadır. Ancak, özellikle kentsel ve kırsal alanlarda kullanılan küçük ölçekli rüzgâr türbinlerinin performansı, genellikle düşük ve yüksek oranda değişken rüzgâr hızları nedeniyle sınırlı kalmaktadır. Bu çalışma, çatıya monte edilen rüzgâr türbinlerinin performansını hava akışı karakteristiklerini optimize ederek artırmak amacıyla özel olarak geliştirilmiş yenilikçi bir rüzgâr yoğunlaştırıcı sistemini sunmaktadır. Sistem, rotorun çevresine dairesel olarak yerleştirilen içbükey yoğunlaştırıcı kanatları kullanarak gelen hava akışını hızlandırmakta ve kontrollü bir girdap oluşturarak türbine ulaşan rüzgâr hızını artırmaktadır. Deneysel ve teorik analizler, yoğunlaştırıcı sistemin türbin dönme hızını yaklaşık %39 oranında artırdığını ve böylece, aksi halde durmasına neden olacak düşük rüzgâr hızlarında da türbinin çalışmasını mümkün kıldığını göstermektedir. Güç katsayısı ölçümleri, yoğunlaştırıcı olmadan 0.15 olan değerin yoğunlaştırıcı ile 0.20'ye yükseldiğini ve bu durumun 9.5 m/s rüzgâr hızında yaklaşık üçte bir oranında güç artışına karşılık geldiğini göstermektedir. Ayrıca, yoğunlaştırıcı sistem, konvansiyonel bir rüzgâr türbininin ihtiyaç duyduğu rotor alanının yalnızca altıda biriyle benzer düzeyde enerji üretimini mümkün kılmaktadır. Bu bulgular, sistemin özellikle merkezi olmayan ve şebekeden bağımsız uygulamalarda küçük ölçekli rüzgâr enerjisinin uygulanabilirliğini artırma potansiyelini vurgulamakta ve dağıtık yenilenebilir enerji çözümlerinin geliştirimine katkı sağlamaktadır.

Keywords: Rüzgâr enerjisi, Rüzgâr türbini verimliliği, Rüzgâr yoğunlaştırıcı sistemi, Girdap dinamiği, Rüzgâr enerjisi dönüşüm sistemleri (WECS)

1 Giriş

Wind energy is fundamentally driven by solar radiation, as the uneven distribution of heat across the Earth's surface leads to variations in atmospheric pressure. These pressure differences generate wind patterns that circulate globally [1], [2]. The primary driver of wind formation is the temperature gradient between the equatorial and polar regions, which induces large-scale atmospheric convection currents [3].

Consequently, wind constitutes a consistent and renewable energy source that can be harnessed for various applications, including electricity generation [4]. Despite its intermittent nature, wind power remains a dependable energy source on an annual basis and has been widely

* Sorumlu yazar / Corresponding author, e-posta / e-mail: zeynep.ilkilic@omu.edu.tr (Z. İlkılıç Aytaç)
Geliş / Received: 07.05.2025 Kabul / Accepted: 05.07.2025 Yayımlanma / Published: 15.10.2025
doi: 10.28948/ngumuh.1694150

integrated into power grids worldwide [5], [6]. Wind turbines convert the kinetic energy of wind into mechanical power, which can either be used directly or transformed into electricity through a generator [7]. While large-scale wind farms play a pivotal role in global electricity production, small-scale wind turbines are vital for decentralized energy solutions, particularly in rural and off-grid areas [8]. Despite continuous advancements in wind energy technology, efficiency constraints remain a significant challenge for turbines installed on rooftops or in regions with low-wind-speeds [9].

Numerous system integration studies indicate that the intermittency of wind energy does not present a significant obstacle to its large-scale deployment [10]. Historically, wind power has played a crucial role in energy generation; for example over 10,000 windmills in 19th-century Britain [11]. In modern energy systems, wind power is increasingly integrated into power grids to provide sustainable energy [6]. Utility-scale wind turbines typically have capacities ranging from 50 kW to several megawatts, while smaller turbines-often rated at 50 kW or less-are [12] used for residential applications, telecommunications, and water pumping. Wind energy represents a clean and sustainable technology that is being adopted worldwide. The electricity produced by wind turbines is distributed through power networks to various consumers, and Wind Energy Conversion Systems (WECS) also supply electricity to remote areas that lack access to centralized grids.

Despite advancements in wind turbine technology, small-scale wind turbines-particularly those installed in urban and rooftop environments-suffer from low efficiency due to fluctuating wind speeds and suboptimal aerodynamic performance. Conventional wind turbine designs are based on natural wind conditions, which limit their effectiveness in regions with inconsistent airflow. In the built environment, highly turbulent airflow around structures further complicates energy capture, even though the shape of a building, such as a pitched roof, can locally accelerate wind speeds [13]. To overcome these challenges, researchers have explored various methods, including advanced blade designs, variable pitch control, and wind concentrator systems that aim to increase wind velocity before it reaches the rotor. For example, diffuser-augmented turbines (or “wind-lens” designs with flanged shrouds) have shown enhanced performance by creating low-pressure regions that draw wind into the system [14]. Recent studies on small wind turbines have demonstrated that incorporating concentrator structures can significantly improve performance; Heragy et al. reported that a concentrator with flanged plates increased the maximum power coefficient of a small turbine by 108%, from 0.12 to 0.25 [15]. Such augmentation devices emphasize the potential for substantial gains in energy capture. However, many existing approaches involve bulky diffusers or complex guide vanes, which may be impractical for rooftop installations.

This study introduces a novel concentrator system developed to address the need for a compact, roof-mounted wind augmentation device. Unlike conventional designs that primarily depend on static shrouds or diffusers, the proposed system utilizes a set of concentrator blades to generate a controlled vortex effect, actively directing and accelerating airflow toward the turbine rotor. This approach optimizes the interaction between the airflow and turbine blades, resulting in a significant increase in rotational speed and overall efficiency. Previous studies have not fully explored the application of vortex-based concentrators for rooftop turbines, and our work is the first to experimentally demonstrate the benefits of this configuration. Both experimental and theoretical investigations were conducted to analyze the system’s impact on wind speed, vortex formation, and turbine efficiency. Experimental results indicate a notable performance improvement, with an average increase of 39% in rotational speed, implying a substantially higher power output compared to conventional setups.

The structure of this paper is as follows:

*Section 2 provides the theoretical background, including Betz’s limit and wind energy conversion principles,

*Section 3 describes the design and operational mechanism of the proposed wind concentrator system,

*Section 4 details the experimental setup and methodology,

*Section 5 presents the experimental results along with a discussion,

*Section 6 concludes the study by summarizing key findings and proposing directions for future research.

2 Betz’ theory for available energy from wind

Wind turbines extract energy from moving air, and the theoretical maximum efficiency of this energy conversion is determined by Betz’s limit [16]. Prior to introducing our concentrator design, we briefly review the relevant theory to ensure clarity and consistency in mathematical expressions.

Consider a streamtube of air flowing through a turbine rotor with area S, as illustrated in Figure 1. The wind speed far upstream is V_1, at the rotor plane is V, and far downstream is V_2. The corresponding pressures at these points are P_1, P, and P_2, while the cross-sectional areas are S_1 and S_2 upstream and downstream, respectively. The mass flow rate through the rotor is given by Equation. 1.

$$\dot{m} = \rho S V \tag{1}$$

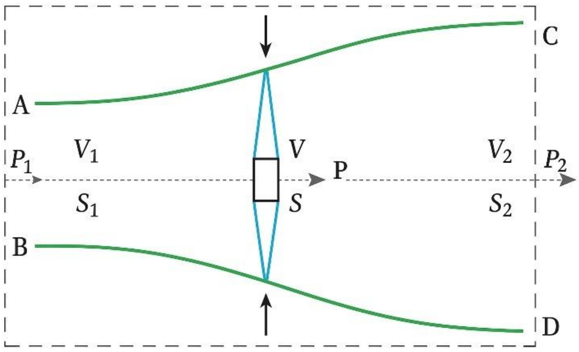

Figure 1. Streamtube representation of airflow through a wind turbine rotor

For incompressible flow, the continuity equation holds as follows (see Figure 1): $\rho S_1 V_1 = \rho SV = \rho S_2 V_2$

The force exerted by the wind on the rotor, known as the thrust (*F*), can be derived using Euler's turbine theorem and, for steady one-dimensional flow, is given by Equation 2 [17].

$$F = \rho SV(V_1 - V_2) \tag{2}$$

Here, ρ denotes the air density (kg/m³). The power extracted by the rotor, representing the flux of kinetic energy removed from the wind, is given by Equation 3.

$$P = FV = \rho SV^2(V_1 - V_2) \tag{3}$$

This extracted power represents the loss in kinetic energy of the air, as illustrated between the upstream and downstream sections in Figure 1, and the change in kinetic energy per unit time is given by Equation 4.

$$\Delta E_{kin} = \frac{1}{2}\rho SV_1(V_1^2 - V_2^2) \tag{4}$$

By equating the power extracted to the change in kinetic energy, the wind speed at the rotor plane is found as given in Equation 5.

$$V = \frac{V_1 + V_2}{2} \tag{5}$$

This result implies that the wind speed at the rotor is the average of the upstream and downstream velocities. Substituting this result into Equation (1), thrust and power can be rewritten solely in terms of V_1 and V_2 as given in Equation (6) and Equation (7):

$$F = \frac{1}{2}\rho S(V_1^2 - V_2^2) \tag{6}$$

$$P = \frac{1}{2}\rho S(V_1^2 - V_2^2)\frac{V_1 + V_2}{2} = \frac{1}{4}\rho S(V_1^2 - V_2^2)(V_1 + V_2) \tag{7}$$

To determine the condition for maximum power extraction, consider P as a function of V_2 (for given V_1 and ρ), and set its derivative with respect to V_2 to zero, as shown in Equation (8):

$$\frac{dP}{dV_2} = \frac{1}{4}\rho S(V_1^2 - 2V_1V_2 - 3V_2^2) = 0 \tag{8}$$

Solving Equation (8) yields two solutions: $V_2 = -V_1$ and $V_2 = \frac{V_1}{3}$, which corresponds to maximum power extraction. Substituting $V_2 = \frac{V_1}{3}$ into Equation (7) (or directly into $P = \frac{1}{2}\rho SV_1^3 a(1-a)^2$ with $= \frac{1}{3}$, where a is the axial induction factor) yields the maximum power, as given by Equation (9):

$$P_{max} = \frac{16}{27}\left(\frac{1}{2}\rho SV_1^3\right) = \frac{8}{27}\rho SV_1^3 \tag{9}$$

For standard air density $\rho = 1.225$ kg/m³, this becomes numerically: $P_{max} \approx 0.37SV_1^3$. The fraction of wind power that can be captured by an ideal turbine is described by the power coefficient, $C_p = \frac{P}{P_{wind}}$, where the total power in the wind is given by Equation 10.

$$P_{wind} = \frac{1}{2}\rho SV_1^3. \tag{10}$$

From Eq. (9), the theoretical maximum value of C_p is therefore given by Equation (11):

$$C_{p,max} = \frac{P_{max}}{\frac{1}{2}\rho SV_1^3} = \frac{8}{27} \approx 0.5926 \tag{11}$$

This value-approximately 59%-is known as Betz's limit [18]. In practice, real wind turbines operate below this limit: well-designed horizontal-axis wind turbines typically achieve peak C_p values between 0.35 and 0.45 (35-45%) [19], depending on blade aerodynamics and tip speed ratio. When considering the complete wind energy conversion system (including rotor, transmission, generator, etc.), the overall efficiency usually falls within 10-30% [20].

These theoretical principles serve as a baseline for evaluating any performance enhancement. A concentrator or augmenter should effectively increase the wind speed V_1 (or, equivalently, increase the mass flow rate through the rotor) to boost power output. However, the fundamental Betz limit still applies to the total intake area of the combined system. In summary, Betz's analysis demonstrates that maximizing energy extraction requires a careful balance: the airflow should be slowed to one-third of its free-stream velocity at the rotor for optimal energy extraction, while allowing sufficient flow to continue through the rotor. Our concentrator system is designed in accordance with these principles-it aims to increase the effective wind speed at the rotor (*V*) without increasing the rotor area (*S*), by guiding and accelerating the airflow, thereby increasing the mass flow rate and captured energy, all while remaining within the theoretical limits of efficiency [21], [22].

3 Wind concentrator system

The horizontal wind energy concentrator system described in this study is characterized by its structural simplicity and lightweight design and is capable of significantly enhancing local wind speed with high efficiency. This system consists of a wind turbine and a vortex-type concentrator structure. The wind turbine is installed near the edge of a building's roof and is strategically positioned to utilize wind flow that is passively concentrated by the building's vertical facade. As the wind ascends and flows over the roof, it accelerates and forms a vortex; the turbine operates within this region of high-velocity airflow. The additional vortex concentrator is specifically designed to further focus and accelerate the wind onto the section of the turbine that faces away from the roof edge, thereby maximizing energy capture. As illustrated in Figure 2, the incoming wind approaches from the left, is deflected by the building's rooftop edge, and generates concentrated updraft at the edge, which drives the turbine positioned within this high-velocity region. The concentrator, also referred to as a baffle or augmenter, plays a critical role in directing wind into the turbine. While its specific geometry may vary-and in some cases, it may even be omitted-the preferred configuration incorporates a concentrator to optimize air intake.

The horizontal wind concentrator system is specifically designed to improve power generation efficiency in medium- and small-scale applications. In contrast, vertical-axis concentrator systems require very large structures to enclose a tower, which significantly increases the complexity of their design. The WECS equipped wind concentrators incorporate aerodynamic and structural considerations from various engineering disciplines. The WECS presented in this study is specifically developed for an axial-flow wind rotor and functions by directing wind flow into a targeted region, enabling the turbine to operate at higher effective wind speeds and consequently achieve greater power output.

Numerous studies have been conducted on wind concentrator concepts in prior research efforts [23], [24]. The WECS examined in this study is designed to increase lift on the turbine blades while optimizing induced drag, thereby allowing for efficient extraction of kinetic energy from the wind. The energy is captured through the shed vortex system and subsequently converted into rotational motion of the rotor. By utilizing the vortex effect, the system minimizes the frontal resistance of the turbine while simultaneously increasing its rotational velocity with minimal additional energy dissipation. To maximize the utilization of this rotational energy, a high-speed wind turbine is strategically positioned within the core of the rolled-up wingtip vortex generated by the concentrator.

As demonstrated in Figure 2, a vortex forms at each wing (concentrator blade) edge within the open center of the wind concentrator. The wind rotor is strategically positioned at the core of this vortex spiral, where interacting vortices generate a multiple spiral-system. This configuration enhances wind energy capture and optimizes turbine performance by maintaining a high-energy airflow region around the rotor.

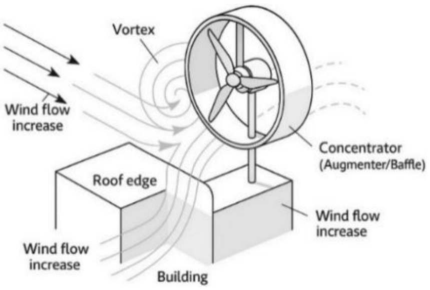

Figure 2. Wind flow and vortex formation in a horizontal wind energy concentrator system

The functionality of the WECS depends on the aerodynamic behavior of high-lift airfoils, which generate significant drag to extract kinetic energy from the wind [25]. This extracted energy is efficiently converted into rotational motion, remaining within the vortex system rather than dissipating away from the rotor plane [26]. The concentrator blades generate both an inner and an outer vortex structure: the inner vortex accelerates the airflow through the rotor, while the outer vortex rotates in the opposite direction, thereby drawing additional flow into the system [27]. As a result, the WECS increases the airflow velocity in front of the turbine blades, leading to a higher rotational speed of the rotor compared to a system without a concentrator. The trailing vortex sheet generated by the concentrator blades rapidly rolls up, concentrating a substantial amount of wind energy within the wingtip vortex core. The high angular velocity generated within this core vortex enables the wind turbine to reach greater rotational speeds compared to traditional open-flow designs. Additionally, the lightweight and compact structure of the system minimizes alignment issues and ensures stable performance under varying wind conditions.

The WECS is designed to concentrate wind energy into a specific area, thereby enhancing power output. The prototype concentrator has a tubular form with a circular cross-section and a predominantly planar leading-edge ring. Its function is to channel wind flow into a confined space where the wind turbine can operate with greater efficiency. As air flows over the concentrator blades-from the planar leading edge to the trailing edge-a region of reduced pressure region is formed due to the Bernoulli effect. This low-pressure zone is located adjacent to one or more slots or gaps positioned immediately behind the leading edge and extending toward the widest section of the concentrator. The presence of these slots serves to accelerate the wind as it passes through the device and optimizes the distribution of airflow. Although the concept of using shrouds or concentrators is not entirely new, such systems have attracted increasing research interest in recent years due to their capacity to significantly improve the performance of axial-flow rotors.

In our design, a circular disc structure with multiple radially arranged stationary blades (airfoil-shaped concentrator blades) is positioned upstream of the turbine. These stationary concentrator blades capture and channel the incoming wind, directing it through the central opening and onto the downstream wind turbine. The diameter of the turbine's rotor is matched to that of the concentrator orifice to ensure efficient energy transfer. Figure 3 presents a schematic illustration of this orifice-type concentrator system.

The Bernoulli effect, together with the counter-rotating eddies formed at the concentrator's leading edge, plays a critical role in increasing the wind speed within the device. The design promotes a continuous flow of air through the turbine, thereby enhancing its overall performance. However, the design of an optimal WECS presents several challenges. A low tip-speed ratio, combined with small airfoil dimensions due to the concentrator's size constraints, necessitates meticulous aerodynamic optimization of the concentrator blades.

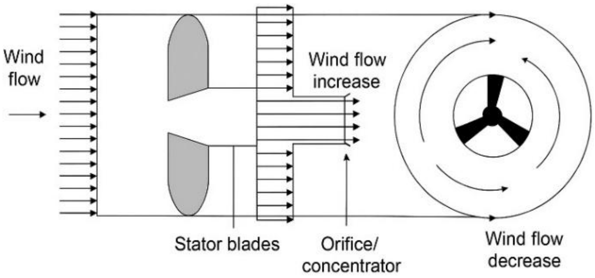

Figure 3. Schematic of an orifice system with stator blades for wind speed increase

The placement of the WECS is also critical: the most effective position is on top of or alongside a building, where the natural wind flow is accelerated by the structure and is not significantly disrupted by surrounding obstructions. Proper alignment of the concentrator with the prevailing wind direction is essential for maintaining optimal turbine performance, particularly given the variability of natural wind direction. In practice, installing turbines at roof edges (as in our case) leverages the updraft and acceleration effects present at the edge, thus increasing rotor speed without necessitating significantly taller structures.

4 Experimental setup and methodology

Section 4 of this study provides a detailed description of the experimental setup and methodology used to evaluate the proposed wind concentrator system. To empirically assess system performance, a series of controlled experiments were conducted using a small horizontal-axis wind turbine mounted near a roof-edge simulator, both with and without the concentrator device. The key components of the experimental setup are as follows:

4.1 Wind turbine and concentrator model

A small three-bladed horizontal-axis wind turbine (HAWT) was utilized for the testing. The turbine rotor has a diameter of approximately 0.5 m, and the blades possess an aerofoil cross-section that is specifically designed for operation at low Reynolds numbers. The turbine was coupled to a small generator for loading purposes, or, in some tests, allowed to spin freely in order to measure the free-run rotational speed. The concentrator system consists of a circular arrangement of stationary concentrator blades (vanes) that surround the turbine rotor. In the prototype, eight flat-plate concentrator vanes, evenly spaced at 45° intervals around the rotor circumference, were attached to a supporting ring structure positioned on the roof model. These vanes are oriented to form a funnel-like orifice around the turbine, as illustrated in Figure 4. The concentrator blades were fixed relative to the turbine; however, the entire assembly could be yawed together with the turbine to investigate the effects of wind direction (yaw misalignment).

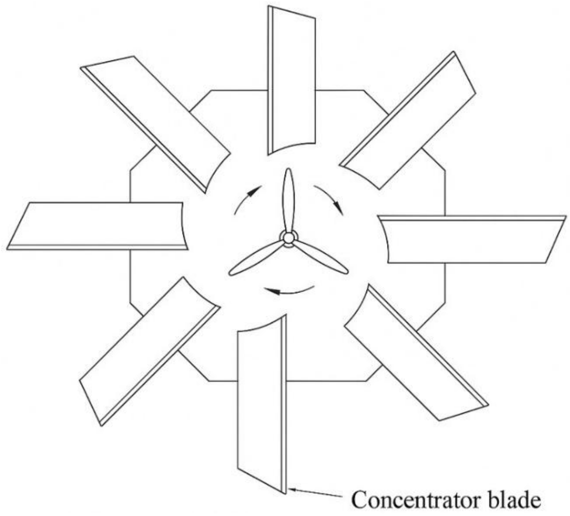

Figure 4. Front view of HAWT with eight concentrator blades at 45° intervals

4.2 Roof edge and mounting

To simulate a rooftop installation, the turbine and concentrator were mounted at the edge of a flat-roofed building model. The building model was constructed from wood and PVC sheets and was sized sufficiently large to ensure that the approaching flow profile resembled that of a full-scale roof edge (the model was approximately 1.5 m tall with a sharp roof corner). The turbine hub height was positioned just above the roof surface at the edge, where wind flowing up the building facade would naturally accelerate over the edge. This configuration simulates a roof-mounted turbine placed to take advantage of the roof acceleration effect.

4.3 Wind source

Experiments were conducted in a controlled environment using both a wind tunnel and an open-jet wind source. For steady and repeatable results, a large axial flow fan and a custom duct were utilized to generate a horizontal airstream. The wind speed could be adjusted by varying the fan power, providing a range from approximately 2 m/s to 14 m/s at the test section where the turbine was located. The flow in the test section exhibited a slight turbulence intensity (on the order of a few percent) to simulate natural wind fluctuations. Furthermore, to examine the effect of wind direction, the entire turbine-and-concentrator assembly could be rotated (yawed) relative to the incoming flow. Tests were conducted for concentrator yaw angles of 0° (direct head-on flow), 15°, 25°, and 35° to simulate scenarios where the wind is not perfectly aligned with the roof and concentrator.

4.4 Instrumentation and measurements

An anemometer (both hot-wire and vane type) was used to measure the free-stream wind speed at the height of the turbine, both with and without the presence of the building model. The rotational speed of the turbine (in revolutions per minute, RPM) was measured using a digital laser tachometer, which detected rotor RPM via a reflective marker attached to the shaft. Since no electrical loading was applied during the experiments, only free-run performance was assessed based on airflow and rotor speed. All measuring instruments were calibrated prior to testing: the anemometer had an accuracy of ±0.1 m/s, and the tachometer had an accuracy of ±1 RPM. Data were recorded using a data acquisition system after reaching steady-state conditions at each wind speed setting.

4.5 Testing procedure

For each configuration (with concentrator vs. without concentrator, and different concentrator angles), the wind speed was incrementally increased from the lowest to the highest value in steps of approximately 0.5-1 m/s. At each step, the turbine's steady rotational speed (and power output, if measured) was recorded. Each measurement was repeated at least three times to ensure repeatability. The results reported are the averages of these repeated measurements. The variability between repeats was generally small; the standard deviation in rotational speed was typically under 5% of the mean, even at lower wind speeds. We conducted an uncertainty analysis for the key measurements: the uncertainty in wind speed is approximately ±2%, and the uncertainty in the rotational speed measurement is about ±1% (at high speeds, corresponding to roughly ±5-10 RPM). We also estimated the uncertainty in the computed power output (for the loaded cases) to be within ±5%, accounting for instrument precision and experimental fluctuations.

4.6 Data presentation

The experimental results are presented in both tabular and graphical form for clarity. Wind speed (in m/s) and the corresponding turbine rotational speed (in revolutions per minute, RPM) are tabulated for each scenario. We use the notation "WECS" to represent the presence of the wind concentrator system and "without WECS" to refer to the baseline turbine without the concentrator. For the yawed configurations, the angle (e.g., 15°, 25°, 35°) represents the angle between the central axis of the concentrator (and turbine) and the wind direction. In the figures, data points are plotted, and curves are fitted to illustrate trends. Error bars (where visible) represent the variability in repeated measurements, but in many cases, the spread is smaller than the symbol size.

By implementing the above experimental methodology, we ensured that the evaluation of the concentrator system was both systematic and reliable. The controlled environment and repeated measurements provide confidence that the observed performance differences are due to the concentrator's effect and not random fluctuations. In the following section, we present the experimental results and discussion, comparing the turbine performance with and without the concentrator under various conditions.

5 Experimental results and discussion

The performance of the wind turbine, both with and without the concentrator (WECS), was evaluated based on its rotational speed under different wind speeds and setup configurations. Initially, baseline tests were performed without the concentrator to establish a reference. These results are summarized in Table 1 and Figure 5. Subsequently, tests were repeated with the concentrator in place (aligned with the wind, 0° yaw), as shown in Table 2 and Figure 6. Finally, the turbine and concentrator assembly were tested at yaw angles of 15°, 25°, and 35° relatives to the wind direction to assess how misalignment affects performance; the results for 15°, 25° and 35° are presented in Tables 3-5 and Figures 7-9. (In these tables, the data are organized in two columns for clarity, but each pair of columns corresponds to the same test condition.)

The obtained baseline results (without any concentrator in front of the propeller blades) are presented in Table 1.

Table 1. Variation of the wind turbine's rotational speed with wind speed without WECS (baseline)

Wind Speed	Rotation	Wind Speed	Rotation
2.5	70	7.7	376
3.7	81	7.9	391
3.8	97	8.1	414
4.7	120	8.7	468
5.1	143	9.7	536
5.4	178	10.3	578
5.8	218	11.7	603
7.0	327	11.9	630

Wind speed in m/s; Rotation in rev/min

The rotational speed of the wind turbine increases almost linearly with wind speed in this regime, as shown in Figure 5. For instance, at a wind speed of 9.5 m/s (approximately corresponding to the 9.7 m/s entry in Table 1), the wind turbine reaches approximately 536 rev/min (RPM). This linear trend is expected for a free-running turbine at relatively low tip-speed ratios, where aerodynamic drag increases with speed, but no load is applied. These baseline measurements serve as a reference for quantifying the improvement resulting from the concentrator.

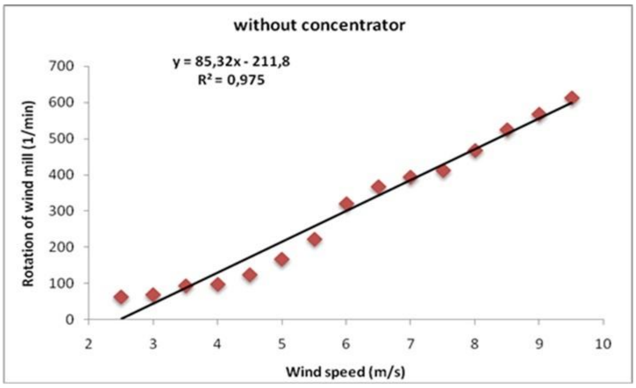

Figure 5. Variation of wind turbine rotational speed with wind speed without the WECS (baseline case)

When the concentrator (WECS) is added (Table 2 and Figure 6), the turbine's rotational speeds at equivalent wind velocities are significantly higher than the baseline. For example, without the concentrator, approximately 536 RPM was observed at ~9.7 m/s, whereas with the concentrator, approximately 580 RPM was achieved at 9.5 m/s and 643 RPM at 9.8 m/s, indicating a significant improvement.

Table 2. Variation of the wind turbine's rotational speed with wind speed with the concentrator (WECS, 0° alignment)

Wind Speed	Rotation	Wind Speed	Rotation
2.6	93	8.7	498
3.1	115	9.5	580
3.6	140	9.8	643
3.8	158	10.3	738
4.1	190	10.9	795
5.6	216	11.3	890
6.2	280	13.7	1077
7.7	429	13.9	1130

Wind speed in m/s; Rotation in rev/min

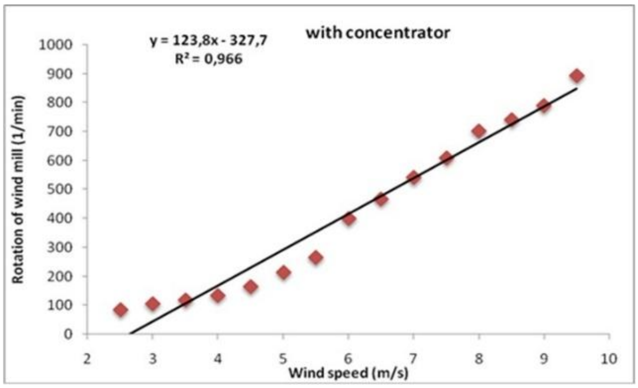

Figure 6. Variation of wind turbine rotational speed with wind speed with the WECS (0° concentrator angle)

When the concentrator (WECS) is added (Table 2 and Figure 6), the turbine's rotational speeds at equivalent wind velocities are significantly higher than the baseline. For example, without the concentrator, approximately 536 RPM was observed at ~9.7 m/s, whereas with the concentrator, approximately 580 RPM was achieved at 9.5 m/s and 643 RPM at 9.8 m/s, indicating a significant improvement. At lower wind speeds, the relative gain is even more pronounced: at approximately 3.8 m/s, the turbine rotated around 97 RPM without WECS, whereas the concentrator enabled around 158 RPM at a similar speed (3.8 m/s) – an increase of approximately 63%. On average, the concentrator system increased the free-running rotational speed by approximately 39% across the tested wind speed range, indicating a significant improvement in performance. This enhanced rotation implies that the concentrator is successfully channeling more wind through the rotor or increasing the effective wind speed at the rotor. It is worth noting that the highest rotational speeds recorded (e.g., 1130 RPM at 13.9 m/s with WECS) are significantly higher than those in the baseline (630 RPM at 11.9 m/s), reflecting how the concentrator allows the turbine to capture more of the wind's energy. If the turbine were connected to a generator under load, this higher rotational speed (at a given wind speed) would result in greater power output. In fact, based on these results, the power output of the turbine with the concentrator is estimated to be significantly higher than without it. A rough calculation suggests an increase of approximately 50% or more in the low-to-mid wind speed range, since power scales with the cube of wind speed and the concentrator effectively raises the wind speed seen by the turbine. This estimation is consistent with other studies that showed significant increases in power coefficient with augmentation [15].

After establishing the baseline (0°) performance, we investigated the effect of wind direction misalignment on the system. The concentrator was yawed by 15°, 25°, and 35° relative to the incoming wind while measuring performance both with and without the concentrator. The results for a 15° yaw angle are presented in Table 3 and Figure 7.

Table 3. Effect of wind speed on wind turbine rotational speed for WECS at 15° concentrator angle

Wind Speed	Rotation	Wind Speed	Rotation
3.3	92	7.8	360
3.6	118	9.2	470
3.9	166	10.0	554
4.6	198	10.5	692
4.8	231	11.6	732
5.6	251	12.5	815
6.2	273	13.3	920
7.7	347	13.7	984

Wind speed in m/s; Rotation in rev/min

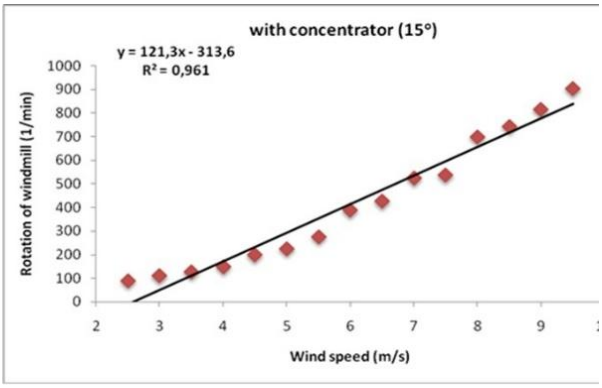

Figure 7. Effect of wind speed on the turbine's rotational speed for WECS at 15° concentrator angle

When the concentrator (and turbine) is turned 15° relative to the wind direction, the relationship between wind speed and rotor RPM is shown in Figure 7. We also compared this to the scenario without the concentrator at 15° (not all the data is shown in the table, but key points were observed). For the 15° yaw case, we found that the concentrator still provides a benefit, but its effectiveness is somewhat reduced compared to the head-on (0°) case. For the case without the concentrator at 15°, although the shaft's rotational speed improved slightly compared to the original orientation (0°, no concentrator) due to the turbine effectively encountering some crosswind, it remained slightly lower than the case with the concentrator at 15° for most wind speeds. In other words, even with a 15° misalignment, the WECS still provided higher RPM than the scenario without the WECS. However, as the yaw angle increases, the concentrator's advantage diminishes. At larger misalignment angles, the turbine without the concentrator may perform better than with the concentrator, especially if the concentrator is not facing the wind directly. In the 15° case examined here, the difference between having the concentrator and not having it was smaller than in the 0° case. At high wind speeds in the 15° scenario, the performance of the turbine with the concentrator versus without became very similar-the curves in Figure 7 converge at the upper end, indicating that at high wind speeds, a 15° yawed concentrator offers little advantage, and both configurations yield nearly the same rotational speed.

For a larger yaw angle of 25°, similar trends were observed, but they were more pronounced. The data for the 25° concentrator angle are shown in Table 4 and Figure 8.

Table 4. Effect of wind speed on wind turbine rotational speed for WECS at 25° concentrator angle

Wind Speed	Rotation	Wind Speed	Rotation
3.1	88	8.2	374
3.6	116	9.3	472
4.0	165	10.1	550
4.3	185	10.6	690
4.9	229	11.9	743
5.8	248	12.3	807
6.6	279	13.6	915
7.8	345	13.9	970

Wind speed in m/s; Rotation in rev/min

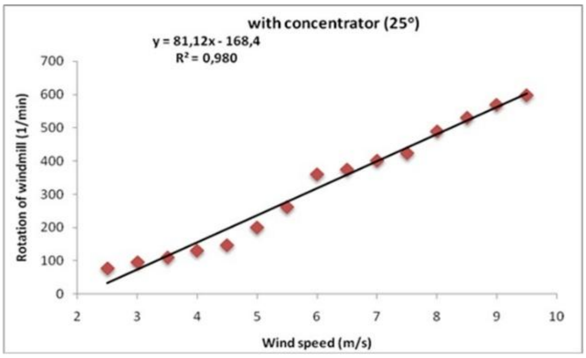

Figure 8. Effect of wind speed on the turbine's rotational speed for WECS at 25° concentrator angle

With a 25° yaw misalignment, the turbine's rotational speed with the WECS (Figure 8) is noticeably lower than in the 0° and 15° cases, as expected. Although the rotor speed with the concentrator at 25° is still higher than the corresponding case without the concentrator (25° no-WECS) at most wind speeds, it is lower than the performance at the initial 0° position. In other words, the concentrator provides diminishing returns as it turns away from the wind. The "best" performance was at 0° (direct alignment), and at 25° we observed a drop in RPM across all wind speeds. For example, at approximately 13.5 m/s, the 25° WECS case reaches about 970 RPM, whereas the 0° WECS case (Table 2) achieved over 1100 RPM at a similar speed. The non-concentrator case at 25° (not shown fully) yielded slightly lower RPMs than the concentrator case, but the gap between them has narrowed compared to smaller yaw angles. This suggests that if the wind direction deviates significantly (25° or more) from the concentrator's orientation, the benefit of the concentrator can be largely negated. It emphasizes the importance of either designing the concentrator to be somewhat rotational or using a yaw control system to keep it aligned with the wind for maximum benefit.

Finally, tests were conducted at a 35° misalignment angle. The results are summarized in Table 5. In this extreme case, the concentrator is largely turned away from the wind, so we expect minimal benefit or even adverse effects.

Table 5. Effect of wind speed on wind turbine rotational speed for WECS at 35° concentrator angle

Wind Speed	Rotation	Wind Speed	Rotation
2.7	81	8.2	361
3.1	105	8.8	442
3.8	145	9.7	469
4.4	160	10.0	583
5.1	192	10.8	612
5.9	211	11.2	684
6.4	237	13.1	764
7.8	325	13.5	801

Wind speed in m/s; Rotation in rev/min

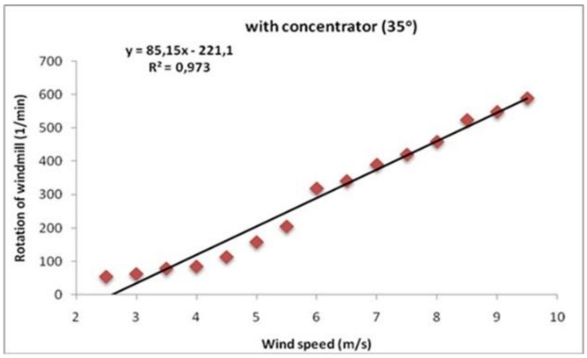

Figure 9. Effect of wind speed on the turbine's rotational speed for WECS at 35° concentrator angle

As seen in Figure 9, the rotation of the wind turbine decreases steadily with the increasing misalignment angle of the concentrator. By the time we reach a 35° yaw (which is significantly misaligned), the concentrator provides very little advantage. In fact, the data show that at many wind speeds, the turbine's RPM with the concentrator at 35° is roughly on par with (or only slightly above) what we would expect without a concentrator. The trend from 0° → 15° → 25° → 35° clearly demonstrates that the more the concentrator is turned away from the wind, the less effective it becomes at channeling airflow to the turbine. The lowest rotational speeds of all the tested configurations were observed around the 30° concentrator angle, which suggests that there may be an optimal angle somewhere between 25° and 35° where performance drops the most. (The 30° case was not plotted as a separate figure, but intermediate measurements showed it produced the lowest RPM values, slightly below the 35° case in some instances.). This non-linear behavior might be due to how the wind starts to spill around the concentrator at certain angles, creating turbulent eddies that actually impede the rotor for moderate misalignment before the flow fully bypasses the concentrator at larger angles. In summary, keeping the concentrator aligned within about ±15° of the wind direction yields the best performance, whereas large yaw misalignments severely reduce the system's efficacy.

Overall, the experimental results demonstrate that the proposed wind concentrator system can significantly improve the performance of a small roof-mounted wind turbine when aligned with the wind. The presence of the concentrator increased the turbine's rotational speed by up to ~40% on average under direct wind conditions, which implies a substantial boost in potential power output (since power is proportional to the cube of speed). Even with minor misalignments (such as 15°), there was still a measurable performance benefit, though reduced. At large misalignments (25° and 35°), the benefit diminishes and essentially disappears, highlighting a limitation of the static concentrator approach: it is directional in nature. This could be addressed by adding a yaw control mechanism to keep the concentrator facing into the wind or by designing the concentrator in an omnidirectional manner, though the latter is challenging.

From a fluid dynamics perspective, these results also indirectly support the vortex formation mechanism described in Section 3. The improved performance with the concentrator aligned suggests that the concentrator blades successfully generate a vortex and pressure distribution that draws more air through the rotor. We did not directly visualize the airflow in this experiment (e.g., using smoke or particle image velocimetry), so we infer the vortex behavior from the performance gains. Nonetheless, the trends observed are consistent with what vortex augmentation theory predicts: more airflow and higher wind speeds at the rotor yield higher rotational speeds. The slight drop in performance at extremely high wind speeds (notice in Table 2, from 13.7 to 13.9 m/s the RPM increase is small) could be due to the turbine reaching its aerodynamic limits or increased turbulence in the concentrator at high Reynolds numbers, a phenomenon that warrants further investigation.

In the next section, we summarize the key findings of this study, discuss its contributions, and outline the limitations and future work.

6 Conclusion

Recent developments in wind turbine technology have been driven by efforts to enhance energy conversion efficiency, particularly for small-scale and building-integrated turbines. In this research, both theoretical analysis and experimental investigations were employed to assess the impact of a novel concentrator system on the performance of a roof-mounted wind turbine. A newly designed vortex-based wind concentrator was implemented around the turbine to regulate airflow by accelerating the incoming wind and directing it at an optimal angle before it reaches the rotor blades. The primary objective was to demonstrate the benefits of incorporating a concentrator around a rooftop wind turbine and to quantify its role in improving overall efficiency.

The results of the study demonstrate that adding a wind concentrator leads to a significant improvement in turbine performance. In free-running (unloaded) conditions, the wind rotor's rotational speed increased by an average of approximately 40% with the WECS, highlighting the concentrator's effectiveness in enhancing small-scale wind energy generation. The increase in rotor speed suggests that significantly greater mechanical power could be extracted when the turbine is under load. For instance, at a representative wind speed, the concentrator-enabled turbine produced notably higher RPM (and thus higher tip-speed ratio) than the conventional setup, which would result in higher electrical output for a given generator. The concentrator effectively reduced the required rotor swept area by a factor of about six to achieve the same rotational speed as the baseline case. In other words, a much smaller turbine with the concentrator can achieve the same rotational speed as a larger turbine without it, reflecting a dramatic focusing of airflow. Compared to conventional shrouds or diffusers studied in the literature, the proposed concentrator system in this study is not only lighter and simpler to construct but also more effective in directing airflow to the rotor. It leverages the natural acceleration of wind over the roof edge and augments it with a vortex concentrator to achieve higher local wind speeds at the turbine plane.

One of the practical advantages of our design is its relevance to urban or off-grid settings: wind turbines in such environments must account for variable wind flow patterns and often require low-noise operation. The placement of the turbine-concentrator system at the edge of a building's roof ensures that the energetic airflow (which the building's presence helps create) is efficiently captured. This design thereby improves wind energy extraction by utilizing the naturally occurring updraft and vortex over the roof, leading to enhanced power generation and improved operational stability of the turbine. Additionally, the adjustable nature of the WECS (in terms of yaw) provides some flexibility in addressing changes in wind direction, mitigating one of the challenges of fixed concentrator installations. We found that within a ±15° yaw misalignment, the concentrator still offers performance benefits, which suggests that a simple passive yaw mechanism (like a tail vane) could be employed to keep the system near optimal alignment most of the time.

In summary, this study's contribution lies in demonstrating a viable method to significantly improve the efficiency of small roof-mounted wind turbines through a specially designed concentrator system. The findings indicate that such a system can make decentralized wind energy more feasible by boosting output in lower wind speed conditions typically found in urban or rural installations on rooftops. The concept fills a gap in the existing body of research by focusing on vortex augmentation in the specific context of a building-integrated turbine, and the positive results underscore the potential for further development of this approach.

However, there are certain limitations to our study that must be acknowledged. First, the experiments primarily measured rotational speed (and inferred improvements in power) under free-running conditions; direct measurements of electrical power output under load were limited. This means that while we expect a roughly proportional increase in power output with the concentrator (supported by our calculations and comparable studies), the exact gain in output power and aerodynamic efficiency (C_p) was not fully characterized here. Second, the internal flow structures (such as the detailed vortex shape and turbulence generated by the concentrator) were not directly observed in this work. Our claims about vortex formation and airflow improvement are inferred from theory and indirectly supported by performance data, rather than visualized via flow diagnostics. This is a limitation because it leaves some uncertainty about how, for example, the inner and outer vortices described actually manifest in practice and whether any unanticipated flow separations occur at certain wind speeds or yaw angles. Additionally, the current prototype was tested at a relatively small scale. While the scale modeling was useful for controlled experiments, real-world conditions (including larger turbines, 3D wind fields around full-scale buildings, and structural considerations) may introduce additional challenges not captured in the small-scale tests.

Despite these limitations, the outcomes encourage several avenues for future work. Future research should focus on refining the concentrator blade geometry (e.g., using curved or airfoil-shaped vanes instead of flat plates) to further optimize airflow and increase energy extraction. Incorporating adaptive features, such as the ability for the concentrator to yaw or even adjust blade pitch with wind direction, could maintain performance gains over a wider range of conditions. Additionally, investigating the scalability of this system for larger wind turbines (or arrays of small turbines) would provide valuable insights into its broader implementation potential. To address the knowledge gap regarding flow details, future studies should include detailed flow visualization or computational fluid dynamics (CFD) analyses of the concentrator-turbine system. Such analyses would help validate the vortex formation mechanisms and identify any flow separation or loss mechanisms, enabling further design improvements.

In conclusion, the proposed concentrator system holds great potential for making wind energy more accessible, efficient, and adaptable to various environments, particularly for distributed generation in urban and rural areas. By clearly improving the performance of small-scale wind turbines without complex active control, this technology can contribute to the expansion of decentralized renewable energy solutions. Continued development and testing (both in wind tunnels and real-world installations) will be crucial to address the remaining challenges and fully realize the benefits of vortex concentrator-augmented wind turbines

Conflict of interest

The authors declare that there is no conflict of interest.

Similarity (iThenticate): 13%

References

[1] Z. Şen, Solar energy fundamentals and modeling techniques: Atmosphere, environment, climate change and renewable energy. Springer Science & Business Media, 2008. https://doi.org/10.1007/978-1-84800-134-3,

[2] W. Tong, Fundamentals of wind energy, WIT press Southampton, UK,44 , 2010. https://doi.org/10.2495/978-1-84564-205-1/01.

[3] I. M. Held, Large-scale dynamics and global warming, Bulletin - American Meteorological Society, 74 (2), ,228–241, 1993. https://doi.org/10.1175/1520-0477(1993)074<0228:LSDAGW>2.0.CO;2.

[4] A. Chaudhuri, R. Datta, M. P. Kumar, J. P. Davim, and S. Pramanik, Energy Conversion Strategies for Wind Energy System: Electrical, Mechanical and Material Aspects, Materials, 15 (3), 1232, 2022. https://doi.org/10.3390/ma15031232.

[5] A. İlhan, M. Bilgili, M. Sari, and B. Şahin, Economic analyses of onshore commercial large scale wind turbines installed in Turkey, Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi, 11 (1), 170–176,2021. https://doi.org10.28948/ngumuh.866312.

[6] G. M. Shafiullah, A. M.t. Oo, A. B. M. Shawkat Ali, and P. Wolfs, Potential challenges of integrating large-scale wind energy into the power grid-A review, Renewable and Sustainable Energy Reviews, 20, 306–321, 2013. https://doi.org 10.1016/j.rser.2012.11.057.

[7] R. Belu, Wind Energy Conversion and Analysis, Encyclopedia of Energy Engineering and Technology, Second Edition, 2140–2161, 2014. https://doi.org/10.1081/e-eee2-120048430.

[8] E. Pavlis, Large-Scale Wind Energy Farm Development and its Impacts on the Landscape: A Review of the Greek Case, Journal of Landscape Ecology (Czech Republic), 18, 24–61. 2025. https://doi.org /10.2478/jlecol-2025-0019.

[9] N. Aravindhan, M. P. Natarajan, S. Ponnuvel, and P. K. Devan, Recent developments and issues of small-scale wind turbines in urban residential buildings- A review, Energy and Environment, 34 (4), 1142–1169, 2023. https://doi.org/10.1177/0958305X221084038.

[10] J. Dowds et al., A review of large-scale wind integration studies, Renewable and Sustainable Energy Reviews, 49, 768–794, 2015. https://doi.org/10.1016/j.rser.2015.04.134.

[11] M. Ragheb, History of harnessing wind power, in Wind Energy Engineering: A Handbook for Onshore and Offshore Wind Turbines, Elsevier, 11–20, 2023. https://doi.org/10.1016/B978-0-323-99353-1.00017-7.

[12] O. Probst, O. Monroy, J. Martínez, and J. Elizondo, Small Wind Turbine Technology 5 Small Wind Turbine Technology, Wind turbines, 107–136, 2011. https://www.researchgate.net/publication/221911664. Accessed 15 March 2025

[13] K. Calautit and C. Johnstone, State-of-the-art review of micro to small-scale wind energy harvesting technologies for building integration, Energy Conversion and Management: X, 20, 100457, 2023. https://doi.org/10.1016/j.ecmx.2023.100457.

[14] S. H. Chang, Q. H. Lim, and K. H. Lin, Design of a wind energy capturing device for a vehicle, in Proceedings - International Conference on Intelligent

Systems, Modelling and Simulation, ISMS, 2015-Septe, 435–440, 2015. https://doi.org/10.1109/ISMS.2014.80.
[15] M. Heragy, T. Kono, and T. Kiwata, Investigating the effects of wind concentrator on power performance improvement of crossflow wind turbine, Energy Conversion and Management,255, 15326, 2022. https://doi.org/10.1016/j.enconman.2022.115326.
[16] R. Carriveau, Fundamental and Advanced Topics in Wind Power. BoD–Books on Demand, 2012. https://doi.org/10.5772/731.
[17] D. Le Gourieres, Wind power plants: theory and design. Elsevier, 1982. https://doi.org /10.1115/1.3267641.
[18] L. Dodson, K. Busawon, and M. Jovanovic, Estimation of the power coefficient in a wind conversion system, in Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference, CDC-ECC '05,2005, 3450–3455,2005. https://doi.org /10.1109/CDC.2005.1582696.
[19] V. P. Khambalkar, D. S. Karale, and S. R. Gadge, Performance evaluation of a 2 MW wind power project, Journal of Energy in Southern Africa, 17 (4), 70–75, 2006. https://doi.org/10.17159/2413-3051/2006/v17i4a3232.
[20] B. Desalegn, D. Gebeyehu, and B. Tamirat, Wind energy conversion technologies and engineering approaches to enhancing wind power generation: A review, Heliyon, 8 (11), e11263, 2022. https://doi.org/j.heliyon.2022.e11263.
[21] A. Betz, Introduction to the Theory of Flow Machines. Elsevier, 1966. https://doi.org/10.1016/c2013-0-05426-6.
[22] Y. Keleshibieke, Wind turbine optimization, Nazarbayev University, 2019. https://nur.nu.edu.kz/handle/123456789/3760. Accessed 16 May 2025
[23] M. Shoaib, I. Siddiqui, S. Rehman, S. Khan, and L. M. Alhems, Assessment of wind energy potential using wind energy conversion system, Journal of Cleaner Production, 216, 346–360, 2019. https://doi.org/10.1016/j.jclepro.2019.01.128.
[24] R. C. Bansal, T. S. Bhatti, and D. P. Kothari, On some of the design aspects of wind energy conversion systems, Energy Conversion and Management, 43 (16), 2175–2187, 2002. https://doi.org/10.1016/S0196-8904(01)00166-2.
[25] G. Tefera, G. Bright, and S. Adali, Theoretical and computational studies on the optimal positions of NACA airfoils used in horizontal axis wind turbine blades, Journal of Energy Systems, 6 (3), 369–386, 2022. https://doi.org/10.30521/jes.1055935.
[26] V. Nelson, Vertical Axis Wind Turbines, Innovative Wind Turbines,1 (40), 63–90, 2019. https://doi.org/10.1201/9781003010883-4.
[27] J. Svorcan, O. Peković, A. Simonović, D. Tanović, and M. S. Hasan, Design of optimal flow concentrator for vertical-axis wind turbines using computational fluid dynamics, artificial neural networks and genetic algorithm, Advances in Mechanical Engineering, vol. 13(3), 16878140211009008, 2021. https://doi.org/10.1177/16878140211009009.