

SMALL-SCALE WIND TURBINE ENERGY PRODUCTION IN AN URBAN ENVIRONMENT

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In this study, a commercial small-scale wind turbine (400 W, horizontal-axis wind turbine) is installed in an urban environment. A custom-built current and voltage monitoring system is developed to record the turbine's power and energy production. The design and implementation of this system are presented in this study. Urban environments contain various obstacles and are generally not favourable for wind power generation. In this study, we investigate the realistic energy production potential of such a small-scale wind turbine under urban conditions. Windiness varies substantially in these areas, and significant fluctuations can occur within a single day. Our results show that a small-scale wind turbine with a nominal power of 400 W can produce approximately 10–15 Wh per day under favourable wind conditions. The measured peak power is around 85 W, which is considerably lower than the turbine's nominal rating. Unlike manufacturer specifications and simulation-based studies, this study presents real-world measured power and energy data from an urban pico wind turbine installation.

Keywords: Horizontal-axis wind turbine, wind power generation, wind turbine.

1. INTRODUCTION

The green energy transition has introduced new alternatives for generating electricity also in typical households. Solar panel installations have become increasingly popular due to improvements in efficiency and, in particular, decreasing prices that have accelerated their adoption. However, solar power has inherent limitations

and is not always an optimal solution in the northernmost regions, and, of course, at nighttime. Small-scale wind power generation may serve as a valuable complement to solar power in windy areas, as it can provide additional energy production during long winter periods and nighttime hours.

A limitation of wind power in urban

areas or for individual households is that the physical dimensions of the turbine must remain within certain constraints. The power ratings typically feasible for installation in urban small-house settings are below 1 kW. Wind turbines within this range are classified as pico wind turbines (PWDs), characterised by rotor swept areas smaller than 4.9 m² [1]. This study focuses on PWDs. Several studies have examined the efficiency and economic viability of small-scale wind turbines [2], [3], with promising results. Both self-constructed and commercially available small-scale wind turbines have been employed in previous research [4]–[7].

The small-scale wind power system consists of a commercial wind turbine with a nominal power of 400 W. The wind turbine is a horizontal-axis wind turbine (HAWT) with three blades. It is equipped

with a three-phase generator. The wind turbine's three-phase, variable-voltage AC output is connected to a power electronics unit that converts the AC voltage to DC voltage. This conversion is integrated into a maximum power point tracking (MPPT) unit. The MPPT unit is also commercial and was supplied together with the wind turbine. Used MPPT is based on a pulse-width modulation (PWM) technique.

The study presents a constructed wind turbine system, including monitoring and control components. Furthermore, the actual power and energy production performance of the wind turbine is reported for three different days. Finally, the suitability and practical usability of the wind turbine are discussed. In addition, some improvements and alternative solutions for traditional VAWTs are presented.

2. A SMALL-SCALE WIND POWER PLANT MEASURING SYSTEM

The commercial wind turbine (VEVOR 400 W) was selected for this installation. The choice was based on recommendations and its suitability for northern, cold-weather conditions, with price also being a key factor. The manufacturer states that the wind turbine can operate at temperatures as low as -35 °C. This is important because the site is located in Finland, where winter temperatures can drop significantly. The combined cost of the wind turbine and charge controller was less than 150 euros. The wind turbine is a traditional three-blade design with a rotor radius of 65 cm. Figure 1 shows the wind turbine installation. The wind turbine reaches about one meter above the roof ridge.

It is crucial to continuously monitor

the power output of the wind turbine. To enable continuous monitoring, a custom current and voltage measurement system was developed. The output of the wind turbine's MPPT (maximum power point tracking) is designed for use with a 12 V battery, and thus its voltage output is approximately 12 V. The MPPT ensures a stable voltage output under varying wind conditions. The nominal power of the wind turbine (400 W) is achieved at a wind speed of 12 m/s, according to the manufacturer's datasheet. Although the nominal output corresponds to a current of 33.3 A (400 W / 12 V), a more realistic maximum output under typical conditions is around 200 W, corresponding to 16.7 A (200 W / 12 V).



Fig. 1. The wind turbine installation. The crossbeam shown in the picture prevents lateral movement and vibration of the wind turbine mast. The crossbeam was not included in the original design, but after initial experience, it proved necessary. The MPPT is located under the eaves, protected from moisture, while the other electronics are housed in a heated building. The MPPT cannot be installed inside the building, as the cable length would be too long in that case.

For current measurement, an ACS712T current sensor with a maximum current rating of 20 A was selected. The sensor outputs a voltage proportional to the current, where 2.5 V represents 0 A, and the sensitivity is 100 mV/A. For example, a voltage reading of 3.2 V corresponds to a current of 7 A. The theoretical maximum sensor output is 5 V, corresponding to 25 A. An Arduino Uno microcontroller, which features a 10-bit analog-to-digital converter (ADC) with a 0–5 V input range, is used for data acquisition. The Arduino Uno ADC provides a resolution of approximately 5 mV. The ACS712T current sensor can be connected directly to the Arduino. No additional calibration was performed beyond factory calibration for voltage and current sensors.

The wind turbine's output voltage, however, ranges from 0–12 V and cannot be read directly by the Arduino microcontroller. Therefore, the wind turbine output is connected to a voltage conversion board (WPSE350, voltage sensor module) that scales the 0–12 V output to the 0–5 V range

suitable for the microcontroller. The wind turbine output is also connected to the battery and load control unit, which converts 12 V DC to 230 V AC. The battery voltage is continuously monitored, and if it drops below 13 V, the load is disconnected, allowing the battery to charge exclusively. Load control is implemented using a solid-state relay (SSR) controlled by the Arduino. The SSR prevents excessive battery discharge, thereby prolonging battery lifetime. A common 12 V, 5 Ah lead-acid battery is used. One disadvantage of using an SSR is the associated small power loss (below 1 W).

The microcontroller is connected to a server via a serial bus, and voltage and current readings are recorded every 60 seconds in separate files. Both the maximum and average values over each 60-second interval are saved. A separate file is generated for each day, containing 1440 voltage and current measurements. Based on this data, it is possible to estimate the wind turbine system's long-term energy production and power output with reasonable accuracy and

realism. The same software that runs on the microcontroller also controls the SSR and reads and records voltage and current values. Figure 2 illustrates the overall structure of the wind turbine system, including the monitoring and control components.

The system has been designed to minimise overall maintenance. Only the battery condition needs to be checked semiannually, and the mechanical fastenings should be inspected at least once per year. Otherwise, the system is virtually maintenance-free.

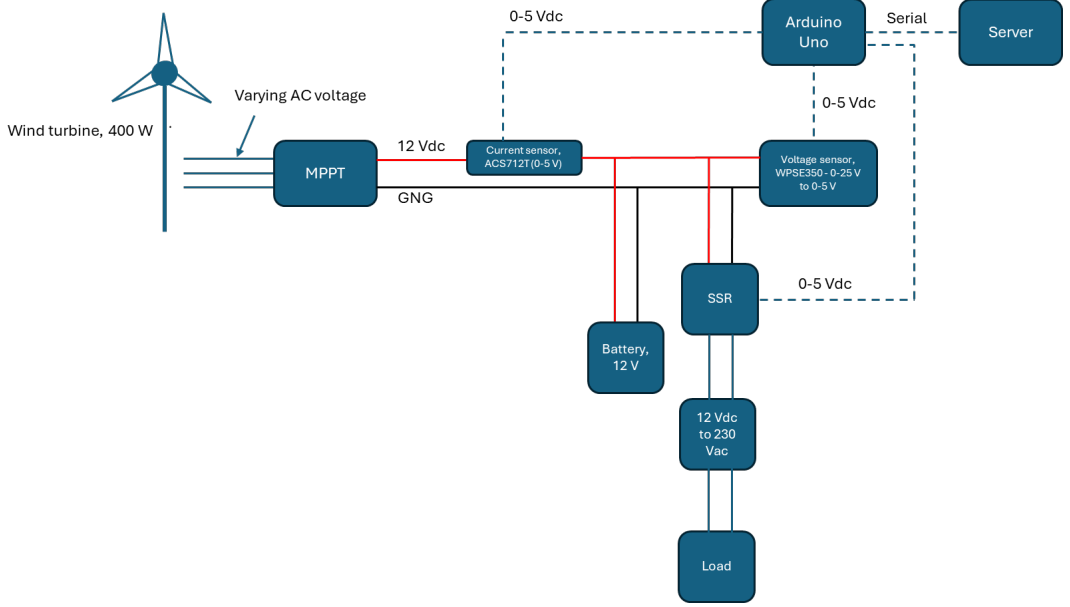


Fig. 2. The schematic and operating principle of a small-scale wind turbine system. Dashed lines represent monitoring and control lines, while solid lines represent power lines.

The wind turbine is installed at a height of approximately 4 meters above ground level. From one direction (south), the turbine is partially blocked by a building, making the location suboptimal. The other three main directions are mainly free from obstacles. The surrounding terrain is mostly flat. The turbine is a traditional horizontal-axis, three-blade model with a blade radius of 0.65 m. The theoretical power output (P) of the turbine can be calculated as follows:

$$P = \frac{1}{2} v^3 \rho \pi R^2 C_p \eta_{ele},$$

where R is the radius of the wind turbine blades, v is the wind speed, ρ is the air density, C_p is the power coefficient of the tur-

bine, and η_{ele} is the estimated efficiency of the power electronics and generator (0.95).

According to Betz's law, the maximum theoretical value of the power coefficient is 0.593 (59.3 %) [1]. In practice, the power coefficient is lower; for a well-designed turbine, C_p is typically around 0.35 [4]. The efficiency of the power electronics (MPPT and voltage conversion) must also be considered. Modern power electronic systems generally have high efficiencies, often exceeding 90 %. Figure 3 illustrates the wind turbine's power output performance: the curve formed by red dots is provided by the manufacturer, while the blue dots represent the theoretical performance.

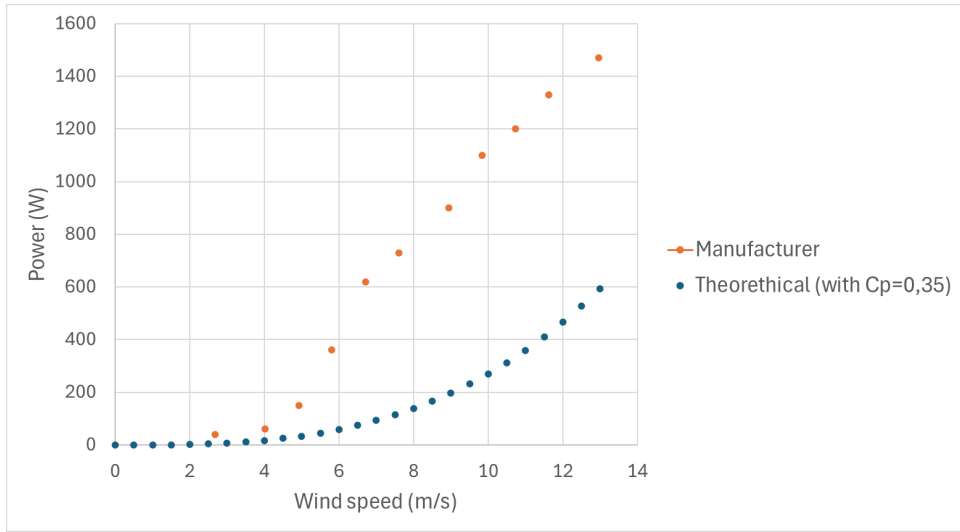


Fig. 3. Wind turbine power output as a function of wind speed. The red dots represent the manufacturer’s reported power output, while the blue dots show the theoretical power output.

The theoretical values differ from the manufacturer’s specifications, particularly at higher wind speeds (> 5 m/s), as shown

in Fig. 3. The manufacturer’s power output curve appears to be overestimated.

3. THE PRACTICAL PERFORMANCE OF THE WIND TURBINE

We selected three days in November 2025 (28th–30th) to illustrate the energy generation of the wind power plant. The first two days represent relatively windy conditions at the site, while the last day corresponds to moderate or low wind conditions. As mentioned earlier, one-minute average values of voltage and current were recorded, and these values were used to estimate the energy production. In addition, the maximum peak power values represent the total potential power output of the wind power plant.

Figure 4 shows both the average and maximum power production. The peak power during this day was approximately 80 W, and the average power level was

around 15 W. It can be observed that the day was windy throughout, with the windiest period occurring before 12:00. Based on the 60-second average voltage and current values, the total daily energy production is 6.66 Wh.

The second selected day (29 November 2025) was also windy. The strongest winds occurred between 6:00 a.m. and 12:00 p.m., meaning that the period of high wind intensity lasted for roughly one quarter of the day. Figure 5 shows the power production profile for 29 November 2025. The peak power during this day was approximately 85 W, and the average power level was around 16 W. The total energy production for this day was 8.58 Wh.

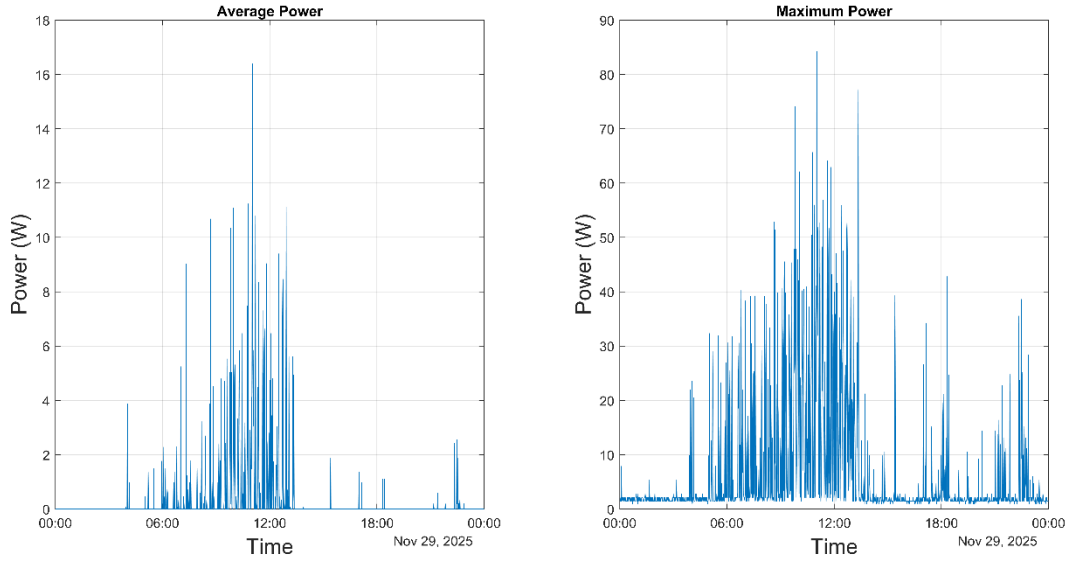


Fig. 4. Wind turbine power production on 28 November 2025. The left panel shows the average power production, while the right panel shows the maximum power production.

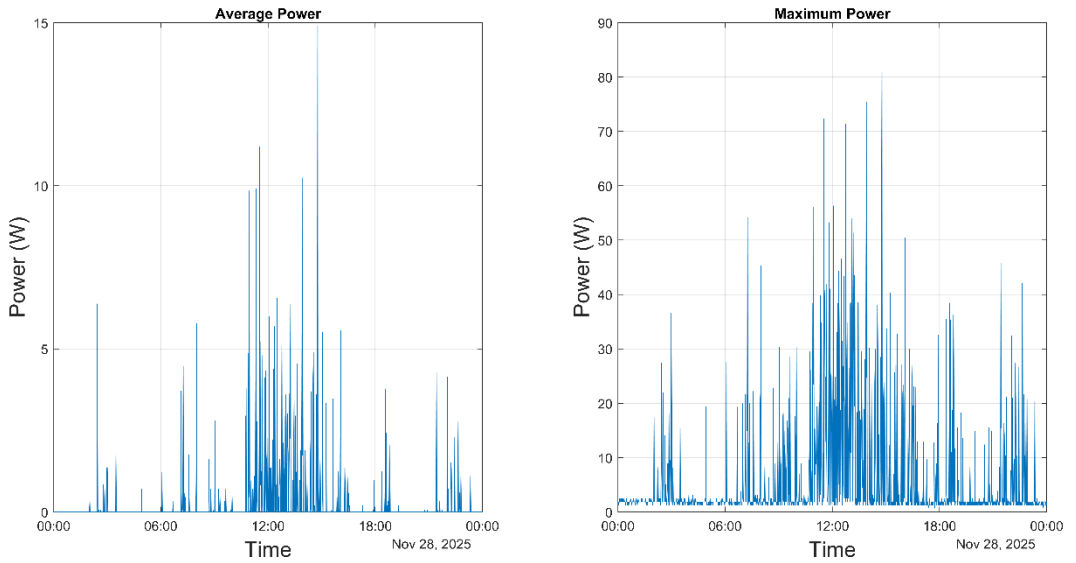


Fig. 5. Wind turbine power production on 29 November 2025. The left panel shows the average power production, while the right panel shows the maximum power production.

The third day represents a typical day with very low wind intensity (Fig. 6). Only a few gusts occurred during the early hours of the day. The total energy production was

only 0.8 Wh. The peak power during this day was approximately 34 W, while the average power level was around 5 W.

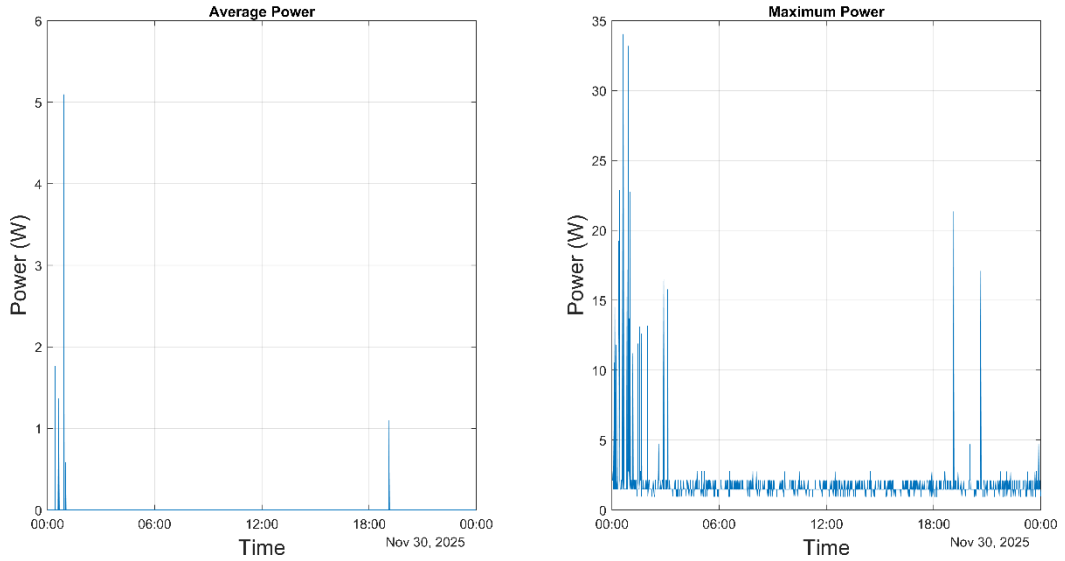


Fig. 6. Wind turbine power production on 30 November 2025. The left panel shows the average power production, while the right panel shows the maximum power production.

These examples highlight the variability of wind conditions in urban areas. There are days with almost no wind and days with relatively favourable wind conditions. Moreover, even on windy days, wind intensity rarely remains constant throughout the entire day. These characteristics make the estimation of wind energy production challenging. However, based on the examples presented, a realistic daily energy yield during a consistently windy day could reach approximately 10–15 Wh at maximum. This corresponds to charging a small battery (e.g., 7.2 Ah / 12 V) in roughly five

days, which is relatively modest.

In 2025, the average spot electricity price was 0.0494 €/kWh. The total cost of the described wind turbine system is approximately 500 euros, which means the wind power plant must produce 10121.46 kWh to cover the payback. Under current Finnish electricity prices, grid-connected economic payback is not achievable for the present installation. However, it is important to note that such turbines are primarily designed for locations without access to the power grid, and the payback time is not the most important criterion.

4. DISCUSSION AND CONCLUSION

Suburban environments typically contain numerous obstacles, such as buildings and trees, which create unfavourable conditions for wind power generation. These obstacles can create turbulence, which further reduces energy production. In the pres-

ent installation, as previously mentioned, obstacles are also present. When the prevailing wind comes from the direction of these obstacles, the wind turbine may not rotate, and consequently, it does not generate energy. This effect was clearly observed

in our installation. Identifying a proper location for the wind turbine is therefore the most important factor when assessing the effectiveness of small-scale wind turbines in suburban areas.

In addition, a higher-quality MPPT can improve the wind turbine's energy production, particularly at low wind speeds. The current MPPT is a standard type or simple PWM (Pulse-width Modulation) controller and is not optimised for lower wind speeds. Since wind speeds are generally low in suburban areas, a 5-bladed wind turbine could be more practical. Five-bladed turbines begin to rotate at lower wind speeds, which could enhance energy production in suburban applications. Increasing the tower height would also improve energy capture; however, this requires more complex mechanical structures, such as guy ropes, and may necessitate construction permits, complicating the installation process. The effect of tower height on wind speed can be estimated using the following formula:

$$v_h = v_{ref} \times \left(\frac{h}{h_{ref}} \right)^\alpha,$$

where v_h is the wind speed at height h , v_{ref} is the wind speed measured at a reference height h_{ref} and α is a surface roughness exponent, typically 0.1–0.3. For urban areas, a wind shear exponent value of 0.22 has been used [8].

This implies that increasing the tower height from 4 meters to 6 meters would result in an average wind speed approximately 10 % higher. Since the power output of a wind turbine is proportional to the cube of the wind speed, even a modest increase in wind speed can lead to a significant increase in power generation. The surface roughness exponent is higher, for example, during gusts. In coastal and archipelago regions, the wind turbine under study is capable

of achieving significant power output and electricity generation.

The total cost of described wind turbine system is approximately 500 euro. This sum also includes cost of parts of mechanical installation and voltage and current monitoring/recording system. The recording system is not mandatory and removing that reduces cost around 100 euro. Based on this experience, it is difficult to draw definitive conclusions regarding the financial profitability of a small-scale wind turbine. In suburban areas, in particular, profitability is uncertain due to generally suboptimal wind conditions. Under optimal wind conditions, however, the financial outcome could be markedly different. For the present site, the installation is not financially profitable, but at another location, the situation could change entirely. It should also be noted that small-scale wind turbines are primarily intended for locations without access to a power grid, where financial profitability is not the only metric for assessing their usability.

The small-scale wind turbine system is technically relatively simple, even without a dedicated current and voltage monitoring arrangement, which supports its practical usability. Operating the turbine in island mode (off-grid) is particularly advantageous, for example, in combination with solar panels. Together, wind and solar systems can form an efficient and functional electricity generation setup.

Unfortunately, real wind speed data are not available for this installation. One clear improvement would be the addition of a wind speed meter, which would allow energy production data to be correlated with actual wind speeds. Without accurate wind speed measurements, it is not possible to determine how windy the selected location truly is. Additionally, knowledge of the prevailing wind direction is an important

parameter when assessing the overall wind energy potential of a site. With this information, the placement of the wind turbine can be designed more efficiently, even in an urban environment, to determine which side of the roof would be the most suitable location.

Although the selected measurement site represents a typical suburban location, a more accurate assessment of overall performance would benefit from installing a similar wind turbine at an additional site. Unfortunately, the current system is not portable and cannot be easily relocated to an alternative location.

Although the present study focuses on a horizontal-axis wind turbine, alternative turbine concepts may be more suitable for

low-wind urban environments. The potential option could be a vertical-axis wind turbine (VAWT), which is typically designed for lower power ranges. In general, VAWTs exhibit relatively good efficiency at low wind speeds, making them suitable for suburban or low-wind environments. Manufacturers' claims regarding the nominal output power of wind turbines are often significantly overestimated. In practice, the actual output power can be less than half of the advertised nominal power. The use and potential of cross-axis wind turbines, which can be integrated into the roofs of detached houses, have also been studied [9]. These turbines represent a promising and potentially high-efficiency solution for wind power generation in urban areas.

REFERENCES

1. Rosato, A., Perrotta, A., & Maffei, L. (2024). Commercial small-scale horizontal and vertical wind turbines: A comprehensive review of geometry, materials, costs and performance. *Energies*, 17(13), 3125. <https://doi.org/10.3390/en17133125>
2. Jurasz, J., Bochenek, B., Wieczorek, J., Jaczewski, A., Kies, A., & Figurski, M. (2025). Energy potential and economic viability of small-scale wind turbines. *Energy*, 322, Article 135608. <https://doi.org/10.1016/j.energy.2025.135608>
3. Alam, F., & Jin, Y. (2023). The utilisation of small wind turbines in built-up areas: Prospects and challenges. *Wind*, 3(4), 418–438. <https://doi.org/10.3390/wind3040024>
4. Nongdhar, D., & Goswami, B. (2018). Design of micro wind turbine for low wind speed areas: A review. *ADB Journal of Electrical and Electronics Engineering*, 2(1), 36–41.
5. Kishore, R. A., Marin, A., & Priya, S. (2014). Efficient direct-drive small-scale low-speed wind turbine. *Energy Harvesting and Systems*, 1(1–2), 27–43. <https://doi.org/10.1515/ehs-2014-0004>
6. Tummala, A., Velamati, R. K., Sinha, D. K., Indrajaya, V., & Krishna, V. H. (2016). A review on small scale wind turbines. *Renewable and Sustainable Energy Reviews*, 56, 1351–1371. <https://doi.org/10.1016/j.rser.2015.12.027>
7. Barzegar-Kalashani, M., Seyedmahmoudian, M., Mekhilef, S., Stojcevski, A., & Horan, B. (2023). Small-scale wind turbine control in high-speed wind conditions: A review. *Sustainable Energy Technologies and Assessments*, 60, Article 103577. <https://doi.org/10.1016/j.seta.2023.103577>
8. Kong, S., Xiao, Y., Cao, J., & Han, Z. (2025). Adapting wind shear coefficients to urban morphology: Unlocking urban wind energy potential. *Sustainable Cities and Society*, 121, Article 106217. <https://doi.org/10.1016/j.scs.2025.106217>
9. Calautit, K., & Johnstone, C. (2023). State-of-the-art review of micro to small-scale wind energy harvesting technologies for building integration. *Energy Conversion and Management: X*, 20, Article 100457. <https://doi.org/10.1016/j.ecmx.2023.100457>