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A Wind-Powered Generator Using Wasted-Wind Energy from Air Conditioner Condenser Fan

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ABSTRACT

This paper presents the development of a wind-powered generator designed to captures and converts residual wind energy expelled from an air conditioner condenser fan into usable electrical energy. Utilizing a compact Horizontal-Axis Wind Turbine (HAWT), the system is engineered to optimize energy harvesting from low-velocity airflow generated by the condenser. The study evaluates system feasibility, energy storage efficiency, and the effects of turbine blade design and airflow conditions on performance. A custom mounting fixture was also introduced to integrate the generator seamlessly with the condenser unit. The system achieved an output of 5.1 V and 0.1 A, which falls within the standard range for small-scale applications, making it suitable for powering low-power devices or recharging compact electronics. Measurements revealed that the HAWT significantly outperformed the VAWT, generating about 3 V compared to 1.5 V, while voltage output increased with blade number, peaking at 2.1 V with 7 blades. This work achieved the shortest charging time among similar generators by introducing a lightweight turbine fixture with disk edge cut-outs that maintains strength and optimises performance. The findings demonstrate that small-scale renewable energy harvesting is both viable and practical, particularly in urban environments where air conditioning systems are prevalent. Through performance testing and comparative analysis, this work highlights a sustainable and efficient approach to reclaiming wasted energy, thereby contributing to enhanced energy recovery in modern Heating, Ventilation, and Air Conditioning (HVAC) systems.

Keywords: Renewable energy; wind energy; wind turbine; electricity generator; HVAC systems

INTRODUCTION

The increase in energy consumption worldwide, especially in regions with elevated temperatures such as Malaysia, can be attributed to the growing reliance on air conditioning systems across residential, commercial, and industrial sectors. Malaysia's humid tropical climate requires air conditioning for interior comfort. The increase in electricity consumption linked to air conditioning has escalated significantly, leading to elevated energy costs and exerting pressure on the nation's energy supply (Kubota et al. 2011; Fernandez et al. 2024). According to a study by Naja et al. (2021) on the daily use of air conditioning in 20 targeted households in Malaysia, 75% of residents used air conditioning almost every day for five to six hours per day, as shown in Figure 1.

Air conditioning condenser fans transfer heat from a building's interior to the outside environment. In doing so, the external fans create airflow that is typically released into the atmosphere and wasted. This wasted wind energy could be a promising opportunity for sustainable electricity generation (Azhar et al. 2018). However, there is a lack of accessible and efficient systems to convert this low-velocity wind energy into electricity. Additionally, challenges such as improving turbine design, handling varying wind speeds, and creating flexible mounting solutions are still not fully addressed (Al-Rawajfeh et al. 2023; Raed A. Jessam, 2022; Hemanth et al. 2018).

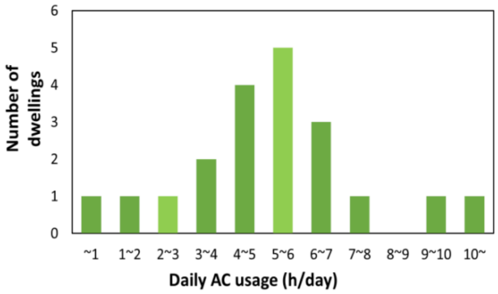


FIGURE 1. Daily hours of AC usage (Naja et al. 2021)

Addressing these issues could unlock an untapped renewable energy resource while reducing reliance on conventional energy sources, which are rapidly depleting and contributing to global environmental concerns.

However, the turbine's performance was highly sensitive to exhaust airflows, with non-uniform air streams lowering efficiency. The hybrid wind-solar system by Munira et al. (2021) showed good adaptability in low wind-speed conditions, charging small devices like cell phones in urban environments. However, the increased complexity of hybrid systems adds to the cost and maintenance. Hazran et al. (2022) demonstrated the use of dual DC generators connected to air conditioner exhausts. While the first generator failed to provide adequate voltage under low wind conditions, the second generator achieved stable power, proving that even slight optimizations in turbine placement and blade design can lead to better energy capture. Kadir et al. (2024) developed a VAWT integrated directly with a split-type air conditioner condenser unit. Their design successfully delivered steady output for low-power electronics, emphasizing the importance of aligning turbine geometry with the actual flow pattern of HVAC exhausts. However, it takes long hours to fully charge the battery.

This work demonstrates a compact wind-powered generator incorporating six HAWT units, designed to optimize energy capture from the low-velocity airflow produced by the condenser. For comparative analysis, various turbine types, blade numbers and airflow distribution were examined. The generator is supported by a custom-made mounting system that enables seamless integration of the generator with the air conditioning condenser unit. The system provides sufficient output for small-scale applications such as powering low-consumption devices and recharging portable electronics.

METHODOLOGY

Figure 2 shows the workflow for the development of the wind-powered generator system. The work is divided into three main phases: initial design and fabrication, performance optimization, and mounting system development. Each phase is organized sequentially to ensure a logical and efficient approach to the goals.

First, a preliminary design was constructed, integrating all selected components into a functional prototype for the wind-powered generator system. The constructed prototype was then tested under varying wind speed, position, and loads to observe how efficiently it converts wind energy into electrical energy. When the system does not meet the desired performance, optimization was made to improve the wind generator's efficiency, which involved modifying blade design, component alignment, and system calibration. Next, a mounting structure was designed to support and position the generator to maximize wind exposure. Installation was followed by performance testing to ensure system functionality. If results are unsatisfactory, the mounting system will be adjusted for height, tilt angle, or structural design to improve usefulness and efficiency. This cycle continues until performance is satisfactory.

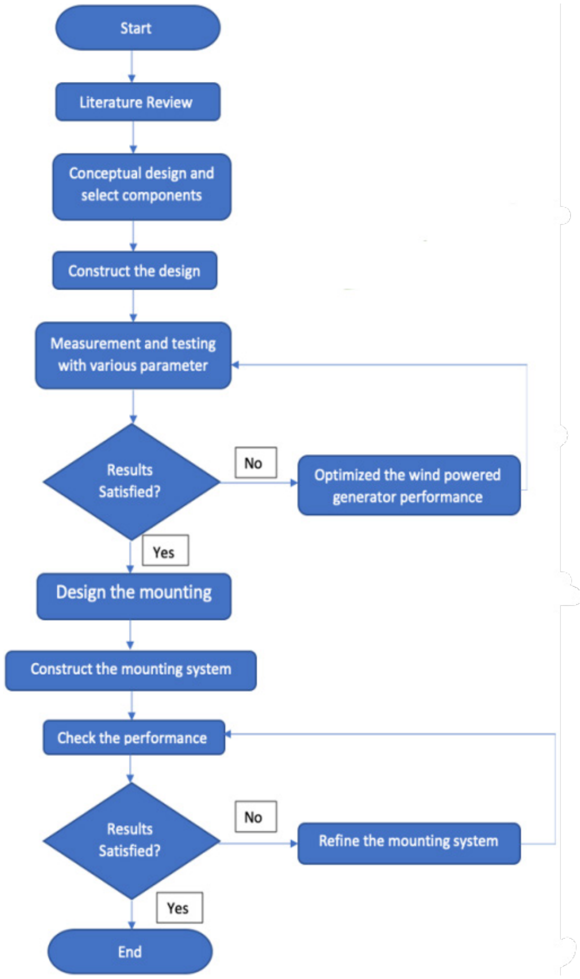


FIGURE 2. Workflow for the development of the wind-powered generator system

Figure 3 illustrates the block diagram that encompasses the input, system, and output components. The input or source of the device system was the wasted wind generated by the air conditioner compressor. The system is the component where the electricity generation process occurs. The system comprises wind turbine blades, a DC generator, a buck converter, and a charge controller. The output represents the consumer load, with appliances like lamps or bulbs utilised for system testing, and a 3.7 V rechargeable battery for portable electronics.

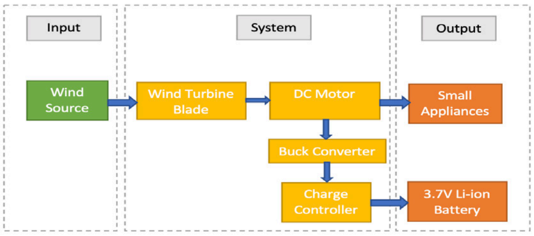


FIGURE 3. Block diagram of the system

The schematic diagram represents the electrical setup for the wind-powered generator is shown in Figure 4. It outlines the connections between key components such as the motors, step-down converter, charge controller, Arduino Uno, and voltage sensor. This system is designed to monitor the voltage produced by the wind turbines, to charge the battery, and to power small electrical appliances.

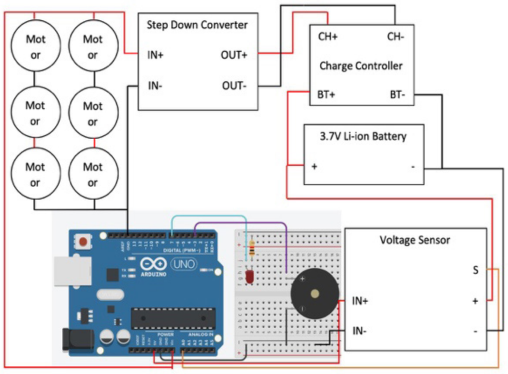


FIGURE 4. Schematic Diagram for the Electrical Setup

Wind turbines generate voltage through the spinning of their blades, which convert the kinetic energy of the wind to mechanical energy. This mechanical energy drives the generator, which produces electrical voltage through electromagnetic induction principle. Referring to the motor configuration shown in Figure 4, which consists of two rows of three turbines connected in series and arranged in parallel, a total output of 5.13 V and 0.102 A was generated. This output falls within the standard parameters for small-scale applications, rendering it appropriate for energising low-power devices or recharging compact electronics. A buck converter was used to safely step down the wind turbine output voltage to 4.2 V to meet the charging system requirements. The charge controller prevents the battery from being overcharged by regulating the power generated from the wind turbine.

A real-time battery monitoring and management system was integrated in the system to continuously monitor the battery voltage in real time using a voltage sensor directly connected to the battery. The sensor transmits voltage data to a microcontroller (Arduino, which continuously tracks the battery's state of charge. When the battery voltage reaches 3.7 V, the Arduino activates a buzzer that emits three beeps to notify the user that the battery is fully charged. This automated audible alert ensures that the user is promptly informed of the battery's condition without the need for manual monitoring. When the battery voltage falls to the predefined low-voltage threshold value, the system automatically initiates the recharging process, restoring the battery to its optimal operating voltage. This automated control mechanism ensures that the battery remains functional and ready for use at all times. An LED indicator was used to display the system's output, likely signalling operating status or powering tiny electrical equipment. An LCD screen was installed to display the battery voltage and charging percentage.

Figure 5 shows the 3D design of the turbines fixture, a circular disk with a central hole for accommodating a shaft, ensuring the fixture is securely mounted and aligned within the system. The six evenly spaced holes around the disk were specifically sized to hold the motors that drive the wind turbine blades. Motors can be securely attached to these holes for effective blade rotation. The disk's edge cut-outs minimise the weight while maintaining structural integrity, ensuring it can withstand mechanical stress while optimizing the performance of the wind-powered generator. Turbine placement in front of the condenser fan may induce back-pressure, employing light weight turbine with low-resistance designs mitigate this effect. The proposed disk's edge cut-outs fixture could help minimise drag and preserve airflow. The foundation shape and cut-outs were created in SolidWorks using Extrude, Cut-Extrude, and Revolve. Parametric modelling in SolidWorks makes it easier to adapt and modify parts depending on testing and performance data. The symmetrical design is crucial for components that are subjected to rotational forces, ensuring smooth and efficient operation within the overall wind turbine system.

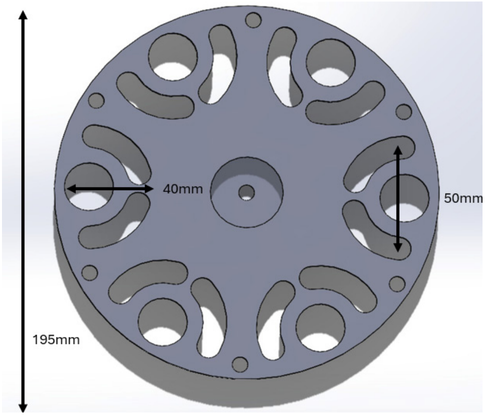


FIGURE 5. 3D Design of the Turbine Fixture

The fixture was 3D-printed using Acrylonitrile Butadiene Styrene (ABS) material for its strength, impact resistance and ability to withstand high temperatures, making it a suitable material when exposed to mechanical stress and outdoor conditions. The 7-blade turbine has a diameter of 70 mm, a chord length of 14 mm, and a blade pitch of 15°, and is made of ABS material. The turbines are designed to harness wasted wind or airflow. As the wind interacts with the blades, it produces mechanical energy, which is subsequently converted into electrical energy.

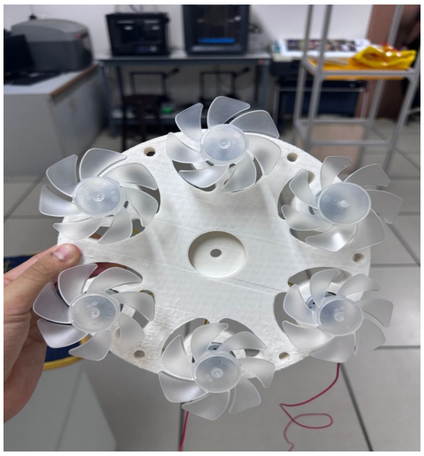
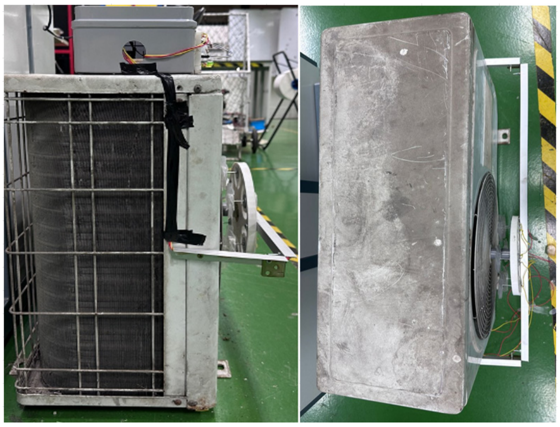


FIGURE 6. Turbine Fixture with 6 Position

The design of the wind-powered generator's mounting system is guided by the structural layout and accessibility of a 2 HP air conditioner condenser unit. Figures 7 and 8 provide front, top, and side views of the wind-powered generator installed on the air conditioner condenser unit. The front view highlights the central fan as the primary wind source, requiring clear airflow for efficiency. The top view suggests the potential use of the flat surface for lightweight brackets while avoiding electrical interference.

FIGURE 7. Front View of the Aircon Condenser Unit



(a) Side View (b) Top View

FIGURE 8. Side View and Top View of the Aircon Condenser Unit

Side views reveal maintenance zones and possible locations for external supports. The mounting system ensures structural stability, ease of installation, and operational safety without hindering the condenser's core functions. Lightweight and corrosion-resistant materials such as aluminium are chosen for the bracket to ensure outdoor durability.

RESULTS AND DISCUSSION

The 2 HP air conditioner was chosen as the primary wind source due to its widespread residential use and ability to produce consistent airflow. A single turbine was positioned 5 cm in front of the air-conditioner condenser unit to measure and compare output voltage generation. Figure 9 shows a comparison of output generation between two types of wind turbines, horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). Testing revealed that the HAWT significantly outperformed the VAWT, generating approximately 3 V compared to the VAWT's 1.5 V. The HAWT's efficiency stems from its aerodynamic blade alignment with airflow, whereas the VAWT's larger blades and multi-directional design led to reduced rotational speed and energy output. Based on these results, the HAWT was chosen as the turbine for harnessing wind energy from the 2 HP unit.

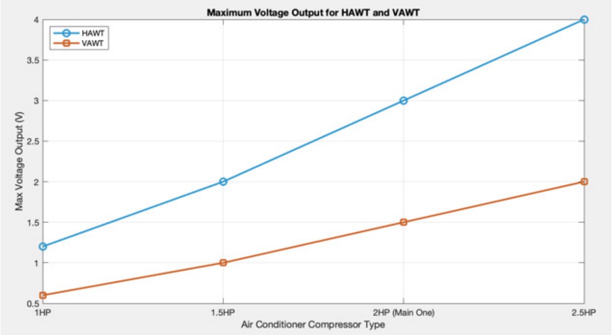
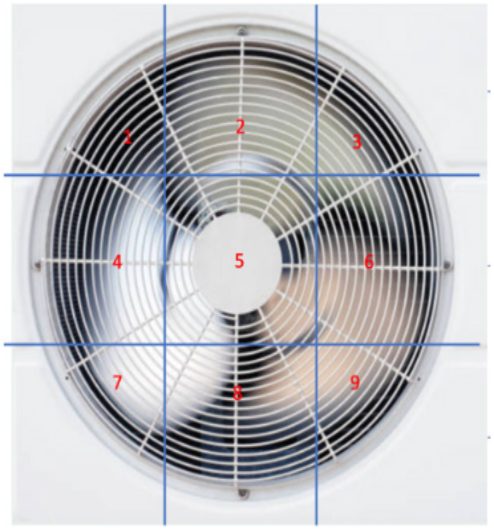


FIGURE 9. Comparison of maximum output voltage generated by HAWT and VAWT (single turbine, wind speed: 4 m/s, position: center 5)

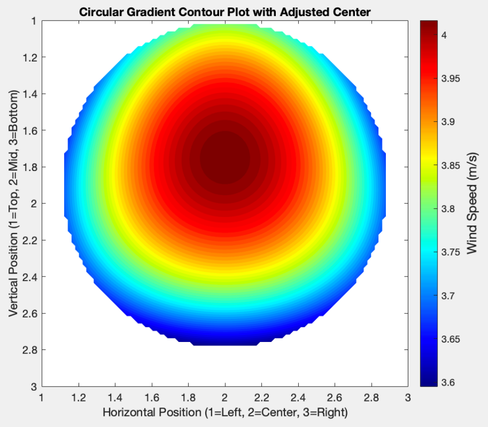
A 9 grids layout was used to systematically measure wind speed at the air conditioner compressor outlet, dividing the area into key zones for comprehensive airflow analysis, as shown in Figure 10. An anemometer (HOLDPEAK HP-866B) was positioned 5 cm in front of the air-conditioner condenser unit to measure wind speed, with average values recorded over a 60-second duration. The wind speed distribution plot shows that the center (Position 5) consistently recorded the highest wind speed, especially in the 2 HP unit, due to direct fan alignment. The wind speed decreased progressively toward the corners and edges. The study focused on circular outlet designs, revealing a radial airflow pattern with peak speeds at the center. These findings highlight optimal turbine placement near the outlet center for efficient wind energy capture, offering valuable insights for applications in wind-powered systems. The kinetic power of the airflow from the air conditioner compressor outlet can be calculated using

$$P_{air} = \frac{1}{2}\rho A v^2 \qquad (1)$$

Where ρ is the air density is, A is the swept area, and v is the wind speed at the wind turbine. Given the electric output of 0.523 W, the conversion efficiency is about 45.6 %.



The Measurement Points (Position)



Wind Speed Distribution

FIGURE 10. The measurement points (position) and its wind speed distribution of the air conditioner condenser fan

The measurements continued using turbines with varying numbers of wind blades to evaluate their effect on electrical output. Figure 11 provides a comparison of the voltage generated by different blade counts at a constant wind speed of 4m/s. The results demonstrated that the number of blades significantly affects turbine voltage output. As the number of blades increased from 2 to 7, the generated voltage rose from 0.4 V to a maximum of 2.1 V, indicating more effective wind energy capture and improved torque generation at lower rotational speeds. This trend suggests that additional blades enhance airflow interaction with the turbine, leading to higher energy conversion efficiency under low wind-speed conditions. However, performance declined with higher blade counts beyond 7 blades, due to increased aerodynamic drag, airflow blockage and inter-blade interference that reduce rotational efficiency. These findings highlight the trade-off between energy capture and aerodynamic losses. Overall, the 7-blade configuration achieved the best balance between torque and rotational speed, making it most efficient design, highlighting the importance of optimizing blade number for maximum energy output.

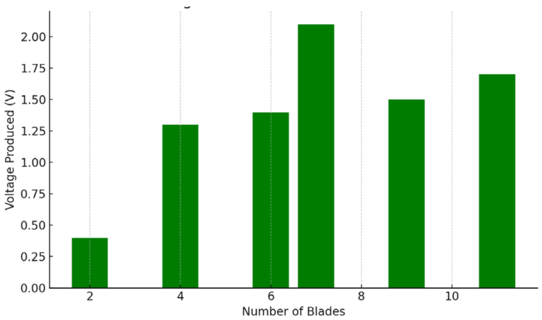


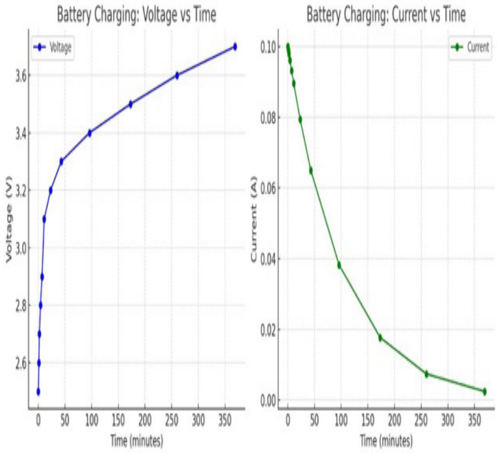
FIGURE 11. Comparison of the voltage generated with different numbers of wind blade (single turbine, wind speed: 4 m/s, position: center 5)

Table 1 shows a comparison of wind speeds measured at various positions for residential air-conditioning compressors with different horsepower (HP) ratings, namely 1HP, 1.5HP, 2HP and 2.5HP. The results indicate a proportional relationship between wind speed and compressor horsepower, where smaller units, such as the 1HP, produced lower airflow, while larger units, such as the 2.5HP compressor, generated higher wind speeds. The center position 5 consistently recorded the highest wind speed across all the HP ratings. In contrast, the corner positions, specifically positions 1, 3, 7, and 9, exhibited the lowest wind speeds due to the dissipation of airflow as it moves outward from the center. At the same time, the midpoints along the edges (Positions 2, 4, 6, and 8) recorded moderate wind speeds due to their proximity to the centre, while still being influenced by dispersion effects.

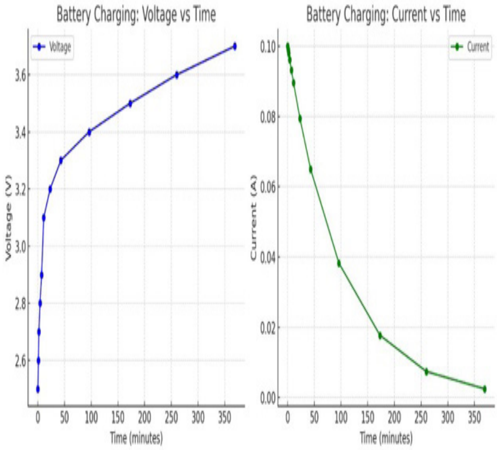
TABLE 1. Comparison table for Wind Speed at various positions on different HP Compressors (1 HP, 1.5 HP, 2 HP, 2.5 HP)

Compressor [HP]	1 (Top Left)	2 (Top Mid)	3 (Top Right)	4 (Mid Left)	5 (Center)	6 (Mid Right)	7 (Bottom Left)	8 (Bottom Mid)	9 (Bottom Right)	Average Wind Speed (m/s)
1.0 HP	2.2	2.5	2.2	2.4	2.8	2.4	2.0	2.3	2.0	2.3
1.5 HP	2.8	3.2	2.8	3.0	3.6	3.0	2.6	3.0	2.6	3.0
2.0 HP	3.2	3.8	3.2	3.6	4.0	3.6	3.2	3.4	3.2	3.5
2.5 HP	3.8	4.3	3.8	4.1	4.5	4.1	3.6	4.0	3.6	4.0

The output power generated by the wind-powered generator, utilizing the wasted wind energy from the air conditioner condenser, was stored in a battery. The charging profile of the battery is a key indicator for assessing the performance and practicality of the generator. The corresponding battery charging curve is shown in Figure 12. This curve shows how a battery charges when the voltage slowly rises from 2.5 V to 3.7 V as energy is stored. At the initial stage of charging, when the battery voltage was relatively low, a rapid rise in voltage was observed. This behavior can be attributed to the lower internal resistance of the battery and the greater potential difference between the charging source and the battery terminals, which enable the battery to accept charge more efficiently. As the charging process continued, the rate of voltage rise gradually decreased, indicating a transition towards a higher state of charge. This trend is characteristic of lithium battery electrochemistry, where increasing internal resistance and reduced ion mobility progressively constrain the charging rate at elevated voltage levels (Nitta et al. 2015). In contrast, the Current vs. Time shows the current drawn by the battery during the charging process. The current starts at 0.1 A but drops rapidly over time. By around 150 minutes, the current has dropped to roughly 0.02 A, indicating that the battery is approaching a higher state of charge. This decline indicates that the battery is charging more slowly as it nears full voltage, with the current nearing zero at maximum charge. As the battery charges, its internal resistance increases, requiring less current to continue the process. The battery required a total of 369 minutes to charge from 2.5 V to 3.7 V. Although the charging process is relatively slow, the successful increase in battery voltage from 2.5 V to 3.7 V confirms the technical feasibility of integrating a wind turbine with air-conditioning compressor unit for renewable energy harvesting. Nevertheless, it also underscores the need for further improvements to increase charging efficiency and practical applicability.



(a) Voltage vs. Time



(b) Current vs. Time

FIGURE 12. Battery charging curve

Figure 13 shows the comparisons of battery charging time with similar works on wind-powered generator using wasted airflow from an air conditioner condenser fan. This work demonstrates the shortest charging time (369 minutes) among the three generators, proven that the proposed design enhances energy storage efficiency.

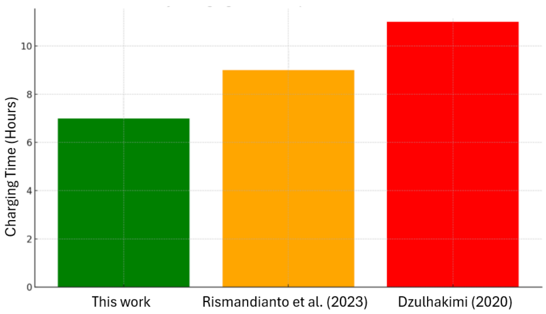


FIGURE 13. Comparison of charging time with similar works on wind-powered generator

CONCLUSION

The development of a wind-powered generator that utilizes wasted airflow from an air conditioner condenser fan has successfully demonstrated its feasibility. The system effectively captures residual airflow and converts it into usable electrical energy, proving that low-speed wind sources can be harnessed via appropriate turbine design and system optimisation. Experimental evaluations of different turbine configurations helped identify a more efficient design for energy harvesting under low wind speed conditions. The integration of a charge controller and battery storage further enhances system reliability by enabling stable energy storage. The system offers a cost-effective and sustainable approach to micro-energy generation, particularly in densely populated urban settings where conventional renewable energy installations may be limited by space. Moreover, this study lays the groundwork for future innovations in urban energy recovery systems. Nevertheless, the system's relatively low power output limits its ability to operate larger appliances and limits its potential for significant energy savings at residential or commercial scales. This study primarily focused on demonstrating system feasibility under fixed load conditions. As such, comprehensive electrical characteristics, including current-voltage (I–V) and power-voltage (P–V), time-dependent voltage V(t) and current profiles I(t) traces, and comparative A/B measurements are left for future work. Future work may explore the integration of thermoelectric generators (TEGs), such as Peltier modules, to convert heat differences into electricity. Attaching these modules to the condenser's heated surfaces would allow the system to capture both wind and thermal energy at the same time, thereby improving overall energy output and performance.

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DECLARATION OF COMPETING INTEREST

None.

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