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Investigation of a Renewable Energy System Using HVAC Condenser Fans for Low-Power Surveillance Systems

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ABSTRACT

This study presents an innovative approach to sustainable energy generation by integrating energy harvesting mechanisms into outdoor air conditioning units. The proposed system employs miniature generators embedded within the fan assembly to capture mechanical energy produced during operation. A pulley-driven transmission system converts this mechanical energy into electrical power, which is stored in a rechargeable battery and subsequently used to power Closed-Circuit Television (CCTV) systems. To regulate and optimize the electrical output, the system incorporates a DC-DC buck converter to adjust voltage to a usable range, and a solar charge controller to monitor current and voltage during the charging process. The prototype was implemented on a 1-horsepower outdoor air conditioning unit, with operational testing conducted under typical usage conditions to evaluate system behaviour and ensure performance reliability with two types of testing conducted. The first involved evaluating different pulley ratios. Results show higher pulley ratios produced higher power output both before and after DC-DC conversion, indicating improved mechanical-to-electrical efficiency. The second test examined system performance under two ambient conditions, 24°C during nighttime and 30°C during daytime. Results indicate that the battery reaches a full state of charge more rapidly at 30°C compared to 24°C, primarily due to the longer duty cycle and extended operation of the condenser fan under higher thermal load. The system successfully powered the 5W CCTV unit without relying on grid electricity, demonstrating its feasibility as a renewable and environmentally friendly energy solution for residential and commercial infrastructure.

Keywords: Sustainable energy harvesting, air conditioning unit, CCTV system, renewable energy prototype, off-grid power supply

INTRODUCTION

Malaysia's electricity demand is projected to increase significantly, rising from 18,808 MW in 2020 to approximately 24,050 MW by 2039, a growth of nearly 28% driven by population expansion, urbanization, and industrial development. Residential buildings currently consume 24,709 GWh annually, while commercial buildings account for up to 38,645 GWh (Munir et al. 2020). This upward trend is expected to be accompanied by rising energy costs and mounting pressure on the national grid.

Considering these challenges, there is an urgent need to identify and harness renewable energy sources within residential and commercial environments. Malaysia's equatorial climate, characterized by year-round heat and humidity, has made air conditioning a pervasive necessity across homes, offices, and industrial facilities. However, the widespread use of air conditioning systems significantly elevates national energy consumption (Kubota et al. 2009). Most systems are designed solely for indoor cooling, overlooking the potential to recover energy from external components such as compressors, condensers, and fan assemblies.

Outdoor units generate substantial mechanical and thermal energy that is typically wasted. Elements such as fan rotation, vibration, airflow, and temperature gradients represent untapped sources of recoverable energy (Gaba & Kalra 2025; Nik Hazran et al. 2022). In densely populated urban areas, where air conditioning usage is intensive, neglecting these energy streams contributes to inefficiency and missed opportunities for sustainable innovation.

This study responds to escalating concerns over energy sustainability and environmental preservation by exploring the untapped potential of outdoor air conditioning systems as a source of renewable energy. Conventional units are primarily designed for indoor climate control, often disregarding the mechanical energy generated by outdoor components, particularly the condenser fan. This research addresses that gap by introducing an innovative system that converts the rotational energy of condenser fans into usable electrical power for CCTV systems.

As cities and homes increasingly deploy surveillance systems, the demand for renewable energy incentivizes the development of integrated and decentralized energy systems. CCTV surveillance systems are typically installed outdoors and require a continuous 24-hour power supply, which translates into high electricity costs, complex wiring, and a disruptive and expensive installation. To solve these problems and the general lack of energy access, the system integrates a miniature generator and a repurposed condenser fan, the energy of which is processed through a DC-DC buck converter and controlled via the charge controller. A rechargeable battery is used to buck-boost the system to enable continuous and stable operation. Without utilizing any external cables, CCTV systems can overcome limitations in energy access enabling more safe, stable, and freely installed CCTV systems.

This method presents a practical and affordable way to generate energy by making use of systems that are already in place. Instead of relying solely on grid electricity, it taps into underutilized mechanical components and turns them into useful energy sources an approach that reflects real-world innovation in energy engineering. Beyond lowering electricity costs for households (Fang et al. 2020), the setup also improves safety and simplifies installation by removing the need for external wiring, which can be hazardous.

LITERATURE REVIEW

Energy harvesting is all about capturing the hidden potential in everyday surroundings, turning ambient energy sources into usable electricity. Often referred to as energy scavenging or power harvesting, this technique makes clever use of natural phenomena to generate power without relying on the conventional grid. While the idea has been around for a while, solar energy remains the most familiar and widely adopted example.

But the possibilities go far beyond solar panels. Researchers are now exploring how to tap into radio frequency (RF) signals, vibrations from piezoelectric materials, and temperature differences to produce energy in a wide range of environments (Sojan & Kulkarni 2016; Sodano et al. 2004). Studies have shown promising results in capturing mechanical vibrations, recovering heat from thermal gradients, and even integrating these technologies into HVAC systems to boost efficiency (Zhang et al. 2019). Wind energy harvesting is another exciting frontier that is being developed to convert airflow into electricity, opening new paths for clean and renewable power (Gumilar et al. 2019).

Air conditioning systems are multifunctional technologies designed to perform several tasks concurrently. They not only condition and circulate air but also deliver it efficiently to targeted indoor zones. Depending on the configuration whether centralized plants or rooftop units, these systems can provide both heating and cooling functionalities. Beyond temperature control, they also regulate humidity, airflow, air purity, acoustic levels, and pressure, all within defined parameters to ensure occupant comfort, health, and, in some cases, to meet the environmental requirements of sensitive processes.

The term HVAC&R, which stands for Heating, Ventilation, Air Conditioning, and Refrigeration, encompasses this integrated suite of operations and reflects the contemporary understanding of air conditioning systems (Wang 2001). Given the wide range of system types available, this study specifically concentrates on single-room air conditioning units, which are prevalent in residential environments and represent a practical focus for energy recovery applications.

Air conditioning systems operate based on the vapor compression refrigeration cycle, comprising three essential components which are the compressor, condenser, and evaporator. These elements work in tandem to regulate indoor climate by transferring heat from the conditioned space to the external environment. The compressor and condenser, both housed in the outdoor unit, are of particular interest for energy harvesting due to their exposure to mechanical motion, thermal gradients, and airflow dynamics.

Temperature differential between the cold evaporator and the hot condenser presents a viable opportunity for thermoelectric energy harvesting. Thermoelectric generator (TEG) modules exploit this gradient to convert waste heat into electrical energy, offering a passive and scalable solution for low-power applications such as sensors and surveillance systems (Sun et al. 2020; Jeng et al. 2018; Ibrahim et al. 2025).

Piezoelectric materials can convert vibrational energy into electrical output when subjected to cyclic mechanical stress. For instance, (Yang et al. 2021) developed a non-intrusive vibration harvesting system using PZT-5H sensors mounted on condenser units, achieving root-mean-square voltage outputs exceeding 500 mV under optimized airflow and temperature conditions. Similarly, compliant airfoil designs attached to piezoelectric strips have demonstrated effective energy conversion from airflow-induced oscillations near compressor outlets.

Another promising avenue involves harvesting kinetic energy from the condenser fan. As the fan propels high-velocity air through heat exchange fins, it generates substantial airflow and pressure conditions suitable for micro wind energy conversion. Studies have shown that integrating small-scale wind turbines with DC active rectifier circuits can store harvested energy efficiently. For example, a model developed by (Nik Hazran et al. 2022) successfully extracted up to 22W of power from residual airflow, demonstrating the feasibility of this approach in real-world conditions.

Additionally, the rotating shaft of the condenser fan can be repurposed to drive a miniature DC generator through a coupling mechanism. This dynamo-based setup converts rotational kinetic energy into electrical power, which can be stored in batteries for continuous operation of low power devices. DC generators are particularly suitable for small scale applications due to their simplicity, reliability, and compatibility with energy storage systems (Slamet et al. 2020). However, existing literature offers limited insight into the long-term reliability and mechanical performance of such shaft-coupled systems, highlighting a critical gap for future research and optimization.

Although earlier studies have examined HVAC-based energy harvesting using air flow-driven micro-turbines, thermoelectric modules, or direct shaft coupling, these approaches often remained at conceptual or laboratory scale, with limited repeatability analysis and uncertainty evaluation. The present study distinguishes itself by experimentally validating a pulley-driven PMDC generator integrated with a condenser fan, tested under multiple ambient temperature scenarios. Furthermore, the system is directly applied to powering CCTV units, demonstrating a practical and low-cost pathway for renewable energy integration into existing HVAC infrastructure.

Comparative studies reveal that thermoelectric modules typically yield less than 5 W of output under condenser temperature gradients (Sun et al. 2020; Jeng et al. 2018, Yildiz et al. 2015), while piezoelectric vibration harvesters achieve voltage outputs in the range of 0.5-1 V but face long-term reliability issues due to mechanical fatigue (Yang et al. 2021). Airflow-driven micro-turbines integrated into HVAC units have demonstrated power levels up to 22 W, though their performance is highly dependent on airflow variability and duct geometry (Nik Hazran et al. 2022). Shaft-driven generators, while mechanically simple, rarely report statistical reliability or long-term performance metrics, limiting confidence in their applicability (Slamet et al. 2020). In contrast, the present study introduces a pulley-driven PMDC generator integrated with a condenser fan, producing stable outputs in the range of 25-30 V at approximately 0.7 A, with statistical reliability confirmed through repeated measurements and error analysis. This comparison underscores the relative efficiency, robustness, and retrofit-friendly nature of the proposed system compared to earlier approaches.

This research aligns with several United Nations Sustainable Development Goals (SDGs). By harvesting mechanical energy from HVAC condenser fans, the system contributes to SDG 7 (Affordable and Clean Energy) through the provision of decentralized, renewable power for surveillance systems. The innovative integration of existing infrastructure supports SDG 9 (Industry, Innovation, and Infrastructure), while enhancing urban safety and resilience addresses SDG 11 (Sustainable Cities and Communities). Furthermore, by reducing dependence on grid electricity and lowering carbon emissions, the system advances SDG 13 (Climate Action). Collectively, these contributions demonstrate the potential of the proposed system to support both local energy efficiency and global sustainability targets.

METHODOLOGY

To address the increasing demand for sustainable energy technologies and mitigate dependence on conventional non-renewable resources, this study presents an integrated energy harvesting mechanism for residential air-conditioning systems. The condenser fan, conventionally operating as a passive cooling component, is reconfigured to serve as a mechanical driver for auxiliary power generation. Through the incorporation of a miniature generator coupled to the fan shaft via a pulley-driven transmission system, the rotational kinetic energy produced during normal operation is effectively converted into usable electrical power.

The overarching goal is to develop an Energy Harvesting Outdoor Unit Air Conditioning System capable of supplying continuous power to closed-circuit television systems, thereby enhancing energy efficiency and installation flexibility in residential environments. The methodology focuses on analyzing the rotational speed of the condenser fan shaft to determine its suitability for energy harvesting, designing and implementing a pulley-coupled generator system tailored for integration with standard 1-hp outdoor air conditioning units, and evaluating the system's performance in terms of electrical output, battery charging efficiency, and its ability to reliably power CCTV units under varying thermal conditions, specifically across different ambient temperature settings.

SYSTEM BLOCK DIAGRAM

The proposed energy harvesting system is designed to utilize the rotational motion of the outdoor unit fan in a conventional air conditioning system as a renewable energy source. This approach leverages the continuous operation of the fan during cooling cycles to generate supplemental electrical power, thereby enhancing system efficiency and promoting sustainable energy integration in residential applications. The method centers on converting mechanical energy into electrical energy through a compact and cost-effective setup that supports low-power devices such as CCTV systems.

The process begins with the rotation of the outdoor fan, which simultaneously drives a permanent magnet direct current (PMDC) generator via a pulley mechanism. As the fan shaft rotates, mechanical energy is transferred to the generator, where it is converted into direct current (DC) electrical energy. To ensure compatibility with downstream components, the raw DC output is conditioned using a DC-DC buck converter with an input voltage range of 5-30V DC and an adjustable output voltage range of 12-24V DC, which regulates the voltage to a stable and usable range. The regulated power is then stored in a rechargeable battery, forming a reliable energy reservoir for the CCTV system. This configuration ensures uninterrupted surveillance capability, even during brief power outages or fluctuations. Figure 1 illustrates the block diagram of the complete energy harvesting and supply system.

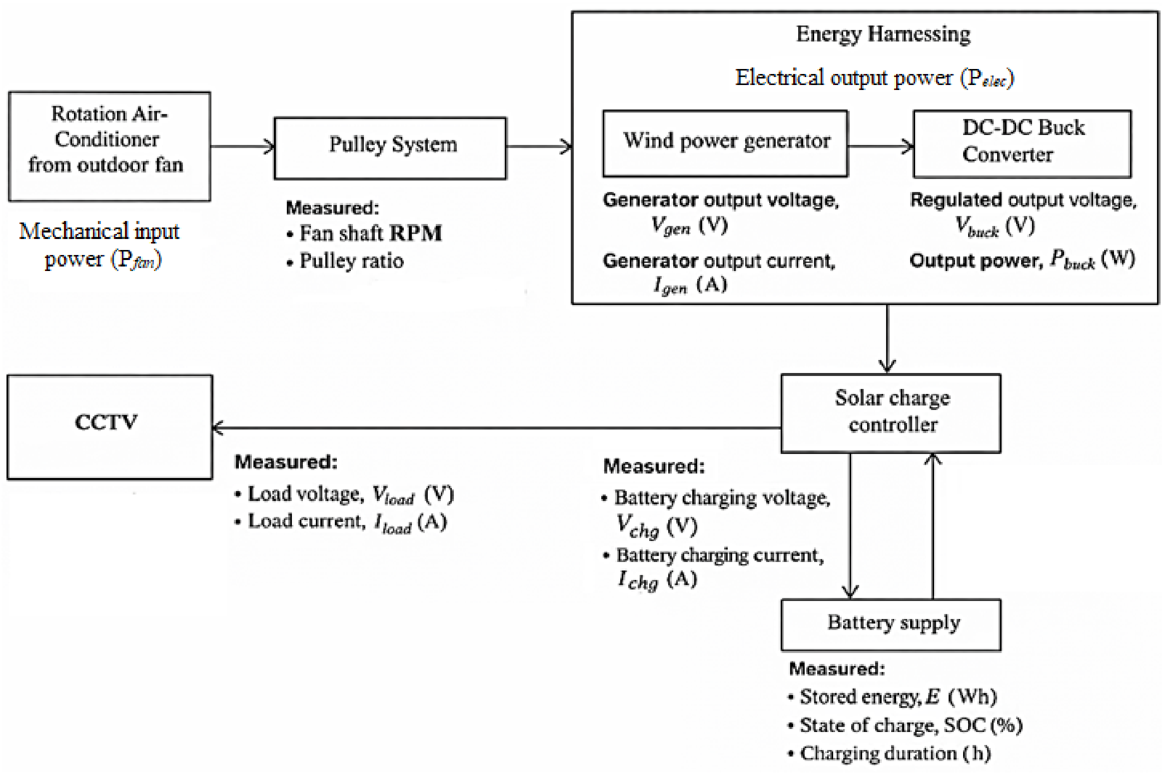

FIGURE 1. System Block Diagram

DESIGN AND IMPLEMENTATION OF HVAC-BASED ENERGY HARVESTING

The prototype development phase focuses on validating the mechanical integration between the outdoor air conditioner fan rotor and the PMDC generator via a pulley transmission system.

This prototype system is designed to harvest mechanical energy from the condenser section of a residential outdoor air conditioning (AC) unit and convert it into electrical power for low-voltage applications. The system integrates a permanent magnet direct current (PMDC) generator with the condenser fan via a pulley transmission mechanism. The generated power is used to charge a 12V battery, which subsequently supplies energy to a 5V CCTV surveillance system. A comprehensive system requirements analysis was conducted to identify and document both functional and non-functional parameters, including mechanical, electrical, and environmental considerations, ensuring the feasibility, efficiency, and reliability of the design.

At the core of the design is the York AC condenser fan, model YWM 15F-AFAF, which operates at 220-240V, 50 Hz single-phase, consuming 1345 W at 6.1 A under normal conditions and 1581 W at 7.0 A under high ambient conditions. Its rated cooling capacity is 3.810 kW (13,000 Btu/hr) in standard conditions and 2.931 kW (10,000 Btu/hr) in elevated temperatures, using refrigerant R-22. The fan is constructed with durable materials suitable for outdoor use, featuring a sealed motor and aerodynamically optimized blades for efficient airflow.

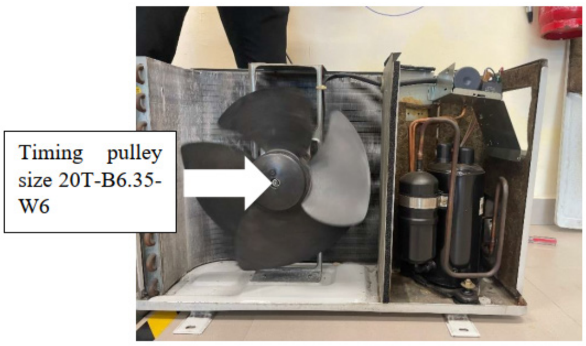

FIGURE 2. Mounting of Pulley-Driven PMDC on Outdoor AC Unit

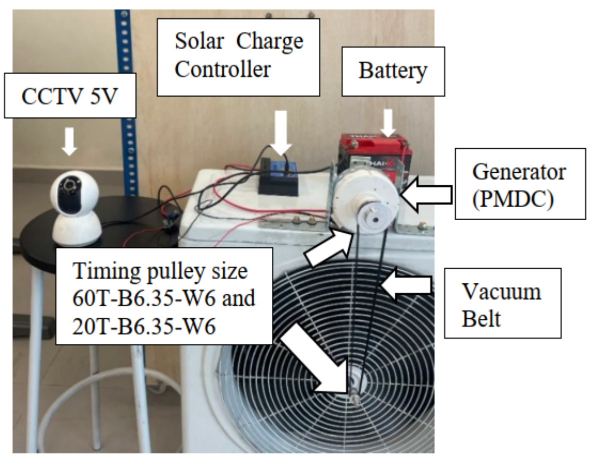

FIGURE 3. Final Design of the Project

The PMDC generator, known for its compact size and high efficiency typically between 70% and 90%, converts mechanical energy into electrical energy using permanent magnets, eliminating the need for external excitation and reducing maintenance. To transmit rotational energy from the fan to the generator, a timing pulley system is employed, consisting of two pulleys which are the 20T-B6.35-W6 (driver pulley) mounted on the fan shaft, and the 60T-B6.35-W6 (driven pulley) attached to the generator shaft. Both pulleys have a bore diameter of 6.35 mm and a width of 6 mm, with the 3:1 gear ratio effectively increasing the generator's rotational speed. A timing belt connects the pulleys, ensuring synchronization and slip-free energy transmission as shown in Figures 2 and 3.

The system also includes a DC-DC buck converter to step down the generator's high voltage output to a stable level suitable for battery storage. The stored energy powers the Xiaomi Smart Camera PTZ Version 2K, which operates at 5V, 1A and features a resolution of 2304×1296, an F1.4 aperture, and a 110° viewing angle, providing high-quality video output and wide coverage. This integrated system demonstrates a sustainable approach to powering low-voltage devices using ambient mechanical energy from existing infrastructure.

A detailed energy flow model was developed in Figure 1 to illustrate the conversion pathway from mechanical input at the condenser fan to usable electrical output at the CCTV load. The model incorporates generator efficiency, power conversion losses, and net usable electrical power. Mechanical input power (P_{fan}) is defined as the product of torque (T) and angular velocity (ω), while electrical output power (P_{elec}) is calculated as the product of voltage (V) and current (I). The efficiency of the generator is defined as the ratio of the electrical power produced to the mechanical power supplied by the fan, expressed as a percentage. The conversion efficiency through the DC-DC buck converter and charge controller is determined by comparing the output power to the input power. Battery efficiency is measured as the proportion of discharge power relative to the charging power. Finally, the overall system efficiency is evaluated by comparing the power consumed by the CCTV unit to the mechanical power delivered by the fan, expressed as a percentage. Losses occur at each stage of the system, including pulley friction and belt slip, copper and iron losses in the generator, voltage drops in the converter, regulation losses in the charge controller, and charging/discharging inefficiencies in the battery. However, detailed data on the mechanical components are not the focus of this paper. Future work will therefore incorporate torque sensors and power analyzers to directly measure mechanical input and electrical output, enabling more precise benchmarking against existing energy harvesting systems.

RESULTS AND DISCUSSION

The energy harvesting module was successfully assembled and tested under controlled outdoor conditions to evaluate its performance in capturing mechanical energy from the condenser fan of a residential air conditioning unit. The integration of the PMDC generator with the fan shaft via a timing pulley system demonstrated effective mechanical coupling, with minimal slippage and consistent rotational transmission. Preliminary testing was conducted using three different pulley sizes, and the resulting output voltage and current were analyzed to determine the most suitable configuration for powering a CCTV application. The final selection of a 3:1 gear ratio, achieved through 20T and 60T timing pulleys, significantly increased the generator's rotational speed, enabling a stable voltage to output suitable for downstream conversion and energy storage with minimal errors during the testing stage.

This phase of the study focused on assessing the effectiveness of coupling the outdoor fan rotor of a residential air-conditioning unit with a generator through a pulley-driven mechanism. The experimental setup revealed that the mechanical integration between the condenser fan and the PMDC generator functioned seamlessly, with the fan maintaining uninterrupted rotation throughout operation. Importantly, the air conditioner's internal cooling performance remained stable, indicating that the energy harvesting system did not interfere with its primary function. This outcome highlights the resilience and precision of the pulley arrangement, demonstrating its ability to coexist with conventional air conditioning components while enabling auxiliary power generation. Successful integration not only confirms the viability of the mechanical setup but also highlights its potential as a smart, sustainable energy solution for residential use.

To evaluate the system's performance under realistic operating conditions, a series of experimental tests were conducted focusing on the electrical output generated by the PMDC unit and regulated by the DC-DC buck converter. These tests were performed across varying ambient temperatures and air conditioner settings, while also observing differences in rotor speeds on both the fan and generator shafts. Beyond power generation, the study examined the time required to fully charge the battery and the duration it could sustain CCTV operation during discharge cycles. Additional assessments explored the resilience and efficiency of various battery types and CCTV models to determine optimal configurations. The generator's output was specifically tested under two ambient temperature scenarios which are 30°C during daytime and 24°C at night by using a 1-horsepower (hp) air conditioning unit to replicate typical residential conditions. These trials provided valuable insights into the system's adaptability, confirming its potential for stable energy harvesting across fluctuating environmental parameters.

OPERATIONAL DATA OF PULLEY MECHANISM, SHAFT SPEED, AND TEMPERATURE VARIATIONS IN A 1-HP AC UNIT

Preliminary testing was conducted to determine the most suitable pulley ratio for this project. The comparison of different pulley configurations highlights their impact on the generator's rotational speed (RPM) and the corresponding voltage and current output. By varying the pulley size on the generator while maintaining a constant speed from the air conditioner fan, the system's energy conversion efficiency can be optimized. Table 1(a) summarizes the results obtained for three pulley ratios, highlighting the relationship between fan speed, generator RPM, and electrical output at both the generator and DC-DC buck converter stages across three repeated measurements. The findings verify that the driven pulley operates at a lower speed than the driver pulley, consistent with the specified ratio. Three pulley ratios were tested, which are 3:1, 2:1, and 1:1. Among these, the 1:1 configuration produced the highest electrical output in terms of voltage and current. This is likely due to the generator rotating at the same speed as the fan, allowing for greater energy transfer and being suitable for higher load applications. Equation (1) and Equation (2) were used to verify the outputs presented in Table 1.

$$Pulley\ Ratio = \frac{Driven\ Pulley\ Size}{Driver\ Pulley\ Size} \tag{1}$$

$$Output\ RPM = \frac{Input\ RPM}{Pulley\ Ratio} \tag{2}$$

Table 1(b) and Table 1(c) present the error analysis for mechanical and electrical outputs across three pulley ratios. The mechanical data shows consistent fan and generator shaft speeds, with low standard deviation (SD) of about 3-4 RPM and standard error (SE) between 0-3 RPM, confirming stable rotational performance. Electrical outputs also demonstrate high repeatability, with voltage and current values showing minimal variation across trials, with SD ≤ 0.2 V and SE ≤ 0.1 V for voltage, while SD ≤ 0.02 A and SE ≤ 0.006 A for current. The DC-DC buck converter successfully regulated the output to match device requirements. These results validate the reliability of the system and confirm that the pulley-driven generator delivers consistent performance suitable for low-power applications.

For subsequent testing, the 3:1 pulley ratio was selected because its output voltage and current were more stable, exhibited minimal errors, and better matched the requirements of the CCTV system, particularly the DC-DC buck converter ratio. This choice is consistent with findings from previous studies, which reported that pulley-driven generator systems demonstrated improved stability and efficiency compared to direct 1:1 coupling, especially in HVAC-based energy harvesting applications (Nik Hazran et al. 2022; Slamet et al. 2020; Zhang et al. 2019, Mohammad et al. 2022). By reducing the driven pulley's RPM, the generator operates within its optimal range, thereby ensuring consistent output suitable for downstream conversion and storage.

In the early stage of testing, the study focused on measuring the electrical output of a PMDC generator system driven by airflow from a 1-hp residential air-conditioning unit. The system was evaluated across air-conditioner temperature settings ranging from 16°C to 30°C under two ambient conditions, 24°C and 30°C. Tables 2(a)-2(c) present three sets of measurement data for the 24°C ambient condition, while Table 2(d) summarizes the mean, standard deviation, and standard error for both mechanical and electrical outputs. Similarly, Tables 3(a)-3(c) show three sets of measurement data for the 30°C ambient condition, with Table 3(d) providing the corresponding error analysis. The performance of the DC-DC buck converter across these environmental parameters is also included in the results.

At both ambient temperatures, the system demonstrated consistent mechanical behavior. Although the condenser fan is designed to operate at a fixed speed, its actual RPM showed slight variation depending on loading conditions and ambient temperature. As the pulley-generator assembly introduced a minor mechanical load, the fan shaft RPM decreased with higher air-conditioner temperature settings, which in turn reduced the generator shaft RPM due to the fixed pulley ratio. For example, in Table 2, at 16°C the fan rotated at 730 RPM, driving the generator at 250 RPM with a 3:1 pulley ratio. This configuration produced a generator output of 26 V, stepped down by the DC-DC buck converter to 15.3 V and 0.5 A, suitable for charging a 12 V battery and powering a 5 V, 1 A CCTV system.

Error analysis further confirmed the stability of the output. At 24°C ambient, the fan shaft speed showed low variability with SD around 2.5-4.5 RPM and SE around 1.5-2.6RPM, while generator shaft speed errors remained below 2 RPM with SE $\leq$ 1.2. Electrical outputs were equally stable, with generator voltage deviations limited to SD $\leq$ 0.08 V and SE $\leq$ 0.04 V, and current variation negligible around SD $\leq$ 0.01 A and SE $\leq$ 0.006 A. At 30°C ambient, similar consistency was observed in which fan shaft SD values around 2–3.6 RPM, generator shaft SD $\leq$ 1.5 RPM, and voltage SD $\leq$ 0.12 V. These small errors validate the repeatability of the measurements and confirm that the system delivers reliable mechanical and electrical performance under varying thermal and loading conditions.

Overall, the results demonstrate that the system's performance is strongly influenced by both ambient and operating temperatures. Higher ambient conditions enhanced airflow, elevated generator RPM, and improved power output. The pulley-driven mechanism effectively transferred torque from the fan to the generator, consistently producing outputs in the range of 25-30 V at approximately 0.7 A. These values were successfully stepped down to 15.3 V through the buck converter, confirming the system's suitability for low-voltage applications such as battery charging, surveillance equipment, and IoT devices. Compared to airflow-driven micro-turbines integrated into condenser units (Nik Hazran et al. 2022), which achieved up to 22 W but were highly dependent on airflow variability, the present system produced comparable power levels with simpler mechanical coupling and greater repeatability. Thermoelectric harvesting approaches (Sun et al. 2020; Jeng et al. 2018) typically yield less than 5W, highlighting the higher efficiency of the pulley-generator configuration. Furthermore, unlike piezoelectric vibration harvesters (Yang et al. 2021), which may suffer from mechanical fatigue, the proposed system maintained consistent performance across ambient conditions without affecting the cooling capacity of the air-conditioner, underscoring its robustness and reliability in real-world residential settings.

It should be noted that while the pulley and generator assembly introduces minor mechanical resistance to the condenser fan, operational testing confirmed that the air-conditioner's cooling performance and overall power consumption remained unchanged. This indicates that the added load is negligible under typical residential conditions. Future work will include direct measurement of fan input power before and after pulley integration to evaluate any incremental energy requirement more precisely.

Alternative coupling methods such as direct shaft coupling and magnetic coupling have been explored in previous energy harvesting studies. Direct shaft coupling can minimize mechanical losses and improve efficiency. However, it requires precise alignment and may increase mechanical stress on the fan motor, potentially affecting long-term reliability. Magnetic coupling offers non-contact energy transfer, reducing wear and maintenance requirements, but its implementation is more complex and costly. In comparison, the pulley-driven mechanism adopted in this study provides a practical balance between effectiveness, simplicity, and affordability. It can be easily retrofitted to residential air-conditioning units without significant modification, making it a suitable choice for low-power applications such as CCTV systems. Future work may investigate hybrid approaches that combine the simplicity of pulley systems with the efficiency of direct or magnetic coupling to further enhance performance.

EVALUATION OF BATTERY CHARGING PERFORMANCE

The analysis investigates the dynamics of battery charging under varying durations of air conditioning system operation, with a target ambient temperature of 16°C. The evaluation focuses on the output power delivered by the DC-DC buck converter, the cumulative energy stored in the battery expressed in watt-hours, and the corresponding battery state of charge (SOC). Experimental data was obtained under two reference ambient conditions which are 24°C and 30°C using a 12V battery interfaced with a buck converter and shown in Table 4 and Table 5.

At 24°C, the converter consistently delivered 7.65 W over an 8-hour period, resulting in a linear SOC progression. The battery reached full charge (100% SOC) after 8 hours, with a total energy accumulation of 61.20 Wh. This indicates stable energy harvesting and conversion efficiency under moderate thermal conditions. Conversely, at 30°C, the system demonstrated a marked increase in converter output rising to 10.71 W. This enhancement accelerated the charging process, enabling the battery to reach full SOC after 6 hours of operation, with a total harvested energy of 87.92 Wh. The observed increase in power output at elevated temperatures is attributed to the higher thermal load on the condenser unit, which extends the fan's duty cycle and results in longer continuous operation. Figure 4 presents a comparative analysis of battery charging performance at ambient temperatures of 24 °C and 30 °C, based on air-conditioner operating durations. The data indicate that both accumulated energy (Wh) and state of charge (SOC) increase steadily with longer runtime under both temperature conditions. Notably, the system operating at 30 °C achieves full battery charge after 6 hours of air-conditioner operation, whereas at 24 °C, full charge is only reached after 8 hours. This improved performance is primarily due to extended fan operation under higher thermal load, which sustains airflow and generator activity, thereby enhancing cumulative energy conversion. The steeper gradients of both Wh and SOC curves at 30 °C further highlight the system's responsiveness to thermal conditions, suggesting that elevated ambient temperatures can accelerate battery charging in HVAC integrated energy harvesting configurations through longer duty cycles rather than increased fan speed. In addition, varying load conditions within the refrigeration cycle such as compressor demand and condenser heat rejection can introduce minor fluctuations in fan torque and slip, resulting in small variations in effective shaft speed and airflow (Zakula et al. 2012; Elsayed & Hariri, 2015). These combined effects explain why more energy was harvested at 30 °C compared to 24 °C, consistent with findings on ambient temperature sensitivity in HVAC systems (Yusof & Omar, 2023; Ismail et al. 2024).

These findings underscore the sensitivity of the energy harvesting system to ambient temperature variations. Elevated temperatures appear to positively influence fan induced airflow and mechanical energy conversion, thereby improving overall charging efficiency (Abdullah & Rahman, 2025). In contrast, operation at the target temperature of 16 °C may yield reduced airflow and lower generator output, potentially extend the charging duration and diminish energy transfer rates. This highlights the critical role of environmental parameters in the design and optimization of renewable energy harvesting systems, particularly those integrated with HVAC infrastructure (Gupta et al. 2023).

TABLE 1(a). Generator outputs based on different pulley ratio

Technical data			Measurement set 1		Measurement set 3			Measurement set 3		
Driver/ Driven pulley number of teeth (fan shaft/ generator)	Pulley ratio	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)
20/60	3:1	940	313	30.01V, 0.70A	945	315	30.10V, 0.71A	938	313	29.90V, 0.69A
20/40	2:1	940	470	33.00V, 0.80A	942	471	33.10V, 0.81A	935	468	32.80V, 0.79A
20/20	1:1	940	940	36.00V, 1.00A	938	938	36.20V, 1.01A	932	932	35.80V, 0.99A

TABLE 1(b). Mechanical outputs error analysis

Pulley ratio	Fan shaft (RPM)			Generator (RPM)		
	Mean	SD	SE	Mean	SD	SE
3:1	941	3.606	2.082	313.667	1.155	0.667
2:1	939	3.606	2.082	469.667	1.528	0.882
1:1	936.667	4.163	2.404	936.667	4.163	2.404

TABLE 1(c). Electrical outputs error analysis

Pulley ratio	Generator Output voltage (V)			Generator Output voltage (A)			DC-DC Buck Output (V, A)
	Mean	SD	SE	Mean	SD	SE	
3:1	30.003	0.1	0.058	0.7	0.01	0.006	15.30V, 0.50A
2:1	32.967	0.153	0.088	0.8	0.01	0.006	16.00V, 0.70A
1:1	36	0.2	0.115	1	0.01	0.006	18.00V, 0.70A

TABLE 2(a). Data outputs when ambient temperature is 24°C (Measurement set 1)

Air conditioner temperature (°C)	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)	DC-DC Buck Output (V, A)
16	730	250	26.01V, 0.5A	15.3V, 0.5A
18	678	249	25.91V, 0.5A	15.3V, 0.5A
20	657	235	25.78V, 0.5A	15.3V, 0.5A
22	643	220	25.78V, 0.5A	15.3V, 0.5A
24	643	220	25.78V, 0.5A	15.3V, 0.5A
26	Cutoff	Cutoff	-	-

TABLE 2(b). Data outputs when ambient temperature is 24°C (Measurement set 2)

Air conditioner temperature (°C)	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)	DC-DC Buck Output (V, A)
16	735	252	26.10V, 0.51A	15.3V, 0.5A
18	682	248	25.95V, 0.50A	15.3V, 0.5A
20	660	236	25.85V, 0.50A	15.3V, 0.5A
22	645	222	25.80V, 0.50A	15.3V, 0.5A
24	642	221	25.80V, 0.50A	15.3V, 0.5A
26	Cutoff	Cutoff	-	-

TABLE 2(c). Data outputs when ambient temperature is 24°C (Measurement set 3)

Air conditioner temperature (°C)	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)	DC-DC Buck Output (V, A)
16	726	248	25.95V, 0.49A	15.3V, 0.5A
18	675	245	25.85V, 0.50A	15.3V, 0.5A
20	655	234	25.75V, 0.50A	15.3V, 0.5A
22	640	219	25.70V, 0.50A	15.3V, 0.5A
24	638	218	25.70V, 0.50A	15.3V, 0.5A
26	Cutoff	Cutoff	-	-

TABLE 2(d). Mechanical and Electrical outputs error analysis for ambient temperature of 24˚C

Air conditioner temperature (°C)	Fan shaft (RPM)			Generator (RPM)			Generator Output voltage (V)			Generator Output current (A)		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
16	730.33	4.51	2.60	250	2	1.155	26.02	0.075	0.044	0.5	0.01	0.00577
18	678.33	3.51	2.028	247.33	2.082	1.202	25.90	0.050	0.0291	0.5	0	0
20	657.33	2.52	1.453	235	1	0.577	25.79	0.051	0.0296	0.5	0	0
22	642.67	2.52	1.453	220.33	1.528	0.882	25.76	0.053	0.0306	0.5	0	0
24	641	2.65	1.528	219.67	1.528	0.882	25.76	0.053	0.0306	0.5	0	0
26		Cutoff			Cutoff		-	-	-	-	-	-

TABLE 3(a). Data outputs when ambient temperature is 30°C (Measurement set 1)

Air conditioner temperature (°C)	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)	DC-DC Buck Output (V, A)
16	940	313	30.10V, 0.7A	15.3V, 0.7A
18	890	297	29.50V, 0.7A	15.3V, 0.7A
20	870	290	29.20V, 0.7A	15.3V, 0.7A
22	855	285	28.60V, 0.7A	15.3V, 0.7A
24	840	280	28.35V, 0.7A	15.3V, 0.7A
26	830	277	28.35V, 0.7A	15.3V, 0.7A

TABLE 3(b). Data outputs when ambient temperature is 30°C (Measurement set 2)

Air conditioner temperature (°C)	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)	DC-DC Buck Output (V, A)
16	945	315	30.20V, 0.71A	15.3V, 0.7A
18	892	297	29.60V, 0.70A	15.3V, 0.7A
20	872	291	29.30V, 0.70A	15.3V, 0.7A
22	857	286	28.80V, 0.70A	15.3V, 0.7A
24	842	280	28.40V, 0.70A	15.3V, 0.7A
26	832	277	28.40V, 0.70A	15.3V, 0.7A

TABLE 3(c). Data outputs when ambient temperature is 30°C (Measurement set 3)

Air conditioner temperature (°C)	Fan shaft (RPM)	Generator shaft (RPM)	Generator Output (V, A)	DC-DC Buck Output (V, A)
16	938	312	30.00V, 0.69A	15.3V, 0.7A
18	885	295	29.40V, 0.70A	15.3V, 0.7A
20	868	289	29.10V, 0.70A	15.3V, 0.7A
22	853	284	28.60V, 0.70A	15.3V, 0.7A
24	838	279	28.30V, 0.70A	15.3V, 0.7A
26	828	276	28.30V, 0.70A	15.3V, 0.7A

TABLE 3(d). Mechanical and Electrical outputs error analysis for ambient temperature of 30˚

Air conditioner temperature (°C)	Fan shaft (RPM)			Generator (RPM)			Generator Output voltage (V)			Generator Output voltage (A)		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
16	941	3.61	2.08	313.33	1.53	0.88	30.1	0.1	0.06	0.7	0.01	0.006
18	889	3.61	2.08	296.33	1.16	0.67	29.5	0.1	0.06	0.7	1E-16	8E-17
20	870	2	1.16	290.00	1.00	0.58	29.2	0.1	0.06	0.7	1E-16	8E-17

continue...

... cont.

22	855	2	1.16	285.00	1.00	0.58	28.67	0.12	0.07	0.7	1E-16	8E-17
24	840	2	1.16	279.67	0.58	0.33	28.35	0.05	0.03	0.7	1E-16	8E-17
26	830	2	1.16	276.7	0.58	0.33	28.35	0.05	0.03	0.7	1E-16	8E-17

TABLE 4. Battery charging when ambient temperature is 24°C

Time operation of air conditioning (hours)	Output DC-DC buck Converter (W)	Battery Charging without load (Wh)	Battery Condition	SOC of Battery (%)
4	7.65	30.60	Not full	51
5	7.65	38.25	Not full	63.75
6	7.65	45.9	Not full	76.5
7	7.65	53.55	Not full	89.25
8	7.65	61.20	Full	100

TABLE 5. Battery charging when ambient temperature is 30°C

Time operation of air conditioning (hours)	Output DC-DC buck Converter (W)	Battery Charging without load (Wh)	Battery Condition	SOC of Battery (%)
4	10.71	43.96	Not full	73
5	10.71	54.95	Not full	92.58
6	10.71	65.94	Full	100
7	10.71	76.93	Full	100
8	10.71	87.92	Full	100

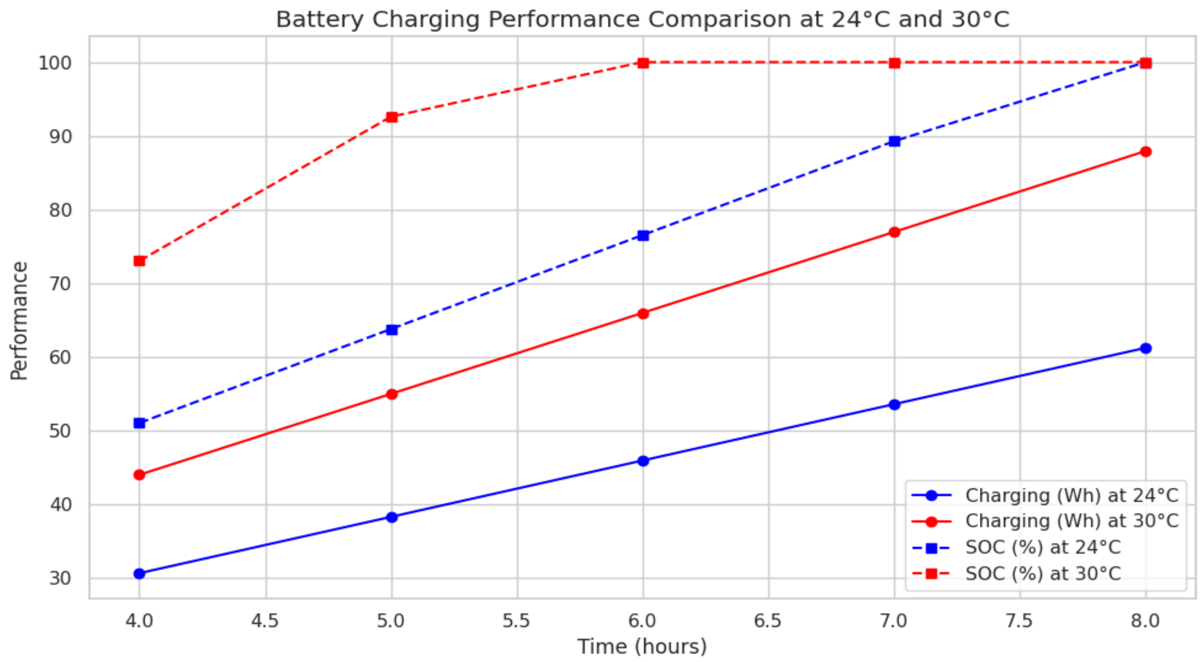

FIGURE 4. Battery charging comparison at 24˚C and 30˚C

TABLE 6. Estimated battery sizing for 5W and 10W CCTV with 12V system voltage

CCTV capacity (W)	Autonomy (days)	Battery size (V, Ah)	Nseries	Nparallel	DODd<DODmax	Acceptable or Unacceptable
5	1	12V, 9Ah	1	3	37%<50%	YES
5	1	12V, 12Ah	1	2	41.7%<50%	YES
5	2	12V, 9Ah	1	5	33.3%<50%	YES
5	2	12V, 12Ah	1	4	41.67%<50%	YES
10	1	12V, 9Ah	1	5	44.4%<50%	YES
10	1	12V, 12Ah	1	4	41.67%<50%	YES
10	2	12V, 9Ah	1	9	49.38%<50%	YES
10	2	12V, 12Ah	1	7	47.62%<50%	YES

BATTERY LIFE FOR CONTINUOUS CCTV OPERATION

This section presents the battery modelling used to estimate the appropriate size and connection configuration for supporting CCTV power requirements. The calculations consider different battery types and capacities to ensure reliable operation under varying load conditions. Equations (3)-(7) (SEDA, 2026) are applied to determine the required battery sizing based on the concept of day autonomy, which accounts for periods when the air-conditioning unit is not operating and the generator is unable to supply power. In this context, autonomy represents the number of consecutive days the battery system must sustain CCTV operation without recharging. The total capacity required, $C_{requried\_daily}$, is calculated based on the CCTV load demand for one day ($E_{requried\_daily}$) with a system voltage (SV) of 12 V. The battery bank capacity, $C_{bank\_required}$, is then determined according to the ability of the battery to meet energy demand for one or more days ($T_{autonomy}$) and the maximum allowable depth of discharge (DoD). For a 12 V battery powering CCTV systems, the recommended maximum DoD is about 50% for leadacid batteries and up to 80–90% for lithiumion batteries (SEDA, 2026). Leadacid batteries should not be discharged beyond 50% regularly, while lithium batteries can safely operate at higher DoD levels, ensuring longer battery life and reliable backup autonomy. The number of batteries in series (N_{series_bank}) and parallel ($N_{parallel\_bank}$) can be calculated using Equations (5) and (6). Finally, the selected battery bank capacity ($C_{bank\_selected}$) is analyzed to verify whether the estimated daily DoD (Dod_d) remains lower than the maximum allowable DoD (Dod_{max}). If this criterion is satisfied, the battery design is considered acceptable.

Table 6 summarizes the estimated battery sizing configurations for a 5 W and 10W CCTV load under different autonomy requirements. For a oneday autonomy, a 12 V 9 Ah battery requires three units in parallel, resulting in a daily depth of discharge (Dod_d) of 37%, which is below the maximum allowable 50% DoD for leadacid batteries. Similarly, using 12 V 12 Ah batteries, only two units in parallel are needed, with Dod_d at 41.7%, also within the acceptable limit. For two days autonomy, the required capacity increases, with five 12 V 9 Ah batteries in parallel yielding a of 33.3%, and four 12 V 12 Ah batteries in parallel yielding 41.67%. Both values remain below the 50% threshold, confirming that the configurations are acceptable.

$$C_{required\_daily} = \frac{E_{required\_daily}}{SV}$$

$$C_{bank\_required} = C_{required\_daily} \times \frac{T_{autonomy}}{DOD_{max}}$$

$$N_{series\_bank} = \frac{SV}{Nominal\ battery\ voltage}$$

$$N_{parallel\_bank} = \frac{C_{bank\_required}}{C_{per\_battery}}$$

$$C_{bank_{selected}} = N_{parallel_{bank}} \times C_{per_{bank}}$$

$$DOD_d = \frac{C_{required\_daily}}{C_{bank\_selected}}$$

Table 6 summarizes the estimated battery sizing configurations for a 5 W and 10W CCTV load under different autonomy requirements. For a oneday autonomy, a 12 V 9 Ah battery requires three units in parallel, resulting in a daily depth of discharge (Dod_d) of 37%, which is below the maximum allowable 50% DoD for leadacid batteries. Similarly, using 12 V 12 Ah batteries, only two units in parallel are needed, with Dod_d at 41.7%, also within the acceptable limit. For two days autonomy, the required capacity increases, with five 12 V 9 Ah batteries in parallel yielding a Dod_d of 33.3%, and four 12 V 12 Ah batteries in parallel yielding 41.67%. Both values remain below the

50% threshold, confirming that the configurations are acceptable.

These results demonstrate that even with small capacity batteries, the system can reliably support CCTV operation for one to two days of autonomy without exceeding recommended discharge limits. The analysis highlights the importance of parallel connections in meeting load demand while maintaining battery health. By ensuring $Dod_d < Dod_{max}$, the proposed configurations provide a practical and sustainable solution for lowpower surveillance applications.

When an additional load is introduced, such as a 10 W CCTV unit, the number of batteries required in parallel increases. However, many parallel batteries are not suitable for outdoor installation without proper mechanical design and housing. It is also observed that the percentage of daily depth of discharge approaches the maximum allowable discharge, which indicates an insufficient margin of safety. Consequently, if multiple CCTV units are connected, the required battery capacity must be increased accordingly. To simplify the design and reduce the number of parallel connections, the system voltage can be raised to 24 V by connecting two 12 V batteries in series. In this case, the DC-DC buck converter must be adjusted to ensure compatibility with charging 24 V battery strings. This approach improves efficiency, reduces current flow, and minimizes cable losses. In addition, if longer autonomy is required, it is recommended to hybridize the system with other renewable energy sources, such as solar PV, to ensure continuous operation during extended periods without generator input. Incorporating charge controllers and proper battery management systems (BMS) is also essential to prevent over-discharge and extend battery lifespan. Overall, the proposed battery sizing strategy demonstrates flexibility, scalability, and compatibility with hybrid renewable energy systems, making it suitable for reliable CCTV operation in residential and off-grid applications.

SYSTEM LIMITATIONS AND EFFICIENCY CONSIDERATIONS

A comprehensive energy balance and system efficiency evaluation is critical for validating the performance of energy harvesting systems. In the present study, voltage and current outputs were recorded at various stages; however, direct measurement of mechanical input power such as torque and fan shaft RPM was not conducted due to prototype constraints. As a result, the overall system efficiency could not be experimentally quantified. Nevertheless, several loss mechanisms were identified, including belt slippage and friction in the pulley system, voltage drop across the DC-DC buck converter, regulation inefficiencies in the charge controller, and battery charging/discharging losses. These factors indicate that efficiency is significantly influenced by both mechanical coupling and electrical regulation. Future work will incorporate torque sensors and power analyzers to directly measure mechanical input and electrical output, enabling a complete energy balance and rigorous benchmarking against existing energy harvesting systems.

CONCLUSION

This study demonstrates the feasibility of harvesting mechanical energy from the outdoor unit of a residential air conditioning system to power low voltage CCTV devices. By coupling the condenser fan shaft to a permanent magnet DC generator via a pulley system, rotational kinetic energy was successfully converted into electrical output. Experimental results showed that the generator produced a stable DC voltage regulated through a buck converter, with sufficient capacity to charge a 12V battery and sustain continuous CCTV operation. The system maintained consistent performance across varying ambient temperatures, confirming its robustness under different thermal conditions and validating its potential for decentralized energy applications.

Beyond proving technical viability, the work highlights the broader sustainability impact of repurposing HVAC infrastructure for micro-scale renewable energy generation. The integration of mechanical, electrical, and control components was achieved with minimal complexity, aligning with global efforts to reduce dependence on grid electricity and promote smart building solutions. Future improvements will focus on enhancing efficiency through mechanical optimization such as refining pulley ratios, reducing frictional losses, and exploring alternative coupling methods like direct or magnetic coupling to improve torque transfer. On the electrical side, advanced power management and hybrid energy harvesting approaches will be investigated, paving the way for more reliable, durable, and higher-yield systems suitable for long-term deployment in residential and urban environments.

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DECLARATION OF COMPETING INTEREST

None.

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