Energy Harvesting from Vehicle-Induced Wind for Enhanced Communication Efficiency in Autonomous Electric Vehicles

Mukil Alagirisamy
School of Engineering, Asia Pacific University of Technology & Innovation, Kuala Lumpur, Malaysia
mukil.alagirisamy@apu.edu.my

Yvette Shaan-Li Susiapan
School of Engineering, Asia Pacific University of Technology & Innovation, Kuala Lumpur, Malaysia
shaan@apu.edu.my (corresponding author)

R. Priyadarshini
Vellore Institute of Technology, Chennai, India
rspdarshini@gmail.com

T. V. Padmavathy
Vellore Institute of Technology, Chennai, India
padmavathy.tv@vit.ac.in

Vinesh Thiruchelvam
School of Engineering, Asia Pacific University of Technology & Innovation, Kuala Lumpur, Malaysia
dr.vinesh@apu.edu.my

Venu Durumutla
School of Engineering, Asia Pacific University of Technology & Innovation, Kuala Lumpur, Malaysia
TP062430@mail.apu.edu.my

Emmanuel Kwame Mensah
Department of Mathematics and Statistics, Faculty of Engineering, Ghana Communication Technology University, Accra, Ghana
emensah@gctu.edu.gh

Eyram Kwame
Department of Mathematical Science, Regional Maritime University, Accra, Ghana
eyram.kwame@rmu.edu.gh

Received: 2 July 2025 | Revised: 30 August 2025 | Accepted: 9 September 2025

ABSTRACT

The increasing demand for sustainable transportation solutions presents a challenge in minimizing Electric Vehicles' (EVs) reliance on external power sources while ensuring effective communication and control. This study addresses the issue by integrating wind energy harvesting and optimizing internal communication systems to support autonomous EV operation. The proposed framework utilizes vehicle-mobility-induced wind energy, supplemented by solar Photovoltaic (PV) cells, to power essential vehicle functions, thus reducing dependence on traditional charging methods and infrastructure. Wind turbine sensors attached to a 3D-printed dynamo assembly convert ambient kinetic energy into electrical energy,

which is subsequently stored in a battery pack. This power is intelligently managed and distributed through a system coordinated by an ESP32 controller and Arduino UNO, enabling seamless communication across subsystems. Autonomous control is executed via a joystick interface that transmits steering, acceleration, and braking commands to actuators, with real-time adjustments enabled by motor drivers. Automated transceivers facilitate continuous data exchange among energy-harvesting units, controllers, and actuators, ensuring synchronization and effective power management. The integration of Free Real-Time Operating System (FreeRTOS) enables real-time scheduling and dynamic energy management, supporting responsive operation under changing environmental conditions. By integrating IoT communication with renewable energy sources, this approach provides an energy-efficient, adaptable solution for autonomous EVs, supporting the goal of self-sustaining, eco-friendly transportation systems.

Keywords-wind energy harvesting; electric vehicles; autonomous control; IoT-based communication; renewable energy integration

I. INTRODUCTION

The rising demand for environmentally friendly transportation has increased the pressure on the automotive industry to lessen the dependence on external power sources. EVs have become a promising solution [1, 2], however, challenges remain in managing power circuits and ensuring seamless communication between subsystems [3]. Although EV power sources are inherently limited, incorporating renewable energy, especially wind and solar, provides a practical way to address these limitations. This study proposes a system that uses IoT communication and renewable energy management to facilitate real-time data exchange and efficient power distribution across the vehicle's components [4, 5]. The approach employs ESP32 and Arduino UNO controllers to optimize charging and discharging cycles based on environmental inputs and the status of onboard energy storage [6, 7]. By harnessing wind energy and leveraging enhanced communication protocols, the proposed system aims to develop an energy-autonomous vehicle with minimal reliance on external sources [8, 9]. The research advances EV technologies and promotes the development of more efficient, sustainable solutions for environmentally friendly mobility [10, 11].

The proposed Vehicle-Mobility Wind Energy Harvesting System (VMW-EHS) is designed to harness renewable wind energy with an emphasis on integration, thereby eliminating the supplementary carbon footprint associated with traditional energy consumption and promoting awareness of autonomous vehicular operation [12, 13]. The objective of this research is to contribute to the development of a novel category of EVs capable of internal power generation, thereby improving urban environmental quality and advancing sustainable transportation solutions within green communities [14-17]. Regarding energy challenges and the enhancement of these vehicles' communication systems, this research is at the forefront of transportation technology that responds to today's society. Although wind and solar energy harvesting have been studied separately, this study is unique in harnessing vehicle-generated wind energy in real time during motion, integrating it with solar input, and featuring autonomous operation using an ESP32 with FreeRTOS. The key contributions of the article are:

1. The study effectively integrates vehicle-mobility wind energy and solar photovoltaic cells to decrease dependence on external power sources substantially.
2. The proposed methodology employs automated transceivers and an ESP32 controller to ensure seamless communication among different subsystems.
3. Utilizing a FreeRTOS for data processing, the system enables real-time energy management and dynamic power resource allocation adjustments.
4. The joystick-based interface facilitates intuitive control of the vehicle, enabling real-time adjustments in steering, acceleration, and braking.

Related research [18] proposed a highway energy management system that uses Unmanned Aerial Vehicles (UAVs) - based wireless energy transfer, supported by IoT infrastructure and 6G-enabled data aggregation. While cost and reliability analyses confirm their feasibility in terms of setup, maintenance, and environmental resilience, challenges persist in UAV coordination, IoT system robustness, and privacy/security risks associated with extensive data collection. A different approach [19] introduced an energy-harvesting shock absorber that uses a barrel cam follower mechanism to capture low-frequency vibrations from vehicle suspensions. The system demonstrated promising potential to enhance energy efficiency and adaptability across various road conditions, underscoring its relevance in the automotive industry.

Another study [20] developed a pendulum-based energy harvester designed to capture low-frequency vibrations. It uses a Magnetic Repulsion and Restoration (MRR) mechanism, combined with spur gears and a sprag brake. At a resonance frequency of 1 Hz, it achieved a power output of 20.62 W/g² and an efficiency of 43.5%, as confirmed by numerical modeling. While attractive for powering Unmanned Surface Vehicle (USV) communications and extending operational duration, the system's limitations include unverified performance in marine environments, scalability challenges, and limited real-world deployment data, especially under varying wave conditions [21]. Further progress has been made in the development of a Rotational Switched-mode Water-based Triboelectric Nanogenerator (RSW-TENG) [22], designed to convert rotational kinetic energy into electrical power for sensors in adaptive vehicles. The study showed that the device's electrical output is inversely related to road slope and directly proportional to rotational speed, providing insights into how it responds in different driving conditions.

To explore the latest developments in Connected and Autonomous Vehicles (CAVs), the study focuses on CAVs' OBCU hardware, communication technologies, and implementation issues [23]. It suggested an adaptive architecture that can be modified to meet changing processing and communication needs. A recent study [24] examined Quality of Service (QoS) parameters influencing the performance of EVs and their users, and highlighted progress in EVs and charging station communications. It identified a QoS parameter reference map and access to charging infrastructure as the main current challenges.

This is the first approach in vehicles that utilizes airflow generated by movement to convert into electrical energy. In contrast, previous research has focused on combining solar and wind energy to power stationary or slow-moving systems. Unlike stationary wind harvesting [16, 17], this approach leverages natural movement to maximize energy use, reduce reliance on the environment, and allow energy harvesting even while in transit.

II. PROBLEM STATEMENT

Current EV systems primarily rely on grid-connected charging, which limits their effectiveness in remote regions and impedes seamless integration with renewable energy sources. Moreover, battery constraints limit both efficiency and mobility. This study introduces a hybrid energy harvesting model that combines vehicle-generated wind and solar energy to enhance energy autonomy. By combining smart energy distribution with improved communication systems, the solution optimizes power use and storage, addressing key challenges of conventional charging methods. This approach not only improves operational efficiency but also enables real-time data processing, thereby helping create a more sustainable and resilient EV infrastructure [20].

III. PROPOSED VEHICLE-MOBILITY WIND ENERGY HARVESTING SYSTEM

Figure 1 illustrates a vehicle powered by renewable energy, specifically a combination of solar and wind energy conversion, data analysis, and control systems. Solar photovoltaic cells and wind turbine sensors produce energy, which is monitored by a main ESP32 controller, while an Arduino UNO handles telemetry. The Intelligent Plug-in Hybrid Electric Vehicle (I-PHEV) captures the generated energy and transfers it to the battery pack, where the vehicle's actuators and motor drives are located. Commands from the end user are transmitted to the actuators via a joystick-based controller to manage functions such as steering, stopping, and accelerating the vehicle, thereby facilitating smooth operation. Inter-module interaction among actuators, energy sources, and controllers [25] is enabled by automated transceivers, which enhance synchronization. It is also tested on a small-scale EV prototype to demonstrate the system's application and energy efficiency.

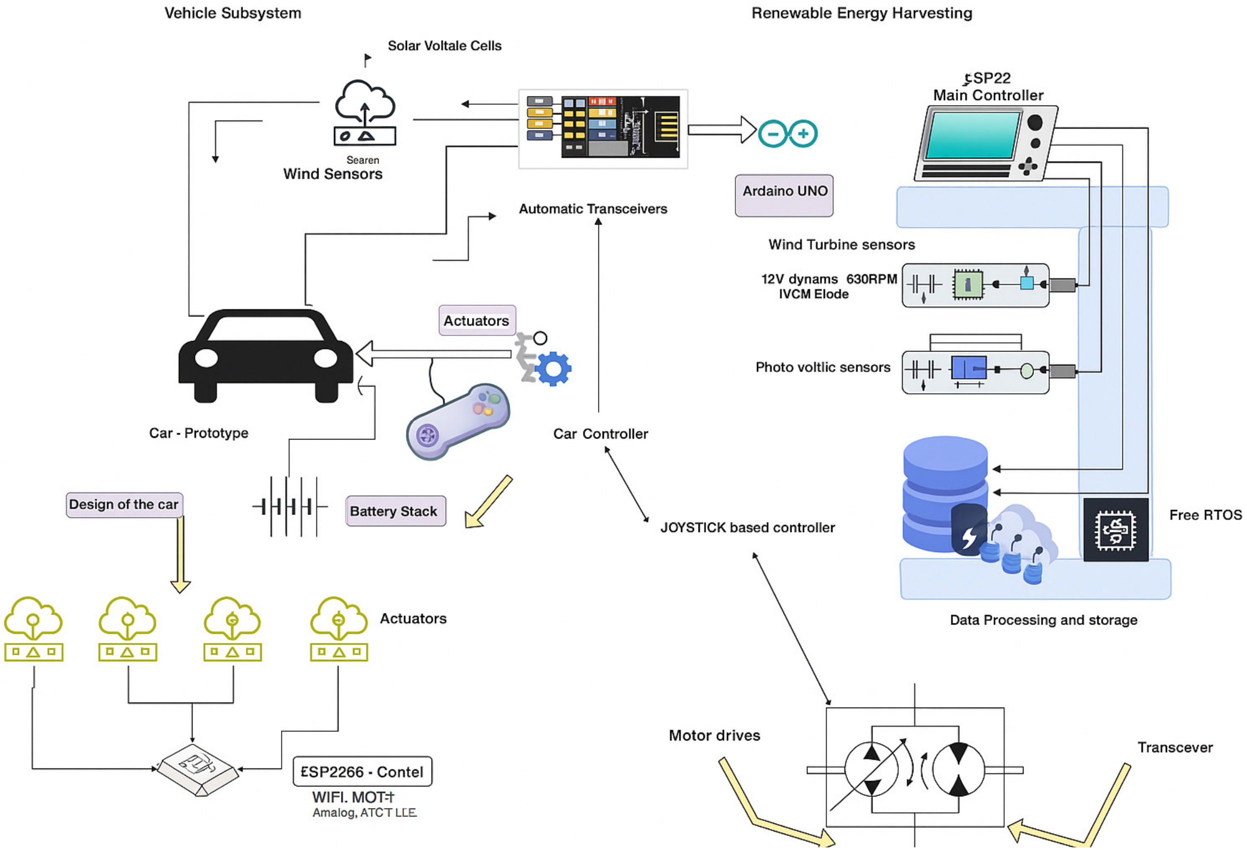

Fig. 1. Proposed architecture for harnessing energy from renewable sources.

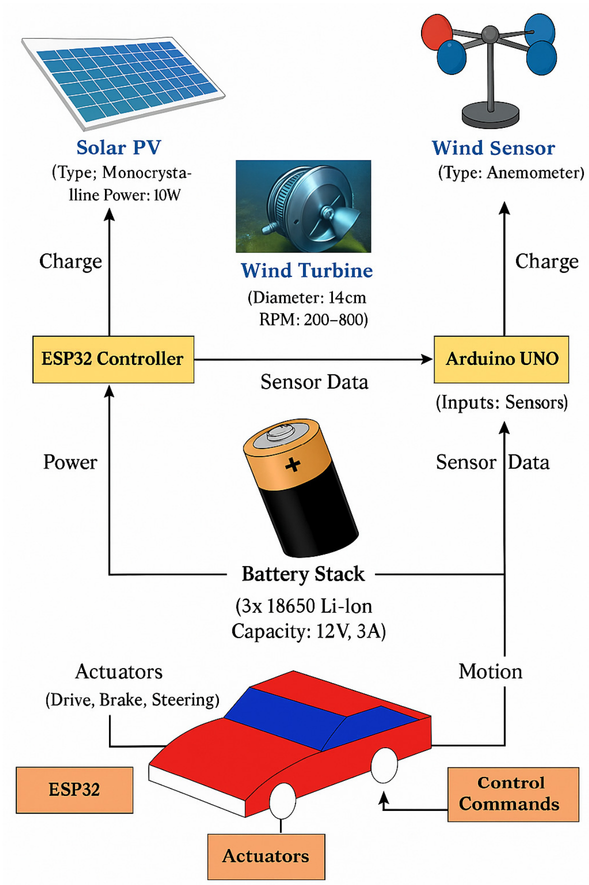

Fig. 2. System-level block diagram of the VMW-WEH.

A. *Design of the Car and Chassis*

The car is built with structural elements from renewable energy sources, such as rooftop solar PV cells for electricity and inductive wind sensors to collect kinetic energy. The 3D-printed turbine-dynamo converts rotational power to 12V. The idea is to integrate energy-harvesting systems into the vehicle chassis, enabling efficient energy capture without compromising structural integrity. The design balances sustainability and functionality to optimize energy recovery while maintaining aerodynamic and mechanical performance, as shown in Figure 2.

B. *Renewable Energy Harnessing*

1) *Solar Voltaic Cells*

Sufficient sunlight on the vehicle's surface generates an electric current by kicking electrons that power all systems in the car, including those made from solar voltaic cells. They store energy in batteries for times without light, such as during darkness or at higher altitudes where the sun isn't shining. Solar cells enhance sustainability by providing additional conventional fuel and reducing reliance on fossil fuels. Positioning to maximize sun exposure ensures cleaner energy production, which leads to improved efficiency and a more environmentally friendly performance.

2) *Wind Turbine Sensors*

In addition to solar power, the vehicle is equipped with wind turbine sensors that measure wind velocity, enabling the system to harness energy from air movement. Wind energy is collected using a wind turbine. During the rotation of the dynamo, electricity is generated, producing a voltage of 2 to 12 volts for vehicle use. This dynamic mode guarantees that the vehicle can store energy even in the absence of sunlight, thereby equipping it with a solar and wind power system.

The energy generated by wind turbines is derived from the conversion of the kinetic energy of moving air into mechanical energy, which is then converted into electrical energy by a generator. This process is initiated by wind moving across the turbine blades, causing them to rotate. This conversion efficiency is highly dependent on factors such as wind speed, blade design, turbine type, and environmental conditions. Finally, the performance of a wind energy system depends on how effectively it harnesses the wind energy available in an area.

The wind turbine has a blade diameter of 14 cm, a 25-degree pitch angle, and operates at 200-800 RPM. The dynamo is a brushed DC generator rated at 12 V and 1.5 A. The battery pack consists of a 3-cell Li-ion 18650 stack (3.7 V, 3000 mAh each) connected in series, totaling 12 V and 3 Ah.

C. *Revolutions per Minute (RPM) and Angle Twist*

RPM is a unit that measures how many full rotations an object makes around its axis in one minute. It is a key parameter in applications like wind turbines and engines, where tracking rotational speed helps improve power output, efficiency, and system stability. The angle of twists indicates how much an object rotates, typically measured in degrees or radians. It depends on torque, material properties, and the shape of the rotating part.

D. *PV Sensors*

Optimal solar energy conversion is achieved by PV sensors that monitor light intensity to ensure efficient use of the power supply. Along with wind power, this system provides vehicle components with a constant power supply, making the system climate-proof and energy self-sufficient.

E. *Battery Stack and Power Distribution*

Solar wind, along with other energy sources, powers the battery system to ensure energy availability even during days with low light or minimal wind [26]. It efficiently directs power to actuators, motor drives, and other essential services. Strong storage and smart distribution will improve the vehicles' ability to withstand weather extremes, reduce reliance on external power, and maximize renewable energy use for operations.

F. *Actuation and Control*

The vehicle is operated using a joystick that controls its actuation system, including steering, acceleration, and braking. The ESP8266 system is used to connect with the joystick and handle actuator control signals due to its lightweight processing needs. At the same time, the ESP32 acts as the main controller, managing energy control, communication, and task timing with FreeRTOS. Together, they form a distributed microcontroller network that provides responsive and real-time control of vehicle subsystems. A joystick interface was chosen due to its simplicity, cost-effectiveness, and suitability for prototype testing. It can be manually controlled with high precision, which is why it is used to test energy harvesting and actuation systems. Unlike AI-based approaches, it can be intervened by humans in real time, increasing safety and reliability during early development and experimental testing.

G. Data Processing and Motor Control

Renewable energy inputs are controlled by the vehicle's data processing system for efficient storage and extraction, ensuring optimal vehicle performance through renewable energy optimization. Pattern recognition is used to plan charging and distribute power most effectively. Motor drives convert functional data into physical movements, enabling speed control and greater energy efficiency. When combined, these systems improve performance, allow low-power operation, and maximize sustainability. The combination facilitates smooth operation at the lowest possible energy costs while meeting situational requirements and environmental dynamics.

```
Algorithm 1: Hybrid energy harvesting and control
Input:
 V_wind  ← Voltage from wind turbine
 V_solar  ← Voltage from photovoltaic (PV) cells
 I_wind  ← Current from wind turbine
 I_solar  ← Current from PV cells
 Battery_V ← Battery voltage level
 Load_Demand ← Real-time load current demand
 T_interval ← Sampling time interval
Initialize:
 Initialize system hardware:
  Configure ADC channels for voltage and current sensing
  Initialize serial communication (UART/I2C/SPI)
  Setup GPIOs for actuator interfaces
  Initialize FreeRTOS scheduler and timers
 Initialize communication with ESP8266 (Joystick input)
 Initialize data logging/storage
 Start the following FreeRTOS tasks:
  Task_EnergySampling
  Task_EnergyDecision
  Task_ActuatorControl
Task_EnergySampling:
  At each T_interval:
  Read V_wind, I_wind from wind sensors
  Read V_solar, I_solar from PV sensors
  Calculate P_wind ← V_wind × I_wind
  Calculate P_solar ← V_solar × I_solar
  Send power data to Task_EnergyDecision
Task_EnergyDecision:
 If Battery_V < 90% capacity:
  Direct P_wind and P_solar to charge battery
 Else If Battery_V ≥ 90% and Load_Demand ≠ 0:
  Direct energy to load operation
 If P_total < Load_Demand:
  Raise alert or engage alternate source (if available)
 Log voltage, current, and energy flow data
Task_ActuatorControl:
 Receive input from joystick (ESP8266)
 Generate PWM signals for:
  Steering
  Acceleration
  Braking
 Adjust outputs based on real-time feedback (if enabled)
Output:
 Stable energy flow to battery and load
 Real-time actuator control signals
```

Algorithm 1 presents a real-time energy-harvesting and control system using FreeRTOS. It collects wind and solar inputs, oversees battery charging and load sharing, and manages joystick-driven vehicle control through ESP32 and ESP8266 in a task-oriented way.

IV. RESULTS AND DISCUSSION

In the results section, the findings and outcomes achieved through the proposed VMW-EHS are thoroughly discussed and further expanded through a synthesis of detailed concepts. This section highlights key parameters that determine energy production, efficiency, and system behavior across various working modes. The following sub-sections detail various data collected to support the proposed renewable energy approach for meeting EV demand compared to other options.

A. Experimental Setup

All results are calculated and presented based on experimental measurements of a small-scale EV prototype. The wind turbine also underwent an outdoor test using a controlled airflow system to simulate vehicle speeds of 5-20 km/h. The wind speed was measured using a digital anemometer, whereas the ESP32 microcontroller with FreeRTOS task management measured the voltage and current outputs. The battery voltage, charge rate, and motor signals were also checked. To assess dynamic performance, the system was tested under varying motion conditions—acceleration, cruising, and sudden stops. All the data are physical measurements; no simulations or theoretical models were performed. Table I presents the simulation and hardware parameters used to validate the system's energy harvesting and control performance.

TABLE I. SIMULATION PARAMETER

Parameter	Value
Vehicle Speed	0 – 20 km/h
Wind Speed	1 – 12 m/s
Turbine Blade Diameter	14 cm
Blade Pitch Angle	25°
Turbine Blade Material	ABS Plastic
Output Voltage (Turbine)	2 – 25 V
Output Voltage (Solar Panel)	30 V
Battery Stack Capacity	12 V, 3 Ah
Sampling Rate (Data Logging)	1 Hz
Microcontrollers	ESP32, Arduino UNO
Operating System	FreeRTOS
Joystick ADC Resolution	10-bit
Test Duration	0 – 10 hours
Turbine Efficiency	35–40%
Task Scheduling (FreeRTOS)	Real-time, multitask

B. *Efficiency and Power Curve of a Single Solar Cell*

The efficiency and power curves of a single cell are shown in Figure 3, which indicates the solar cell's performance under different irradiation levels and other operating conditions, such as temperature. Using irradiance boosts power output and efficiency, which increase to maximum levels, then decline due to heat effects on the PV material and saturation.

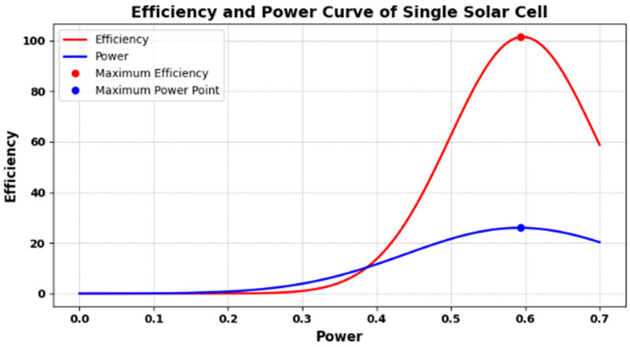

Fig. 3. Efficiency and power curve of a single solar cell.

C. *Air Velocity against Different Speeds*

The airflow speed is proportional to the vehicle speed to capture more wind energy, as shown in Figure 4. However, above a critical airflow velocity, the transition to airflow increases turbulence and drag, leading to a decline in aerodynamic efficiency. This phenomenon is referred to as the efficiency plateau. The optimal speed range balances energy collection with airflow and drag. This point is essential for electric vehicles, as optimal aerodynamic conditions can facilitate charging without harming the system's structural or operational integrity.

D. *Voltage Generation against Different Speeds*

In the wind energy system shown in Figure 5, the voltage output varies with vehicle speed, but the increase diminishes at higher speeds due to aerodynamic drag and mechanical constraints. This indicates an optimal speed range where this system can achieve maximum voltage, beyond which efficiency levels off or declines. The results highlight the need to calibrate EV wind-harvesting systems to operate within an optimal speed range where energy output is maximized and inefficiencies at high speeds are avoided, which only lead to diminishing returns.

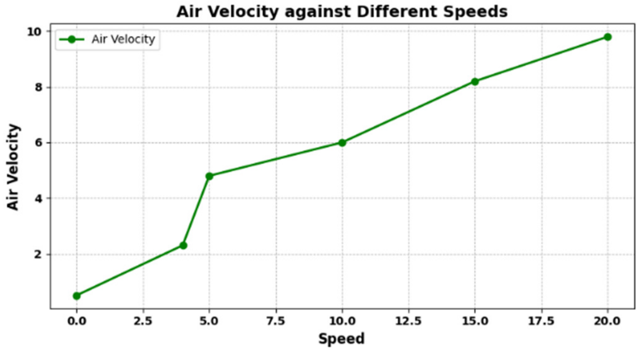

Fig. 4. Air velocity against different speeds.

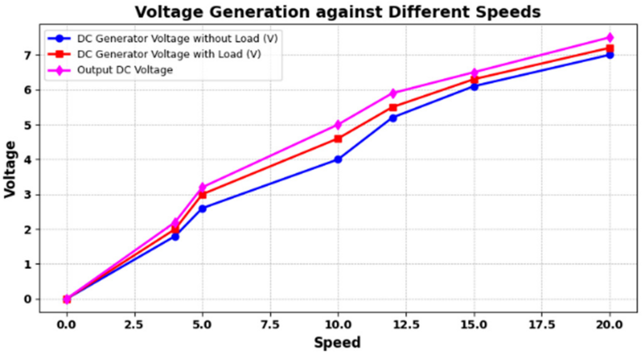

Fig. 5. Voltage generation against different speeds.

E. *Electrical Voltage and Current Output against Different Speeds*

Figure 6 illustrates how the electrical voltage and current outputs of the wind energy-harvesting system vary with airflow velocity. The voltage and current outputs increase consistently at lower vehicle speeds, indicating effective energy conversion. But as speed increases, the system eventually reaches a limit at which the energy conversion efficiency drops significantly. An optimized system balances energy capture and aerodynamic constraints, making wind energy harvesting sustainable and enabling long-term vehicle use.

F. *Efficiency vs Cost Analysis*

Figure 7 presents a comparative study of energy-harvesting efficiency versus cost for various energy-harvesting methods in EVs. The VMW-EHS is highly efficient and cost-effective, demonstrating the superiority of the system over traditional methods.

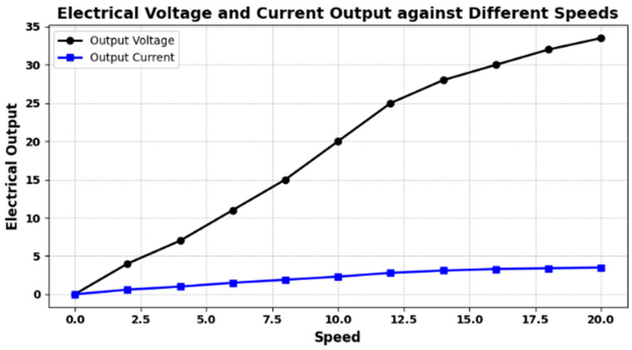

Fig. 6. Electrical voltage and current output against different speeds.

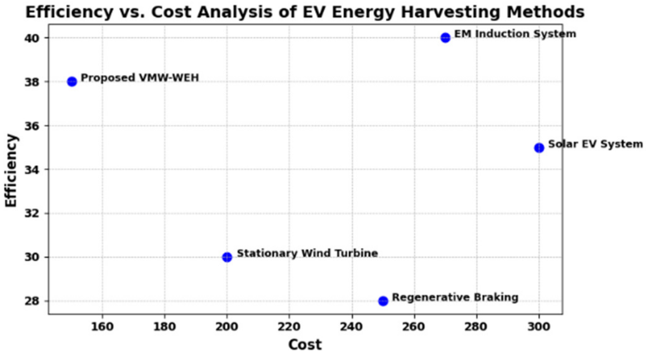

Fig. 7. Efficiency vs cost analysis.

G. Electrical Power Output against Different Speeds

Efficient wind-to-electricity conversion, with power output increasing rapidly as speed rises at sub- and near-rated operating conditions, as shown in Figure 8. Speeds above this will generate more power, but at an increasingly slower, diminishing rate due to drag, inattention, and inefficiencies, until reaching maximum capacity. This indicates that there must be an optimal speed range for peak efficiency. Turbine designs must be optimized for this power range to maximize sustainable energy production, especially with EVs, where balanced performance is critical for safety.

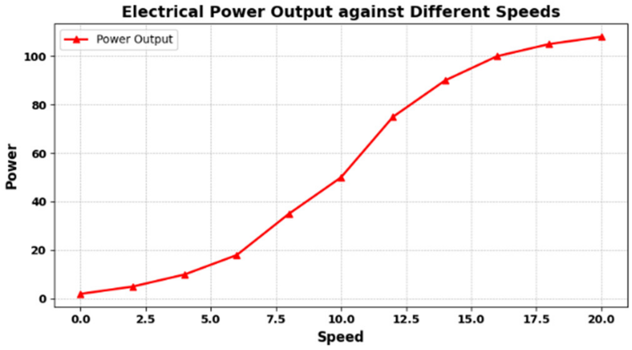

Fig. 8. Electrical power output against different speed.

H. Performance Evaluation under Real Conditions

Experimental results showed that the average energy harvested was 85W at 15 km/h, with a peak voltage of 25V. The system's hourly energy budget was 62Wh. Communication latency between an ESP8266 and an ESP32 averaged 27 ms, making it suitable for real-time control of prototype EVs.

I. Battery Charging Trend with Time

Figure 9 shows the charging curve of the battery using renewable energy. Initially, charging is quick because the system efficiently scavenges energy. When capacity approaches full, the charge decreases due to internal resistance and becomes 'saturated' because of absorbed or reduced energy, since over-charging is a protective measure. This slide, from fast charging to trickle charging, highlights the need for adaptive charge controllers to maximize charging speed without damaging the battery. An intelligent two-phase approach optimizes the balance between rapid energy storage and battery lifespan, preventing excessive charging rates and temperature-related degradation.

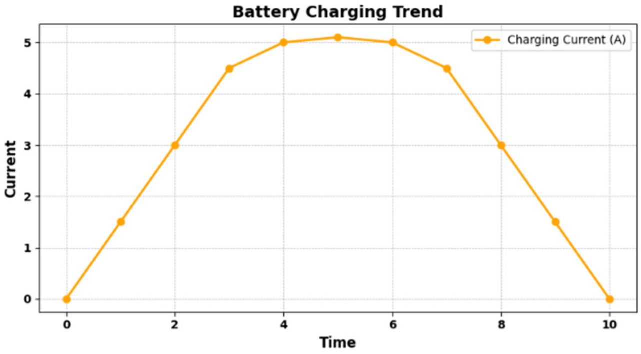

Fig. 9. Battery charging trend with time.

J. Performance Metrics

Table II displays the adaptive performance of the proposed system under various environmental conditions. On windless nights, power is sustained through battery storage, which can support only a limited number of functions. Wind energy continues to produce moderate power during rainy weather, even when solar input is low. This hybrid architecture enables the vehicle to continue operating even in less-than-ideal weather conditions, making it more reliable and autonomous.

TABLE II. PERFORMANCE METRICS OF THE PROPOSED METHOD

Environmental Condition	Energy Source (s)	Measured Output Voltage (V)	Estimated Power Output (W)	Efficiency (%)
Clear Sunny Day	Solar + Wind	22 – 25 V	90 – 100 W	~30–35
Cloudy but Windy	Wind only	16 – 22 V	60 – 80 W	~25–30
Windless Day (Sunny)	Solar only	20 – 24 V	70 – 90 W	~40
Windless Night	Battery only (from storage)	10 – 12 V	30 – 40 W	~18–22
Rainy with Wind	Wind + Battery	14 – 18 V	40 – 60 W	35–40
Overcast and Windless	Battery only (minimal charge)	8 – 10 V	20 – 30 W	Efficiency (%)

K. Practical Considerations

The system is safe because it includes short-circuit protection and thermal control. It is modular, making it scalable, and the 3D-printed turbine has proven stable at speeds up to 25 km/h, enhancing its mechanical resilience in real-world use.

L. Comparison with Existing Methods

Table III lists different sources of EV energy harvesting: stationary wind turbines (20V/80W), solar EVs (4 solar EVs with 18V/70W), and regenerative braking systems (15V/50W). These are compared with the proposed VMW-WES with a 25V/100W output, which offers greater efficiency in capturing vehicle-motion-driven wind energy, unlike the ambient approach. The performance values of the proposed VMW-WES (25V, 100W) are tested experimentally at vehicle speeds of 5-20 km/h under moderate wind and full sunlight. The values for other systems were obtained from published literature and adjusted to similar conditions where possible. These figures should be used for performance benchmarking and feasibility comparisons. VMW-WES is compared to the standard energy harvester because it produces higher outputs (25V/100W) by utilizing vehicle motion to generate wind energy, unlike stationary wind turbines (20V/80W) that rely on wind forces. Unlike stationary wind turbines (20V/80W) that are regulated by wind, VMW-WES is a Weh energy harvester in motion. It provides refreshment for regenerative braking (50W) and electromagnetic induction (70W), offering consistent power for continuous EV operation. This study compares the dual-mode TENG system in [16], which is primarily designed for static or low-motion conditions but leverages high-speed vehicle-induced airflow to generate more consistent, scalable power.

TABLE III. COMPARISON WITH EXISTING METHODS

Method	**Energy Source**	**Voltage Output (V)**	**Power Output (W)**
Traditional Wind Turbine [10]	Wind (Stationary)	18–22 V	75–85 W
Solar-Powered EVs [1]	Solar (PV Panels)	28–32 V	85–95 W
Regenerative Braking [19]	Mechanical (Braking Energy)	13–17 V	45–55 W
Electromagnetic Induction [16]	Mechanical (Vibration/Movement)	16–20 V	65–75 W
Proposed VMW-EHS	Wind (Vehicle-Mobility)	22–25 V	90–100 W

Additionally, the system described in [17] is conceptually integrated into smart cities, although it lacks real-time actuation control and FreeRTOS-based communication, which are the main points of this design. The dynamic use cases of this proposed method are experimentally confirmed, and the energy output can be measured (up to 100 W), making it more suitable for mobile, autonomous EVs. Conventional technologies like regenerative braking and stationary wind turbines offer intermittent and limited energy harvesting. Conversely, the VMW-WES proposed utilizes vehicle-generated wind during movement and enables real-time energy harvesting. Combined with solar input and onboard control, it offers a continuous, scalable, and autonomous power solution for EVs. Although the VMW-WES supplies more energy to EV subsystems, it involves trade-offs such as adding approximately 1.2 kg to the structure and causing slight additional aerodynamic drag due to external turbine mounting. By integrating mobility with energy capture, VMW-WES promotes sustainable mobility beyond traditional transport and provides a scalable, implementable solution to enhance EV autonomy, advancing it as a next-generation alternative to existing static or intermittent energy-harvesting technologies.

M. System Limitations and Mitigation Strategies

The proposed system faces several practical challenges, including environmental variability, mechanical losses, aerodynamic drag, and low energy output during periods of low wind or solar conditions. These factors can reduce overall system efficiency and reliability. Initially, installing wind turbines creates aerodynamic drag, which may slightly decrease the vehicle's efficiency at high speeds. Mechanical losses from friction in the turbine shafts and gears also affect the net energy output. Additionally, harvesting effectiveness may be limited by environmental variability, such as still traffic or overcast days. To address these issues, future efforts will focus on aerodynamic optimization, the use of lightweight materials, advanced power electronics, and energy buffering with supercapacitors or hybrid storage.

V. CONCLUSION AND FUTURE WORK

The study shows that self-sufficient power for smart vehicles can be achieved through vehicle-generated wind energy and solar harvesting, reducing dependence on existing charging infrastructure. The VMW-WES combines IoT-enabled control and FreeRTOS-based real-time processing to enable optimal energy allocation in intelligent, responsive EVs. Although this research involves a small-scale prototype, the modular and lightweight system can be expanded to full-sized EVs with larger turbines and batteries. Future work will include field testing of the system in various environmental and speed conditions, implementing machine learning for adaptive energy management, and expanding the architecture to cover micro-mobility and smaller EVs. Additional efforts aim to improve durability, refine power electronics, and enhance long-term performance across seasonal and terrain variations. This development marks a milestone toward sustainable transportation by integrating autonomous energy harvesting with intelligent vehicle control.

REFERENCES

[1] H. K. Channi, M. Malik, C.-L. Chen, H.-C. Chen, R. Sandhu, and C. Prabha, "A Solar-Integrated Wireless Charging System for Electric Vehicles," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 19349–19353, Feb. 2025, https://doi.org/10.48084/etasr.8840.

[2] M. E. Bendib and A. Mekias, "Solar Panel and Wireless Power Transmission System as a Smart Grid for Electric Vehicles," *Engineering, Technology & Applied Science Research*, vol. 10, no. 3, pp. 5683–5688, June 2020, https://doi.org/10.48084/etasr.3473.

[3] A. Ali, K. Mahmoud, and M. Lehtonen, "Optimal planning of inverter-based renewable energy sources towards autonomous microgrids accommodating electric vehicle charging stations," *IET Generation,*

Transmission & Distribution, vol. 16, no. 2, pp. 219–232, 2022, https://doi.org/10.1049/gtd2.12268.

[4] C. Sun, J. Guanetti, F. Borrelli, and S. J. Moura, "Optimal Eco-Driving Control of Connected and Autonomous Vehicles Through Signalized Intersections," *IEEE Internet of Things Journal*, vol. 7, no. 5, pp. 3759–3773, Feb. 2020, https://doi.org/10.1109/JIOT.2020.2968120.

[5] H. Fathabadi, "Novel stand-alone, completely autonomous and renewable energy based charging station for charging plug-in hybrid electric vehicles (PHEVs)," *Applied Energy*, vol. 260, Feb. 2020, Art. no. 114194, https://doi.org/10.1016/j.apenergy.2019.114194.

[6] B. Qiao and J. Liu, "Multi-objective dynamic economic emission dispatch based on electric vehicles and wind power integrated system using differential evolution algorithm," *Renewable Energy*, vol. 154, pp. 316–336, July 2020, https://doi.org/10.1016/j.renene.2020.03.012.

[7] D. Phan, A. Bab-Hadiashar, M. Fayyazi, R. Hoseinnezhad, R. N. Jazar, and H. Khayyam, "Interval Type 2 Fuzzy Logic Control for Energy Management of Hybrid Electric Autonomous Vehicles," *IEEE Transactions on Intelligent Vehicles*, vol. 6, no. 2, pp. 210–220, June 2021, https://doi.org/10.1109/TIV.2020.3011954.

[8] M. Massar, I. Reza, S. M. Rahman, S. M. H. Abdullah, A. Jamal, and F. S. Al-Ismail, "Impacts of Autonomous Vehicles on Greenhouse Gas Emissions—Positive or Negative?," *International Journal of Environmental Research and Public Health*, vol. 18, no. 11, Jan. 2021, Art. no. 5567, https://doi.org/10.3390/ijerph18115567.

[9] W. Wang, L. Liu, J. Liu, and Z. Chen, "Energy management and optimization of vehicle-to-grid systems for wind power integration," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 1, pp. 172–180, Jan. 2021, https://doi.org/10.17775/CSEEJPES.2020.01610.

[10] X. Wu, H. Li, X. Wang, and W. Zhao, "Cooperative Operation for Wind Turbines and Hydrogen Fueling Stations With On-Site Hydrogen Production," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2775–2789, July 2020, https://doi.org/10.1109/TSTE.2020.2975609.

[11] M. A. Figliozzi, "Carbon emissions reductions in last mile and grocery deliveries utilizing air and ground autonomous vehicles," *Transportation Research Part D: Transport and Environment*, vol. 85, Aug. 2020, Art. no. 102443, https://doi.org/10.1016/j.trd.2020.102443.

[12] R. Bayani, S. D. Manshadi, G. Liu, Y. Wang, and R. Dai, "Autonomous Charging of Electric Vehicle Fleets to Enhance Renewable Generation Dispatchability," *CSEE Journal of Power and Energy Systems*, vol. 8, no. 3, pp. 669–681, Feb. 2022, https://doi.org/10.17775/CSEEJPES.2020.04000.

[13] D. Maurya *et al.*, "3D printed graphene-based self-powered strain sensors for smart tires in autonomous vehicles," *Nature Communications*, vol. 11, no. 1, Oct. 2020, Art. no. 5392, https://doi.org/10.1038/s41467-020-19088-y.

[14] S. Manne, E. L. Lydia, I. V. Pustokhina, D. A. Pustokhin, V. S. Parvathy, and K. Shankar, "An intelligent energy management and traffic predictive model for autonomous vehicle systems," *Soft Computing*, vol. 25, no. 18, pp. 11941–11953, Sept. 2021, https://doi.org/10.1007/s00500-021-05614-7.

[15] C. Chen, T.-B. Xu, A. Yazdani, and J.-Q. Sun, "A high density piezoelectric energy harvesting device from highway traffic — System design and road test," *Applied Energy*, vol. 299, Oct. 2021, Art. no. 117331, https://doi.org/10.1016/j.apenergy.2021.117331.

[16] L. He *et al.*, "A Dual-Mode Triboelectric Nanogenerator for Wind Energy Harvesting and Self-Powered Wind Speed Monitoring," *ACS Nano*, vol. 16, no. 4, pp. 6244–6254, Apr. 2022, https://doi.org/10.1021/acsnano.1c11658.

[17] Z. A. Khan, H. H. R. Sherazi, M. Ali, M. A. Imran, I. U. Rehman, and P. Chakrabarti, "Designing a Wind Energy Harvester for Connected Vehicles in Green Cities," *Energies*, vol. 14, no. 17, Jan. 2021, Art. no. 5408, https://doi.org/10.3390/en14175408.

[18] M. A. Rahman *et al.*, "Renewable Energy Re-Distribution via Multiscale IoT for 6G-Oriented Green Highway Management," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 12, pp. 23771–23780, Sept. 2022, https://doi.org/10.1109/TITS.2022.3203208.

[19] A. Ali, L. Qi, T. Zhang, H. Li, A. Azam, and Z. Zhang, "Design of novel energy-harvesting regenerative shock absorber using barrel cam follower mechanism to power the auxiliaries of a driverless electric bus," *Sustainable Energy Technologies and Assessments*, vol. 48, Dec. 2021, Art. no. 101565, https://doi.org/10.1016/j.seta.2021.101565.

[20] J. Graves, Y. Kuang, and M. Zhu, "Scalable pendulum energy harvester for unmanned surface vehicles," *Sensors and Actuators A: Physical*, vol. 315, Nov. 2020, Art. no. 112356, https://doi.org/10.1016/j.sna.2020.112356.

[21] S. Kassan, J. Gaber, and P. Lorenz, "Autonomous Energy Management System Achieving Piezoelectric Energy Harvesting in Wireless Sensors," *Mobile Networks and Applications*, vol. 25, no. 2, pp. 794–805, Apr. 2020, https://doi.org/10.1007/s11036-019-01303-w.

[22] C.-D. Le, T.-H. Nguyen, D.-L. Vu, C.-P. Vo, and K. K. Ahn, "A rotational switched-mode water-based triboelectric nanogenerator for mechanical energy harvesting and vehicle monitoring," *Materials Today Sustainability*, vol. 19, Nov. 2022, Art. no. 100158, https://doi.org/10.1016/j.mtsust.2022.100158.

[23] I. W. Damaj, J. K. Yousafzai, and H. T. Mouftah, "Future Trends in Connected and Autonomous Vehicles: Enabling Communications and Processing Technologies," *IEEE Access*, vol. 10, pp. 42334–42345, 2022, https://doi.org/10.1109/ACCESS.2022.3168320.

[24] R. Ramraj, E. Pashajavid, S. Alahakoon, and S. Jayasinghe, "Quality of Service and Associated Communication Infrastructure for Electric Vehicles," *Energies*, vol. 16, no. 20, Jan. 2023, Art. no. 7170, https://doi.org/10.3390/en16207170.

[25] K. S. Vaidya, P. M. Patil, and M. Alagirisamy, "Hybrid CNN-SVM Classifier for Human Emotion Recognition Using ROI Extraction and Feature Fusion," *Wireless Personal Communications*, vol. 132, no. 2, pp. 1099–1135, Sept. 2023, https://doi.org/10.1007/s11277-023-10650-7.

[26] S. Srinivasan, A. A. Athithan, M. Alagirisamy, and A. A. N. Sowan, "Dynamic behavior analysis for optimally controlled wind turbine system via metaheuristic techniques," *AIP Conference Proceedings*, vol. 3161, no. 1, Aug. 2024, Art. no. 020069, https://doi.org/10.1063/5.0229406.