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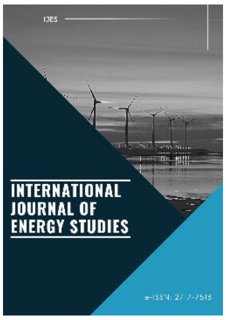

Research Article

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Highway wind energy conversion with a savonius-darrieus hybrid turbine

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Highlights

- A new hybrid vertical axis wind turbine (VAWT) has been designed by combining three-bladed Savonius and two-bladed Darrieus turbines.
- The newly proposed double VAWT design achieved the best performance with a maximum power coefficient (C_P).
- The annual energy amount to be obtained from vehicle speeds on highways was evaluated with the newly proposed double VAWT design.

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ABSTRACT

The need for electrical energy for applications such as self-powered traffic signals, highway lights, and battery charging of electric vehicles has led to ongoing efforts to develop specially designed turbines that can efficiently convert wind energy generated by vehicles traveling on highways into electricity. In this study, a new hybrid vertical axis wind turbine (VAWT) is designed by combining three-bladed Savonius and two-bladed Darrieus turbines on a vertical axis. This newly designed double VAWT was manufactured, and the power outputs at a wind speed of 5 m/s obtained experimentally were compared with the results of Savonius and Darrieus turbines. The energy production of the double VAWT design using wind generated by various vehicles on highways, including cars, minibuses, mini trucks, buses, and trucks, has been evaluated. The optimum positioning of the turbine on highways that provides the highest power output with a double VAWT was determined. All calculations are based on measured voltage and current values at the generator connected to the turbine. The results show that the newly proposed double VAWT design achieves the best performance with a maximum C_P value of 0.223. Furthermore, the optimal horizontal and vertical positioning of the turbine with respect to the roadside of highways was determined. The maximum speed recorded at the turbine was 3.7 m/s, obtained with a truck. The best power output of the turbine was obtained from trucks among the five vehicles mentioned. It has been estimated that the hybrid wind turbine designed, produced, and tested in this study can generate approximately 35 kWh of electricity per year on a highway with heavy vehicle traffic.

Keywords: Renewable energy, Power generation, Wind turbine, Savonius, Darrieus, Double turbine, Highways

1. INTRODUCTION

The growing global energy demand and the need to reduce the environmental impact of fossil fuels have accelerated research into renewable energy sources. The need to develop highly efficient turbines, especially in regions with low and variable wind speeds, has become increasingly important. The potential to generate electricity by harnessing the turbulent wind conditions created by highway traffic has attracted the attention of researchers. With the rapid increase in the number of electric vehicles, the use of wind energy on highways has become even more significant. Part of the energy required to charge these vehicles can be sourced from the wind generated by moving vehicles on highways. Understanding the characteristics of the wind caused by vehicle movement presents a great opportunity to enhance energy efficiency. In this context, the development and testing of innovative wind turbine designs are among the solutions that can support energy generation on highways. Wind turbine technologies developed for low wind speeds have been the subject of extensive research, with a focus on various application areas and methods. These studies often target different scenarios such as urban settings, highway environments, and low-cost energy solutions.

The adaptation of vertical axis wind turbines (VAWTs) equipped with directional deflectors for urban environments was investigated by Chong et al. [1]. The study focused on efficiently directing wind flows around tall buildings and integrating VAWTs into these settings. Flow directing devices were employed to increase wind speed and ensure a steady airflow in a fixed direction within urban areas. The results showed that using flow directing apparatus in conjunction with VAWTs significantly enhanced the capture of wind energy and improved turbine performance. These findings offer adaptable strategies for efficiently utilizing low and variable wind speeds in environments such as highways.

A study evaluating the potential of harnessing energy from the wind currents generated by vehicles, focusing on low and variable wind speeds, was conducted by Morbiato et al. [2]. The study highlighted that wind flows created by moving vehicles along roads pose challenges, particularly for turbines to operate efficiently at low speeds. The research emphasized the need to determine optimization requirements and develop more suitable turbine designs for such scenarios. The findings revealed that wind turbines placed alongside highways have significant energy generation potential. However, the study also indicated that further research is needed to improve turbine efficiency in these conditions.

The potential for generating energy from the wind currents produced by moving vehicles on highways using low-cost VAWTs was explored by Rathore et al. [3]. The study examined the turbulence and wind flows caused by traffic and demonstrated that VAWTs offer a suitable solution for harvesting energy from these wind currents. The results indicated that low-cost turbines could be effectively deployed in high-traffic sections of highways for energy production. However, the study also emphasized the need for improved aerodynamic designs to enhance the efficiency of these turbines further.

Al-Aqel et al. [4] conducted field tests to assess the feasibility of deploying small wind turbines along highways in Malaysia, focusing on the optimal placement of turbines and the variability of wind sources. The study revealed that the primary challenges in turbine deployment were insufficient wind speeds and the difficulty of maintaining the turbines. Furthermore, the research highlighted that a thorough analysis of wind resources and the optimization of turbine placement could significantly enhance energy production. This underscores the importance of strategic planning in the use of small wind turbines for highway energy generation.

The rotational behavior of Savonius turbines placed along highways during different monsoon seasons was examined by Santhakumar et al. [5], investigating the impact of environmental conditions on turbine performance. The study demonstrated that varying wind speeds during monsoon seasons significantly influenced the performance of Savonius turbines, showing that these turbines were able to rotate even at low wind speeds. The ability of the turbines to operate efficiently under such conditions highlights their suitability for deployment in highway areas with fluctuating wind patterns, making them particularly viable in regions with unpredictable wind conditions.

The Hybrid model, which combines Savonius and Darrieus turbines, was introduced to explore the efficiency of hybrid turbine designs by Pallotta et al. [6]. The study analyzed how these turbines perform under different wind speeds and conditions. It was observed that hybrid turbine designs, by integrating the strengths of both turbine types, can produce energy efficiently across a wider range of wind speeds. The combination optimizes the starting capability of the Savonius turbine at low wind speeds while leveraging the efficiency of the Darrieus turbine at higher wind speeds, offering a balanced and adaptable solution for various wind conditions.

Siddiqui et al. [7] experimentally investigated the performance of hybrid vertical axis turbines. The study revealed that these hybrid turbines perform better at low wind speeds, making them particularly suitable for urban and highway environments. The findings highlighted the potential of hybrid designs to operate efficiently in locations where wind conditions are less predictable, thus enhancing their applicability in areas with variable and lower wind speeds.

The impact of semi-cylindrical flow deflectors on the performance of hybrid turbines was examined by Kumar et al. [8]. The study concluded that these deflectors play a significant role in enhancing the energy output of the turbines by improving the efficiency of wind capture. The deflectors helped channel the wind flow more effectively towards the turbine blades, leading to increased power generation, especially in environments with variable wind conditions.

CFD (Computational Fluid Dynamics) analyses to investigate the effects of radius ratio and blade connection(settle) angle on the performance of Darrieus-Savonius hybrid turbines were conducted by Liang et al. [9]. The study revealed that turbine geometry, particularly the radius ratio and blade settle angle, plays a critical role in determining energy production. The findings emphasized that optimizing these geometric parameters can significantly enhance the efficiency of hybrid turbine designs, especially in scenarios with varying wind speeds. This highlights the importance of geometrical optimization in hybrid turbine development for better energy harvesting.

Asadi and Hassanzadeh [10] analyzed the effects of rotor parameters on the performance of two-bladed Darrieus and two-bladed Savonius hybrid turbines. Their study explored how different rotor geometries impact energy production and demonstrated how optimal geometric configurations can enhance hybrid turbine performance. The research particularly highlighted that the combination of Darrieus and Savonius turbines provides a good balance at low wind speeds and allows for energy harvesting over a broader range of wind speeds. The findings contribute valuable insights into parameter optimization for future hybrid turbine designs, aiming to improve their efficiency and adaptability in various wind conditions.

A CFD study on energy recovery from wake turbulence generated by vehicles was conducted by Tian et al. [11]. The study simulated turbulent airflows created by highway traffic to investigate the potential for energy extraction from these flows. It tested the capacity of VAWTs to harvest energy from wake turbulence and examined the effects of various parameters, such as wind speed, turbine placement, and flow direction, on turbine performance. The results demonstrated that energy harvesting from these wind flows is feasible, particularly in high-traffic highway environments.

Factors affecting the performance of VAWTs in highway environments were optimized using numerical simulations by Lee and Baby [12]. Their study focused on determining the optimal locations and designs for turbine installation on highways. Simulation results revealed that wind direction and speed significantly impact turbine efficiency, and these parameters need to be optimized. The study concluded that strategic turbine placements along highways could maximize energy production potential.

Pan et al. [13] developed systems for harvesting storable renewable wind energy in high-speed railway tunnels. Their study aimed to generate energy using airflows within tunnels, testing the performance of VAWTs in enclosed spaces. The results demonstrated that it is possible to harvest energy from the sudden wind currents generated by high-speed trains. This innovative approach is considered a significant step toward developing energy harvesting systems for enclosed environments like tunnels.

The integration of various renewable energy sources, such as solar and biomass, on highways was examined by Gupta et al. [14]. Their study focused on how different renewable energy technologies could be combined for energy production on highways. The results showed that combining energy sources like solar, wind, and biomass can enhance energy efficiency and that, with proper integration, a significant portion of a highway’s energy needs could be met.

The "Adaptive Blocking Factor Correlation Method" for analyzing the performance of Savonius-type turbines in a wind tunnel was proposed by Roy and Saha [15]. This method was designed to measure turbine performance more accurately in wind tunnel tests. The study developed methods to enhance turbine performance, especially at low wind speeds. The results demonstrate that the aerodynamic performance of Savonius turbines can be optimized using such methods.

Yang et al. [16] explored the planning of electric vehicle (EV) charging in highway environments and its impact on energy infrastructure. The study identified the infrastructure requirements for charging EVs along highways and focused on integrating renewable energy sources, such as wind energy, into these charging stations. The results indicate that with proper planning, the energy needs for EV charging can be substantially met.

A comprehensive review of hybrid kinetic turbines was conducted by Kumar and Nikhade [17]. Their study assessed the potential for generating energy using kinetic energy sources and examined the technological advancements required to optimize the performance of such systems. The research emphasized the significant potential of hybrid models of VAWT and Savonius turbines in utilizing kinetic energy sources effectively.

Sheldahl et al. [18] presented performance data for 2-blade and 3-blade Savonius rotors measured in a wind tunnel and examined how these rotors behave under varying wind speeds and turbulence conditions. The experimental study demonstrated that Savonius rotors can efficiently generate energy even at low speeds and in turbulent flows. Additionally, it was found that the number of rotor blades directly affects turbine performance, with a higher blade numbers providing better performance at lower wind speeds.

The effects of wind turbulence on Darrieus turbines were analyzed by Molina [19] using both experimental and numerical methods. The study highlighted that the turbines' energy production capacity decreases in highly turbulent areas and emphasized the need for design optimization to address this issue. To mitigate the effects of wind turbulence, the study recommended improving the aerodynamic design of turbine blades.

The effects of design parameter ratios on the performance of hybrid Darrieus-Savonius turbines were investigated by Roshan et al. [20]. The study demonstrated that factors such as rotor dimensions, number of blades, and set angles directly impact energy production. The results indicated that with the correct design parameters, these hybrid turbines can achieve high performance even in low and variable wind speeds.

Uddin et al. [21] presented an innovative design for a smart vertical axis wind turbine tailored for use on highways and detailed the novel approaches involved in its integration. The study demonstrated that smart turbines, which self-optimize based on wind direction and speed, could significantly enhance the energy production potential along highway edges. The design incorporates a range of automated systems that increase energy output and reduce maintenance costs.

These studies highlight the diversity of turbine designs and optimization methods aimed at improving efficiency at low wind speeds. Innovative hybrid turbine models and cost-effective VAWT solutions have the potential to provide sustainable energy production in highway and urban environments. These research efforts offer various solutions to enhance energy production potential, especially in challenging environmental conditions such as highways.

In this study, a hybrid turbine design is proposed that differs from the common designs found in the literature, featuring 3 Savonius blades on the inside and 2 Darrieus blades on the outside. While existing research on hybrid turbine design has generally focused on optimizing rotor radii, height, and other dimensional ratios, there has been insufficient experimental focus on their suitability for low and variable wind speeds on highways. This study experimentally investigates the variation in wind speeds produced by 5 different vehicles and the energy generation capacity of the proposed new design. Additionally, 9 different scenarios regarding the optimal placement of the turbine along the roadside have been examined.

This study contributes to the literature in the field of renewable energy by focusing on methods of generating energy from wind created by vehicle movement. The hybrid turbine design combines the advantages of Savonius and Darrieus turbines, offering high efficiency, especially in low and variable wind speeds. In the literature, hybrid turbines have shown great potential in areas like highways, where wind speeds are irregular but energy potential is high, making them suitable for such environments. The unique contribution of this study is its real-world examination of the energy generation potential using wind generated by vehicles. Previous research often focused on experiments conducted in wind tunnels or with steady wind streams, whereas this study evaluates the performance of hybrid turbines in real-world conditions at different roadside positions and with various vehicle speeds. Furthermore, it analyzes the power performance of the turbine at different placement positions, providing valuable insights into optimal placement strategies.This study expands the literature by exploring both the performance of hybrid turbine designs and potential energy generation sites along highways. With the increasing interest in alternative renewable energy sources, further research into the real-world applications of such hybrid turbines is necessary.

2. METHODOLOGY

In this study, a hybrid turbine was designed and manufactured by combining a three-blade Savonius and a two-blade Darrieus turbine, with the turbines placed concentrically. The optimal configuration was investigated using three different Darrieus rotor diameters. To achieve this, the power performance of the turbines was measured at a wind speed of 5 m/s generated by a blower, and the results were compared. The power performance of the best-performing hybrid turbine was then tested with the wind generated by five different vehicles traveling at 100 km/h on the highway. Additionally, the power output of the turbine was measured at nine different roadside positions, and the optimal position was identified. Finally, the potential energy production of the turbine over the course of one year was estimated. This study examines the feasibility of a new vertical axis wind turbine (VAWT) design combining Savonius and Darrieus blades to harness wind energy from passing vehicles on highways.

2.1. Manufacturing of the Prototype Turbines

Prototype turbines were 70 cm in diameter and 37 cm in height. The design was developed using SolidWorks, selecting a two-bladed Darrieus and three-bladed Savonius based on previous research for optimal performance.The current study adopted the dimensions of these turbine models, along with the design of the rotor shaft, the chord connecting the blades to the rotating shaft, and the iron structure. Figure 1 shows the model design.

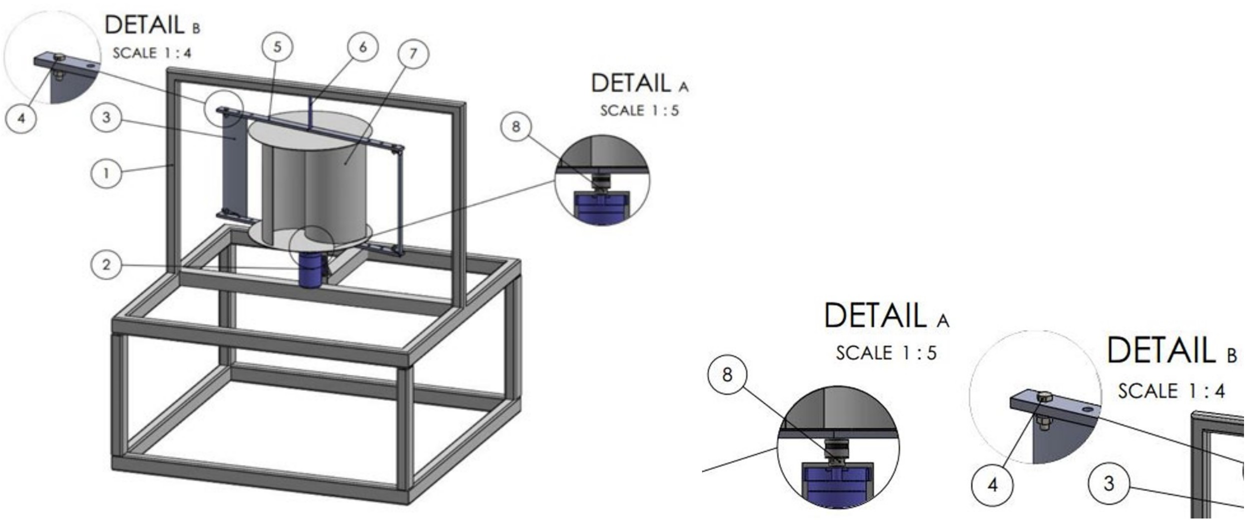

Figure 1. Details of the newly proposed double VAWT

The part names of the newly proposed double turbine are given in Table 1.

Table 1. The part names of the double WAVT

No	Name of the part
1	Frame
2	Motor
3	Darrieus blade
4	Bolt
5	Chord
6	Shaft
7	Savonius blade
8	Link connections

An Ender 5 Plus model 3D printer by Creality was utilized to fabricate three Savonius blades, two Darrieus blades, and the connecting chord. Bioplastic PLA was chosen as the material for these components, while iron was employed for the rotating shaft and the protector frame of the proposed model. Figure 2 shows the proposed double turbine manufactured.

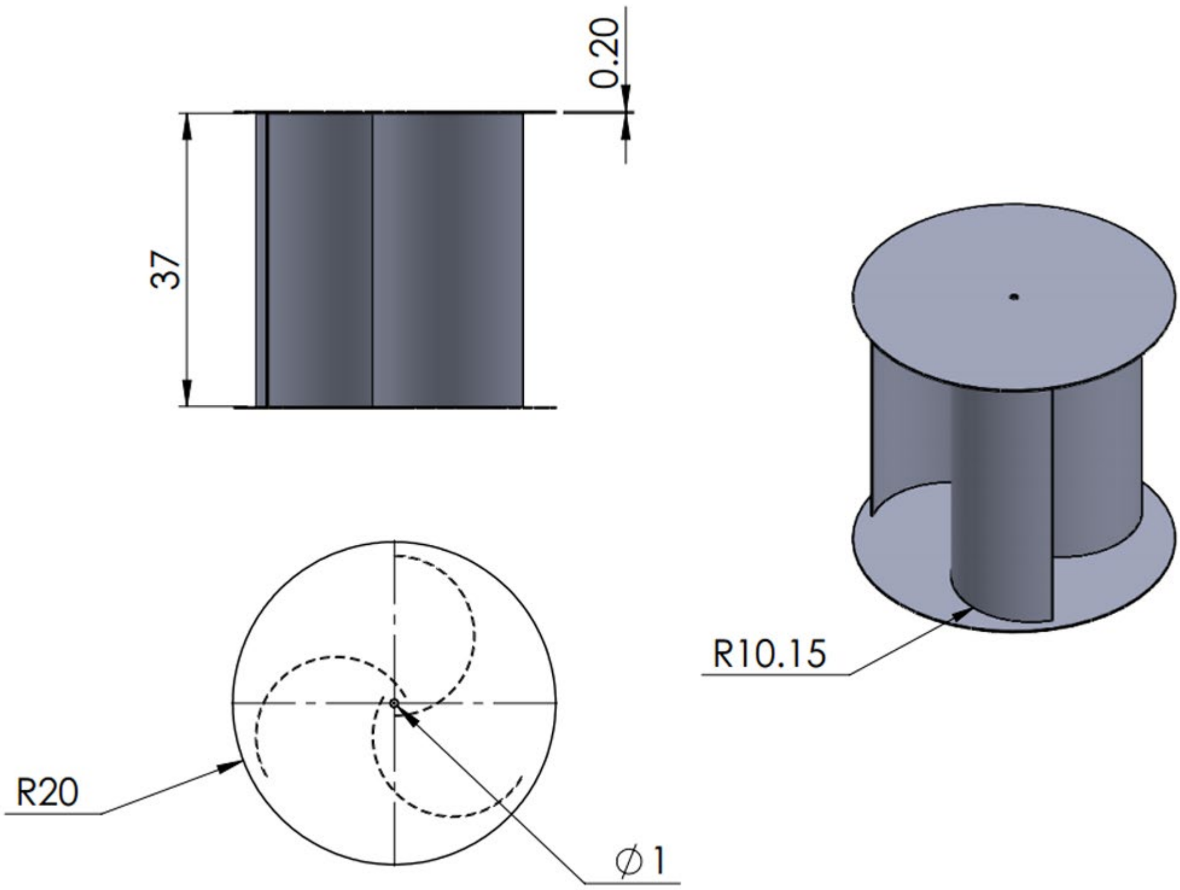

Figure 2. Dimensions of the savonius turbine

DU-06-W-200 airfoil was used for the blade crossections of Darrieus. Two blades of Darrieus are shown in Figure 3. This airfoil, developed by Delft University, is an aerodynamic profile designed specifically for wind turbines operating at low speeds and low Reynolds numbers. These characteristics make it ideal for small-scale wind turbines operating at low wind speeds. It offers efficient aerodynamic performance with a high lift and low drag coefficient. It is optimized to perform optimally at low Reynolds numbers (typically in the range of 200,000 to 500,000). It is preferred for small-scale wind turbines operating at low wind speeds. Its wide lift range allows it to maintain high efficiency at different wind speeds. It ensures stable performance with good pressure distribution and low turbulence generation. This aerodynamic profile has been extensively studied in the literature and featured in various academic investigations [24].

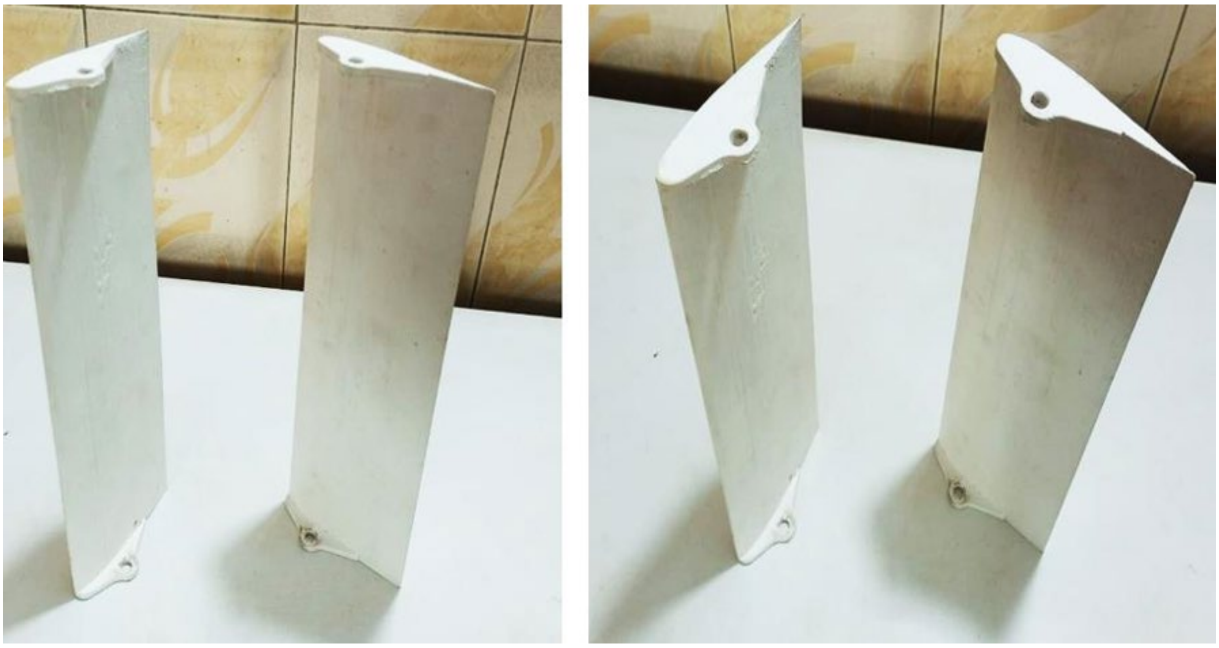

Figure 3. Darrieus blades manufactured

A modular frame system was designed and manufactured to install the produced turbine along the highway side. This is shown in Figure 4.

2.2. Experiments

Experiments were conducted to firstly comparing the new design with conventional turbines, secondly optimizing turbine placement along highways, lastly evaluating the energy extraction for different vehicle types (cars, minitrucks, minibuses, buses and trucks). Power was calculated by measuring voltage and current from the turbine-connected generator, with resistance values adjusted for different rotational speeds, following the method of Santhakumar [5].

Indoor tests used constant wind speed (5 m/s) with varying resistance (2 Ω to 8 Ω). Outdoor tests kept resistance at 2 Ω and measured wind speed, turbine rotation, voltage, and current during vehicle passage. The study focused on single-vehicle effects, excluding multiple vehicles and generator counter-torque.

Figure 4. Photo of a fabricated prototype of the newly proposed double VAWT

The dimensions and number of blades for the savonius, the darrieus and the new design double turbine are given in Table 2. In the double turbine (new hybrid) design, three different scenarios (A, B, C) were initially created for the spacing between Darrieus blades. Subsequently, power performance tests were conducted for these three scenarios, and the turbine with the highest efficiency was used in external tests measuring power performance during vehicle passages.

Table 2. Dimensions and number of blades for Savonius, Darrieus and Double Turbine

Turbine Type		Number of blades	The length (cm)	The diameter (cm)
Savonius		3	37	40
Darrieus		2	37	60
The double turbine	A	5	37	70
	B	5	37	65
	C	5	37	60

This study incorporated a BOOST PUMP type FF-BP-75GPD DC electric motor. This motor operates at a voltage of maximum 24 volts and consumes a current ranging from 0.1 A to 1.8 A. Its notable features include exceptionally low noise and vibration levels, an environmentally friendly design, low power dissipation, high efficiency. Figure 5 shows the electric motor.

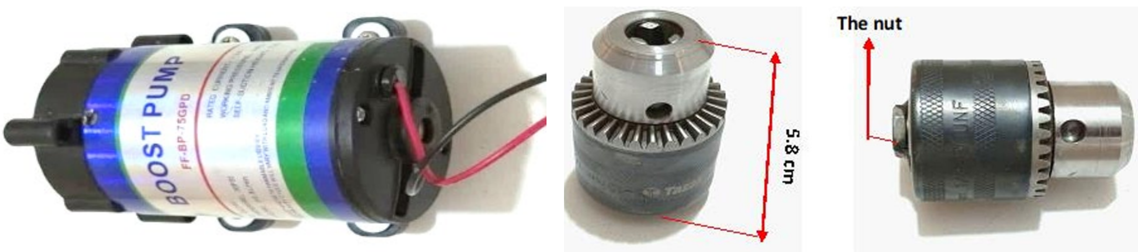

Figure 5. The generator and the link connections used for the wind turbines tested

Accurate and reliable measurements are crucial for obtaining meaningful results in experimental studies. This study employed a range of measuring devices to collect essential data on the performance of the proposed VAWT. These devices included electrical current and voltage measurement device. This device shown in Figure 6, consisting of a group of variable resistors and a screen for displaying current and voltage readings, functions based on the principles of electrical circuits. It played a critical role in measuring the electrical output of the VAWT, providing insights into its power generation capabilities.

Modern digital voltmeters typically have an accuracy ranging from ±0.5% to ±1% of the reading plus a few least significant digits (LSD). Modern digital ammeters usually have an accuracy like digital voltmeters, around ±0.5% to ±1% of the reading plus a few LSD. Tachometer used was model DT-2234A+. This device was utilized to measure the rotational speed of the VAWT blades, a key parameter for assessing turbine performance. The rotational speed directly impacts the power output of the turbine, making it an essential metric to monitor. The DT-2234A+ digital handheld tachometer is known for its accuracy, but like any measurement device, it has a certain degree of measurement error. According to the manufacturer specifications, the typical accuracy of the DT-2234A+ tachometer is ±0.05% + 1 digit (LSD). Anemometer used was model GM 816. This device was employed to measure the wind speed at the location of the VAWT. Wind speed is a crucial factor influencing the turbine's performance, as it directly affects the amount of energy available for conversion into electricity. The typical accuracy for the GM 816 anemometer is usually stated as ±5% of the reading. The careful selection and utilization of these measuring devices ensured the collection of accurate and reliable data throughout the experimental study. The data obtained from these devices was instrumental in evaluating the performance of the proposed VAWT and drawing conclusions regarding its effectiveness in harnessing wind energy from vehicles traversing highways. Figure 6 shows the devices (a set of voltmeters, ampermeter and variable resistance, tachometer, anemometer) used in the experimental study.

Figure 6. Photographs of the measuring devices used in the experiments

During the experiments, conducted in a controlled environment using a blower to generate artificial wind speeds, the rotation speeds of the turbines were determined, and the voltage and current values generated in the generator were measured. Wind speeds generated by the blower were measured per second during the test process, and the performance of the turbines was calculated particularly at wind speeds of 5 m/s. These tests were referred to as "internal tests," and the results are detailed in the article. ‘Internal tests’, ‘External test’ and ‘Types of vehicles tests’ were summarized in Figure 7.

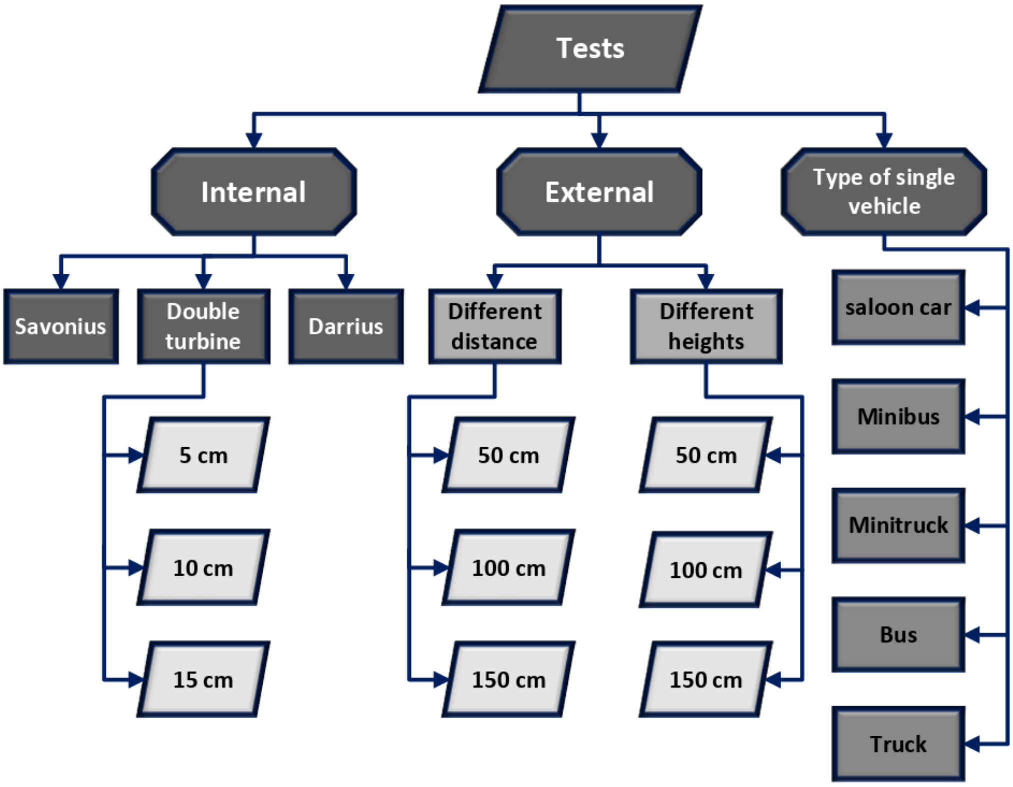

Figure 7. The schematic diagram of the experiments

This study includes a comprehensive testing process conducted in three distinct phases, internal tests, external tests, and vehicle types tests to arrive at the optimal design and positions in addition to obtaining the highest efficiency and determining the total energy production. In this study, three different designs were examined: a hybrid turbine consisting of Savonius, Darrieus, and a combination of Savonius and Darrieus turbines. Additionally, performance measurement tests were conducted on three different designs based on varying arm lengths as 5, 10, and 15 cm to determine the optimal placement of Darrieus blades in the hybrid turbine. When the turbine started to move in an unstable state, the data from the first 5 minutes was not considered. Five minutes after the turbine began moving, the resistance connected in series to the generator was systematically increased from 2 Ω to 8 Ω over a period of 10 minutes, allowing the turbine to rotate at different speeds. During the 10-minute period, data was recorded every second with a data logger. There were 600 data points collected for each of the wind speed (v), number of revolutions (N), voltage (V), and current (I) values. Every second, the wind speed was measured and recorded at the generator output with a data logger. In experiments conducted with the blower, the wind speed varied between 4 m/s and 6 m/s within 10 minutes. However, calculations were made using only the measurement data obtained when the wind speed was 5 m/s. In field tests conducted on highways, the wind speed measured at the turbine location ranged from 1 m/s to 10 m/s. Since it was observed that values greater than 5 m/s were caused by outdoor wind, these data were not considered.

The test suite focuses on evaluating the power enhancement of the proposed turbine design through a comparative analysis involving conventional Savonius and Darrieus turbines. The aim is to determine the optimal spatial configuration between the Darrieus and Savonius blades inside the proposed turbine by testing different blade separation distances of 5, 10, and 15 cm between the holes on both ends of the chord. So, three different diameters of Darrieus were 60, 65, 70 cm as shown in Figure 8.

These tests were carried out in controlled laboratory conditions with a fixed distance between the turbine and the blower. The Savonius turbine was tested first, followed by the Darrieus turbine, and then the double turbine. Testing all three turbines under the same conditions ensured accurate results and allowed for an evaluation of the highest performance of each turbine design. Figure 9 shows ‘internal tests' done by using the blower.

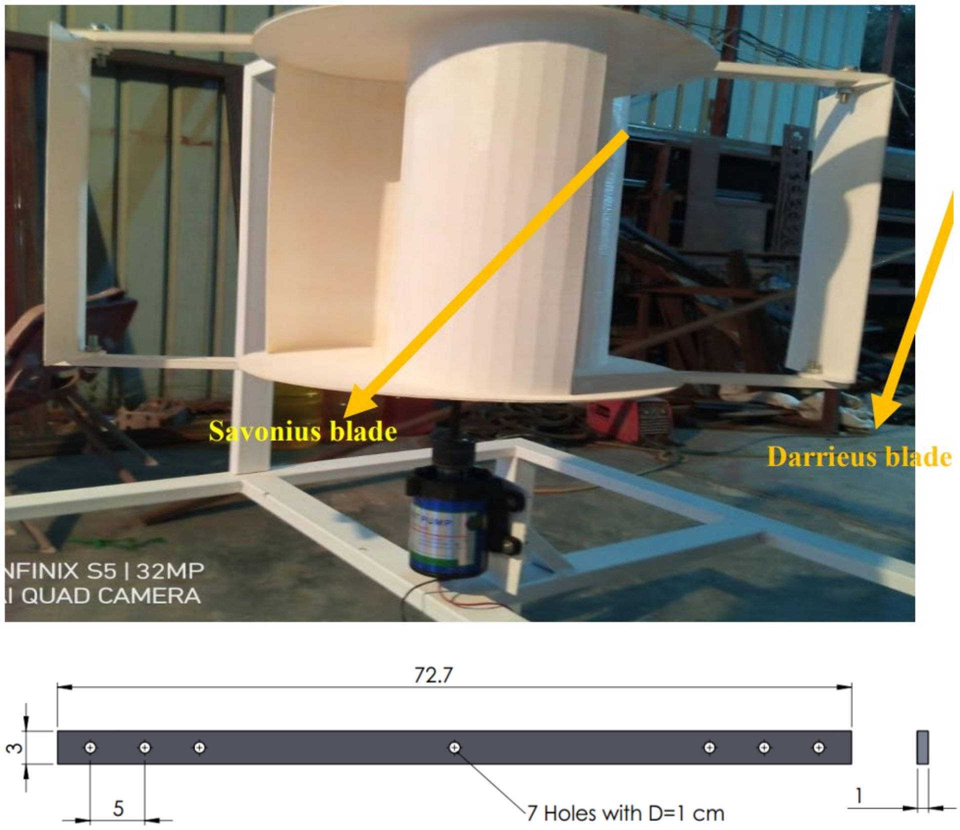

Figure 8. Three different distances for designs of the double VAWT

Figure 9. The photograph of the double WAVT and the blower for the internal tests.

In this study, various tests were conducted on a hybrid turbine, optimally designed as a combination of Savonius and Darrieus turbines, on a selected highway road. These tests were named 'external tests'. The turbine's performance was measured by placing it at distances of 50 cm, 100 cm, and 150 cm from the roadside and heights of 50 cm, 100 cm, and 150 cm above the road surface. These measurements were repeated for 5 different vehicles, resulting in 45 different outcome values. These results were then evaluated by considering the averages of the values obtained in the repeated tests. These tests involve the deployment of the proposed double turbine model in real-world conditions by installing it on an international highway to evaluate its optimal performance under practical circumstances. Several tests for five different vehicles i.e., car, minibus, minitruck, bus and truck are conducted to determine the best distance between the proposed double turbine and the highway. This comprehensive testing approach aims to identify the optimal configuration for achieving the proposed turbine's best performance and maximum efficiency. Figure 10 shows some examples on the distance and the height tests for the double turbine.

The experiments encompass a comprehensive evaluation of the proposed double turbine's performance with various vehicle types on highways. The objective was to determine the total energy harnessed by the turbine from each vehicle category. These vehicles were saloon car, minibus, mini truck, bus, and truck. This was achieved by strategically positioning the turbine and measuring the energy output as each test vehicle passed by; all vehicles traveled at a constant speed of 100 km/h. Energy readings were recorded before the vehicle reached the turbine, during its passage in front of the turbine, and after the vehicle passed. The total duration was 10 seconds. This evaluation assessed the energy capture capabilities across different vehicle types and operating conditions.

To establish a robust foundation for comprehending the phenomena and mechanisms underlying this study, we employ set of mathematical equations. These equations are essential for determining the critical values and parameters required to achieve the results. The maximum power of the wind can be calculated from this equation [15].

Figure 10. Tests for the optimum positon of the best double turbine

2.3. Uncertainty Error Analysis

Some assumptions have been made in the calculations using the data obtained in the experiment. The power value obtained in the generator will not be equal to the mechanical power value obtained in the turbine. Some of the mechanical power obtained from the turbine will be lost as heat in the generator. Mechanical losses in the turbine and electrical losses in the generator were not taken into account in the calculation of the C_p value. This is because it was assumed that the loss ratios were the same for different conditions. However, it can be assumed that there are errors ranging from 1% to 3% in the readings of the measuring devices. We can anticipate a 2% error in reading voltage and current values, a 1% error in reading the number of revolutions, and a 3% error in reading wind speed. We observed that ensuring a constant wind speed was not achieved at the desired level in our experiments. This indicates the necessity of conducting error analysis.

$$P_{max} = \frac{1}{2}\rho A v^3 \tag{1}$$

$$A = DH \tag{2}$$

ρ, A, D, H, v are air density, area, diameter, height, wind velocity respectively. And the angular velocity(ω) of the turbine and tip speed ratio(λ) can be calculated with the following equations [15]:

$$\omega = \frac{2\pi N}{60} \tag{3}$$

$$\lambda = \frac{\omega r}{v} \tag{4}$$

And the electric power (P_e) can be calculated as derived from the obtained electric current and voltage readings with the equation [14, 16],

$$P_e = VI \tag{5}$$

The power coefficient of the wind turbine (Cp) can be calculated using the following equation:

$$C_P = \frac{P_a}{P_{max}} \tag{6}$$

The total energy (E) produced by a turbine in tests is calculated using this formula:

$$E = \int_0^t P(t)dt \tag{7}$$

Uncertanity error for P with Eqn 5:

$$\Delta P_e = \sqrt{(\frac{\partial P_e}{\partial V}\Delta V)^2 + (\frac{\partial P_e}{\partial I}\Delta I)^2} \tag{8}$$

$$\frac{\partial P_e}{\partial V} = I \tag{8.a}$$

$$\frac{\partial P_e}{\partial I} = V \tag{8.b}$$

ΔP_e, ΔV, ΔI are relative percentage uncertainty errors in *P, V, I* respectively. Uncertanity error for λ with Eqn 4:

$$\Delta\lambda = \sqrt{(\frac{\partial\lambda}{\partial N}\Delta N)^2 + (\frac{\partial\lambda}{\partial v}\Delta v)^2} \tag{9}$$

$$\frac{\partial\lambda}{\partial N} = \frac{\pi r}{30v} \tag{9.a}$$

$$\frac{\partial\lambda}{\partial v} = -\frac{\pi N r}{30v^2} \tag{9.b}$$

$\Delta\lambda$, ΔN, Δv are relative percentage uncertainty errors in *λ, N, v* respectively. Uncertanity error for C_P with Eqn 6:

$$\Delta C_P = \sqrt{(\frac{\partial C_P}{\partial P_e}\Delta P_e)^2 + (\frac{\partial C_P}{\partial P_{max}}\Delta P_{max})^2} \tag{10}$$

$$\frac{\partial C_P}{\partial P_e} = \frac{2}{\rho v^3 DH} \tag{10.a}$$

$$\frac{\partial C_P}{\partial P_{max}} = \frac{-4P_e}{(\rho DHv^3)^2} \tag{10.b}$$

$$\Delta P_{max} = \frac{1}{2}\rho DH((v+\Delta v)^3 - (v-\Delta v)^3)) \tag{11}$$

ΔC_P, ΔP_e, ΔP_{max} are relative percentage uncertainty errors in C_P, P_e, P_{max} respectively. It was assumed that there were no errors in length and resistance measurements, but the estimated error range for the measurements of rotational speed, wind speed, voltage, and current was taken to be between 1% and 3%, with some exaggeration. An uncertainty error analysis was conducted based on the obtained data.

3. RESULTS AND DISCUSSION

The results of the experimental study are comprehensively discussing and analysing, drawing upon comparisons, to establish the proposed turbine's efficiency and identify the maximum performance achievable through these experiments. In the experiments conducted, the main variable in the internal tests is the resistance connected to the generator, and the turbine's performance was examined at different resistance values under a constant wind speed. In the external tests, the main variable was the wind speed, and the turbine's performance was measured at a constant resistance value as the wind speed varies over time.

Each internal test was conducted for approximately 15 minutes. Data obtained within the first 5 minutes after the turbine started to rotate were not considered, as it was necessary to wait for stable airflow. During the remaining period, data were recorded every second using a data logger. Calculations were based on other data (voltage (V), current (A) values at the generator output (Pe), turbine rotor rotation speed (N) obtained when the wind speed was 5 m/s. The experimental testing of the Savonius turbine under a constant wind speed range of (3.8 to 5.5) m/s revealed a substantial increase in the rotational speed of the turbine blade during the initial stages of wind vortex capture. This characteristic, considered a significant advantage of the Savonius turbine, demonstrates its self-starting capability. The rotational speed of the Savonius turbine blades continued to increase until it reached its peak. Intermittent measurements during the experiment were employed to calculate the P_{max} and λ based on the turbine blade rotation speed. A series of electrical current and voltage readings were obtained through the device during the test. These readings were utilized to determine the electrical energy calculation, representing the available energy in this test, and to calculate maximum C_P for the Savonius turbine, which is essential for evaluating its efficiency.
The Darrieus turbine test, conducted under identical conditions as the Savonius test, demonstrated a direct correlation between the rotational speed of the Darrieus turbine blades and the increase in wind speed until reaching its peak. Observations during this turbine experiment confirmed the positive relationship between wind energy (P_{max}) and wind speed (v) increases, as evidenced by the calculation of peak wind power (P_e) and tip speed ratio (λ) based on the turbine blade rotation speed. In this test, a series of current and voltage measurements were obtained from the device designated for calculating electrical power, representing the power available in this test. These measurements were used to determine C_P and evaluate the efficiency of the turbine.

The proposed double turbine was tested under the same conditions as the Savonius and Darrieus turbines. Three tests (A, B, C) were conducted, varying the distance between the Savonius and Darrieus blades (15, 10, and 5) cm, to identify the optimal spacing between the blades of the proposed turbine. Table 3 presents the results for the optimum values of the *N, λ* and maximum value of C_P for the double VAWTs having three different diameters.

Table 3. Experimental results for the double VAWTs having three different diameters

Test Name	Distance	N(rev/min)	TSR(λ)	P_e (W)	C_P
A	15 cm	554.3	3	2.014	0.223
B	10 cm	531.45	2.8	1.41	0.207
C	5 cm	465.83	2.6	1.106	0.161

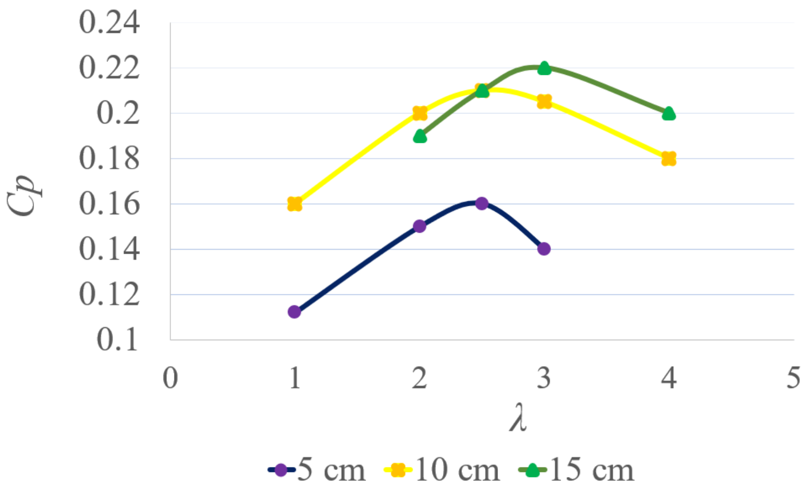

Figure 12. Comparison of C_p-λ graphs for the double VAWTs having three different diameters

These data clearly demonstrate the superior performance of the double turbine configuration, particularly in Test A. The double turbine achieved its maximum efficiency when the blades were spaced 15 cm apart. These results are shown by graphs in Figure 12, which compares the test results across different blades distances in the double turbine.

Figure 13 and Table 4 show the results and comparison of the best double turbine and Savonius and Darrieus.

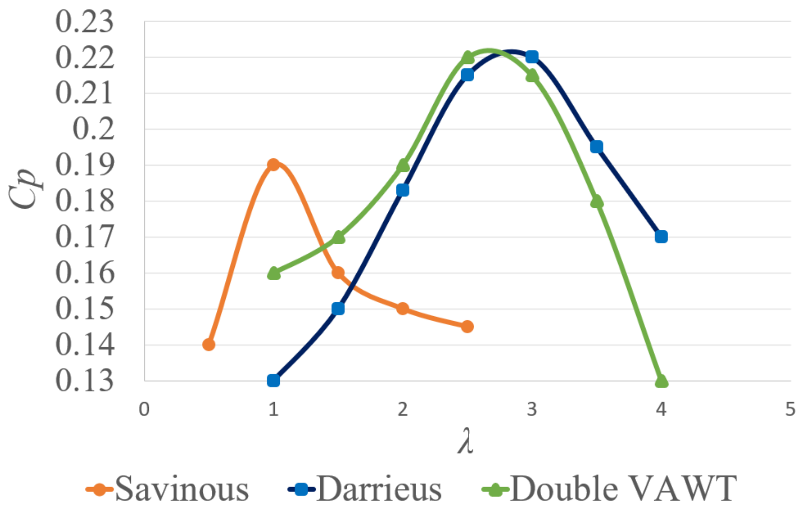

Figure 13. Comparison of $C_p - \lambda$ graphs for the best double VAWT, Savonius, Darrieus turbines.

Table 4. Results and values of the best double VAWT and Savonius and Darrieus

Test Name	*N*	TSR optimum	*P*	C_P
Double WAVT	554.3	2.9	2.014	0.223
Savonius	458.8	1.2	1.29	0.189
Darrieus	637.39	3	1.97	0.220

Table 4 and Figure 13 show the test results and values for the best double turbine, as well as the Savonius and Darrieus turbines. These data demonstrate the superior performance of the best double turbine configuration over other conventional turbines. As shown, the best double turbine achieves higher C_P values over a wider TSR range achieve the highest C_P value. Error analysis was conducted using the uncertainty analysis method. The results for the double VAWT having 10 cm distance case B test are provided in Table 5.a and Table 5.b.

Table 5.a Uncertainty analysis of the double WAVT for case B (10 cm) test results

Test	v(m/s)	N(rev/min)	ω (rad/s)	λ (TSR)	V(volt)	I (A)
1	5	143	15	0.75	3.62	0.79
2	5	191	20	1.00	3.24	0.95
3	5	382	40	2.00	3.08	1.24
4	5	477	50	2.50	2.84	1.42
5	5	573	60	3.00	2.46	1.60
6	5	764	80	4.00	2.14	1.61

The units of *v, N, ω, λ, V, I* are m/s, rpm, rad/s, unitless, volt (V), ampere (A) respectively in Table 5.a.

Table 5.b Uncertainty analysis of the Double WAVT for case B (10 cm) distance test results

Test Number	P_e	C_P	ΔC_P	$\Delta\lambda$
1	2.87	0.15	7.02	4.43
2	3.06	0.160	6.66	4.43
3	3.83	0.200	5.60	4.43
4	4.02	0.210	5.41	4.43
5	3.92	0.205	5.50	4.43
6	3.45	0.180	6.06	4.43

The unit of P_e is Watt (W). The uncertainty of C_p ranges between 5.41% and 7.02%. The uncertainty of TSR (λ) is 4.43%. This result is for the double VAWT as 10 cm distance case. The uncertainty relative percentage error values for the other tests are very close to this result.

Since there is limited experimental data on the performance of hybrid turbines in the current literature, this study provides valuable insights into how hybrid turbines perform in real-world applications. The primary contribution of this research to the literature is the detailed experimental data it offers on the performance of hybrid Savonius-Darrieus turbines installed along highways. Additionally, by demonstrating that the wind currents generated by vehicles can be effectively harnessed for energy production, and by revealing that the hybrid design ensures high efficiency across a broader range of wind speeds, the study offers a new perspective for research in the field of renewable energy. The present experimental results were compared to the results obtained by Roshan et al. [20] in Table 6.

Table 6. Validation for the internal test results [20]

	Values	Literature(CFD)	Present Study(Experimental)
Savonius	Diameter	95 cm	35 cm
	Hegiht	100 cm	37 cm
	Blade number	2	3
	Velocity	7 m/s	5 m/s
	TSR range	0.5<TSR<1.8	0.3<TSR<2
	Optimum TSR	1	1
	Cp max	0.25	0.19
Darrieus	Diameter	103	70 cm
	Hegiht	145	37 cm
	Blade number	3	2
	Velocity	7 m/s	5 m/s
	TSR range	0.5<TSR<3.5	0.5<TSR<5
	Optimum TSR	3	3
	Cp max	0.35	0.2
Hybrid VAWT	Diameter	95 cm	70 cm
	Hegiht	100 cm	37 cm
	Blade number	3 (Darrieus)+2 (Savonius)	2 (Darrieus)+3 (Savonius)
	Velocity	7 m/s	5 m/s
	TSR range	0.5<TSR<3.5	0.5<TSR<4.5
	Optimum TSR	2..7	3
	Cp max	0.15	0.22

Most of the results are the same or very close to each other, but there are some differences. This is probably due to variations in geometry. The results of the three distance experiments (50, 100, and 150 cm) aimed at determining the optimal spacing between the double turbine and the highway are shown in Table 7 and Figure 14.

Table 7. Results and some parameter values of distance tests of the double VAWT

Test Name	**Distance (cm)**	***N*(rev/min)**	**λ(TSR)**	**P_e (W)**	**C_P**
Test D	50	705.75	4	2.939	0.222
Test E	100	761.6	4.2	3.229	0.232
Test F	150	644.82	3.8	2.669	0.204

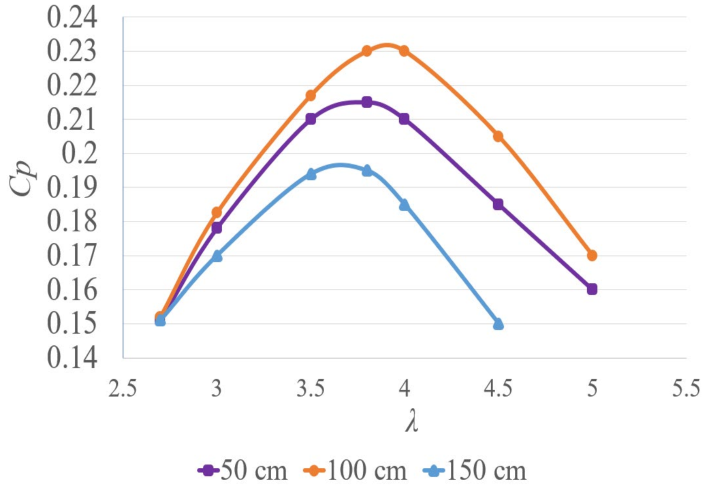

Figure 14. Comparison on C_p-λ graphs of the double turbine for the distance tests

The results shows that the efficiency of the double turbine is superior in test E when the distance is 100 cm between the location of the double turbine and the highways. After identifying the optimal horizontal placement of the double turbine for the highway, the next crucial step involved determining the ideal height at which the turbine should be positioned above the ground. A series of tests were conducted at three distinct 50, 100, and 150 cm as heights to ascertain the height that would maximize the double turbine's performance. The values, readings, and data obtained from these tests, like those obtained from the distance tests, revealed that the optimal height for the double turbine above the ground is 100 cm. At this height, the turbine exhibits its highest efficiency, as demonstrated in Table 8 and Figure 15.

Table 8. Results and values of height tests of the double VAWT

Test Name	Distance (cm)	N(rev/min)	λ(TSR)	P_e (W)	C_P
Test G	50	685.6	4	2.987	0.223
Test H	100	794.83	4.1	3.108	0.233
Test I	150	612.48	3.6	2.812	0.200

It has been determined that the results of this study on where to place the wind turbine horizontally and in height on the highways to maximize the energy obtained from the wind produced by different vehicles are compatible with the results of the study conducted in Malaysia [4]. In our experiments, it was observed that as the turbine's rotation increases, the current obtained from the generator also increases. This trend continues until high rotation speeds, and even with further increases in rotation, the current value remains unchanged. This phenomenon has also been documented in Santhakumar's study [5].

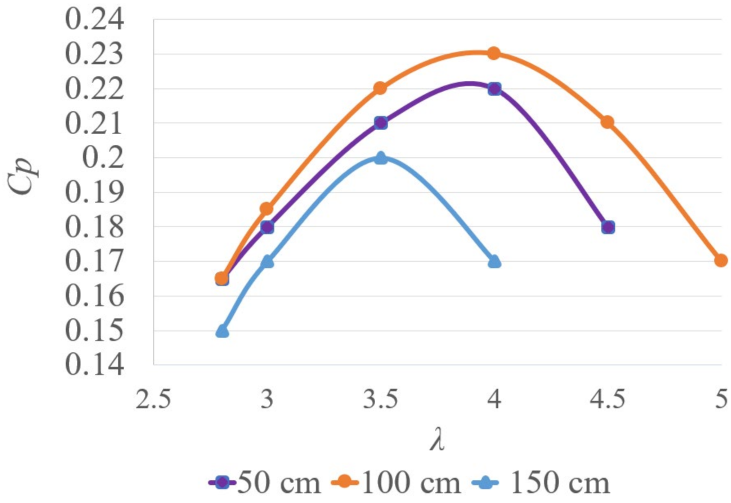

Figure 15. Comparison on C_p-λ graphs of the double turbine for the height tests

A lot of articles in literature states that the self-starting ability of the Savonius turbine is good, but its power efficiency is low. The results obtained in this study confirm this finding. Our study has demonstrated that the Darrieus turbine is more efficient than the Savonius turbine, as indicated in the article by Kumar [17].

In most references [5, 20], the speed ratio of the Darrieus turbine is typically observed to be in the range of 1 to 5, while that of the Savonius turbine is generally found to be in the range of 0.1 to 2. The results of the present study which are given in Figure 16 are also consistent with these data. The TSR range of the Double VAWT has been determined to beas the interval [0.2, 4.5].

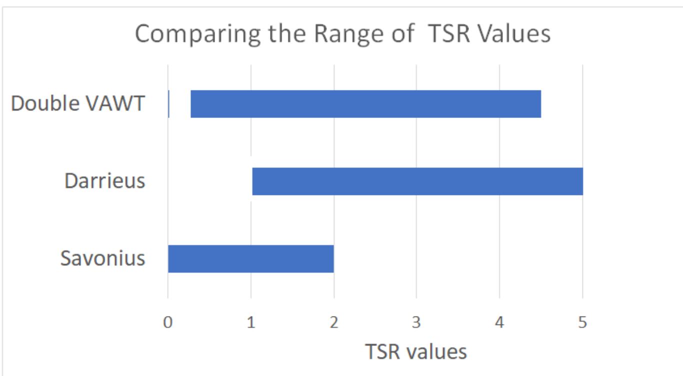

Figure 16. Comparing TSR range of Savonius, Darrieus, Double VAWT

The total power generated by the double turbine was calculated for each vehicle test case, and the necessary measurements were obtained to perform the calculations that yielded the desired results during the 10-second test period. During the tests, the vehicles traveled at a speed of 100 km/h in front of the double turbines, which were positioned at a height of 100 cm and a lateral distance of 100 cm. In this study, the power values that can be obtained from a single turbine by the passage of a single vehicle on a highway were experimentally measured, and the energy was calculated. The impact of multiple vehicles passing was not included in the scope of this study. Similarly, the optimal spacing of multiple turbines along the roadside was also not addressed. Factors such as the number of turbines, the number of vehicles passing, the varying speeds of the vehicles, atmospheric conditions, and external wind conditions were not considered. The findings from these tests effectively demonstrate the efficiency of the newly proposed double turbine in capturing and evaluating the performance for each type of vehicle commonly found on major highways, including trucks, buses, minitrucks, minibuses, cars. Measured and calculated values for the newly proposed best double turbine under different vehicles are given in Table 9.

Table 9. Vehicle tests results

Vehicle type	v_{max} (m/s)	$P_{\max}$ (W)	I (A)	V (Volt)	P_e (W)
Car	2.8	3.48	0.33	2.42	0.8
Minibus	3	4.28	0.39	2.52	0.98
Minitruck	3.1	4.72	0.40	2.71	1.08
Bus	3.4	6.23	0.45	3.18	1.43
Truck	3.6	7.40	0.48	3.54	1.70

The values of wind velocity measured on the top of the double turbine changing with time for 5 different vehicles are shown by graphs for comparison in Figure 17. Measurements taken in situations where the effect of external wind was felt (when wind speed exceeded 5 m/s) were not included in the calculations. The wind speeds generated by the vehicles were measured at the turbine location. These measurements are valid for vehicle speeds of 100 km/h.

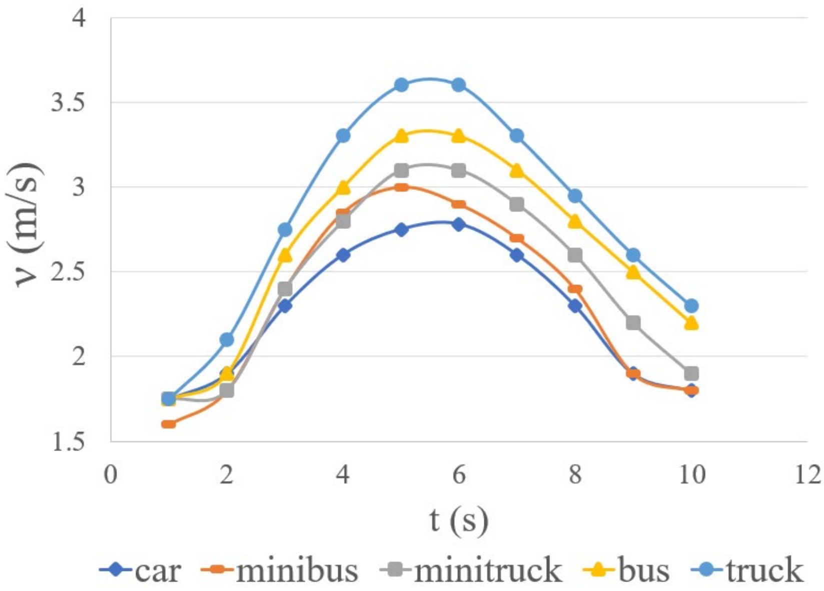

Figure 17. Wind velocity of the vehicles wrt time

To estimate the maximum wind speeds that vehicles can generate at different speeds, the equation $k=v_{wind}/v_{vehicle}$ can be used. The calculated '*k*' coefficient values according to this equation are provided in Table 10.

Table 10. Wind and vehicle speeds relations

Vehicle	Wind speed (m/s)	k
Car	2.78	0.10008
Minibus	3	0.108
Minitruck	3.1	0.1116
Bus	3.3	0.1188
Truck	3.6	0.12396

The '*k*' value is approximately 0.13 for trucks generating wind speed, while it is approximately 0.10 for cars. The power values varying over time for five different vehicles obtained by the double turbine, along with their average shown in green, are depicted in Figure 18 with graphs.

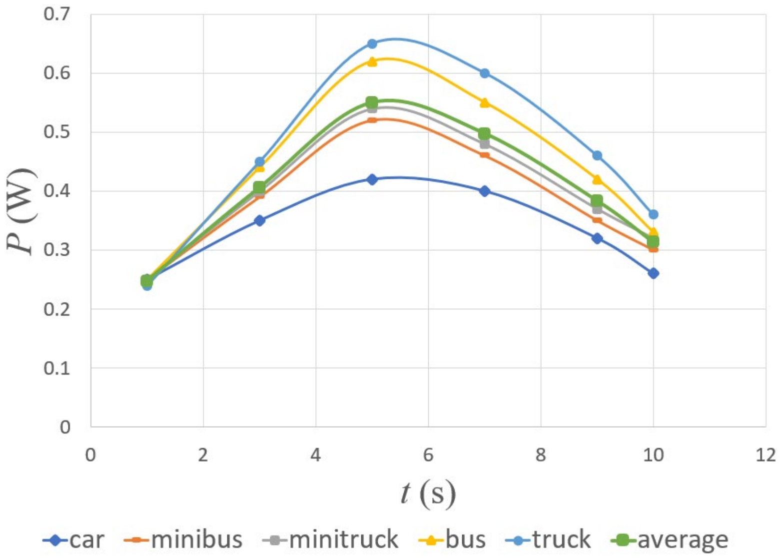

Figure 18. Comparison on *P-t* graphs of the different vehicle tests

As the vehicle moves along the road, it generates wind on the turbine for approximately 9-10 seconds. The amount of energy obtained during the 1-5 second interval that the vehicle approaches the turbine is roughly 30% less than the energy obtained during the 5-10 second interval that the vehicle departs from the turbine. The average power function (green one) wrt time can be expressed by using ‘curve fitting’ as following.

$$\mathrm{P(t)} = (-0.000124901)t^5 + (0.003945437)t^4 - (0.045685516)t^3 + (0.221801587)t^2 - 0.356999107)t + 0.4250625 \quad (12)$$

The comparison of the curve fitting function graph of power's variation over time with the measured values is shown in Figure 19.

$$E = \int_0^{10} P(t)dt \quad (15)$$

And the result is E= 4.2127 J. The energy amounts obtained by the Double turbine are calculated as approximately 3 J for cars, 3.4 J for minibuses, 3.7 J for minitrucks, 4 J for buses, and 4.5 J for trucks, respectively. The energy amounts obtained by different vehicles are compared in Figure 20.

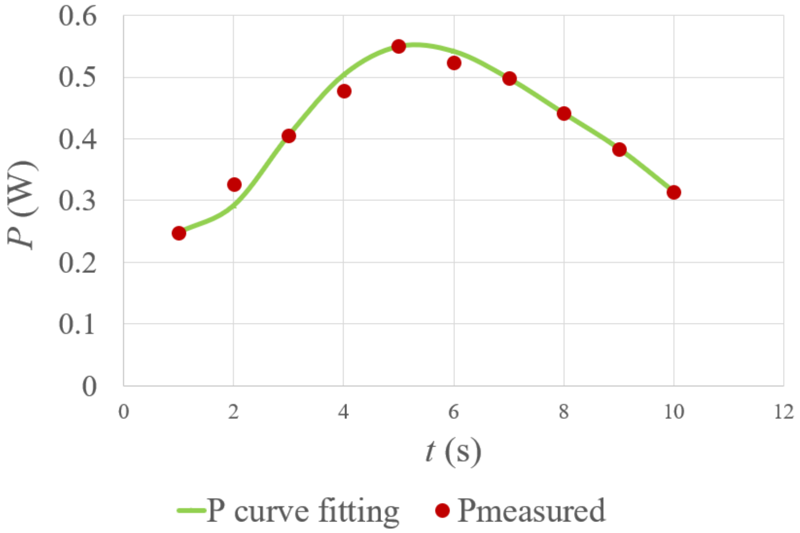

Figure 19. Comparison of the curve fitting function graph of power's variation over time

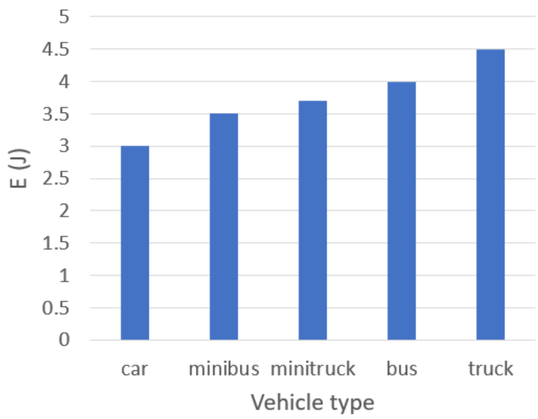

Figure 20. Comparing the energy amounts obtained by different vehicles

Among the various vehicles tested, trucks have been found to produce the highest amount of energy when interacting with the Double VAWT. This observation suggests that vehicles with larger surface areas or higher speeds may contribute more significantly to wind energy generation. Designed and manufactured with a diameter of 70 cm and a height of 37 cm, the hybrid turbine has a power coefficient of 0.223 at a wind speed of 5 m/s. It has been measured that when this turbine is positioned 100 cm horizontally and 100 cm vertically from the roadside, it can generate a minimum of 0.65 W of power from wind at 3.6 m/s produced by a vehicle passing at a speed of 100 km/h. If multiple vehicles pass simultaneously on a highway, the wind speed hitting the turbine will be at least 5 m/s, and with a maximum C_P (0.223) value, it can be confidently stated that the turbine will continuously generate at 4.36 W of power. Assuming that one of these small and compact hybrid wind turbines can provide 4 W power, a total of 400 W power is obtained when

100 turbines are placed on the highway. With this power, the electrical energy needs of 40 of the traffic signs operating with 5 W and 20 of the led road lighting lamps operating with 20 W will be met [21].

The double VAWT turbine designed and manufactured in this study is small, compact, easy to manufacture, and modular. The turbines can be mounted on poles along the roadside with surrounding grid barriers for driver safety. The number of turbines to be installed along the roadside can be determined based on the region's needs and can be used for road traffic signs or lighting. Additionally, they have the potential to charge the batteries of electric vehicles. For example, with the turbine developed and manufactured in this study, approximately 35 kWh of energy can be produced in one year. Considering that a typical electric vehicle consumes 15-20 kWh of energy for 100 km, this energy produced in one year can enable a typical electric vehicle to travel 233.3 km. If 100 turbines are installed along the roadside in a specific area, the energy obtained in one year would be approximately 3500 kWh [22, 23].

To calculate the cost of a turbine with a payback period of 10 years, we consider that a turbine generates 35 kWh of energy per year. Assuming the price of 1 kWh of electricity is 0.15 dollars, the total energy produced by the turbine over 10 years would be 350 kWh. The total value of this energy is calculated to be 52.5 dollars. Therefore, for the turbine to have a payback period of 10 years, its cost should not exceed 52.5 dollars. Considering the mass production of turbines and their small dimensions, such as a diameter of 70 cm and a height of 37 cm, it is feasible to produce turbines at this cost. The spacing between turbines mainly depends on the number and speed of vehicles passing per unit time. As the speed and number of vehicles increase, the distance between the turbines should also increase. It is possible for the airflow from one turbine to affect another, but this effect is expected to be minimal. It should also be considered that drivers' attention should not be distracted when determining the turbine density. The impact of turbines on vehicle dynamics is not considered significant, but a separate study could be conducted on this topic. There is a risk that rotating parts of the turbines could fall onto vehicles and pose a danger. To mitigate this risk, gridded barriers that do not disrupt airflow could be added to the turbines [21].

Wind speed on highways is frequently variable and low. Depending on the number and type of vehicles crossing the road per unit time, the wind speed due to the speed of vehicles can be said to be in the range of 3 to 6 m/s. The ability to start at low wind speed, to generate torque in wind coming from different directions, to be efficient at relatively high speeds and to adapt to changing wind speeds are all required for wind turbines to be used on highways. The following characteristics of the turbines used in this study were observed in the experiments: Savonius wind turbines can start automatically at low wind speeds. However, their power efficiencies are low at high speeds. They are particularly suitable in environments where wind direction changes frequently and wind speeds are low. Darrieus turbines, on the other hand, are not efficient in self-starting at low wind speeds. However, compared to Savonius turbines, they achieve higher power efficiency, especially at relatively higher wind speeds. In cases with frequent fluctuations at low wind speeds, the new design double VAWT proposed in this study has been found to be more efficient.

Therefore, hybrid designs that combine the different advantages of Savonius and Darrieus turbines are gaining importance in research. In this study, a turbine with a total height of 37 cm is designed by combining a Savonius turbine with 3 blades at the center and a Darrieus turbine with 2 blades at the outer radius. While the diameter of the Savonius turbine was 40 cm, optimization tests were performed for three different sizes of the Darrieus turbine. The power coefficient values of the Darrieus turbines with diameters of 60, 65 and 70 cm were tested in a closed environment in front of a blower at a wind speed of 5 m/s. Through experimentation, we have determined that an increase in the diameter of the Double VAWT by 15 cm leads to a significant improvement in the power coefficient value. This finding highlights the importance of optimizing the dimensions of the turbine for maximizing energy output. The hybrid turbine with a diameter of 70 cm was found to have the highest power coefficient value. Our newly designed hybrid VAWT exhibits a higher power coefficient value compared to both Savonius and Darrieus turbines. This suggests that the integration of the two turbine types in our design has resulted in improved performance in terms of power generation efficiency.

This turbine was then tested at a selected highway, measuring the power output from the turbine generator at various combinations of horizontal distances (50, 100 and 150 cm) and ground heights (50, 100 and 150 cm). These experiments were carried out separately for cars, minibus, minitrucks, buses and trucks, all traveling at 100 km/h. The highest wind speed values were obtained at a horizontal distance of 100 cm from the roadside and at a height of 100 cm above the ground. The maximum speed recorded at the turbine was 3.7 m/s, obtained with a truck.

In the literature review in our article, various wind turbine design efforts have been mentioned to obtain electricity from the wind generated by the speed of vehicles on the highway. The small, modular wind turbine designed in this study, which can operate in a wide TSR range and has a maximum *Cp* value of 0.223 in wind conditions with sudden periodic changes and low-speed values, will be an alternative to the turbines proposed in the literature. Strategies for establishing the optimum criteria between darrieus diameter, savonius diameter and turbine height in turbine design are mentioned. In addition, experimental studies on the optimum placement of the turbine on the highways have also contributed to the approaches in this field.

4. CONCLUSION

The proposed double turbine model has demonstrated its effectiveness and potential for harnessing wind energy along highways under diverse conditions. Its consistent performance cross varying wind conditions, scalability with diameter within an optimal range, and adaptability in terms of blade spacing and positioning highlight its versatility and suitability for practical applications. The achieved maximum efficiency with specific blade spacing and optimal positioning further emphasizes the importance of precise turbine geometry and configuration for maximizing power generation. These findings underscore the promising prospects of the double turbine model for harnessing the abundant wind energy available along highways, contributing to sustainable energy solutions. This study brings a significant expansion in the application of hybrid composite turbines in the field of highway energy investment. The results can be summarized as follows:

1. A new hybrid VAWT has been designed by combining three-bladed Savonius and two-bladed Darrieus turbines. The power outputs of the new double VAWT at a wind speed of 5 m/s were compared with conventional Savonius and Darrieus turbines and showed superior performance. The newly proposed double VAWT design achieved the best performance with a maximum power coefficient (C_P) value of 0.23.

2. The energy production of the double VAWT design from various vehicles (car, minibus, mini truck, bus, truck) was evaluated. Among the five types of vehicles, the highest turbine power output was obtained from trucks.

3. The optimal horizontal and vertical positioning of the turbine on highways that provide the highest power output was determined.

4. The annual energy amount to be obtained from vehicle speeds on highways was evaluated with the newly proposed double VAWT design.

Further investigations are warranted to explore additional factors influencing turbine performance, such as blade shape, material composition, and wind conditions. Additionally, the impact of environmental variables, such as terrain and weather patterns, on the efficiency of the double VAWT should be studied in more detail. It would be beneficial to conduct experiments to assess how changes in the dimensions of the double VAWT affect power output and energy generation. By varying parameters such as blade length and diameter, we can gain insights into the optimal design configurations for maximizing turbine efficiency. Investigating the performance of the turbine when subjected to the wind generated by multiple vehicles simultaneously could provide valuable data for real-world applications. This scenario more accurately reflects the conditions encountered in highway environments and can help refine turbine design to better harness wind energy in such settings. Exploring alternative designs for the double VAWTs could lead to further improvements in performance and efficiency. By testing different combinations of turbine types and configurations, we can identify innovative approaches to enhancing wind energy extraction capabilities. Further research in this area is needed to examine in more detail the wind effects created by vehicles moving together at different speeds, using experimental or computational fluid dynamics(CFD), and to consider additional parameters for more comprehensive optimizations. These studies will provide insights for future work in determining the ideal placement and design conditions for wind turbines to be used on highways.

NOMENCLATURE

P_{max}	The wind power(W)	λ	Tip Speed ratio
ρ	The air density (kg/m^3)	P_e	Electrical power (W)
D	The diameter of the turbine (m)	E	Electrical energy (J)
H	The height of the turbine (m)	ω	Rotational speed (rad/s)
A	The turbine swept area (m^2)	N	Revolution number per minutes
v	The wind velocity (m/s)	R	Radius of the turbine
P_e	The electric power (W)	k	Ratio
I	The output current (A)	TSR	Tip Speed ratio
V	The output voltage difference (V)	VAWT	Vertical axis wind turbine
C_P	The power coefficient	CFD	Computational fluid dynamics

P_a	Available power (W)	HAWT	Horizontal axis wind turbine

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that there is nothing necessary for achieving the paper that requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Mehmet Bakırcı: Responsible for experimental planning, data analysis, and drafting the manuscript.

Osama Ahmed Kazal: Conducted literature review, experimental setup, and data acquisition.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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