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DESIGN AND PERFORMANCE OPTIMIZATION OF A HYBRID WIND-SOLAR ENERGY SYSTEM FOR HIGHWAY APPLICATIONS

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Abstract

Rapid advancements in technology and the escalating demands of modern consumers have made energy an indispensable component of daily life, necessitating increased energy production. However, the predominant reliance on finite and depleting conventional energy resources presents challenges to energy security. Therefore, it is imperative to explore alternative and innovative technologies to fulfill energy deficit sustainability. The most viable solution to address this challenge is the adoption of renewable energy sources. Vertical-axis wind turbines, when integrated with solar panels, present an efficient hybrid system for electricity generation. The aim of this project was to maximize the efficient utilization of wind and solar energy to achieve optimal electricity generation. To accomplish this, a highway was selected as the project site, providing wind energy due to continuous movement of traffic. This project consisted of designing and testing of a Savonius Vertical axis wind turbine that harnessed energy from both wind and solar sources, with the generated energy being stored in batteries to subsequently power streetlights and other electrical systems. Measurements of wind speed at different time at location site revealed that the average wind speed in these areas is approximately 8.3 m/s, showing the potential for wind energy generation in such environments. The VAWT prototype has generated a peak power of up to 47.1 watts from moving traffic. It was concluded that Savonius Vertical axis wind turbine is ideally able to supply streetlights and other public amenities with power at an upgradable scale. It is recommended to implement and evaluate alike projects to assess their feasibility and efficiency, thereby contributing to long-term sustainability.

Keywords:
Battery storage system, energy optimization, green energy technologies, sustainable energy generation, VAWT, solar.

Introduction

The demand for power in daily life is far more than the amount of energy that is produced. Since the natural resources will eventually run out, is one of the biggest issues (Shah et al., 2023). The primary contribution of fossil fuels to global warming, generation of greenhouse gases (Sayais et al., 2020). Technology development and population growth are both having exponential effects on electricity usage. In order to fulfill the demands of a growing population, we must simultaneously boost electrical output (Jie et al., 2023). The major drawback of using conventional resources is that they contribute to pollution since they produce several types of pollutants, such as ash when using coal power plants, smoke when using diesel power plants, and radioactive material when using nuclear power plants (Singh and Dubey, 2018). Both developing (5%) and developed countries (1%) are seeing an erratic and haphazard increase in energy use (Fang et al., 2022). Pakistan is a developing nation where the huge increase in energy demand is a result of rapid population growth and modernization (Hassan et al., 2021). Pakistan, like the majority of other nations, mostly relies on fossil fuels to supply its energy needs (Kanwal et al., 2022). Policy makers and planners around the world have been obliged to consider environmentally beneficial alternatives because of the non-renewable energy's exhaustion, increasing demand, and negative environmental effects (Opeyemi et al., 2021). As a result, numerous inventions are being developed to increase the availability of renewable energy worldwide. Unfortunately, the role of renewable energy in Pakistan's present electricity supply situation is a little portion of the whole percentage (Ilyas et al., 2021). Few significant and worthy efforts have been made in recent years for the development of renewable energy sources in Pakistan, there are now many difficulties (Raza et al., 2020). In particular, electricity and gas load shedding (more than 8–10 hours per day), rising prices, a deteriorating legal system, unemployment, and food shortages are preventing the sustainable growth of the national economy (Picatoste et al., 2020). Pakistan has a lot of potential for using renewable energy if the right infrastructure is put in place, similar to what Ireland and Denmark have done. (Wakeel, 2016). Studies have been done, and the average yearly worldwide energy consumption is estimated to be around 16.9 TW. Within the next 40 years, this quantity is predicted to be double. (De Castro et al., 2013) We need to use the newest energy production technologies to solve the issue. The wind power turbines are used in the middle or on either side of highways to convert solar and wind energy into electrical energy (Divya et al., 2012). One of the unconventional energy sources is wind energy, which is accessible in open areas. Using a vertical axis wind turbine, power can be produced (Kulkarni et al., 2016). One of the most significant sources of renewable energy is sunlight. More energy is emitted from the sun in a single hour (4.3x1020 J) than the entire world uses in a year (4.1x1020 J) (Madbouly et al., 2022).

Sunlight provides the Earth with nearly ten times more energy annually than the combined reserves of coal, oil, natural gas, and uranium (Foster et al., 2009). Both solar and wind energy are sustainable forms of energy; however, solar power is accessible only during daylight hours, while wind energy can be generated continuously, particularly through the movement of vehicles on highways. The primary objective of this project is to harness maximum wind energy from moving vehicles on roads. The large volume of compressed air generated by vehicle movement, which would otherwise go unused, is captured to power the vertical axis of a wind turbine. The turbine's kinetic energy is then converted into electrical energy. This project also aims to reduce pollution caused by the combustion of fossil fuels. The energy produced by the vertical-axis wind turbine (VAWT) and solar panels is stored in batteries, enabling its use for powering toll gates, streetlights, and potentially integrating charging nodes into the electrical grid for future electric vehicles.

Methodology

Our proposal aims to use a Savonius vertical wind turbine to solve the present energy crisis. Our study first set a traditional Savonius turbine's performance baseline, compares the findings, and then makes appropriate inferences. Afterwards, the model was constructed and put to the test physically to gather data from experiments that explain rotor's functionality. Therefore, the focus of our study was whether the modern Savonius Turbine Design outperforms the original Savonius Turbine Design. According to strict methodologies that were used, assertions were either be validated or refuted depending on the findings of the study

This project utilized the skills taught in various mechanics, design, and computer simulations for the engineering process. It also strengthened the understanding of the methodology of scientific inquiry and provided an introduction to practical engineering. The project was tested on the roads to obtain the best possible results for further improvements and analysis.

Table 1. Project Specification

Wind rotor	**Rated power**	**100W**
	Cut-in speed	2.2m/s
	Rated speed	10 m/s
	Rotor diameter	1m
	Swept area	1m^2(1 m*1m)
	Gearbox type	1:10 gears set
Generator	Generator type	DC generator
	Electric Transmission	Brushless
Turbine blades	Blade type	Curved plastic blades
	Blade number	5
	Blade material	PVC
	Hub material	Steel
Blade dimension	Length	0.60m
	Width of blades	5 inches
	Area	$0.30m^2$
Lubrication	Lubrication way	Grease

Working principle

This project combines wind and solar energy to power street lights and other electrical equipment. A vertical-axis wind turbine with five blades generates mechanical energy from traffic wind, which is converted to electrical energy via a DC generator with a 1:10 gear ratio to increase RPM. A solar panel also generates electricity, with both energy sources charging a 12V rechargeable battery. The battery is managed by a voltage stabilizer and step-up circuitry, while the solar charge controller ensures the solar panel output remains at 12V. The stored energy is used to power the street lights when needed.

Components used

Vertical Axis Wind Turbine:

The Savonius wind turbine is a low-speed, high-torque device with multiple blades that relies on drag force rather than lift force and can only rotate at the speed of the wind. The constructed prototype as presented in Figure 1 had 2-foot blades in length, a 1-foot overall turbine width, and 5-inch pipes used for the blades. It is equipped with a 3-foot shaft length and a 1-inch diameter shaft. The fundamental benefit of the Savonius wind turbine is that it can catch wind from any direction due to its face. Because of this, unlike the lift turbine, it does not need a device to turn its face into the wind. The Savonius turbine resembles a drum that has been sliced in half and is mounted on the spinning shaft, whereas the Darrius turbine is tiny (Figure 1). The majority of models today are of the Savonius type.

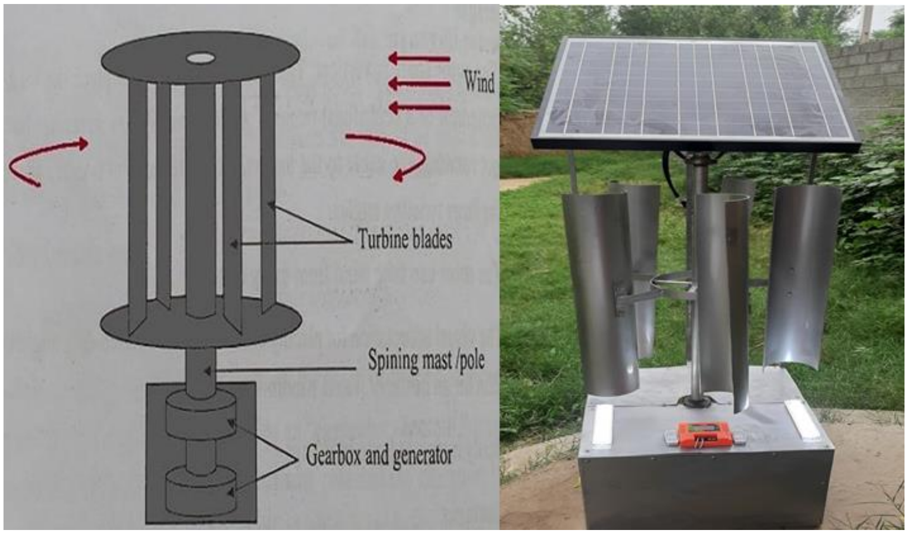

Figure 1. Multiple blade savonius wind turbine (a) and implemented prototype (b).

Direct current (DC) motor

The DC motor used in the project has an output power of 100 watts and a current rating of 9 Amps. It is wound with copper wire and operates at a speed range of 50 to 1200 RPM. The motor is waterproof for added protection and functions with a voltage range of 12 to 18 volts.

Gear set

There were set of two gears used in this project, one was small in size (20 mm diameter) with number of teeth in it were 10 while the other was large in size (153 mm in diameter) with the number of teeth in it are 100, the intention of the gear set used here was to increase the rotation per minute (RPM) for the motor RPM requirement. Both gears are made from plastic, chosen for their key advantages over metal gears, including lighter weight, reduced friction, and lower cost, making them suitable for this project.

Boost converter circuit

A boost converter circuit as shown in Figure 2 was used in the project to increase the low voltage produced by the DC motor to the required level. The boost converter has an input voltage range of 3.5 to 32V and an output voltage range of 5 to 35V. It supports a rated current of 2.5A, with a maximum current of 3A. The circuit provides a load and voltage regulation of ±0.5% and operates within a temperature range of -40°C to +125°C. The maximum power output of the boost converter is 40W.

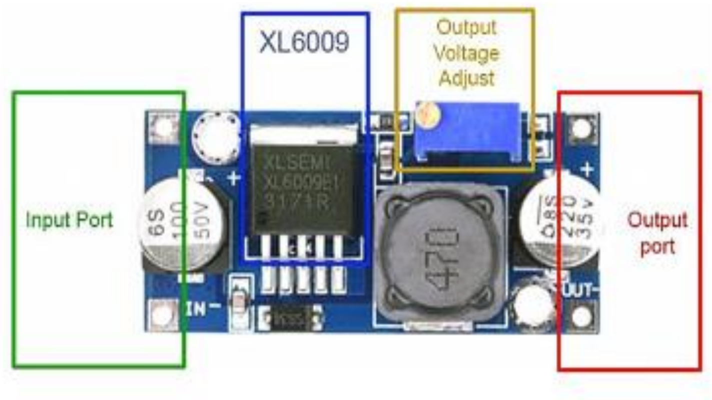

Figure 2. Presentation of boost converter circuit used in the study.

Solar panel

The solar panel (Figure 3) was incorporated to supplement power generation, as there was available space and the necessary physical infrastructure had already been built for the vertical axis wind turbine. Therefore, it was most efficient to install the solar panel to increase power production. The solar panel used in the project has a rated power of 40W, with a peak power (Pmpp) of 40W and a peak power voltage (Vmpp) of 16.6V. The peak power current (Impp) is 2.41A, while the open circuit voltage (Voc) is 23.3V, and the short circuit current (Isc) is 2.68A. The series fuse rating is 5A, and the minimum peak power (Pmpp min) is 36W.

Figure 3. Solar panel used in the experiment

DC lights

DC lights were used for road lighting in the project, designed to emit no UV or IR radiation. Each DC light is controlled by its own switch. The lights operate at a voltage of 12V with a rated power of 12W and a rated current of 0.9A. The maximum current is 1.25A, and the lights have a light efficiency of over 90 LM/W with a beam angle of 120°. They function within a temperature range of -20°C to +90°C and have a maximum power of 15W. The lifespan of each light is approximately 25,000 hours.

Solar charge controller

The system operates within a temperature range of 0°C to 50°C. The maximum size of the solar module is 40W. It provides voltage indications and has a self-consumption of less than or equal to 10mA. The operating voltage is 12V, with a current rating of 5A.

Li-ion Battery

A rechargeable Li-ion battery is used to store the charges, which can be utilized when needed. The specifications of the battery are as follows: it operates at a voltage of 12V, has a current rating of 2.5Ah, and is a sealed lead-acid type battery.

Design and implementation

Block diagram

A block diagram as shown in (Figure 4) was designed for simplicity and better understanding of the project. The turbine, the central component, captures wind energy, which is transferred to a DC generator via a gear set. Electricity generated by both the DC generator and solar panel is stored in a 12V battery, with current flow controlled by a charge controller. The stored energy is then used to power streetlights or other electrical equipment.

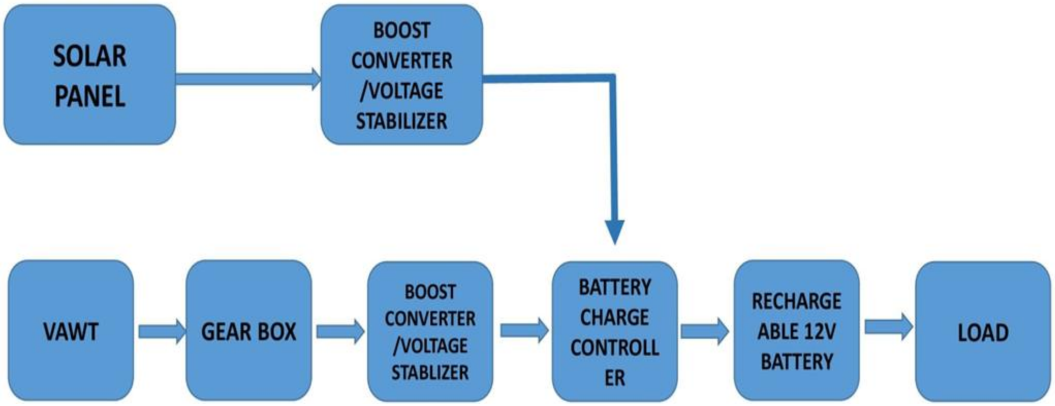

Figure 4. Block Diagram depicting the implementation of project

Construction

The DC generator was connected to the turbine using gears with a 1:10 ratio. The output wires of the DC generator were connected to the step-up converter. The battery terminals were connected to the output terminals of the step-up converter circuit, with a diode placed in series between the DC generator and the step-up converter. The output wires of the solar panel were connected to the solar charge controller and voltage stabilizer, and the output wire of the charge controller was connected to the battery. DC street lights were connected to the battery through switches, with the lights controlled by the switches. The lights were operated by a 12V battery.

RESULTS AND ANALYSIS

This project is tested on different locations to get the best possible results. This project is also tested in different times and weather conditions, in order to examine this project in the best possible way. These results and analysis will help to analyze the project in effective way and it may help the implementer for current and future improvements.

Figure 5 illustrates the fluctuations in wind speed associated with road traffic across three specific locations: Nowshera GT Road, Mardan GT Road and Peshawar GT Road, over a span of 24 hours. The highest wind speed recorded occurred at Peshawar GT Road, which peaked at 11.6 m/s. In contrast, Nowshera GT Road exhibited a moderate wind speed, demonstrating a steady increase throughout the day. However, the wind speed measured on Mardan GT Road remained consistently low, with less discernible peaks. These variations in wind speed may be attributed to factors such as traffic density, environmental conditions and geographical influences, although the precise mechanisms behind these changes require further investigation.

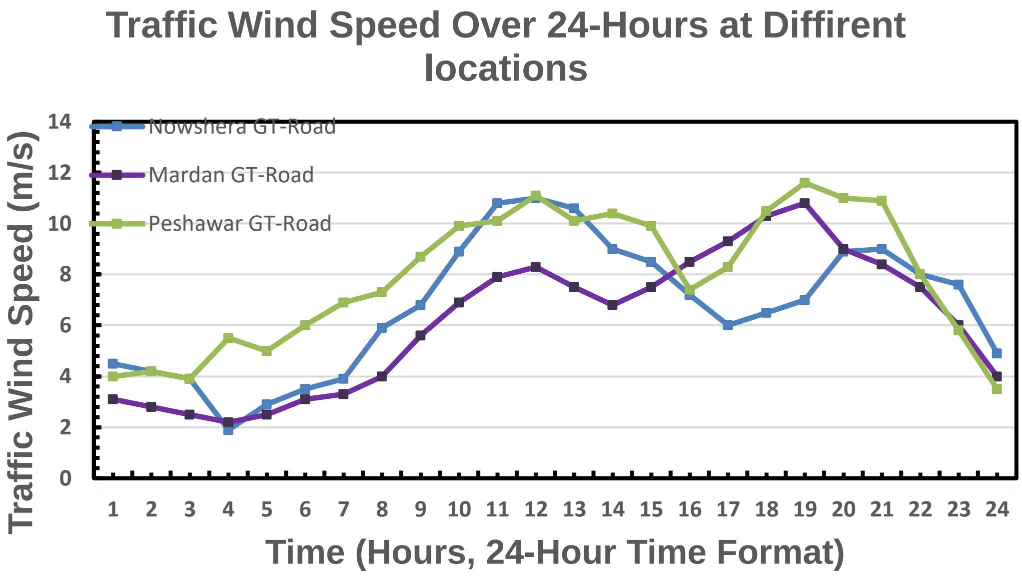

Figure 5. Wind Speed Variations Across Road Traffic Locations: A 24-Hour Analysis

Rotational Speed Analysis of VAWT Shaft with Traffic Wind Velocity

This graph demonstrates the values of rotation shaft of a turbine according to the traffic wind velocity. These measurements of shaft rotation are through TACHOMETER with an accuracy of ±5%. The graph below expresses the relation between wind velocity (m/s) and the rotational speed of a 5-blade Vertical Axis Wind Turbine (VAWT) shaft (in rpm). With the increase of wind velocity the rotational speed of shaft also increases, this shows a direct relation between them. At the lowers speed of road traffic wind at around 2.2 m/s which is the cut-in speed of the turbine, the shaft rotation is minimal. In contrast, at the highest velocity of wind at 14 m/s, the shaft rotation each at 75 RPM this is the peak value (Figure 6).

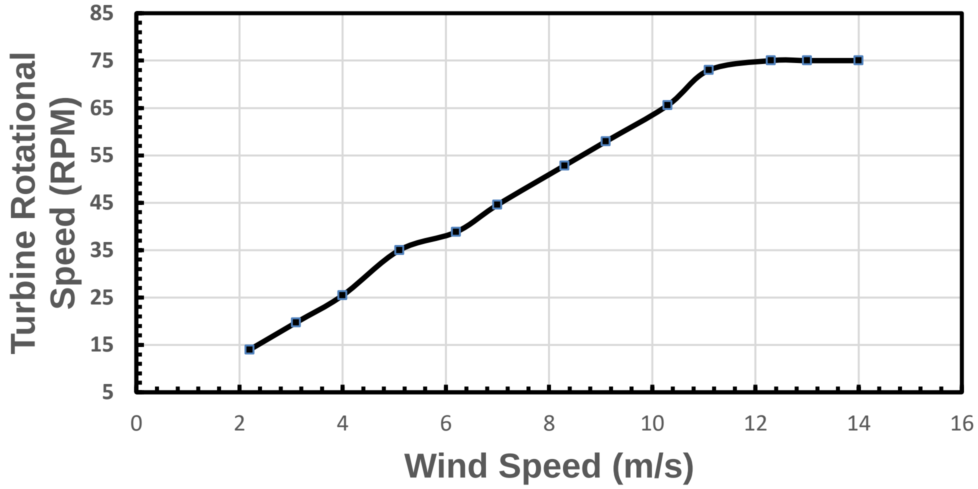

Figure 6. Relation between wind velocity (m/s) and the rotational speed of a 5-blade Vertical Axis Wind Turbine

Performance Analysis of DC Generator Voltage with Respect to Wind speed

Figure 7 demonstrates the relation between the traffic wind velocity (m/s) and the voltage (volts) produced by the DC generator. Wind velocity is directly proportional to the voltage produced. At the wind velocity less than cut-in speed (0-2 m/s), the voltage produced by the DC generator is negligible because of insufficient amount of wind energy. The graph shows that the turbine started to make output when the wind velocity reached between 2.2-14 m/s, shows the efficiency of the generator converting wind energy to mechanical and then to electrical energy. The optimal voltage of 12 V achieved at 10.2 m/s. This shows the efficiency and potential of that project.

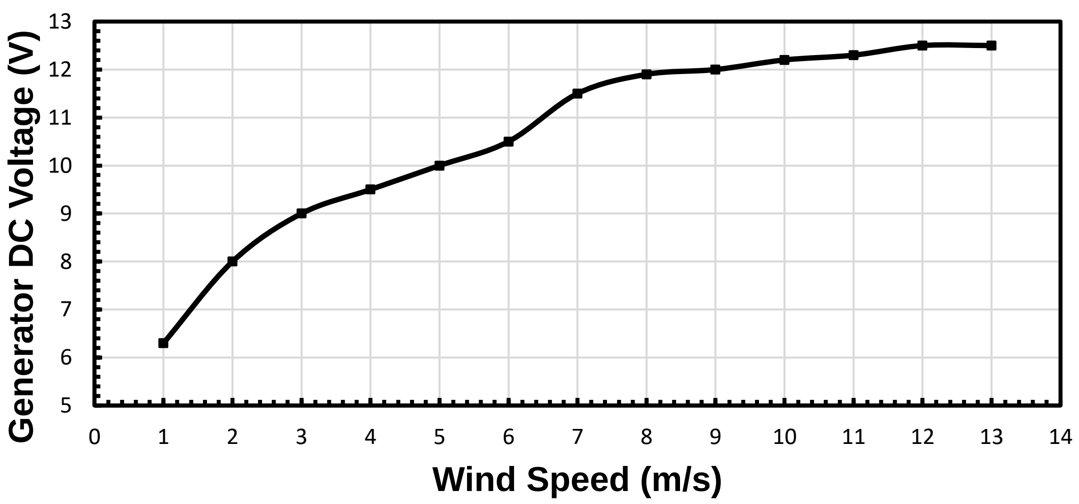

Figure 7. DC generator voltage with respect to wind speed (m/s)

Power Generated by the Wind Turbine vs. Wind Speed

The chart shows the wind speed and the power generated. As wind speed increases from 0 to 14 m/s, power generation increases steadily, showing the system efficiency in harnessing wind energy. However, beyond 8 m/s, the power output starts to level off, indicating that the system has reached its maximum capacity 47.1 W. This pattern is common in wind turbines, where energy production stabilizes beyond a certain wind speed. The chart emphasizes the importance of operating wind systems within their optimal speed range to achieve maximum energy output (Figure 8).

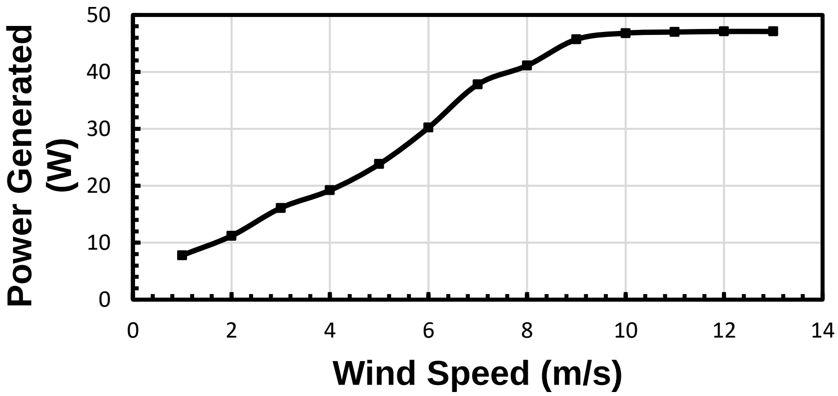

Figure 8. DC generator power by wind speed (m/s).

Analysis of Solar Panel Power Output Over Time

Figure 9 shows the variation in power generation over the day, from 6:00 AM to 5:00 PM. The data reveals a steady increase in power output starting at 6:00 AM, reaching its peak at approximately noon. Afterward, power generation begins to decline gradually until 5:00 PM. The trend aligns with typical solar energy production patterns, where sunlight intensity drives power generation. This information is critical for designing energy systems and optimizing solar panel performance to align with peak production hours, ensuring efficient energy utilization in renewable energy applications.

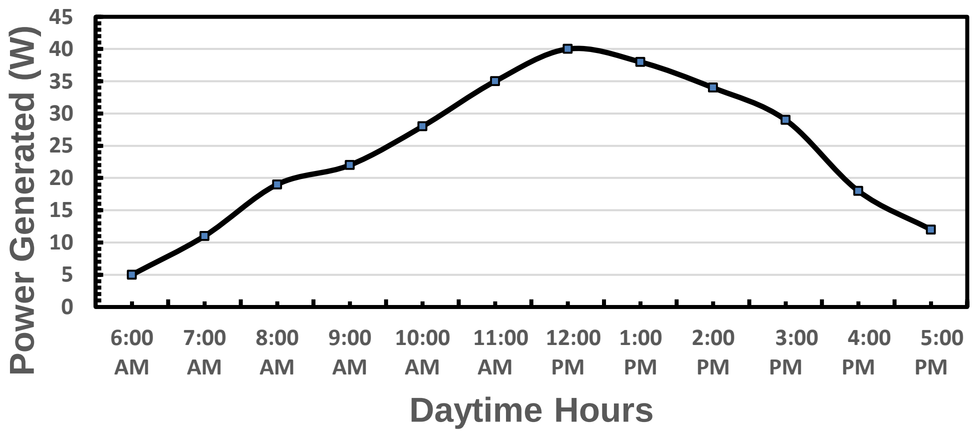

Figure 9. Power generation at different timings during day.

Discussion

The prototype was tested at various locations, timeline, weather conditions and angles, the obtained data shows the efficiency of hybrid renewable energy system that utilizes traffic wind and solar energy. The data collected from the experiment demonstrate the potential and efficiency of this project. Highway traffic wind velocity is measured at various including Nowshera , Mardan , and Peshawar GT-Road significant variations were recorded in the value of wind velocity. The collected data shows periodic change in the rate of change of velocity. Peshawar shows the highest value of traffic wind velocity because of highest road traffic density, and vehicle speed. Peak value of wind was observed at highest velocity at 12 m/s during noon time. On the other hand, Mardan showed the lowest rate of traffic wind velocity peaking at around 9 m/s. While, Nowshera showed the moderate value of traffic wind velocity because of average number of vehicles crossing per minute, with a maximum of 10 m/s. The recorded data is influenced by traffic density, weather conditions, and topographic features on wind energy availability (Ahmad et al., 2023). For better results site specific optimization is needed. Each location has its own unique characteristics in metrological, wind behavior, geographical location, and wind behavior. Measuring and assessment of all these parameters will lead to better design of the project, feasibility, and will ensure to get best results. This is considered as the best approach for deploying project, it will lead to precision and data driven decision (Liu et al., 2025).

The performance of wind turbine directly proportional to the rate of traffic wind, as the wind speed get increases the performance of turbine increases. At the road traffic wind speed of approximately of 10 m/s the turbine achieved the rotational speed of around 75 rpm, the calculated power is 51.2 W, but the actual power the wind turbine achieved is around 47.1 W, the difference between calculated and actual power occur because of various factors including air resistance, gravity, and other affecting factors.

No measureable electric power generation is observed below the cut-in speed of 2.2 m/s, keeping the challenge of generating power at this low speed demonstrating the challenges linked with energy generation at extremely low wind speeds. This observation highlights the limitations of this project in those areas where the traffic wind speed is low wind, where achieving a sustainable and efficient electrical energy output becomes a challenge. The differences between the actual and calculated value of power occurred because of multiple reasons within the system, these includes losses in the electrical generator, mechanical friction of gears, cross wind, and energy dissipation (Bianchini et al., 2022).

For reducing these losses some improvements are made for better efficiency, this include the use of light weight material for blades this can reduce the mechanical friction and energy losses (Martinez-Marquez et al., 2022). Also enhancing the design of wind turbine blades for better performance optimization and aerodynamics has shown significant effects in efficiency improvement (Firoozi et al., 2024). All these improvements have confirmed the improvement in the overall performance of the turbine.

The integration of solar panel with vertical axis wind turbine system provides a more reliable electric power generation because of two input sources and makes it reliable for use. This project is even able to generate some amount power in the absence of any of two resources. During the low wind solar panel will act as a primary source while wind act as a secondary source, and during night time wind will act as primary source and vice versa. The addition of Lithium ion battery will further enhanced the hybrid configuration of project by providing uninterrupted power supply to load. In such situation when neither wind nor solar is available battery will provide power backup to the amenities, meeting the energy demands and this makes this project more feasible. Many advancement has been made to increase overall performance and efficiency of the project one of them is Maximum Power Point Tracking (MPPT) system.

This system helps in the optimization of solar panel generation by continuously adjusting the electrical operating point of the modules (Sutikno et al., 2020).Many experiments and studies confirms that MPPT systems can significantly increase the solar energy yields by as much as 20%, making it an important component of solar based projects (Soudaga et al., 2024). Furthermore, recent discoveries in the solar technology especially in Perovskite solar cells have opened new possibilities for such hybrid systems, this technology offers higher efficiency comparatively to other solar panels, under various diverse weather conditions (Chen et al., 2024). For energy storage and optimization various algorithm is applied with in the hybrid system (Kumar et al., 2020). The combination of wind and solar energy , this project overcome the limitation of other electric power generation project which rely on only one source, and makes it a more reliable and efficient hybrid power generation system.

This approach is particularly beneficial in urban and semi-urban environments, where spatial and environmental constraints often challenge the deployment of standalone systems. The hybrid configuration ensures that energy generation remains consistent and adaptable to varying environmental conditions, making it a promising solution for sustainable energy needs. This technique is best for urban and remote environment, where environmental conditions often changes, such project will work better in such environment because of its standalone system ability, the configuration ensures that the energy generation remains consistent and adaptable to changing environmental conditions, and providing uninterruptible power supply to the needs, making it a sustainable energy solution (Change, 2023).

CONCLUSION:

The energy crises are critical issue especially in the developing countries. Energy consumption used by highway light towers is high. This project has utilized the available renewable resources such as traffic wind and sunlight. The battery backup has enabled this project to work in 24/7 in any weather. This project will provide energy on three busy roads in Pakistan and it is completely independent on national grid.

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