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Feasibility of highway wind and solar energy harvesting using VAWT in Canada

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Abstract— The objective of this experiment was to investigate the potential of using renewable energy sources along highways to generate electricity, focusing on the wind created by passing vehicles and the sunlight that falls on the road surfaces. Vertical-Axis Wind Turbines (VAWTs) were employed to harness the wind energy, while solar power was considered to enhance the energy output. The study explored the theoretical and practical efficiency of VAWTs and the impact of design modifications, such as adding fins to the turbine blades, on power production. A series of statistical tests, including one-sample and two-sample t-tests, were used to compare theoretical predictions with actual energy production. The results were used to estimate the potential energy generation along highways in Canada, combining wind and solar power in a hybrid system. The experiment concluded with estimations for daily power production from VAWTs and solar panels and highlighted the potential of renewable energy along highways.

Keywords- Highway energy, Vertical axis wind turbine, wind energy, solar energy, hybrid wind-solar energy

I. INTRODUCTION

As the world shifts towards renewable energy to address environmental and economic challenges, finding new ways to generate power is becoming more important. Wind and solar energy are two of the most popular renewable sources, but wind energy can be unreliable due to its changing nature. One promising solution is using the wind created by fast-moving vehicles on highways to generate electricity.

This study looks at the possibility of generating renewable energy from both wind and solar power along highways. Highways, with the constant flow of traffic, create wind patterns that could be harnessed for energy. Vertical-Axis Wind Turbines (VAWTs) are a good choice for this purpose because they can capture wind from any direction, making them ideal for the wind created by passing vehicles. The study also explores combining wind and solar power to create a system that can produce energy all year round.

Research in places like Malaysia and Kuwait has shown that the wind generated by moving vehicles is strong enough to power small devices such as streetlights and traffic signals. This wind energy could be captured using turbines along highways, offering a more sustainable and cost-effective energy solution.

In Canada, while using wind turbines on highways is still a new idea, it has the potential to support the country's renewable energy goals and reduce the use of fossil fuels. However, challenges like inconsistent wind speeds and wear and tear on turbines need to be overcome for the system to work well in the long term. A hybrid system that combines both wind and solar energy could help provide a steady energy supply throughout the year.

This research focuses on evaluating how well VAWTs can capture wind energy along highways and testing different turbine designs, such as adding fins to the blades, to improve performance. It also looks at the potential for combining wind and solar energy to estimate how much power can be generated along highways in Canadian cities like Montreal, Toronto, and Calgary. The goal is to help create a more sustainable energy future.

II. BACKGROUND

The world is increasingly using renewable energy sources for both economic and environmental reasons. These sources, such as tidal energy, solar energy, and wind energy, are becoming more important in Canada [1]. Wind energy is the fastest-growing source of clean energy worldwide. However, a big challenge with wind energy is that the wind is not always consistent, making it unreliable as a sole energy source. One possible solution to this is using the wind created by fast-moving vehicles on highways.

In Kuwait, even though natural wind speeds are low, highways provide a steady source of wind energy due to the moving vehicles [2]. Although this wind is not strong enough for large-scale power production, it can be used for smaller needs, like powering streetlights, traffic signals, and signs. These applications require very little energy, but using traditional infrastructure and fossil fuels for them is not very cost-effective. Placing wind turbines along highways could be a more sustainable and affordable solution, using the wind from vehicles to generate clean energy.

In Malaysia, studies show that moving vehicles on highways waste a lot of energy — about 1.2 million tons of oil equivalent each year [3] . This suggests a lot of energy could be captured from the wind created by these vehicles. Research also shows that wind speeds generated by vehicles can reach up to 24 m/s, which can power turbines at speeds of up to 6 m/s. This means a lot of energy can be captured from vehicle-generated wind.

Energy could be collected from highways by recovering some of the energy lost by fast-moving vehicles, along with natural wind [4]. To make this work, any extra energy could be stored in batteries, so it can be used when traffic is light. Vertical-axis wind turbines (VAWTs) are often considered for this kind of use because they don't need to be aimed directly at the wind, making them perfect for the fluctuating winds caused by passing vehicles. There are two main types of VAWTs: the Savonius turbine, which is easy to build and good for small-scale projects, and the Darrieus turbine, which is more efficient and can generate more energy at higher speeds, making it better for large-scale production [5]. However, the Darrieus turbine is more complex and not suitable for small-scale urban use, while the Savonius turbine's lower efficiency limits its use for large-scale production.

Although large-scale VAWTs were explored in the 1970s and 1980s, the rise of horizontal-axis wind turbines (HAWTs) led to less development of VAWTs, as more money was invested in HAWTs, and fossil fuel prices fell. Still, VAWTs are gaining renewed interest due to environmental concerns and energy security, especially in cities. Mahale et al. describe VAWTs as easy to install, quieter, and more eco-friendly, making them ideal for urban areas. Studies suggest that VAWTs work better as traffic volume increases because more vehicles create stronger winds [6]. Studies show that energy harvested by wind turbines on highways increased by 317% when vehicles were passing, compared to when no vehicles were moving [7]. This shows the potential of using highway-based wind turbines to generate a lot of energy.

In Canada, the idea of using wind turbines on highways to produce renewable energy is growing. However, there are challenges. Highways often have inconsistent wind speeds, and VAWTs are generally less efficient than HAWTs. The turbulence caused by vehicles could also wear down the turbines over time, shortening their lifespan. To overcome these challenges, new turbine designs and hybrid systems combining wind and solar power will be needed. Hybrid systems could provide energy year-round, even when wind or sunlight is not constant.

The goal of designing wind turbines for highways is to help the world move towards renewable energy. While traditional wind turbines are usually placed in rural areas, the aim of this research is to develop turbines that can use the wind generated by vehicles on highways to create electricity. This could help reduce pollution from burning fossil fuels and encourage the use of clean energy in cities. This approach could integrate renewable energy production into existing infrastructure and reduce reliance on traditional energy sources.

III. METHEDOLOGY

The methodology for this study involved several steps to assess the wind energy potential of highways, including measuring wind and power, testing the impact of fins on Vertical Axis Wind Turbines (VAWTs), scaling up the turbine design, using traffic data, and integrating solar power. Wind speed was measured at various highway sections using an anemometer. To replicate the wind conditions found on highways, a wind tunnel was created in the lab, and air was blown through a blower to simulate these conditions on a VAWT model. The theoretical power potential of the VAWTs was estimated using an online calculator based on the recorded wind speeds. To validate the theoretical estimates, actual power outputs from the turbines were measured and compared to the calculated values using a one-sample t-test. The efficiency of the turbines was determined by calculating the theoretical-to-practical ratio.

Since adding fins to Horizontal Axis Wind Turbines (HAWTs) has been shown to improve their power output, a similar test was done on VAWTs. A finned VAWT was compared to a modified non-finned turbine with the same mass to see if fins would have the same effect. The results were analyzed using a two-sample t-test to check if the fins made a significant difference in power production.

To estimate the power production of larger turbines on highways, a small-scale VAWT (0.01 m x 0.06 m) was scaled up by a factor of 10, creating a turbine size of 1 m x 0.6 m. Using the theoretical-to-practical ratio, the power output of the larger turbine was calculated at an average wind speed of 2.65 m/s, which is typical for highways. Wind speed data from other highways, such as Highway 17 in Ontario with an average wind speed of 5.5 m/s, was also used to provide a more accurate estimate of energy production.

Traffic data from highways in Montreal, Toronto, and Calgary were collected from statistics Canada to support the power calculations. The Average Daily Traffic (ADT) data, which measures the number of vehicles passing a point on the highway each day, was used to estimate the wind energy that could be generated from the traffic. By combining the ADT data with the calculated turbine power outputs, the potential energy production from highways in these cities was estimated.

To create a more complete energy production model, solar power was added to the system. An online tool, PVWatts (by NREL), provided by the National Renewable Energy Laboratory (NREL), was used to find the best tilt angles for solar panels in Toronto, Montreal, and Calgary. These optimal angles were then used to create a hybrid wind-solar system model, which simulated energy production throughout the year. This hybrid system was designed to ensure a reliable and continuous energy supply by capturing both wind and solar energy, even during periods when one of the resources was weaker.

IV. RESULTS AND DISCUSSION

The results of the experiment focused on harnessing renewable energy from both wind and solar power generated by vehicles passing on highways. The power produced by the vertical-axis wind turbines (VAWTs) was measured and compared to theoretical calculations to assess efficiency. As the wind speed on highways varies with vehicle movement, the power output depends on the wind speed generated by passing cars. The wind speed impacting the turbine blades should be measured to accurately estimate the expected wind power. Wind power was calculated using the formula:

$$Wind\ power = \frac{1}{2}\rho A v^3$$

where v is the wind velocity (m/s), ρ is the air density (1.225 kg/m^3), and A is the cross-sectional area of the rotor, determined by the diameter (D) and height (H) of the rotor. For this experiment, the reference air density used was the standard sea-level value of 1.225 kg/m^3.

The power extracted by the VAWT is determined by the equation:

$$Power\ extracted = \frac{1}{2}\rho A v^3 \eta C_p$$

where C_p is the power coefficient, which represents the efficiency of the wind turbine's design, and η is the mechanical efficiency of the drive unit. Wind turbines cannot convert all available wind energy into mechanical work due to the limitations defined by the Betz limit, which establishes that the maximum power coefficient C_p is 0.3 for VAWT. Achieving this theoretical limit is challenging in practical applications, and the efficiency is further influenced by the mechanical drive unit's performance. Additionally, the swept area of the turbine plays a critical role in determining the total power output—larger swept areas allow for more wind to pass through the rotor, resulting in higher energy conversion for the same wind conditions.

The theoretical calculations predicted that a small VAWT (0.01 m x 0.06 m) would generate 7mW of power based on a wind speed of 2.65 m/s, which is approximately the speed of wind produced by vehicles. However, actual measurements showed an average of only 6 mW, with a one-sample t-test indicating a significant difference between the theoretical and measured outputs. This difference led to the calculation of efficiency through the theoretical-practical ratio. The turbine's efficiency was further tested by adding fins to the blades, a modification designed to increase power output based on previous studies with horizontal-axis wind turbines (HAWTs). Contrary to the hypothesis, the finned VAWTs produced less power (5 mW), while the non-finned turbines achieved higher outputs, suggesting that the fins negatively impacted the wind turbine's performance.

After scaling the VAWT to 1 m x 0.6 m, the theoretical power output was estimated to be 18 W, assuming a power coefficient (Cp) of 0.3 and an air density of 1.225 kg/m^3. This highlights the significant role of wind speed in power generation. Using Average Daily Traffic (ADT) data from highways in Montreal, Toronto, and Calgary, it was estimated that more than 150,000 vehicles pass daily on Highway 400, Highway 401, Deerfoot Trail in Calgary, and Metropolitan Autoroute in Montreal. Additionally, over 10,000 vehicles pass daily on highways in Northern Ontario. Considering this traffic volume, a single turbine could generate approximately 750 Wh per day on major highways. To further optimize energy production, solar power was integrated into the calculations. The optimal panel angles were determined to be 30° for Toronto and 40° for Montreal and Calgary. If a 100 W solar panel is installed alongside each turbine, it could contribute an additional 350 Wh per day, increasing the total daily energy production to 1,100 Wh. This power generation would scale up with the number of hybrid wind-solar units installed. The study highlights how efficient wind power extraction is dependent on wind speed, swept area, and turbine design, with further improvements possible through better engineering and optimization of mechanical components.

V. Conclusions

This study shows that highways have strong potential for generating renewable energy from wind and solar power. Vertical-Axis Wind Turbines (VAWTs) can capture wind energy created by passing vehicles, although there are challenges like inconsistent wind speeds and turbine efficiency. The addition of fins to the turbines did not improve performance, indicating that more work is needed to optimize turbine designs.

When the turbines were scaled up and combined with solar power, the system could produce an estimated 1100 watt-hours of energy per day in cities like Montreal, Toronto, and Calgary. This combination of wind and solar energy could provide a reliable power source for small devices and reduce the need for traditional energy sources.

The results highlight the possibility of using highways to generate clean energy, which could help reduce reliance on fossil fuels. While there are still challenges to address, the study suggests that highways could play a key role in Canada's renewable energy future. With improvements to turbine design and system optimization, renewable energy from highways could become an important part of clean energy generation.

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