Energy Harvesting from Highway Traffic Vehicles Movement via VAWT

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Energy Harvesting from Highway Traffic Vehicles Movement via VAWT

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Abstract: *The majority of the resources used for producing energy are conventional, which are limited and diminish quickly. So, it's critical to find out alternative options for energy generation. The wind, which is the cleanest and most accessible renewable energy source generated by highway vehicles, is completely wasted. A vertical axis wind turbine (VAWT) may use this energy to generate electricity and store it in a battery if needed. The turbine shaft is connected to the U-coupler through the bearing, and the coupler is then connected to the motor shaft, which generates electricity. Here, we have harnessed electricity using VAWT, which could be installed on highway dividers in Bangladesh. We have produced an open circuit voltage of ~10 V by a 12 V, 200 rpm DC motor at a cut-in speed of 2.3 ms^{-1}. The generated power is fed to charge a mobile phone indicating a constant electrical power supply.*

Keywords: Energy harvesting; Renewable energy; Savonious; VAWT; Wind.

1. INTRODUCTION

The consumption of all forms of energy is growing quite rapidly because of ever-swelling overpopulation, overconsumption, urbanization, and advance in living standards. It is a matter of time to shut down coal or diesel power plants because of expensive generation costs [1]. For instance, it is about 8 taka per unit in Bangladesh. Whereas for gas-based power plants, the energy cost is ~2.8 taka per unit; however, the total amount of gas present in nature is limited. The world-meter evidence that approximately 6923 trillion cubic feet (Tcf) of gas reserves in the world, i.e., 52 years of gas is left considering current consumption levels and excluding unproven reserves [2]. Approximately 42% of universal CO_2 gas release in 2013 was the consequence of electricity and heat largely from fossil energy resources. International Energy Agency (IEA) has said that CO_2 emissions will increase by more than 215 Mt in 2021 [3]. In 2020 due to the COVID-19 outbreak, emission of CO_2 was 79%, which is ~5% less than the previous due to extensive lockdown, vehicle limitations, and reduction of compact oil consumption in the transport sector [4]. Over-consuming reserved relic energy resources affect instability in fuel rates. It also causes severe ecological difficulties, for example, global warming and acidic rain. As a result, careful consideration is required in the design of environmentally appropriate energy systems. The Global Wind Energy Council (GWEC) reports say that the world has a total install capacity of 837 GW of wind energy and a growth of 12.4% compared to 2020. About 94 GW of electricity is globally extracted by the wind industry rambling behind the 2020's world energy extraction record [5]. Wind power is the second most available source of energy after solar energy [6]. Wind energy is related to wind speed and their high altitude. When wind thrusts on the blades of the turbine, the turbine rotates and generates electricity. Wind flow to the turbine blades is shown in Fig. 1. The low energy extracted from wind speed is also considered a source of energy exclusively for a spread network. The wind speed depends on roadway traffic; heavy traffic hinders the wind speed, and lighter traffic merges the wind speed and amplitude. So, before exploring wind energy globally, we have to measure the amount of energy that could be harvested through the wind turbines, which potentially move by vehicles.

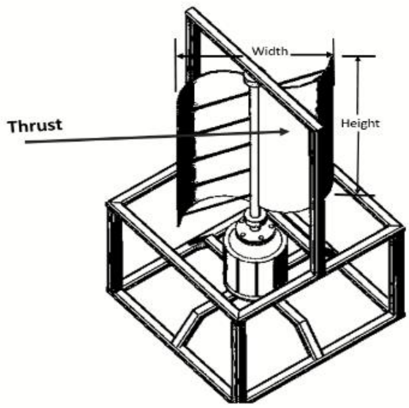

Fig. 1. Axial thrust on blades of the wind turbine.

According to a Malaysian report, the aerodynamic energy loss of moving automobiles on Malaysian roadways has been calculated at approximately 1.23 Million Tons of Oil Equivalent (MTOE) every year since 2002 [7]. A. Hossain et al. have demonstrated a design that looked into the development of vertical axis wind turbines (VAWT). The blade and drag mechanisms are designed to have a 1:3 ratio. When the wind speed is 20 to 25 ms^{-1}, the predicted output of this experiment is 500 to 700 W, respectively [8]. Morbiato et al. performed a statistical study of data material related to highway vehicle speeds and wind speeds. They found that the extracted energy conversion can be greater than 1.5 kW depending on the traffic clusters and traffic-related wind speeds [9]. To obtain the wind profiles of a heavy-duty vehicle, the stimulated air velocity was measured solely from the highway bridge [10]. In addition to normal wind speed that causes rotor blades to revolve and produce additional

electricity, Ishugah et al. explore energy harvesting from highways as a novel technique of re-using partial energy lost by high-speed automobiles in an urban setting [11]. S.S. Hegde et al. did a CFD analysis on a single car model and recommended the VAWT for energy harvesting [12]. VAWTs are available in two different configurations. The wind turbine called the Savonius is straightforward to construct, has an easy geometric shape, and has a nicer appearance than typical wind turbines. However, the speed is restricted. As a result, they aren't particularly popular on an industrial scale. This type of turbine can be highly useful for small-scale tasks. The next is the Darrieus wind turbine, which can reach great speeds and is consequently preferred among large-scale energy producers. However, It's not simple and comes in three different shapes: oval-shape rotor, H-rotor, and helical type, which is lift-driven and extremely efficient [13].
Some considerable researchers took the initiative in vast-scale VAWTs between the 1970s and 1980s, which were installed in the United States and Canada; however, these turbines were gradually curtailed due to falling fossil fuel prices [14]. Because of enormous expenditures made by several countries over the last 20 years, the majority of large-scale windmills erected now are horizontal axis wind turbines (HAWTs), which has hindered the growth of VAWT technology. However, considering the environmental pollution issue and basic needs like energy security in the urban area, researchers are enormously gathering more interest in various forms of VAWTs [15]. VAWTs are considered to be installed simply, including low noise levels, which are environmentally benign for urban projections [16]. Additionally, when it is placed on the highways and the number of passing vehicles rises, the smart VAWTs rotated more successfully [17]. From numerical analysis, it is found that when automobiles cross the roadway, wind power extracted rises by 317% compared to no vehicle driving [18].
In this paper, the energy harvesting system is proposed to harvest energy from the highway traffic vehicle movement using a VAWT. The VAWT for highway application is a form of the renewable energy system. To extract wind energy from highway traffics, the pictorial model, as shown in Fig. 2, is to be implemented.

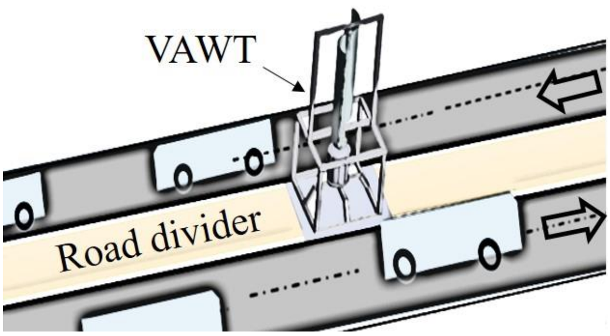

Fig. 2. Wind energy extraction model.

2. METHODOLOGY

2.1 Materials and Methods

Modern VAWTs are classified into three categories: Savonius, Darrieus, and H-rotor [19]. The Savonius type VAWT, which is a drag-type, was utilized in this work. This type of wind turbine can self-start and produces a lot of torque; however, it has a low tip speed ratio (TSR). The energy production processes using a block diagram approach are shown in Fig. 3.

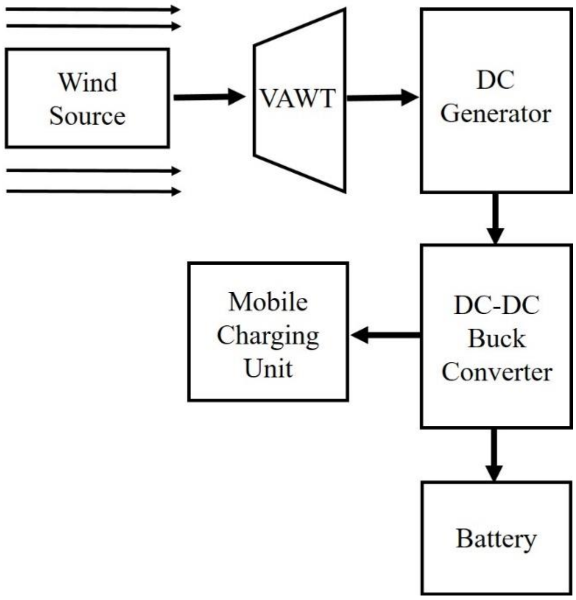

Fig. 3. Block diagram of energy production via VAWT.

When different vehicles run on the busy highway at different speeds, they create air turbulence. The generated wind thrust on the blades of the turbine, which is placed on the divider of the highway, rotates the turbine's rotor. The greater the vehicle speed, the greater the wind velocity generated. The more the wind speed generated, the faster the turbine's rotor will rotate. The blades convert the wind's kinetic energy into mechanical energy. The shaft of the turbine is connected with the motor shaft through ball bearings, and a flexible U-coupler rotates the DC geared motor, which is worked as a DC generator in this case.
The wind speed is higher in June, July, and August than in other months [20]. Noteworthy to mention that when the wind speed is higher, the turbine's rotor rotates rapidly, resulting in more energy generated by the DC geared motor. The motor converts the mechanical energy of the rotor of the turbine into electrical energy. A DC multimeter can measure the generated voltage and current. After multiplying the voltage and current, we get the generated power from the VAWT. To show the application of generated energy, we have used a mobile charging port to charge a mobile phone with this produced energy. Since the energy produced from the VAWT fluctuates according to the fluctuation of vehicle speed, we can't use the fluctuating energy for a stable application. We need a fixed output and it is done using a DC-to-DC buck converter [21]. The whole structure of the proposed VAWT is shown in Fig. 4.

2.2 Wind Profile Analysis

For creating a wind profile, we have chosen a roadside area near CUET, Chattogram, Bangladesh. The geographical location of the chosen spot is 22.4654869 (lat.) and 91.9668483 (long.), which is on the Chattogram – Kaptai highway of Bangladesh. Usually, this highway does not have much traffic and high-speed vehicles. With the help of an anemometer and measuring tape, we measured the wind speed produced by running vehicles at different heights from the road. The complete wind profile is shown in Table 1.

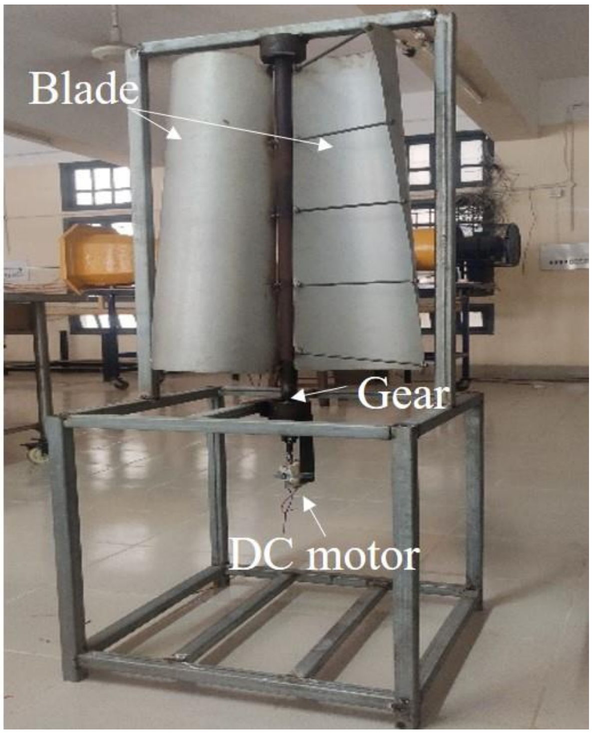

Fig. 4. Mechanical structure of the proposed VAWT.

Table 6. Wind profile data from the roadside area.

Height (m)	Wind Velocity (ms^{-1}) Obs. 1	Obs. 2	Obs. 3	Obs. 4	Average
0.50	2.7	2.9	2.7	3.6	2.98
0.65	4.1	3.9	3.0	3.6	3.65
0.85	4.9	4.6	4.5	4.9	4.73
1.00	5.0	5.2	4.0	5.2	4.85
1.25	4.5	4.9	3.9	4.6	4.48
1.50	4.8	3.5	5.3	4.2	4.45
1.65	3.0	2.9	3.9	3.0	3.2
1.75	2.9	3.0	3.0	3.1	3.0
2.00	3.6	2.9	3.2	3.1	3.2

After plotting all these data from Table 1, we have found the graph which relates the wind speeds concerning height, as shown in Fig. 5. From this graph, it is very easy to find out the height range of maximum wind speed for different types of vehicles. It is found that at different heights, the wind velocity is different. It also differs depending on the height and running speed of the vehicles. At 1.0 m height from the ground, the wind velocity is maximum. After that height, the wind velocity decreases. Since the wind speed is highest at 1.0 m height, the power produced by the wind turbine is also highest at this height. However, our designed structure has a blade height of 0.73 m. So, we need a range of 0.73 m height for the maximum output from the wind turbine. From the wind profile, we see that the wind speed is comparatively higher, from 0.8 m to 1.5 m in height which is perfect for implementing our turbine blades. Since we designed the model to implement on the divider of the busy highway, we considered the divider height also. Generally, the divider height is 0.2 m from the road level in Bangladesh. So, from the divider, the height of the turbine blade is 0.6 m.

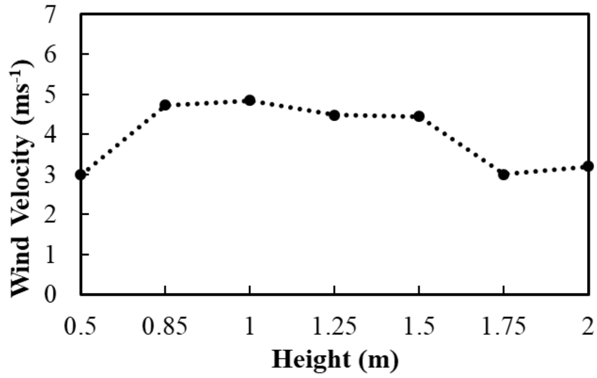

Fig. 5. Wind profile analysis for selecting the best height.

2.3 Theoretical Calculation

The following equations have been used for selecting the tip speed ratio (λ) and power coefficient (C_p).

$$C_p = C_T \lambda \quad (1)$$

Where C_T is the turbine coefficient. To get maximum output from Savonius-type vertical axis wind turbines, λ and C_p are considered as 1 and 0.15, respectively [22].

The air density (ρ) is considered as 1.23 kgm^{-3}. The height and width of our designed blades are 0.73 m and 0.415 m, respectively. So, the swept area (A) of the turbine blades can be calculated by multiplying these two and found as 0.30295 m^2.

DC motor efficiency (η) can be formulated by the below equation:

$$\eta = \frac{Mechanical\ output}{Electrical\ input} = \frac{T\omega}{VI} \quad (2)$$

Where T, ω, V, and I represent torque, angular velocity, rated voltage, and current, respectively. In this work, the used DC motor has 200 rpm with a rated torque of 3.9 kg.cm or 0.382 Nm, rated current of 2.1 A, and rated voltage of 12 V. by putting these values in Eqn. (2), we can obtain a motor efficiency of 31.76 %.

3. RESULTS AND DISCUSSION

3.1 Open Circuit Voltage of 12 V DC Motor (100 rpm)

The designed structure is assembled with a 12 V DC motor with 100 rpm and measured the output parameter. We created a controlled wind environment in the laboratory and recorded wind speed and voltage, as shown in Table 2.

After plotting all these data from Table 2, we have related the open circuit voltage to wind speeds as shown in Fig. 6. Here, the used 12 V 100 rpm geared DC motor has a gear ratio of 1:34. The produced voltage for small wind velocity is good; however, the starting torque is very high. For this reason, the turbine can't start to rotate at the low wind speed that can be created by small size vehicles. For the velocity of 5.6 ms^{-1}, the open circuit voltage produced by the motor is 10.3 V, which is preferable. However, the cut-in speed is very high (around 3.0 ms^{-1}). As a result, there is a possibility that the turbine remains stagnated most of the time. To resolve this issue, we have incorporated a higher rpm DC motor with the proposed structure.

Table 7. Generated voltage with wind variation for a 12 V, 100 rpm DC motor.

Observation	Wind Velocity (ms^{-1})	Voltage (V)
01	3.0	2.91
02	3.2	3.14
03	3.3	3.43
04	3.4	3.68
05	3.5	4.00
06	3.6	4.90
07	3.8	5.40
08	4.1	6.70
09	4.4	7.50
10	4.5	7.61
11	5.4	10.1
12	5.6	10.3
13	6.1	11.2

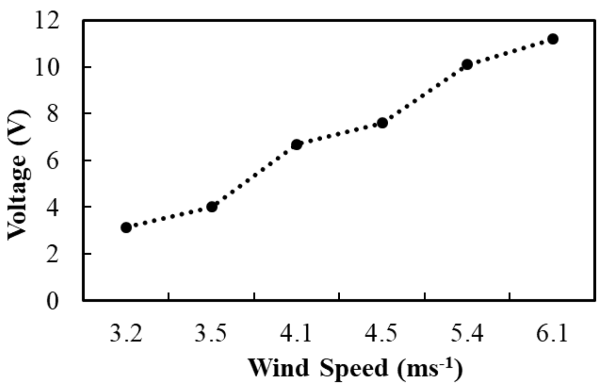

Fig. 6. Voltage vs. wind speed for a 100 rpm DC motor.

Table 8. Generated voltage with wind variation for a 12 V, 500 rpm DC motor.

Observation	Wind Velocity (ms^{-1})	Voltage (V)
01	3.4	2.54
02	3.8	2.99
03	3.9	3.12
04	4.0	3.21
05	4.1	3.28
06	4.2	3.30
07	4.3	3.33
08	4.4	3.39
09	4.5	3.44
10	4.6	3.27
11	4.8	3.39
12	4.9	3.38
13	5.0	3.45
14	5.2	3.53
15	5.4	3.67
16	5.6	3.89

3.2 Open Circuit Voltage of 12 V DC Motor (500 rpm)

In this case, we have used another 12 V DC motor with 500 rpm. At the same wind profile, we have collected data (without load) for a 12 V, 500 rpm DC geared motor, as shown in Table 3. The relation between open circuit voltage and wind speeds for the used motor is shown in Fig. 7.

Here, the motor has a gear ratio of 1:10. Since the rpm is very high and the gear ratio is very low, for small wind velocity, the turbine generates low power compared to the 100 rpm motor. In this case, the starting torque is also high and greater than the 100 rpm motor. So, the rotor of the turbine can't start to rotate at low wind speed and remain stagnated. For wind velocity of 5.6 ms^{-1}, the open circuit voltage produced by the motor is 3.89 V, which is very low. Besides, the cut-in speed for this motor is 3.4 ms^{-1}, which is comparatively high.

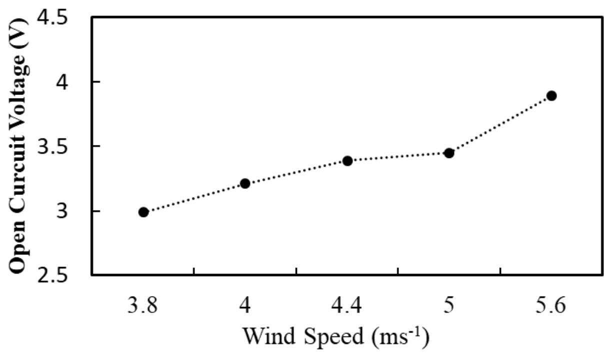

Fig. 7. Open circuit voltage vs. wind speed graph for 500 rpm motor.

3.3 Voltage of 12 V DC Motor (200 rpm) with Load

Here, we have used another motor of 12 V, 200 rpm to select which one is perfect for our work. Again at the same wind profile, we have collected data for this motor by connecting a 100 Ω resistor as a load in series. The collected data for 12 V, 200 rpm DC geared motor are shown in Table 4.

Table 9. Output parameters of the proposed VAWT (12 V, 200 rpm DC motor with a series connecting load).

Obs	Speed (ms^{-1})	Rotation (rpm)	Voltage (V)	Current (mA)	Power (mW)
01	2.3	24	2.23	18.8	41.92
02	2.5	28	2.27	22.2	50.39
03	2.9	30	2.61	35.1	91.61
04	3.5	66	4.00	42.2	168.80
05	3.6	72	3.55	36.5	129.57
06	3.6	80	3.75	41.9	157.13
07	3.8	90	4.50	43.6	196.20
08	3.9	100	4.06	50.6	205.44
09	4.0	111	5.31	53.4	283.55
10	4.2	114	5.67	59.4	336.80
11	4.7	120	6.16	66.6	410.26
12	5.2	126	7.37	78.6	579.28
13	5.3	129	7.48	79.8	596.90
14	5.4	132	7.61	80.9	615.65
15	5.5	163	8.36	84.8	708.93
16	6.0	175	8.41	90.1	757.74

The voltage, current, and power variation with wind speed are shown in Fig. 8. The used DC motor has a gear ratio of 1:30. The main advantage of this motor is that its starting torque is very low compared to the other two motors. As a result, for small wind velocity, the rotor of the turbine starts to rate and produces a significant amount of voltage. For wind velocity of 5.5 ms^{-1}, the voltage (with a 100 Ω load) produced by the motor is 8.36 V, which is superior in terms of the cut-in speed (2.3 ms^{-1}). This cut-in speed is relatively very low compared to other cases. i.e., at very low wind speed produced by small vehicles movement/ and by natural air, the rotor of the turbine could able to rotate and generate electricity. So, by using this configuration of motor, the proposed structure may harvest a reasonable amount of electricity continuously.

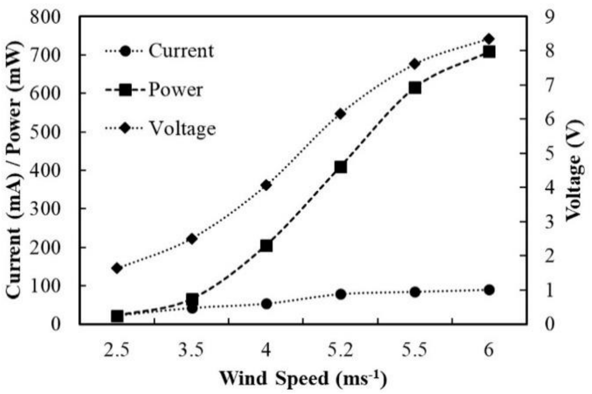

Fig. 8. Voltage, current, power vs wind speed graph for 200 rpm motor.

The above analysis of three different motor outputs is summarized and compared, which is shown in Table 5. It is seen that the DC motor with 200 rpm is the most suitable for the designed structure.

Table 10. Comparison between used different types of 12 V DC motor.

Rotation (rpm)	Gear ratio	Cut-in speed (ms^{-1})	Open circuit voltage (V)
100	1:34	3.0	10.3
200	1:30	2.3	10.1
500	1:10	3.4	3.89

3.4 Charging of a Mobile Phone

The maximum voltage generated at 6 ms^{-1} is 8.41 V, while the current flows as 90.1 mA through a 100 Ω load. Since the output voltage is varied with respect to the wind speed, we have used a DC-DC buck converter. This converter delivers a fixed voltage of 5.0 V. To use this generated voltage, and we have connected a mobile phone for charging, as shown in Fig. 9. Because of this converter, the mobile phone is charging without any interruption and consideration of the wind speed variation. It is shown in the figure that during the charging time, the mobile phone is drawing a current of 0.38 A, while the terminal voltage is fixed at ~5.0 V.

3.5 Recommendation for Future Study

In the future, different features can be added to this work. If a solar cell is integrated with the vertical axis wind turbine, the generated electrical output can be increased significantly. In this work, we have designed the turbine for only two blades. The number of blades can be increased to get a continuous wind strike on the blades, which will further improve the output. Usage of carbon fiber or Fiber Reinforce Plastic (FRP) instead of tin in the blade can also improve the output.

Fig. 9. Charging of a mobile phone with showing the generated voltage and current values.

4. CONCLUSIONS

Energy harvesting using a VAWT may be able to help energy challenges, especially for the power demand in roadside areas. However, power generation by vehicle-driven wind energy is minimal. In this work, we have proposed and designed a VAWT in such a way that the turbine can capture wind from two directions on any busy highway. The efficiency of the VAWT can be boosted if we pay attention to the installed location, size, and shape of the turbine's blades, as well as placing it near rapidly accelerated traffic such as at flyovers, slip downs, and tunnels. Our findings suggest that the Savonius type vertical axis wind energy conversion is feasible and could contribute significantly to the production of clean, renewable, and sustainable electricity from the wind, even under less-than-ideal siting conditions. The generated electricity may feed power to the street light, toll center, and traffic signal lights.

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