PERFORMANCE ASSESSMENT OF A COMBINED SOLAR AND WIND SYSTEM

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الخلاصة :

تقدم هذه الورقة دراسة جدوى لتقويم تأمين الطاقة لطرق المرور السريعة. وتصف تصميم نظام كهربائى نابع من مصدرين للطاقة المتجددة ، هما الطاقة الشمسية والطاقة الهوائية.

و تقدم الدراسة تقويماً لتأمين أحتياجات الطاقة لطرق المرور السريعة مثل الإنارة، والمكالمات الهاتفية لطلب الإسعاف أو النجدة ، واللوحات الإعلانية وغيرها.

وقد تم ـ فى هذه الدراسة ـ تصيم و تصنيع أنموذج جديد من توربينات سافونس الهوائية. ويتكون توربين العضو الدوار من ثلاث طبقات بارتفاع إجمالي قدرُه 2520 مليميتر ، وتتكون كل طبقة من ثلاث لوحات ، قطر كل منها 1220 مليميتر مزاحة عن بعضها بعضاً بـ 120 درجة. وقد تم أجراء تجارب جودة الأداء لقياس و تحديد متغيرات هذا التوربين مختبرياً ، و تم أيضاً تقويم التكلفة المثلى لنظام هجين من نظام توربينات سافونس الهوائية ونظام طاقة الجهد الضوئى.

وبناءً على نتائج الأمثلة تم حساب أعداد مثلى للوحات الطاقة الشمسية عددها 16 لوحة، التوربينات الهوائية 5 توربينة و 278 بطارية مركم وذلك من أجل إنارة كيلومترواحد من طرق المرور السريعة. ويتطلب النظام المقترح تجربته على طرق المرور السريعة .

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Paper Received: 28 September 2008; Accepted 9 February 2009

ABSTRACT

This paper deals with a feasibility study of a solar and wind hybrid system for highway energy requirements. The paper describes the modeling of two emerging electricity systems based on renewable energy: photovoltaic and wind power. The study presents an evaluation of combined solar and wind system for highway energy requirements such as lighting, SOS, billboard, *etc.* A new model Savonius Wind Turbine was used for this study. The Savonius Turbine rotor has 3 stages with total of 2520 mm height; each stage has three plates of 1220 mm in diameter deviated at 120° from each other.

Savonius turbine performance tests were realized to determine its experimental parameters. Also, cost optimization and feasibility of the combined system were evaluated. According to the result of the optimization, optimum numbers for solar panels, wind turbines, and batteries are computed as 16, 5, and 278 respectively for one km highway illumination. The proposed system with the present prototype is to be tested in situ.

Key words: Savonius wind turbine, wind and solar energy, performance assessment, highway illuminating, renewable energy

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1. INTRODUCTION

Depleting oil and gas reserves, combined with the growing concerns about global warming, have made it inevitable to seek alternative/renewable energy sources. The integration of renewable energies such as solar and wind energy is becoming increasingly attractive and is being used widely, for substitution of oil-produced energy, and eventually to minimize atmospheric degradation.

Solar and wind energy are nondepletable, site-dependent, non-polluting, and potential sources of alternative energy options. Many countries are pursuing the option of wind energy conversion systems; in an effort to minimize their dependence on fossil-based non-renewable fuels. Also, presently thousands of photovoltaic (PV) deployments exist worldwide, providing power to small, remote, grid-independent or stand-alone applications.

For both systems, variations in meteorological conditions (solar irradiation and average annual wind conditions) are important. The performance of solar and wind energy systems are strongly dependent on the climatic conditions at the location. The power generated by a PV system is highly dependent on weather conditions. For example, during cloudy periods and at night, a PV system would not generate any power. In addition, it is difficult to store the power generated by a PV system for future use. To overcome this problem, a PV system can be integrated with other alternate power sources and/or storage systems, such as electrolyser, hydrogen storage tank, Fuel Cell systems [1–3].

Combined wind and solar systems are becoming more popular for stand–alone power generation applications, due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. The Economic aspects of these technologies show sufficient promise to include them in developing power generation capacity for developing countries. Research and development efforts in solar, wind, and other renewable energy technologies are required to continue improving their performance, establishing techniques for accurately predicting their output and reliably integrating them with other conventional generating sources.

Prasad and Natarajan presented a new method for optimization of a wind–PV integrated hybrid system. Based on deficiency of power supply probability, relative excess power generated, unutilized energy probability, life cycle cost, levelized cost of energy, and life cycle unit cost of power generation with battery bank, the method addresses a specific location and employs an iterative scheme [4].

Nelson *et al.* performed an economic evaluation of a hybrid wind/photovoltaic/fuel cell generation system for a typical home in the Pacific Northwest. In this configuration the combination of a fuel cell stack, an electrolyzer, and hydrogen storage tanks is used as the energy storage system. This system is compared to a traditional hybrid energy system with battery storage. A computer program has been developed to size system components in order to match the load of the site in the most cost effective way. A cost for electricity, an overall system cost, and a break-even distance analysis are also calculated for each configuration [5].

Grinspan *et al.* presented the development of a Savonius rotor configuration which is simple in design, fabrication and maintenance, and is suitable for small-scale rural application. Initially, the performance studies of Savonius wind turbine rotors have been carried out with conventional three bladed straight and curved rotors. From the experience of these experiments, two distinct blade shapes, *i.e.*, an aerofoil type and a twisted type rotor have been developed and tested in three bladed rotor systems. Performance characteristics of the developed rotor blades have been evaluated and the results obtained are compared and discussed [6].

Mojola examined the performance characteristics of the Savonius windmill rotor under field conditions. Test data is collected on the speed, torque, and power of the rotor at a large number of wind speeds for each of seven values of the rotor overlap ratio. The performance data of the Savonius rotor are also fully discussed and design criteria established [7]. A prototype of a small Savonius rotor for local production of electricity was produced by Menet [8].

In order to decrease the torque variation of a Savonius rotor and improve the starting characteristics, a new type of Savonius rotor, which has three stages with 120-degree bucket phase shift between the adjacent stages, had been designed by Hayashi *et al.* [9].

In this study, a Savonius wind turbine whose design and performance measurements are known, is integrated with PV system. A Savonius type wind turbine has been used for this study because the turbine has been planned for use in highways especially for road lights. This kind of turbine is the best solution for this kind of applications to get the advantage of the wind that is created by the vehicles' speed. An evaluation of the combined solar and wind system for highway energy requirements such as lighting, SOS, billboard *etc.* were analyzed. For this study, a new model Savonius wind turbine was designed and its prototype was manufactured. Experimental results of the Savonius rotor shows that the system can be used effectively to obtain energy requirements on highways. In order to support energy requirements continuously, the system should be used with PV panels.

2. SYSTEM DESCRIPTION

The Savonius rotor is a very simple concept that has been constructed, and used successfully, from oil drums. It includes two half cylinders (nominal diameter *D*, height *H*), with the whole rotor turning around a vertical axis, as shown in Figure 1. The movement is mainly the result of the difference between the drag on the advancing paddle and the drag on the other one. Although the efficiency of the Savonius rotor is relatively low, there are a number of geometrical parameters which affect this efficiency. Among these, the aspect ratio represents the height (*H*) of the rotor relatively to its diameter (*D*); this is a very important criterion for the aerodynamic performances of the Savonius rotor [8].

$$\alpha = {}^{H}\!/_{D} \tag{1}$$

Globally, high values of the parameter should greatly improve this efficiency. Values of α around 4.0 seem to lead to the best power coefficient for a conventional Savonius rotor. It is known that end plates lead to better aerodynamic performances [8].

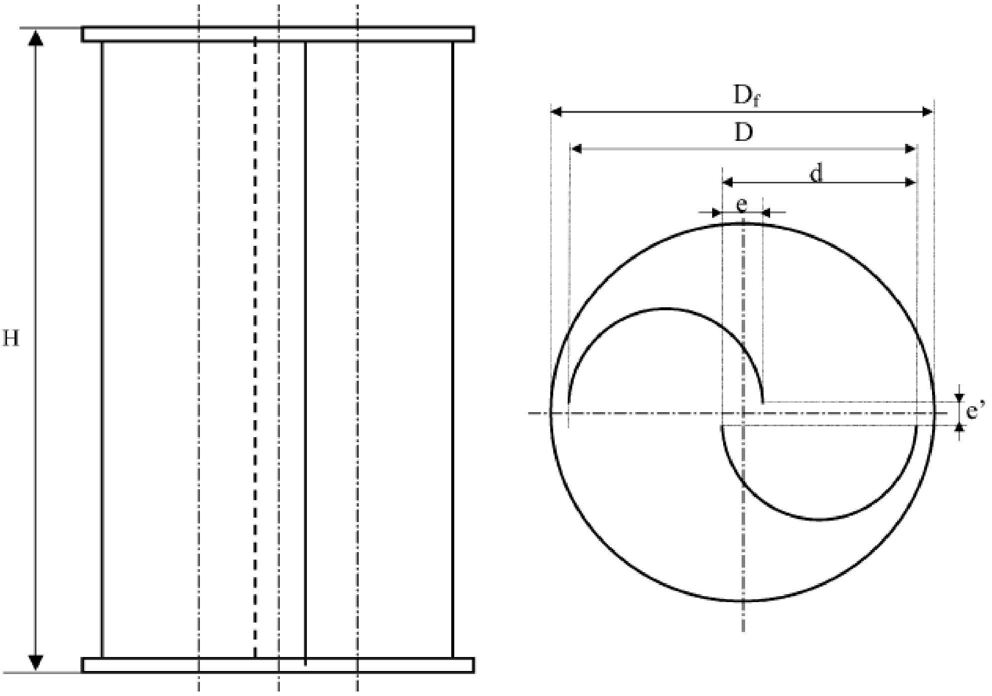

Figure 1. Design and manufacturing criteria of SWT

In Figure 1,

D_f : End plates diameter of the rotor

D : Rotor diameter

d : Diameter of each cylinder paddles

e : Overlap

e' : Separation gap between the paddles

Different criteria were considered for the choice of the material such as low price, ease of building, low weight, good resistance to outside elements (humidity, temperature variation, *etc*.), and good rigidity. After considering all criteria, we decided to use Fiberglas–epoxy material. A prototype of new model Savonius turbine specification is given below:

Three stages, 3.024 m^2 total sweep area, 840 mm stage height, with a total of 2520 mm height, each stage has three plates of 1220 mm in diameter deviated at 120^0 from each others. In order to give natural color to the rotor, the turbine was painted with rainbow colors. The final state of the turbine is shown in Figure 2 [10].

Figure 2. The Savonius wind turbine with rainbow color

The preliminary experiments of the prototype of the SWT were started simply under no load with low wind velocities of 1.2 m/s, which shows that the SWT was able to reach high rotations without occurring vibration problems.

Generally, permanent magnet (PM) alternators are linked to the wind–turbine rotor to produce electrical energy at low rotations. Therefore, a PM alternator was linked to the SWT. Measurement results are given in Table 1.

Table 1. Experimental Parameters of the SWT

Savonius rotor diameter	R= 2.4 m
Savonius total rotor highness	L=2.52 m
Stage height	0.84 m
Total swept area	3.024 m^2
Start up wind speed	1.2 m/s
Power coefficient ~	0.25
Rated wind speed	3 m/s
Rated Power	1000 W
Maximum Power ~	1200 W
Generator	PM Alternator
Output Voltage	48 V DC

2.1. The Proposed System Model

The combined solar and wind power generation system consists of PV array, wind turbine, battery bank, inverter, controller, and other accessory devices and cables. In order to predict the combined system performance, the main components such as PV array and wind turbine need to be modeled first. The combined solar and wind power generation system model is shown in Figure 3. A Savonius wind turbine with permanent magnet (PM) generator was used in this model.

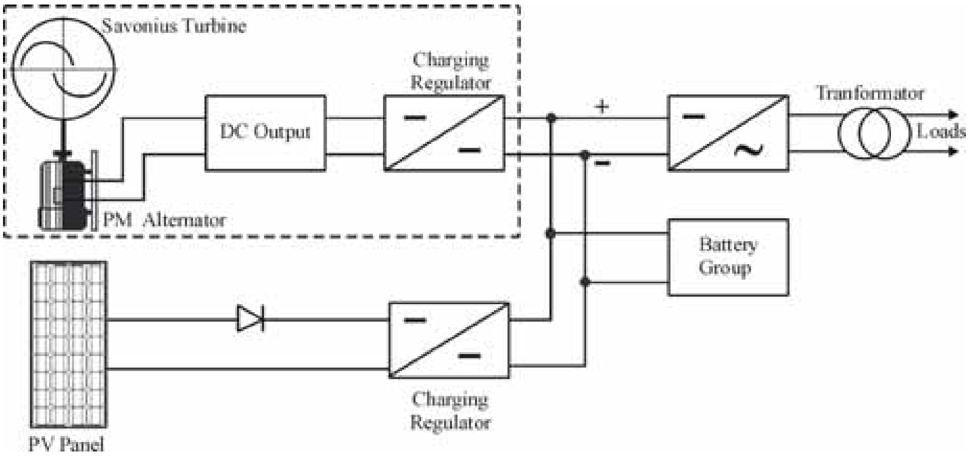

Figure 3. The combined solar and wind system model

The combined system to provide energy requirements of highway illumination, SOS, billboard *etc*. includes SWTs, PV panels and battery groups. The proposed combined solar and wind system illustration on highway is shown in Figure 4.

SWTs should be located to bidirectional highways in central gaps. Also PV panels can be fixed over the illumination pole as shown in Figure 4 concerning with a direction of the longest term solar angle or PV panels may be designed to follow up solar. The electrical energy produced by the hybrid system should be used to supply highway illumination, emergency communication (SOS), advertisement and driver warning billboards, *etc*. with the necessary energy.

Generally, high or low pressure sodium vapor lamps or mercury vapor lamps are used for highway illumination. Among these lamps, sodium vapor lamps are more preferable than mercury ones, due to their high efficiency factor [11].

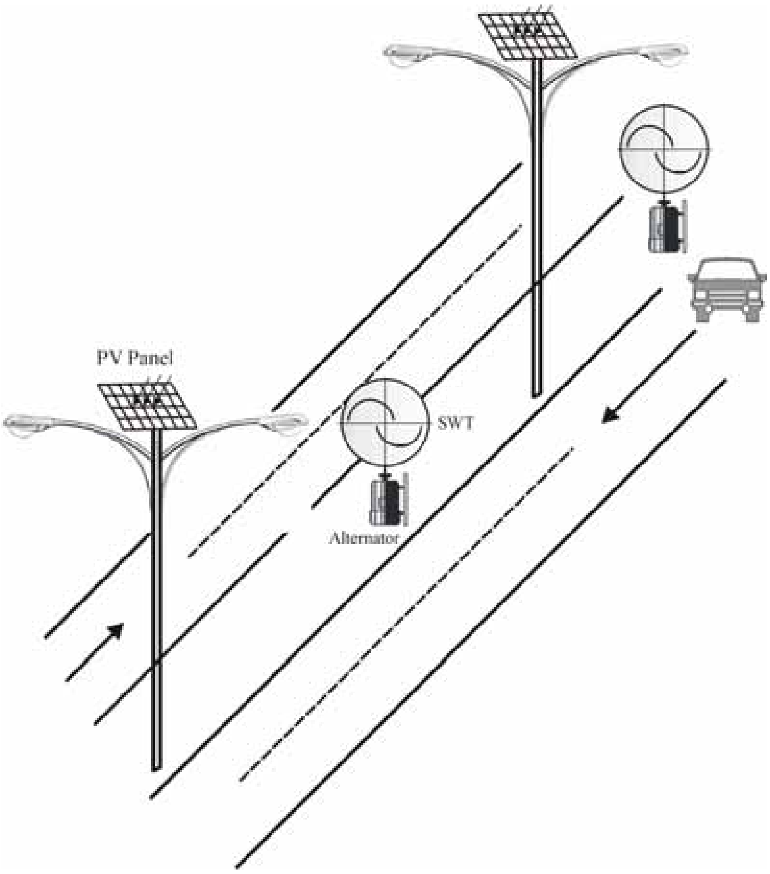

Figure 4. The proposed system schema on a highway

2.2. PV Array Performance Model

The PV module performance depends on weather conditions, especially solar radiation and PV module temperature. A simplified PV simulation model proposed by Zhou *et al.* [12] is used to estimate the actual performance of PV modules under varying operating conditions. PV modules represent the fundamental power conversion unit of a PV system. It is mandatory to connect PV modules in series and in parallel in order to scale up the voltage and current to tailor the PV array output. If a matrix of $N_s \times N_p$ PV modules is considered, the maximum power output of the PV system can be calculated by

$$P_{PV} = N_p . N_s . P_{\text{module}} . \eta_{MPPT} . \eta_{oth} \tag{2}$$

where η_{MPPT} is efficiency of the maximum power point tracking, although it is variable according to different working conditions, a constant value of 95% is assumed to simplify the calculations. η_{oth} is the factor representing the other losses caused by cable resistance and accumulative dust, *etc.* [13].

2.3. Wind Turbine Performance Model

Choosing a suitable model is very important for the wind turbine power simulations. In accordance with the experimental parameters of SWT, power curve was obtained, as seen in Figure 5.

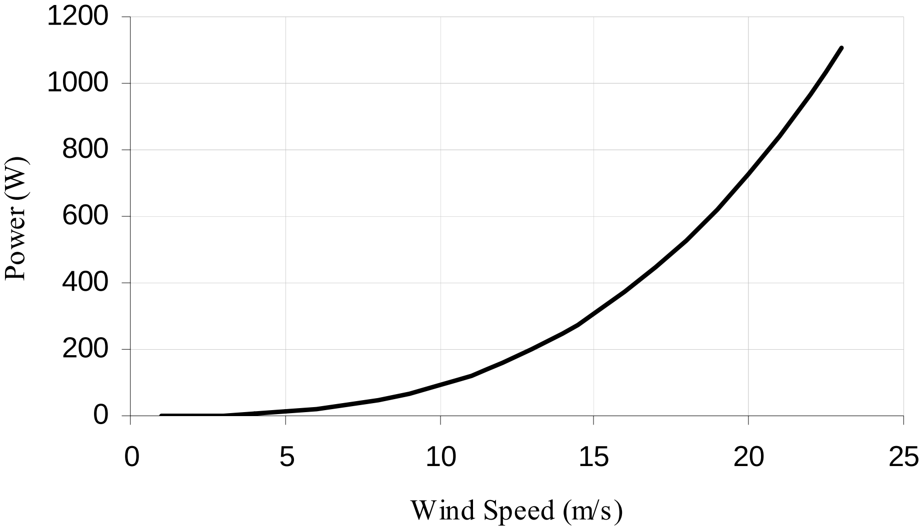

Figure 5. Power curve of the Savonius wind turbine

If the average wind speed reaches 10 m/s and above, SWT can produce electricity at the rated power. In the case of wind speed lower than 10m/s, electricity production is less than the rated power.

3. ANALYSIS

The power output from a combined solar and wind system, P_{CS} may be expressed as

$$P_{CS} = P_S + P_W \tag{3}$$

where P_W the total wind turbine power (*W*) is, P_S is the total solar power (*W*).

$$P_W = n_W . P_{WT} \text{ and } P_S = n_S . P_{PV} \tag{4}$$

The main goal in designing the hybrid power generator is to select the optimum number for n_S, n_W, and n_B for minimum cost and to produce a total power output C_{CS} to meet the demand for power throughout the year. Assuming the cost to be a linear function of the size, the total cost of a hybrid generator C_{CS}, can be written as

$$C_{CS} = n_S C_S + n_W C_W + n_B C_B \tag{5}$$

where C_S, C_W, and C_B represent the cost per unit power potential of individual solar and wind power generators, n_S, n_W, and n_B number of PV panel, wind turbine, and battery respectively.

$$P_d \leq P_S + P_W \tag{6}$$

where P_d is the power demand. Additionally, power demand is less equal than summation of the total of wind turbine power and solar power.

The optimization problem of combined solar and wind systems is expressed by following equation:

$$\text{Minimize } C_{CS} = n_S C_S + n_W C_W + n_B C_B$$

$$\text{Subject to } \left\{ \begin{matrix} P_W = n_W . P_{WT} \\ P_S = n_S . P_{PV} \\ P_d \leq P_S + P_W \end{matrix} \right\}$$

Cost optimization of the combined solar and wind system was also realized. Highway illumination poles intervals were considered as 50 m and total bidirectional highway distance was 1 km for the cost optimization.

Table 2. Components of Energy Supplier and Energy Consumer

Energy Supplier		
Model	**Power (W)**	**Capacity**
Mitsubishi Electric PV-MF125E4N	125W	-
Savonius wind turbine	1000W	-
CSB Battery GP 6120F2 Lead acid battery	-	12 V, 6 Ah
Energy consumer		
Model	**Power(W)**	**Capacity**
PELSAN Sodium vapor lamp	250W	-
SOS Billboard etc.	100W	-

The optimization problem of the systems is solved by using an optimization solver inside Microsoft Office Excel packages.

$$\text{Minimize } (C_{CS} = n_S C_S + n_W C_W + n_B C_B)$$

$$\text{Subject to } \left\{ \begin{matrix} 7kW \leq P_s + P_w \\ 1 \leq P_s \\ 1 \leq P_w \end{matrix} \right\}$$

As a result, optimum numbers of solar panel and wind turbine are computed as 16 and 5 respectively. Total cost of solar wind combined system is equal to the addition of PV cost, wind turbine cost, and battery cost. In order to calculate the total cost, determination of battery number is necessary for the calculation of battery cost. Calculation of battery number is done under some assumptions as follows.

Generally, energy is demanded between 20:00 and 06:00 by the energy consumer. Between 06:00 and 20:00, the battery is charged by the wind turbines and solar panels during an average of 10 hours. Battery and wind turbines together provide all the energy requirements. The energy requirement for 10 hours (daily operation hours) over a 1 km distance is calculated as below.

$$E_{rq} = P_{tc} . t_{oh} . n_m$$

where

E_{rq}: Total energy requirement (Wh)

t_{oh}: Daily operation hours

P_{tc}: Power, consumed by one group of an illumination lamp, SOS, and billboard

n_m : Number of groups including an illumination lamp, SOS, and billboard.

According to this formula, total energy requirement can be calculated as follows:

$$E_{rq} = 350 \times 10 \times 20 = 70000\text{Wh} = 70\text{kWh}$$

70 kWh of energy requirement is been supplied by the Savonius wind turbine and battery between 20:00 and 06:00. The required battery capacity, E_b is calculated as follows:

$$\begin{aligned} E_{cs} &= E_w + E_b \\ E_w &= P_{WT} .n_w .t_{oh} \\ E_w &= 1 \times 5 \times 10 = 50\text{kWh} \\ E_b &= E_{cs} - E_w \\ E_b &= 70 - 50 = 20\text{kWh} \end{aligned}$$

20 kWh battery packs have to be formed to provide all energy requirements interruptedly. This pack contains approximately 278 lead–acid batteries with 6V and 12Ah. After determining the necessary battery numbers, now it is possible to calculate the total cost of combined solar and wind system.

$$C_{CS} = n_S C_S + n_W C_W + n_B C_B$$

$$C_{cs} = 16 \times 610 + \ 5 \times 4640 + \ 278 \times 22.04 = 39084{,}12\$$$

Total cost of the solar and wind combined system is calculated as 39 084 $.

4. RESULTS AND DISCUSSIONS

The efficiency of the designed SWT has to be tested on the highway to get real-time data. The turbine real-time values will give the power–velocity and velocity–efficiency graphics. So, average efficiency can be calculated. If the obtained value from the turbine generator output is enough for the application, then the given power system model must be established on a main road.

Use of photovoltaic panels with the Savonius Wind Turbines support is applicable to the system. Billboards should be used to warn drivers to remember traffic rules and road circumstances, especially on rainy and snowy days. The proposed system is a new subject for renewable energy for highway lighting and other requirements for highway electricity.

The optimization problem is solved by using an optimization solver inside Microsoft Office Excel packages. According to the result of the optimization, optimum numbers of solar panel and wind turbine and battery are computed as 16, 5, and 278 respectively, and the total cost of the system is calculated as 39 084$ for one km of highway illumination.

5. CONCLUSIONS

The prototype of Savonius rotor was built for this study to the supposed energy requirements on the highways. This prototype should be tested in a wind tunnel to verify the design performance; after that, experiments will be realized in situ with PV panels.

The suggested system can be compared with traditional systems as an aspect of economical and feasible features in another study. The performance of the Savonius Turbine can be improved during the production process. The suggested system is an applicable example for highway lighting. When the turbine is used with PV panels, the performance can be improved significantly.

If LEDs are used in highways lighting instead of sodium vapour lamps, a significant amount of energy can be saved so it is possible to use the same system for a greater area. A combined system, wind and PV panels, should be built on a highway as a prototype to discover the application problems and required improvements.

NOMENCLATURE

D_f : End plates diameter of the rotor
D : Rotor diameter

H : Rotor height

d : Diameter of each cylinder paddles

e : Overlap

e' : Separation gap between the paddle

P_{PV} : Solar panel power

P_S : The total solar panel power

η_{MPPT} : Efficiency of the maximum power point tracking

η_{oth} : The factor representing the other losses

P_W : The total wind turbine power

P_{WT} : Wind turbine power

C_{CS} : Total cost of a hybrid generator

C_S : Cost of solar power

C_B : Cost of battery

C_W : Cost of wind power

E_b : Required battery capacity

E_{rq} : Total energy requirement

n_S : Number of solar panel

n_W : Number of wind turbine

P_{CS} : Combined solar and wind system

P_d : Power demand

P_{tc} : Power, consumed by one group of a illumination lamp, SOS and billboard

n_m : Number of group including a illumination lamp, SOS and billboard.

t_{oh} : Daily operation hours

LED : Light Emitting Diode

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