A Feasibility Evaluation of a Combined Solar and Wind Energy System in Taiwan

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Abstract: Solar energy and wind energy can be converted to electrical power by photovoltaic (PV) cell and wind turbine, respectively. A combined generation system using the both energies has widely been adopted in the world especially for isolated areas with high levels of irradiation and wind speed. In this paper, solar radiation upon a single-axis tracked panel and wind speed data in the northern, central and southern regions of Taiwan are analyzed according to different time periods. Both the total energy of the combined system and associated energy ratios are determined too. It is found that the solar and wind energy compensate each other very well, irrespective of the regions studied, and reveal a balance situation near April and September. Generally, during the winter months, wind potential energy is higher while solar energy is lower and vice versa during the summer months. That is, electricity generated by PV cell and wind turbine can be delivered to the same grid system to enhance its reliability. Several numerical examples of design areas for PV cell and wind turbine in the combined system are proposed for a specified power demand.

Keywords: Combined system; solar energy; wind energy; tracked panel; Weibull function.

1. Introduction

Because of the shortage of fossil fuels, seeking alternative energy sources is an urgent business for a country's economic development. There are six major types of renewable energy available in the world, i.e. the solar energy, geothermal energy, wave energy, hydraulic energy, biomass energy and wind energy, which can be converted to electrical power through various devices. Among these, producing electrical power from solar radiation using photovoltaic (PV) cells as well as from wind energy via wind turbines are more popular applications than others. However some drawbacks must be mentioned while using alone a solar or wind energy system. For example, solar energy system itself may not provide a continuous source of energy during nighttime or an overcast day. Similarly wind system itself cannot satisfy a constant load demand because wind speed may vary from time to time. That is, the main problem in separate use of solar or wind energy is their discontinuity. This problem can be solved to a certain extent through an application of a combination of solar and wind energy system. Therein electrical power is separately produced from solar and wind system and was given into the same national grid; solar

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energy supports the combined system when wind energy is insufficient for the grid and vice versa, the reliability of the system is enhanced. The purpose of the present study is to find out whether the solar and wind energy in Taiwan support each other; similar research has rarely been found in literature. A cosine function is proposed by this paper to correlate the relationship between solar and wind energy. Meanwhile empirical expressions for calculating the design area of PV cell and wind turbine are examined for different regions under particular power demand.

To collect more solar energy, practically sun-tracking system is used because it aims at the Sun with a smaller incident angle of sunlight. The extra amount of energy collected by a tracked panel as compared to a traditional fixed panel depends on the operation and climatic conditions. Generally the gains lie between 20% and 40% [1-7]. Basically there are two kinds of tracking systems, single-axis and dual-axis systems, and they operate usually using either electrical or thermal mechanism. In this paper, a single-axis tracked panel which faces due south with yearly optimum tilt angle is considered for the first time in the field; relevant expressions can be found in Chang [8-9].

Taiwan situates between the world's largest continent (Asia) and the largest ocean (Pacific); more than 95% of energy supply comes from imported fossil fuels. In winter and spring the island is visited by the strong northeastern monsoon that often leads to rainy days and lower solar radiation. In summer and autumn, southwestern monsoon prevails in this region and the sunshine duration is longer. In this paper solar radiation data observed at Taipei, Taichung and Kaohsiung meteorological stations, which locate in the northern, central and southern part of the island respectively, will be selected. The radiation data is the averaged global radiation observed at the ground surface by the Central Weather Bureau. The Pyranometer is made by Eppley Laboratory, which measures the total band of shortwave solar radiation with wavelength of 280-2800 nm. Wind speed data is measured from 2006 to 2008 by wind turbines at three wind farms, Dayuan, Penghu and Pingtung, located respectively from north to south near the three studied meteorological stations, conducted by the Ministry of Economic Affairs. Wind speeds at any anemometer heights have been transferred using one-seventh power law to the height of 10m above ground level in the subsequent calculations.

The contents for the remaining sections of this paper are briefly shown as: Section 2 illustrates how much solar energy is received by a single-axis tracked-panel. Section 3 describes how to estimate wind energy potential through Weibull probability density function. Some obtained results are analyzed and discussed in Section 4. Conclusions are remarked in Section 5.

2. Solar energy upon a single-axis tracked panel

For a solar collector installed on a single-axis tracking system, facing due south, tilted at an angle β to the horizontal surface, its position and the incident angle of sunlight change with time. The instantaneous global radiation (I_T) on the tilted collector is the sum of the direct beam, diffusion and reflection from the ground [8-9]:

$$I_T = I_b \cos \theta_{tk} / \cos \theta_z + I_d (1 + \cos \Omega) / 2 + \zeta I (1 - \cos \Omega) / 2$$
(1)

Where, ζ is the ground reflection coefficient; I_b , I_d and I are the beam, diffusion and global radiation on the horizontal surface, respectively, which follow:

$$I = I_b + I_d \tag{2}$$

Notation definitions about the mathematic parameters can be found in nomenclature.

(6)

The instantaneous angle θ_{tk} between the direct beam and the normal of the tracked panel is given by [8-9]:

$$\theta_{tk} = \cos^{-1} \{ \sin \theta_z \cos \psi \sin \beta \cos \alpha - \sin \theta_z \sin \psi \sin \alpha + \cos \theta_z \cos \beta \cos \alpha \}$$
(3)

Here, α is the angle that the tracking system has to rotate through from the position of solar noon to face the Sun. It is limited to a maximum value of 45° in order to avoid damage to the collector. θ_z is the zenith angle and ψ is the azimuth of the Sun given by:

$$\alpha = \tan^{-1} \{ -\sin\theta_z \sin\psi / (\sin\theta_z \cos\psi \sin\beta + \cos\theta_z \cos\beta) \}$$
(4)

$$\cos\theta_z = \sin\delta\sin\phi + \cos\delta\,\cos\phi\cos\omega \tag{5}$$

$$\cos\psi = (\cos\theta_z \sin\phi - \sin\delta) / \sin\theta_z \cos\phi$$

Where ω is the solar hour angle, which changes by 15 degrees per hour (and is zero at solar noon, negative in the morning and positive in the afternoon). ϕ is the geographic latitude. The solar declination δ is the angle between the line joining the centers of the Earth, Sun and the equatorial plane. For any day with the day number dn being counted from January 1st (1-365), it can be expressed as:

$$\delta = 23.45 \sin(2\pi (284 + dn)/365.25) \tag{7}$$

The angle Ω in Eq. (1) is the instantaneous slope of the panel, following that $\cos \Omega$ is the scalar product between the unit normal vector of the panel and the zenith vector:

$$\cos\Omega = \cos\alpha\cos\beta \tag{8}$$

The tilt angle (β) of the tracked panel is the optimum installation angle of a fixed panel for the annual period, which is 20.2°, 19.6° and 18.4°, for Taipei, Taichung and Kaohsiung station, respectively. The radiation data available in the present study is given in the form of daily global irradiation on the horizontal ground surface. Relevant expressions can be used to estimate the instantaneous radiation on the tracked panel [9-10], the gain of the tracked panel as compared to a fixed one can be determined subsequently.

3. Wind potential energy

To estimate wind speeds at different heights, a famous power law is adopted [11]:

$$v = v_{ref} \left(\frac{z}{z_{ref}}\right)^{\lambda} \tag{9}$$

Where v and v_{ref} are the wind speeds at desired height z and referred height z_{ref} , respectively. The power coefficient λ represents the degree of roughness of ground surface. The typical value of 0.14 (one-seventh) for a wide-plain area is used in this study [12-13].

To effectively evaluate the wind power available for a particular site, statistically studying the wind characteristics is necessary. The Weibull function has widely been used to describe the wind speed distribution for its two flexible parameters. Weibull probability density function (pdf) is given as:

$$f(v) = \frac{k}{c} (\frac{v}{c})^{k-1} \exp[-(\frac{v}{c})^{k}]$$
(10)

Where k is the Weibull shape parameter and c is the scale parameter with the same unit as wind speed which can be estimated by the following empirical equations [14-16]:

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{11}$$

$$c = \frac{v}{\Gamma(1+1/k)} \tag{12}$$

Where \overline{v} and σ are the mean and standard deviation of wind speeds, respectively. $\Gamma()$ is the Gamma function given by:

$$\Gamma(x) = \int_0^\infty t^{x-1} \exp(-t) dt$$
(13)

The power of wind is proportional to the cube of wind speed. The amount of wind power per unit area, named wind power density, based on the Weibull probability function, is given as:

$$P = \frac{1}{2} \rho \int v^{3} f(v) \, dv$$

= $\frac{1}{2} \rho c^{3} \Gamma(1 + \frac{3}{k})$ (14)

Where ρ is the air density; for a particular cross-section area of A (the blade sweep area of wind turbine) within a time period of T, the wind potential energy can be calculated by:

$$E_{w} = \frac{1}{2}\rho ATc^{3}\Gamma(1+\frac{3}{k})$$
(15)

4. Results and discussion

Figure 1-3 show the monthly solar energy collected by a single-axis tracked panel as well as the wind potential energy, for the northern, central and southern region of Taiwan, respectively. It reveals a higher level of wind energy in winter months while solar energy is lower and vice versa in summer months for all the regions. That is, an application of a combined system is feasible.

Table 1 summarizes the averaged yearly quantities for both energies. It is shown that the gains of the tracked panel are close to 20% for both the central and southern regions, whereas the ones for the northern region are evidently lower than others due to its lower radiation level that makes the benefit of employing a tracking system worse. In addition to mean wind speed, the statistical Weibull shape and scale parameters are also available in the table. Although the power density of wind is somewhat similar to that of solar radiation, wind potential energy is quite greater than solar energy, independent of the regions studied, since wind blowing may last for 24 hours a day but the sunshine is only in the daytime. Therefore the ratios of wind energy to total energy (i.e. the sum of solar energy of tracked panel and wind energy) reach about 0.6 or more. Especially in the central region, the selected wind farm locates in a wide-open ocean area where wind speed is higher a lot than other regions. On the other hand, due to the lower cost of wind energy production the utilization of wind energy is encouraged.



Figure 1. Monthly solar and wind energy in northern region







Figure 3. Monthly solar and wind energy in southern region

Regions	Northern	Central	Southern
Solar energy- tracked panel (kWh/m ²)	1099.01	1495.16	1443.22
Solar energy- fixed panel (kWh/m ²)	961.25	1260.68	1227.59
Solar energy- horizontal surface (kWh/m ²)	952.11	1225.14	1208.62
Gain of tracked to fixed panel (%)	14.33	18.60	17.57
Gain of tracked to horizontal surface (%)	15.43	22.04	19.41
Solar power density of tracked panel (kW/m ²)	0.264	0.359	0.347
Mean wind speed (m/s)	6.23	7.52	5.82
Weibull shape parameter	1.96	1.95	2.14
Weibull scale parameter (m/s)	7.03	8.48	6.57
Wind power density (kW/m^2)	0.290	0.515	0.220
Wind energy (kWh/m^2)	2540.40	4511.40	1927.20
Total energy (kWh/m ²)	3639.41	6006.56	3370.42
Ratio of wind to total energy	0.698	0.751	0.572
Ratio of solar to total energy	0.302	0.249	0.428

Table 1. Yearly statistical quantities for solar and wind energy

In order to find out more about the relationship between solar and wind energy in a combined generation system, Figure 4-6 show the monthly variation of energy ratios for the three regions. These data are fitted with a cosine curve by the method of least squares as:

 $\varphi = a\cos(x\pi/6 + b) + c$

(16)

Where φ is the energy ratio; x is the month of year; a, b and c are the constants as shown in the figures. The cosine curve was selected in this study because it has a higher coefficient of determination than other polynomial functions. The R-squared coefficient of determination is 0.9282, 0.9188 and 0.8985 for the three regions, respectively. It is found that the solar and wind energy acting upon a unit of area balance around April and September; they might support each other in a combined generation system.

If we consider an ideal combined system, the electrical power produced by solar and wind energy is delivered to the national grid to meet consumers' demands, the yearly electrical energy $(E_{tot}, in kWh)$ generated by the system can be expressed as:

$$E_{tot} = \eta_s A_s E_{sv} + \eta_w A_w E_{wv} \tag{17}$$

Where η_s and η_w are the electrical conversion efficiency for PV cells and wind turbine, respectively, which are device-dependent. In this study, a common value is used, i.e. $\eta_s = 0.1$ and $\eta_w = 0.2$. A_s is the panel area of PV cells; and A_w is the blade area of wind turbine. E_{sy} and E_{wy} are the solar energy and wind energy available per unit area throughout the year, respectively. Therefore, for a given electricity demand, the relationship between the panel area of PV cells and the blade area of turbine can be written as:

$$A_{s} = E_{tot} / 109 .901 - 4.623 A_{w} \text{ for northern region}$$

$$A_{s} = E_{tot} / 149 .516 - 6.035 A_{w} \text{ for central region}$$

$$A_{s} = E_{tot} / 144 .322 - 2.671 A_{w} \text{ for southern region}$$
(18)

For a consumption level of 1800 kWh each person per year (in 2008) in Taiwan, the electrical energy need for 1000 people can be provided by the combination system through various operations as summarized in Table 2. For example, in the northern region, this energy can be singly provided by PV cells with panel area of 16378.4 m² or singly by wind turbine with blade area of 3542.8 m², i.e. rotor radius of 33.58 m is required. Meanwhile for the same panel area, the blade area required for the central region is far less than for other two regions.

Table 2.Numerical examples of design area required in a combination system for a given electrical deman (1.8×10 ⁶ kWh)				
	Regions	Panel area of photovoltaic cells A_{a} (m ²)	Blade area of wind turbine $A_{\rm ur}$ (m ²)	

Regions	Panel area of photovoltaic cells A_s (m ²)	Blade area of wind turbine A_w (m ²)
Northern	0	3542.8
	1000	3326.5
	10000	1379.7
	16378.4	0
Central	0	1994.8
	1000	1829.1
	10000	337.8
	12038.8	0
Southern	0	4669.5
	1000	4295.1
	10000	925.5
	12472.1	0



Figure 4. Monthly variation of energy ratios in northern region



Figure 5. Monthly variation of energy ratios in central region



5. Conclusions

In this paper, both the solar energy incident upon a tracked panel and wind energy in Taiwan were studied considering different time periods and regions. Herein the single-axis tracked panel is analyzed for the first time in the field. The feasibility of application of a combined generation system had been evaluated. The results show that the solar energy and wind energy support each other, which can enhance the reliability of the combination system. When solar energy is lower, in winter, wind energy becomes higher and vice versa in summer. Overall wind potential energy is quite larger than solar energy. Mathematical expressions for the calculation of design area of PV cell and wind turbine are proposed for different regions under a given power demand. Due to a stronger wind blowing, the blade area of turbine required for the central region is less than for other regions under the same PV area. The utilization of green energy had become an important affair, to reveal more detailed characteristics about both solar and wind energy in Taiwan, adopting more spatial-temporal observation data is needed in the future research.

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