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Effects of ambient temperatures, tilt angles, and orientations on hybrid photovoltaic/diesel systems under equatorial climates

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ABSTRACT

Temperature and solar radiation are two main parameters directly affecting PV (photovoltaic) arrays' output. Particularly, solar radiation is dependent upon PV arrays' tilt angles and orientations while PV arrays' temperatures are related to ambient temperatures. Nevertheless, the effects of ambient temperatures, tilt angles, and orientations on PV arrays' output for places with equatorial climatic conditions (and abundant sunshine) are scarcely reported. In this paper, the effects of ambient temperatures, tilt angles, and orientations on the total electricity produced by PV arrays and the total NPCs (net present costs) of hybrid PV/diesel systems were studied using HOMER (Hybrid Optimization of Multiple Energy Resources). Three places with different latitudes off the equator (0° 00′ N, 5° 58′ N, and 11° 14′ N) were analyzed and the results showed that increasing ambient temperatures (10–50 °C) and tilt angles (0–90°) resulted in reductions in PV electricity as much as 18% and 55%, respectively. NPC-wise, however, the variations became less pronounced – the NPC differences caused by changes in ambient temperatures and tilt angles became ~6% and ~25%, respectively, under 0% annual real interest rate. As the annual real interest rate increased to 3% and 5%, the NPC differences reduced further. Meanwhile, at 0–30° tilt angles, PV arrays facing different orientations showed differences in NPCs of less than 5%, albeit that the reductions in PV electricity were much higher. Significantly, the implementation of hybrid PV/diesel systems is feasible at places with equatorial climates.

1. Introduction

Harnessing energy from the sun using solar PV (photovoltaic) systems remain a popular choice of renewable energy technology worldwide. Despite the plunge in fossil fuel prices, both the capacity and energy produced by solar PV systems continued their fast growth in 2015, with the new capacity increased 25% over 2014 [1]. The growth of solar PV systems, once dominated by developed countries, is now equally contributed by emerging markets in the developing world; in 2015, the gap between developed and developing countries in solar investments narrowed to less than $ 1 billion [2]. So far, about 227 GW of PV systems have been installed globally [2,3]. The continued expansion in the PV market is due mainly to the implementation of new renewables programs, the improved competitiveness of PV systems, and the improved awareness of the potential of PV systems in reducing environmental pollution, and rising electricity demands.

In promoting the use of green and renewable energy technology, particularly solar PV systems, developing countries continue to make significant contributions. In Asia for example, China and India have been ranked among the top countries based on the added capacity of solar PV while other countries in the region, including Malaysia, Thailand, Vietnam, the Philippines, and the Republic of Korea, have emerged as crucial markets for solar PV systems [3]. Since many remote and isolated places are still largely powered by standalone diesel generators, especially in Maritime Southeast Asia (with equatorial or tropical climates) where they are often reported to have desirable solar radiation, investment and financing bodies worldwide continue to look into the possible implementation of PV systems in these markets [4–9].

Nevertheless, PV companies and investors at emerging markets are seeking higher PV yields at the expense of higher risks. Ambient temperatures at places near the equator are higher than places located far off the equator and, consequently, temperatures may have detrimental effects on the output of PV systems. Generally, the best performance of a PV array can be achieved by maximizing solar radiation on its surface while minimizing its temperature [10,11]. Based on the experimental work of Ghani et al. [12], the PV array's temperature was generally higher than the ambient temperature – at

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an average ambient temperature range of 27 °C to 33 °C, the PV array's temperature could reach maximum values in the range of 54 °C to 61 °C. For this reason, remarkable effort has been made to estimate PV arrays' temperatures and their effects on the PV arrays' performances [13,14]. Meanwhile, the performance of a PV array is highly influenced by its tilt angle and orientation, since both the tilt angle and orientation affect the amount of solar radiation reaching the surface of the PV array [15]. Lots of investigations have been undertaken to determine optimum orientations and tilt angles for specific sites in different countries [16–28], and they share a common finding: to capture the most sunlight, a PV array has to be arranged so that the sunlight is perpendicular to the surface of the PV array. This enables the PV array to produce as much power as it could.

Optimal PV arrays' tilt angles and orientations depend on local climates, latitudes, and the load consumption temporal profiles [16], and are rarely applicable under all circumstances. The use of tracking devices enables PV arrays to be tilted according to the sunlight, but the use of these devices generally increases installation and maintenance costs of PV systems, and results in more energy consumption during tracking. Furthermore, these devices are not always applicable due to the limitation of the PV installation area. On the other hand, fixed structure PV arrays have lower installation, operation, and maintenance costs than the auto-tracking structure ones, and are usually good for discrete users, such as family houses, which could be integrated to be part of the building structure. Consequently, fixed-structure PV arrays are still largely preferred. Therefore, tilt angles and orientations of fixed-structure PV arrays should be carefully evaluated to obtain the optimum overall output energy; an appropriate approach to determine the optimum installation angle for PV arrays is therefore preferable [20].

As far as the authors were aware, analyses correlating the effects of ambient temperatures and PV arrays' tilt angles and orientations for places with equatorial climates were scarce. Although the effects of ambient temperatures, tilt angles and orientations on PV productions are well known, most studies were conducted for countries commonly experiencing seasonal variations such as summer and winter. Furthermore, the output of PV arrays under various ambient temperatures, tilt angles, and orientations were seldom correlated with the implementation costs of the PV systems, e.g., the NPCs (net present costs) – an important financial indicator for investing in PV systems, especially for emerging markets. In this paper, the effects of ambient temperatures, tilt angles, and orientations on hybrid PV/diesel/battery systems were analyzed using the HOMER (Hybrid Optimization of Multiple Energy Resources) software, for places with equatorial climates, but having different latitudes off the equator: 0° 00′ N; 5° 58′ N; and 11° 14′ N. The effects of ambient temperatures and PV arrays' tilt angles and orientations on the total electricity produced by the PV arrays and the total NPCs are discussed.

2. Theory

A solar PV system converts sunlight (i.e., solar radiation) directly into electricity without the intermediate production of heat. Nevertheless, terrestrial solar radiation varies both in density and the spectral distribution, depending on the position of the earth and the position of the sun in the sky. This will inevitably vary the output of solar PV arrays. For industrial standardization purposes, an AM (air mass) 1.5 spectrum, 1000 W/m^2 maximum luminous power of the sun at ground level, 25 °C PV cell temperature, and no wind are assumed [29]; this is referred to as STC (standard test conditions). It should also be noted that the NOCT (nominal operating cell temperature) of a PV array refers to the conditions where the radiation on a cell surface is 800 W/m^2, the ambient temperature is 20 °C, the wind velocity is 1 m/s, and the mounting of the PV array is on the open back side.

Generally, the design of an optimal solar PV system for a particular location depends on the availability of solar radiation at the location. Although PV arrays can be tilted at different angles and faced at different directions, this will affect the amount of energy captured from the sun to generate PV electricity. In this regard, HOMER assumes that the output power P_0 of a PV array can be calculated using Eq. (1):

$$P_0 = P_r f\left(\frac{G_T}{G_{T,STC}}\right) \tag{1}$$

where P_r is the rated capacity of the PV array under STC (in W), f is the PV derating factor to take into account the effect of soiling, wiring losses, shading, and aging (in %), G_T is the solar radiation incident on the PV array (W/m^2), and $G_{T,STC}$ is the radiation incident at STC (1000 W/m^2). Based on the HDKR (Hay-Davies-Klucher-Reidnl) model [30], HOMER assumes the global radiation incident G_T on the PV array as in Eq. (2):

$$G_T = (G_b+G_dA_i)R_b+G_d(1-A_i)\left[\frac{(1+\cos\beta)}{2}\right]\left[1+h\sin^3\left(\frac{\beta}{2}\right)\right]+G\rho_g\left[\frac{(1-\cos\beta)}{2}\right] \tag{2}$$

where G_b is the beam radiation, G_d is the diffuse radiation, A_i is a measure of the atmospheric transmittance of beam radiation, β is the tilt angle of the PV array measured from the horizontal, h is a factor accounting for horizon brightening, G is the global horizontal radiation on the surface of the earth, ρ_g is the ground reflectance, and R_b is the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface as defined by Eq. (3):

$$R_b = \frac{\begin{pmatrix}\sin\delta\sin\varnothing\cos\beta-\sin\delta\cos\varnothing\sin\beta\cos\gamma+\cos\delta\cos\varnothing\cos\beta\\ \cos\omega\\ +\cos\delta\sin\varnothing\sin\beta\cos\gamma\cos\omega+\cos\delta\sin\beta\sin\gamma\sin\omega\end{pmatrix}}{(\cos\varnothing\cos\delta\cos\omega+\sin\varnothing\sin\delta)} \tag{3}$$

where ϕ is the latitude, β is the tilt angle as defined previously, γ is the azimuth or orientation of the PV surface (the direction towards which the PV array faces), ω is the hour angle, and δ is the solar declination angle (the angle at which the sun's rays are perpendicular to the earth's surface at solar noon). In Eq. (3), the numerator defines the cosine angle of incidence while the denominator defines the cosine zenith angle. The solar declination angle δ can be calculated using Eq. (4):

$$\delta = 23.45\sin\left[360\left(\frac{284+d}{365}\right)\right] \tag{4}$$

where d is the day of the year. By assuming that the sun moves at a rate of 15°/h, the hour angle ω can be a function of solar time t_s as shown Eq. (5).

$$\omega = 15(t_s-12) \tag{5}$$

Since all time-dependent data are specified not in solar time, but in local standard time, Eq. (6) can be used to calculate solar time from local standard time:

$$t_s = t_c+\frac{\lambda}{15}-Z_c+E \tag{6}$$

where t_c is the local standard time corresponding to the midpoint of the time step, λ is the longitude, Z_c is the time zone east of GMT (Greenwich Mean Time) and E is the equation of time, defined as in Eq. (7):

$$E = 3.82(0.000075.0.001868\cos B-0.032077\sin B-0.014614\cos 2B-0.04089\sin 2B) \tag{7}$$

where B can be found from Eq. (8):

$$B = 360\left[\frac{(d-1)}{365}\right] \tag{8}$$

Furthermore, to explicitly model the effects of temperatures on PV