Evaluation of PV power forecasting models using temperature data

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Abstract. The study is based on the temperature data of 2019 as collected from the USAid Venda, one of the South African University Radiometric Network (SAURAN) stations in Vuwani, Limpopo Province. The temperature-based Hargreaves-Samani ($H - S$) empirical model has been used to estimate the global solar radiation in order to forecast the potential solar output. The statistical parameters used for the analysis showed strong correlation between the observed and estimated solar radiation data, giving a $RMSE$ value of 1.84 W.m^{-2}, a MBE value of 1.39 W.m^{-2}, a MPE value of 1.29 W.m^{-2} and a R^2 statistics value of 0.84. The strong correlation validated the $H - S$ model as a reliable input for solar power output models. The annual average power output predicted by the two models were 51 W and 57 W based on the use of a 255-W solar panel. The efficiencies of the models agreed well with that using standard testing condition which is about 20 % of the input values of solar radiation values. The study has proven that the solar power output predictions can be conducted in areas with limited weather data for long- to short-term PV power output forecast to assist in the design of power generation system irrespective of the power of the PV and location where it is to be implemented.

1. Introduction

An electric power-system capable of meeting a prescribed demand requires a high level of prediction accuracy in the planning stage. The accurate estimation of photovoltaic (PV) power output based on the weather information of the local area of the solar panel installation is crucial in many applications. The PV-effect is an electrochemical process that generates voltage or electric current in a photovoltaic cell when exposed to sunlight [1]. The PV power output prediction depends on meteorological variables such as solar radiation, temperature, rainfall, wind speed and relative humidity at the specific site [2]. Global solar radiation (H) is an important input for estimating power output, (P_{PV}) from the PV panel. Relevant instrumentation to measure these parameters such as a pyranometer should be installed, but due to its high cost and scarcity [3], estimation of values become necessary. In such cases local temperature values can be used for estimation by eploying mathematical models as an alternative to measurements [4].

The chosen temperature-based empirical model used for this study was the Hargreaves-Samani ($H-S$) Model. It has an advantage of being effective in areas where the weather data is not available, but temperatures are [5]. The estimated radiation data is validated by comparing with observed values for the year 2019 at the USAid Venda Station located at Vuwani (Latitude of -23.13100052 and Longitude of 30.42399979) which is one of the South African Universities Radiometric Network (SAURAN) stations. SAURAN is a network of stations located across the Southern African region including South Africa, Namibia, Botwsana and Reunion Island that provide ground-based solar radiometric data [6]. The estimated H was used to predict the potential power to be generated by the solar panel that has been installed at the station. Forecasting of the H is the first and most essential step in most PV power predictive systems. Numerous PV solar power forecasting methods including the physical models based on numerical weather prediction and satellite images have been reported in the literature [5].

In the current study, two global solar radiation-based PV power output generation models Skoplaki *et al.* and Ramli *et al.* were used to determine the power output were from the panels installed on site. The performance of the two models was determined by using the calculated solar radiation from equation (1) and the manufacturer's dataset of a 255-W polycrystalline silicon PV panel from the 5kW array on site. Modelling PV power output accurately is hampered by the difficulty of estimating the solar irradiance, especially when influenced by cloud cover. Output power depends also on parameters, such as the PV technology used, module temperature and panel shading as a function of sun angle, among others. The performance of these models was checked for the panel under standard testing (STC) conditions and then under the local weather conditions. A notable advantage of this approach is that it uses only weather variables that are easily obtainable [6]. Furthermore, the correlation between different meteorological data for different sites or locations and power output at any time including the future period was well demonstrated [7]. This paper lays a foundation short- to long-term forecasting of PV power output and the sizing of the system in the design phase which is adaptable to any location with limited weather data information, as well as determining the suitable panels for the site.

2. Methodology

2.1. Weather information

Figure 1 is a graphical presentation of the daily minimum, maximum and average temperature values observed at the USAid Venda SAURAN Station for a period of one year in 2019. The average monthly temperature values were used to estimate solar radiation by employing an empirical temperature-based equation.

2.2. Temperature-based estimation of solar radiation (Hargreaves-Samani Model)

The average monthly temperature values that were measured at research site in 2019 were used as input in equation (1) to estimate the global solar irradiance (H_c). The $H-S$ model uses a simple equation for estimating solar radiation (H_c); it requires only maximum and minimum temperatures (T_{min} and T_{max}) at the research site in Vuwani, and is given by [7]:

$$H_c = k_r H_0 \sqrt{\Delta T} \tag{1}$$

where k_r is an empirical constant of 0.16 for inland region [5]. The average daily extra-terrestrial irradiance H_o (W.m^{-2}) is estimated using equation (2) [8]:

$$H_0 = \frac{1440}{\pi} H_{sc} D_f (\cos\varphi \cos\delta \sin\omega_s + \omega_s \sin\varphi \sin\delta) \tag{2}$$

where H_{sc} is the solar constant (1367 W.m^{-2}) [9], φ is latitude of location being considered (deg), δ_s is the solar declination for the month (deg), and ω_s is the mean sunrise hour angle for a given month (deg). D_f is the eccentricity correction factor of the earth's orbit on the n^{th} day of the year (Julian days from 1 January to 31 December) [10]. The expressions for D_f, δ_s and ω_s are given by equations (3) - (5) below:

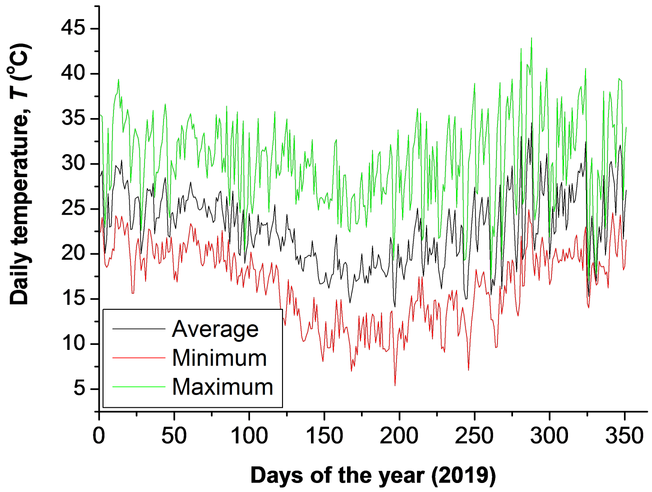

Figure 1. The observed daily temperature at Vuwani in 2019.

$$D_f = 1 + 0.033\cos\left[2\pi\left(\frac{n}{365}\right)\right] \tag{3}$$

$$\delta_s = \frac{23.45\pi}{180}\sin\left[2\pi\left(284 + \frac{n}{365}\right)\right] \tag{4}$$

$$\omega_s = \cos^{-1}\left(-\tan\varphi\tan\delta\right) \tag{5}$$

2.3. PV power output forecast models

The average monthly solar radiation estimated by means of empirical model in equation (1) were used as inputs to determine the performance of two solar power output models given in equations (6) and (8) [10] as Skoplaki Model ($P_{PV,model1}$) and Ramli Model ($P_{PV,model2}$), respectively. Both models include the effects of radiation levels and panel temperature on the solar output power. In addition to radiation and temperature, the $P_{PV,model1}$ considers solar cell properties such as efficiency, temperature coefficient of maximum power, transmittance of the cover system and absorption coefficient of the cell [11], while $P_{PV,model2}$ relies on the theoretical short-circuit current and open-circuit voltage parameters [12] to determine PV power output.

$$P_{PV} = H_c\tau\eta A\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right] \tag{6}$$

where τ, η, β_{ref} and A respectively are the transmittance of the PV cell's outside layer, the module's electrical efficiency (0.16) at the reference temperature T_{ref} (25 °C) and H_T reference irradiance at STC (1000 W.m^{-2}), the temperature coefficient (0.0045 %/°C) and the surface area of the solar panel (1.61 m^2). T_c is the cell temperature given by equation (7) [8]:

$$T_c = T_a + \left[\frac{T_{NOCT} - 20}{800}\right]H_T \tag{7}$$

equation (8) defines the current-voltage relationship based on PV panel's electrical characteristics [10]:

$$P_{PV} = V_{mpp}I_{mpp} \tag{8}$$

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where $V_{mpp} = V_{mpp,ref} + \mu_{V,OC}(T_c - T_{c,ref})$ and $I_{mpp} = I_{mpp,ref} + I_{SC,ref}\left(\frac{H_c}{H_T}\right) + \mu_{I,SC}(T_c - T_{c,ref})$.

The performance of a PV panel is based on ideal conditions or a controlled environment, which is not the case for real outdoor conditions [12]. The two power generation models were used for determining the correlation of maximum power with the dataset provided by the manufacturer of the selected PV panel at STC. The electric power output calculated with the help of each model was used to choose the best model for this study.

2.4. Statistical metrics for H-S model

The estimated solar radiation values using the $H - S$ model were compared with the observed values [13]. The coefficient of determination R^2, root mean square error ($RMSE$), mean bias error (MBE) and mean percentage error (MPE) in equations (9) to (12), were used to analyse the accuracy of the estimated values produced [14]. The metrics are:

$$R^2 = 1 - \frac{\sum (H_{oi} - H_{ci})^2}{\sum (H_{oi} - \bar{H}_o)^2} \tag{9}$$

$$RMSE = \sum_{n=1}^{n} \sqrt{\frac{(H_{ci} - H_{oi})^2}{n}} \tag{10}$$

$$MBE = \frac{1}{n} \sum_{n=1}^{n} (H_{ci} - H_{oi})^2 \tag{11}$$

$$MPE = \frac{1}{n} \sum_{n=1}^{n} \frac{|H_{ci} - H_{oi}|}{H_{oi}} \tag{12}$$

In the above relations, the subscript i refers to the i^{th} value of the solar irradiation and n is the number of the solar irradiation data. The subscripts c and o refer to the calculated and observed global solar irradiation values, respectively.

3. Results and discussion

3.1. Monthly irradiance and power output data

Figure 2 represents the estimated monthly average solar irradiance based on the calculation using the $H - S$ Model and the observed data at the USAid Venda SAURAN Station for 2019. The annual average solar radiation values from the $H - S$ Model and the observation were 222 W.m^{-2} and 211 W.m^{-2}, respectively. The good correlation between the measured and calculated solar irradiance correspond to the calculated values from eauations (10) to (12) giving values for$RMSE$ equal to 1.84, MAE value of 1.39, MBE value of 1.29 and R^2 statistical correlation value of 0.84, which agreed with corresponding findings by other researchers [15]: $MBE \leq MAE \leq RMSE$. Therefore, the $H - S$ model is suitable for estimating the irradiance due to its good fit to the measured data [12].

Solar irradiance can be difficult to model, due to cloud cover and other meteorological effects. The overestimation by equation (1) of solar radiation in October shows the 24 % deviation from the measured data due to about 13 rainy days at Vuwani. The deviation in October demonstrates the limitations of the model under cloudy, rainy days, and wind speed as the temperature hovered around 30°C, 50.94 mm of rain and approximately 13 rainy days in the month with humidity of 57%. Therefore, other empirical models based on sunshine hour, relative humidity and atmospheric pressure need to be explored in the future studies.

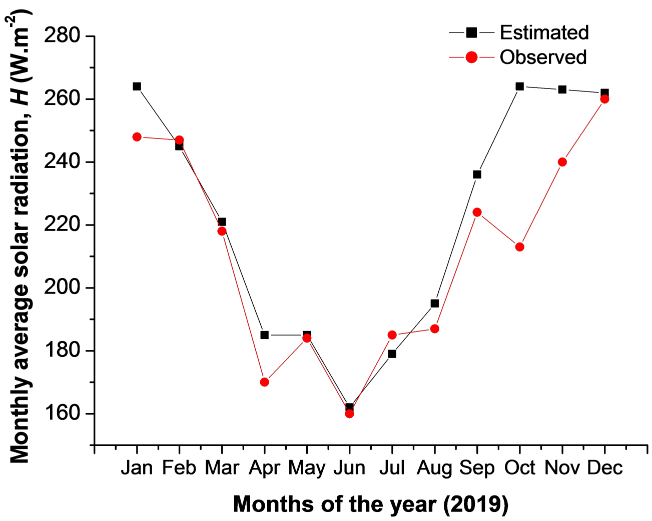

Figure 2. Estimated and observed inter-monthly global solar radiation at Vuwani for 2019.

3.2. Predicted PV power output

The results in figure 3 show that $P_{PV,model2}$ in equation (8) overestimated power output from the PV panel by 10 % as compared to $P_{PV,model1}$ in equation (6). It is also noted that the calculated annual average solar power output values for the two models are about 22 % compared to the manufacturer's supplied maximum power values of the solar panel in datasheet at STC conditions. This trend was consistent with that of measured solar radiation on site against the reference solar irradiance of 1000 W.m^{-2}.

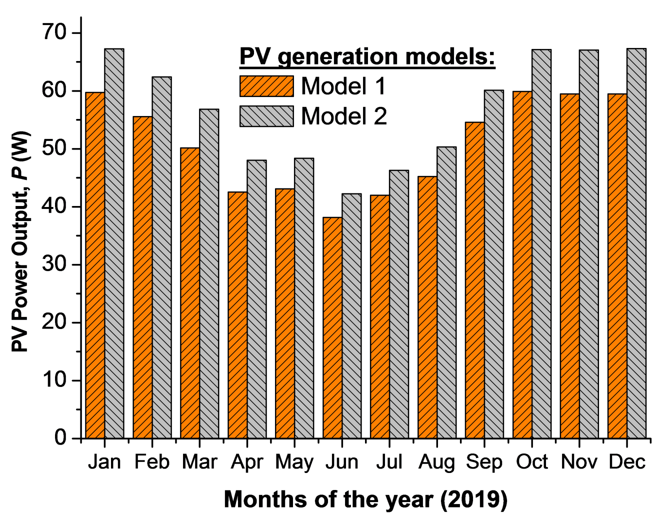

Figure 3. Monthly average power output forecasted at Vuwani for 2019 by the two models using the estimated solar radiation.

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4. Conclusion

The performance of $H - S$ model for estimating H_c has been compared with observed data at Vuwani. Results suggest that the empirical model in equation (1) provides acceptable H_c estimation at any location. Accurate estimation of H_c is important for various applications including PV power forecasting during the design and sizing of a power generation system. This work aimed at examining the capability of empirical models in forecasting PV power output in areas with no other weather data except temperatures. The average measured H_o, 211 W.m^{-2}: ranged from 160 to 260 W.m^{-2} while the empirical model gave an average H_c: 221 W.m^{-2} with values ranging from 162 to 264 W.m^{-2}. The two PV power models $P_{PV,model1}$ and $P_{PV,model2}$ predicted average annual power outputs, respectively of 51 and 57 W, hence about 22 % of the maximum power output of the panel at STC. This performance was found to be consistent with the local solar radiation observed at Vuwani, which was about 21 % of the reference solar radiation of 1000 W.m^{-2}.

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