Evaluation of PV power forecasting models using temperature data

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Abstract. The study ~~reported here~~ is based on ~~the~~ temperature data of 2019 collected from the South African University Radiometric Network (SAURAN), USAid Venda station in Vuwani, Limpopo. The temperature-based ~~empirical model,~~ Hargreaves-Samani $(H-S)$ model has been used to estimate 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 ~~with the~~ data giving $RMSE$ value of 1.84 W.m^{-2}, MBE value of 1.39 W.m^{-2}, MPE value of 1.29 W.m^{-2} and R^2 statistic~~s~~ value of 0.84. The strong correlation validated the $H-S$ model as a reliable input for solar power output models. Therefore, careful site assessment of weather conditions is necessary for a better forecasting of potential PV power output and recommendation of the suitable solar panel. This paper presents ~~a~~ two~~-steps~~ approach ~~to be used in a~~ location ~~with~~ insufficient weather data~~, but only relying on the~~ available temperature. The annual average power output predicted by the two ~~PV power generation~~ models were 51 W and 57 W based on the use of a 255~~-~~W solar panel. The efficiencies of the models ~~at the site~~ agreed well with that ~~at the~~ standard testing condition which is about 20 % ~~as compared to~~ the input~~ted values of~~ solar radiation. The study has proven that ~~the forecast of~~ solar power output can be conducted in areas with limited weather data ~~and the method can be used~~ for long- to short-term PV power output forecast ~~for the sake of proper~~ design of power generation system of any size in any location.

1. Introduction

~~P~~ower-system capable of meeting a prescribed demand requires high level of accuracy in the planning stage. The accurate estimation of photovoltaic (PV) power output based on the weather information of the local area ~~intended for~~ the ~~installation of~~ solar panel is crucial in many applications. PV effect is ~~a~~ process that generates voltage or electric current in a photovoltaic cell when ~~it is~~ exposed to sunlight [1]. The PV power output depends on meteorological variables such as solar radiation, temperature, rainfall, wind speed and relative humidity at ~~a~~ specific site [2]. Global solar radiation (H) is an important input for estimating power output, (P_{PV}) from the PV panel. Relevant instrument to measure such as pyranometer should be installed, but due to its high cost and scarcity [3], estimation ~~is~~ necessary. ~~Therefore,~~ in ~~areas without instruments,~~ local temperature values can be used ~~to estimated~~ by ~~deploying~~ mathematical models as an alternative to ~~measuring~~ [4].

The chosen temperature-based empirical model 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 temperature ~~only~~ [5]. The estimated radiation data is validated by comparing with ~~the~~ observed values ~~during~~ the year 2019 ~~in~~ the South African Universities Radiometric Network (SAURAN) station at Vuwani near Thohoyandou. The estimated H was used ~~for~~ the potential power to be generated by the solar panel that has been installed at the station. Forecasting of global horizontal irradiance (GHI) is the first and most essential step in most PV power ~~prediction~~ 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].

The two global solar radiation-based PV power output generation models were used to determine the power output from the 255-W solar panel ~~that has~~ been installed on site. Modelling PV power output accurately is hampered by the difficulty of estimating solar irradiance, especially ~~due to~~ cloud cover. Output depends also on ~~some~~ parameters, such as the PV technology ~~that is~~ used ~~and~~ 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 conditions (STC) 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. This paper lays a foundation long- to short-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 daily minimum, maximum and average temperature values ~~that have been~~ observed at Vuwani for a period of one year in 2019. The average monthly temperature values were used to estimate solar radiation by employing empirical temperature-based equation.

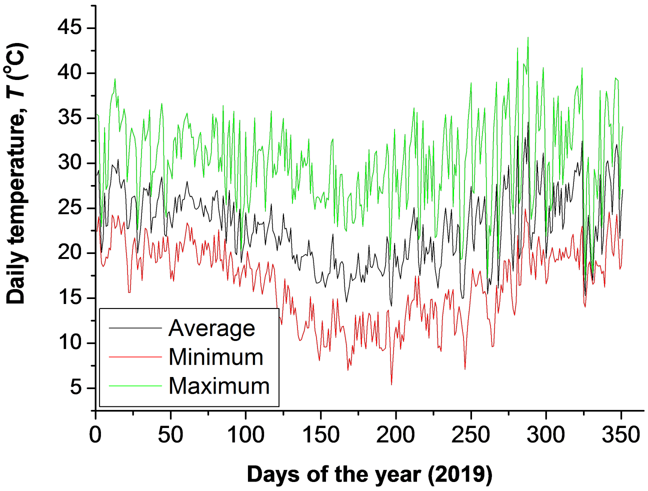

Figure 1. The observed daily temperature ~~in 2019~~ at Vuwani.

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

The average monthly temperature values that were measured at Vuwani through the SAURAN station 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 temperature (T_{min} and T_{max}), and is given by [6]:

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

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) [7]:

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

where H_{sc} is the solar constant (1367 W.m^{-2}), φ is latitude (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 eccentricity correction factor of the earth's orbit on the n^{th} day of the year (Julian days from 1 January to 31 December) [8]. The expressions for D_f, δ_s and ω_s are given by equations (3) - (5) below:

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

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

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

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 ~~are~~ given in equations (6) and (8) [8].

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

~~where~~ where τ, η ~~and~~ β_{ref} and A 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 ~~is~~ refernce irradiance at STC (1000 W.m^{-2}), temperature coefficient (0.0045 %/°C) and the surface area of solar panel (1.61 m^2)~~, respectively~~. T_c is the cell temperature given by equation (7) [7]:

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

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

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

where

$$V_{mpp} = V_{mpp,ref} + \mu_{V,OC}(T_c - T_{c,ref}) \tag{9}$$

and

$$I_{mpp} = I_{mpp,ref} + I_{SC,ref}\left(\frac{H_c}{H_T}\right) + \mu_{I,SC}(T_c - T_{c,ref}) \tag{10}$$

The performance of PV panel is ~~mainly~~ based on ideal conditions or controlled environment, which is not the case for real outdoor conditions [9]. The two power generation models were used for ~~the~~ 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 $H-S$ model were compared with the observed values [10]. The coefficient of determination R^2, root mean square error ($RMSE$), mean bias error (MBE) and mean percentage error (MPE) in equations (11) – (14), were used to analyse the accuracy of the estimated values produced [11]. The metrics are:

$$R^2 = 1 - \frac{\sum (H_{oi} - H_{ci})^2}{\sum (H_{oi} - \bar{H}_o)^2} \tag{11}$$

$$RMSE = \sum_{n=1}^{n} \sqrt{\frac{(H_{ci} - H_{oi})^2}{n}} \tag{12}$$

$$MBE = \frac{1}{n} \sum_{n=1}^{n} (H_{ci} - H_{oi})^2 \tag{13}$$

$$MPE = \frac{1}{n} \sum_{n=1}^{n} \frac{|H_{ci} - H_{oi}|}{H_{oi}} \tag{14}$$

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 ~~a~~ $H-S$ model. The annual measured and estimated average solar radiation at Vuwani in 2019 ~~of~~ 211 W.m^{-2} and 222 W.m^{-2}, respectively. ~~Results show a~~ good correlation between the measured and calculated solar irradiance ~~as supported by~~ $RMSE$ ~~value of~~ 1.84, MAE value of 1.39, MBE value of 1.29 and R^2 statistic~~s~~ value of 0.84, which agreed with ~~the~~ corresponding findings by other researchers [12]: $MBE \leq MAE \leq RMSE$. Therefore, $H-S$ model is suitable for estimating the irradiance due to its good fit to the measured data [9].

3.2. Predicted PV power output

$P_{PV,model2}$ estimated ~~poor~~ output just over 10 % more than that of $P_{PV,model1}$ as shown in figure 3. It is also noted that the calculated annual average ~~values of~~ solar power output for the two models are about 22 % of those ~~that have been~~ calculated under STC, which corresponds to the observed annual average solar radiation at Vuwani ~~as~~ compared to the reference solar irradiance of 1000 W.m^{-2}.

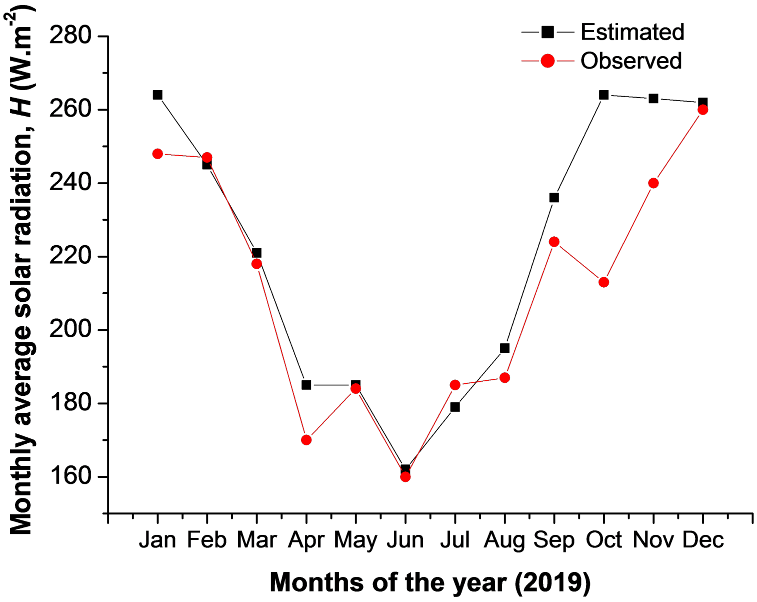

Figure 2. Estimated and observed inter-monthly global solar radiation at Vuwani.

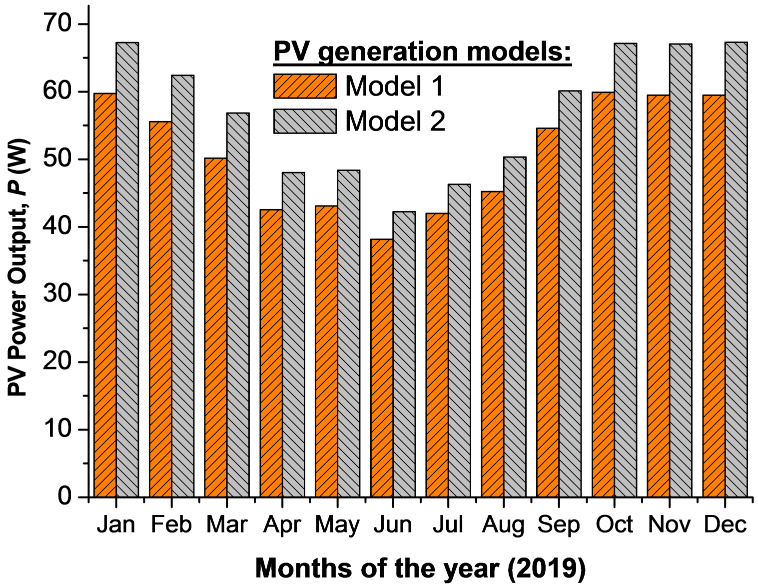

Figure 3. Monthly average power output forecasted ~~through the two models for 2019~~ at Vuwani using the estimated solar radiation.

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 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 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~~, but~~ temperatures~~ only~~. The average measured H_o, 211 W.m^{-2}: rang~~ing~~ from 160 to 260 W.m^{-2} while 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 ~~as follows:~~ 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 ~~that has been~~ observed at Vuwani, which was about 21 % of the reference solar radiation of 1000 W.m^{-2}. Vuwani has a 5 kW solar plant consisting of 20, 255~~-~~W PV panels. ~~One of t~~he two models predicted an annual average power output of 1018 ~~while the other~~ 1135 W.

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