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Multiple Linear Regression Photovoltaic Cell Temperature Model for PVSyst Simulation Software

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Abstract: In this paper, two multiple linear regression models for the determination of photovoltaic (PV) cell temperature and for selection of appropriate thermal loss factor values in PVSyst is presented. One of the linear models can determine the cell temperature with solar irradiation and ambient temperature alone while the second model requires the solar irradiation, ambient temperature and wind speed in order to determine cell temperature. The cell temperature determined from any of the two models can then be used to select the appropriate thermal loss factor for PVSysts simulation. Sample meteorological data extracted from PVSyst software meteo-file for Dakar, the capital of Senegal, in West Africa is used for the study. In agreement, the two models gave the same thermal loss factor U=30.255. Essential, the approach presented in this paper can be used to effectively determine cell temperature, with and without wind speed.

Keywords: Thermal Loss, Cell Temperature, PVSyst, Photovoltaic Effect, Cell Temperature Model, Multiple Linear Regression

1. Introduction

Solar cell efficiency refers to the portion of energy in the form of sunlight that can be converted through photovoltaic (PV) effect into electricity [1, 2, 3]. The PV cell efficiency is dependent on a number of intrinsic and extrinsic factors. Particularly increase in the cell temperature tends to reduce the cell efficiency [4, 5, 6]. During operation, the part of the solar energy falling on the cell is converted to electricity while some part are converted to heat which in turn increases the cell temperature above the ambient temperature. Among other things the solar irradiation, the ambient temperature and wind speed influence the extent to which the cell temperature can rise above the ambient temperate. In addition, the temperature coefficient and the nature of the PV installation also affect the cell temperature.

In PVSysts, cell temperature model is based on the Faiman module temperature model which utilizes ambient temperature, wind speed and solar irradiation in computing the cell temperature [7, 8, 9]. In the model, PVSysts includes some empirically determined parameters that reflects constant heat transfer component and the convective heat transfer component. The two parameters are used to compute the thermal loss factor (U) which is used in computing the cell temperature. However, the two heat transfer parameters are not well defined in PVSyst. Moreover, due to lack of hourly or appropriate wind speed data, PVSyst tends to ignore the convective heat transfer component which makes use of wind speed.

In practice, users are expected to set the value of the two parameters based on their specific PV installation. However, different published works have used or suggested different combinations of the values of two heat transfer parameters in PVSyst. In all, there is no known guide for appropriate selection of the right combination of the values of the two parameters. In view of this, a set of five different combinations of the values of the two parameters are considered in this paper. From the analysis of the resulting cell temperature for a given set of data, a multiple linear regression model is developed for estimating the cell temperature. The model will enable PV designers using PVSyst software to select the right value of the thermal loss factor for computing the cell temperature.

2. Theoretical Background

2.1. PVSyst Thermal Loss Factor

In PVsyst the thermal loss model is based on the single-diode mode while the PV module's thermal behavior is based on the energy balance between ambient temperature and the cell temperature due to irradiance as follows [10];

$$U\ (T_c - T_a)=\alpha(G)\ (1 - \eta_{PV}) \quad (1)$$

$$U = \left(\frac{\alpha(G)\ (1-\eta_{STC})}{T_c - T_a}\right) \quad (2)$$

Where U is the thermal loss factor, α is the absorption coefficient of solar irradiation, T_c and T_a are the module and the ambient temperatures respectively, G is the effective solar irradiance and η_{STC} is the module efficiency at STC. The default value for the absorption coefficient (α) is 0.9.

2.2. PVSyst Cell Temperature Model

Also, PVsyst, implements a cell temperature model based on the Faiman module temperature model given as [11]:

$$T_c = T_a + \left(\frac{\alpha(G)(1-\eta_{PV})}{U_0 + U_1\ (V_{wind})}\right) \quad (3)$$

where

- T_c is cell temperature (°C)
- T_a is ambient air temperature (°C)
- α is the adsorption coefficient of the module (PVsyst default value is 0.9)
- G is the irradiance incident on the plane of the module or array (W/m^2)
- η_{PV} is the efficiency of the PV module (PVsyst default is 0.1)
- U_0 is the constant heat transfer component (W/m^2K)
- U_1 is the convective heat transfer component (W/m^2K)
- V_{wind} is wind speed (m/s)

PVsyst does not provide enough information on the value of U_0 and U_1 . The current default values assume no dependence on wind speed; U_1 =0. The following five different set of values are available from published literatures;

i. For free-standing arrays the current default is: U_0 =29 W/m^2K, U_1 =0 W/m^2K (PVSyst, 2016)

ii. For fully insulated arrays (close roof mount) the current default is: U_0 =15 W/m^2K, U_1 =0 W/m^2K (PVSyst, 2016)

iii. Some PVSyst users proposed, Uc=25 W/m²·k, Uv=1.2 W/m²·k / m/s (PVSyst, 2016)

iv. In old versions old PVsyst, the default values proposed by the program were (PVSyst, 2016) Uc=20 W/m²·k, Uv=6 W/m²·k / m/s

v. SunEdison (SunEdison, 2015) proposed U_0 =Uc=26 W/m²·k, U_1 =Uv=1.4 W/m²·k / m/s

By using $U_0 = U$ and U_1 =0, the value U and hence value of U_0 cane be obtained from the knowledge of T_c and T_a and then using equation 2. In this paper, the approach adopted is to use a multiple linear regression model to determine the cell temperature (T_c) from the values of G, T_a and V_{wind} or G and T_a and then compute the value of U and hence the value of U_0 from equation 2.

3. The Simulation Process

The simulation is conducted with meteorological data extracted from PVSyst software meteo-file for Dakar which is the capital of Senegal, in West Africa. The site coordinate for the data is 14.5° N, 17.0° W and altitude of 5m. The PV used in the study is the monocrystalline silicon (m-Si) PV with module efficiency η_{STC} (%)=18.4%; temperature coefficient of maximal power β_{STC} =-0.38 %/°C; watt peak rating for PV=100Wp and; NOCT=45 °[12, 13]. PVsyst default value for the adsorption coefficient of the module (α) is 0.9.

The cell temperature are computed using the following five set of published combinations of values for U_0 and U1;

i. For fully insulated arrays (close roof mount): U_0 =15 W/m^2K, U_1 =0 W/m^2K(PVSyst, 2016)

ii. For free-standing arrays the current default: U_0 =29 W/m^2K, U_1 =0 W/m^2K (PVSyst, 2016)

iii. Some PVSyst users proposed, Uc=25 W/m²·k, Uv=1.2 W/m²·k / m/s (PVSyst, 2016)

iv. The default value in the old version of PVsyst Uc=20 W/m²·k, Uv=6 W/m²·k / m/s (PVSyst, 2016)

v. SunEdison (SunEdison, 2015) proposed Uc=26 W/m²·k, Uv=1.4 W/m²·k / m/s

4. Results and Discussion

Table 1 shows the cell temperature determined from the five different set of published combinations of values for U_0 and U1. According to Table 1, the cell temperature obtained in Tcell2, Tcell4 and Tcell5 are very close.

i. Tcell2: is obtained from the current PVSyst default value for free-standing arrays where: U_0 =29 W/m^2K, U_1 =0 W/m^2K (PVSyst, 2016)

ii. Tcell4: is obtained from the values proposed by PVSyst users where Uc=25 W/m²·k, Uv=1.2 W/m²·k / m/s (PVSyst, 2016)

iii. Tcell5: is obtained from the values adopted by SunEdison (SunEdison, 2015) where Uc=26 W/m²·k, Uv=1.4 W/m²·k / m/s

Table 1. *The Cell Temperature for the Five Different Set of Thermal Loss Factor Value Uo and U1.*

Global Irradiation on the Tilted Plane (W/m². day)	Ambient Temperature, Ta (°C)	Wind Speed, Vwind (m/s)	Uo=15; U1=0	Uo=29; U1=0	Uo=20; U1=6	Uo=25; U1=1.2	Uo=26; U1=1.4
			Tcell12	Tcell2	Tcell3	Tcell4	Tcell5
49	11.4	5.6	13.79904	12.64088	12.07137	12.53448	12.4634
249	11.7	5.6	23.89104	18.00571	15.11167	17.46499	17.10383
59	29.2	3.1	32.08864	30.69412	30.32253	30.70869	30.62813
85	30	6.1	34.1616	32.15255	31.1029	31.93144	31.8073

Global Irradiation on the Tilted Plane (W/m². day)	Ambient Temperature, Ta (°C)	Wind Speed, Vwind (m/s)	Uo=15; U1=0	Uo=29; U1=0	Uo=20; U1=6	Uo=25; U1=1.2	Uo=26; U1=1.4
			Tcell12	Tcell2	Tcell3	Tcell4	Tcell5
292	31.3	3.1	45.59632	38.69465	36.85556	38.76674	38.36806
243	32	6.1	43.89728	38.15377	35.15299	37.52163	37.16674
869	45	4.5	87.54624	67.00668	58.57859	65.99321	64.75832
761	45.4	3.1	82.65856	64.67167	59.87872	64.85955	63.82051

The average cell temperature obtained in Tcell2, Tcell4 and Tcell5 is computed, as shown in Table 2. Multiple linear regression model was fitted to predict the average cell temperature as a function of solar irradiation (G), ambient temperature (Ta) and wind speed (V_{wind}). The first multiple linear regression model (MLR Model 1) is given as;

$$T_c=0.0243170499 \ G + 1.00086483T_a - 0.1503899177(V_{wind}) + 0.6626925592 \quad (4)$$

Table 2. *The Average Cell Temperature for the Three Best Set of Thermal Loss Factor Value Uo and U1 and the Predicted Average Cell Temperature.*

Global Irradiation On The Tilted Plane (W/m². day)	Ambient Temperature, Ta (°C)	Wind Speed, Vwind (m/s)	Average Tcell (°C)	Predicted Average Tcell (°C) {Using G, Ta and Vwind)	Predicted Average Tcell (°C) {Using G and Ta)
49	11.4	5.6	12.546	12.422	12.424
249	11.7	5.6	17.525	17.586	17.590
59	29.2	3.1	30.677	30.856	30.622
85	30	6.1	31.964	31.838	32.061
292	31.3	3.1	38.610	38.624	38.405
243	32	6.1	37.614	37.682	37.920
869	45	4.5	65.919	66.156	66.253
761	45.4	3.1	64.451	64.141	64.031

In PVSyst, the argument is that there is no available hourly data on wind speed. As such, PVSyst tends to estimate the cell temperature without wind speed. In that case, a second multiple linear regression model is fitted to predict the average cell temperature as a function of solar irradiation (G) and ambient temperature (Ta). The second multiple linear regression model (MLR Model 2) is given as;

$$T_c=0.02431381049 \ G + 1.008665373 \ T_a - 0.2656809218 \quad (5)$$

In all, since G, T_a and V_{wind} or G and T_a are given, the cell temperature, T_c is computed from the multiple linear regression model and then the thermal loss factor, U is computed using $U_0 = \text{U} = \left(\frac{\alpha(G)\,(1-\eta_{STC})}{T_c - T_a}\right)$ and U_1 =0. This set of value can then be used in PVSyst to estimate the cell temperature for PV system simulation. For instance, with α=0.9, $\eta_{STC} = 18.4\%$ and from Table 2 row 3 column 1, G=49 W/m²·, then $\alpha(G)\left(1 - \eta_{STC}\right) = 0.9 * 49 * \left(1 - \frac{18.4}{100}\right)$ =35.9856. Also Average cell temperature from Table 2 row 3 column 4 is T_c =12.5462546°C while the ambient temperature from Table 2 row 3 column 2 is T_a =11.4°C. Then

$$T_c - T_a = 12.5462546 - 11.4 = 1.1462546$$

Therefore, $U_0 = \text{U} = \left(\frac{\alpha(G)\,(1-\eta_{STC})}{T_c - T_a}\right) = \left(\frac{35.9856}{1.1462546}\right) = 31.39407248616494$

However, in practice, T_c and $\alpha(G)\left(1 - \eta_{STC}\right)$ are computed for the given set of data, then the average of $\alpha(G)\left(1 - \eta_{STC}\right)$ is divided by the average of $T_c - T_a$ in order to obtain the value of U. as shown in Table 3, for the given set of data in Table 2, the average of $\alpha(G)\left(1 - \eta_{STC}\right)$=239.3226 and for the two models, the average of $T_c - T_a$ =7.91321056. Then,

$$U_0 = \text{U} = \left(\frac{\alpha(G)\,(1 - \eta_{STC})}{T_c - T_a}\right) = \left(\frac{239.32}{7.91}\right) = 30.255 \text{ and } U_1 = 0$$

Table 3. *The Cell Temperature and Thermal Loss factor Estimated Using The Regression Models.*

Tc–Ta For MLR Model 1	Tc-Ta For MLR Model 2	$\alpha(G)\left(1 - \eta_{STC}\right)$	Actual Average C ell Temperature (°C)	Predicted Average Tcell (°C) Using MLR model 1	Predicted Average Tcell (°C) Using MLR model 2	Predicted Average Tcell (°C) Using U0=30.255, U1=0)
1.02	1.02	35.99	12.55	12.42	12.42	12.59
5.89	5.89	182.87	17.52	17.59	17.59	17.75
1.66	1.42	43.33	30.68	30.86	30.62	30.63
1.84	2.06	62.42	31.96	31.84	32.06	32.06
7.32	7.11	214.44	38.61	38.62	38.41	38.39
5.68	5.92	178.46	37.61	37.68	37.92	37.90
21.16	21.25	638.19	65.92	66.16	66.25	66.10
18.74	18.63	558.88	64.45	64.14	64.03	63.88
Avg.=7.91	Avg.=7.91	Avg.=239.32				

5. Conclusion

Multiple linear regression model for determination of PV cell temperature and for selection of appropriate thermal loss factor values in PVSyst is presented. The linear model can determine the cell temperature with solar irradiation and ambient temperature alone. Another multiple linear regression model is presented which requires the solar irradiation, ambient temperature and wind speed in order to determine cell temperature. The cell temperature determined from the model can then be used to select the appropriate thermal loss factor for PVSysts simulation.

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