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Development of Thermal Loss Factors and Cell Temperature Models For The Design of Onshore and Offshore Solar Photovoltaic Power System

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***Abstract*— In this paper, development of thermal loss factors and cell temperature models for the design of onshore and offshore solar photovoltaic (PV) power system is presented. The thermal loss factors (denoted in Faiman PV module temperature model as U_0 and U_1) were used to determine the PV cell temperature which can be used to determine the operating PV panel energy harvesting efficiency and the effective energy output of PV panel. The thermal loss factor models are derived based on five different thermal loss factor settings and about 4307 meteorological data records obtained from PVsyst software database for location at latitude 14.48°N and longitude -17.01°W and altitude of 5 m. The meteorological data used are the ambient temperature (Ta in °C); the solar irradiance incident on the plane of the PV module (G in W/m^2) and the wind speed (Vw in m/s). In the study, two multiple linear regression cell temperature models were developed; model one with G (W/m²), Ta (°C) and Vw (m/s) as the explanatory variables and model two with G (W/m²) and Ta (°C) as the explanatory variables. The results showed that for both the onshore and the offshore sites, the thermal loss factor obtained is $U_0 = 29.30$ and $U_1 = 0$ for model one whereas the thermal loss factor obtained are $U_0 = 28.36$ and $U_1 = 0$ for model two. Hence, the two thermal loss factors values obtained for the offshore and the offshore PV installation sites are similar to the thermal loss factor setting currently used by PVsyst, namely, U_0 = 29 and U_1 =0. Based on the results, it can be concluded that the current thermal loss factor setting of PVSyst is applicable to both onshore and offshore PV sites.**

Keywords*— *Pvsyst Software, Thermal Loss Factor, Photovoltaic, Meteorological Data, Onshore PV Installation, Offshore PV Installation, Cell Temperature

I. INTRODUCTION

The growing adoption of solar photovoltaic (PV) power systems across the globe poses running challenges to researchers and PV power systems designers on how to improve on the efficiency of the system [1,2,3,4,5,6]. Among other things, the cell temperature significantly affects its power output and energy harvesting efficiency of PV panels [8,9,10,11,12,13]. More so, in some of the analytical expressions used in the determination of cell temperature, thermal loss factor is a key parameter [14,15,16,17,18]. Particularly, in PVSyst simulation software, a given thermal loss factor value is used to determine the cell temperature for any given PV installation site. Furthermore, in the PVSyst simulation software, ambient temperature, solar irradiance and wind speed are the key parameters used in the determination of the cell temperature along with the thermal loss factor settings in the software.

According to the PV user's manual, the thermal loss factor setting was empirically determined [19,20,21,22,23]. However, users are advised to select their thermal loss factor settings based on their specific environment. Regrettably, there is no comprehensive guideline provided by PVSyst software developers on how to determine the appropriate thermal loss factor for any given PV installation site. Thermal loss factor setting is therefore left at the discretion of the user. Consequently, in this paper analytical approach for determination of the thermal loss factor settings in PVsyst software for onshore and offshore PV sites is presented. The study is based on available published thermal loss factor settings for PVSyst software along with meteorological data records obtained from PVSyst meteorological database.

II. METHODOLOGY

The mathematical models for thermal loss factor settings in PVsyst software are based on the cell temperature model used in the PVsyst software. As such, the underlying PVsyst thermal loss factor model and PVsyst cell temperature model are first presented. Secondly, the available published thermal loss factor values used by researchers and PV system designers around the globe are presented. Thirdly, the approaches used to derive the cell temperature model and PVsyst thermal loss factor model for a given set of meteorological parameters are presented. Fourthly, the cell temperature model and PVsyst thermal loss factor model are employed to study the cell temperature and PVsyst thermal loss factor settings for onshore and offshore PV installations.

A. PVsyst thermal loss factor in PVsyst Software

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 is given by [24]as;

$$U\,(T_{cell} - T_a) = \alpha(G)\,(1 - \eta_{PVSTC}) \quad (1)$$

$$U \;=\; \left(\frac{\alpha(G)\,(1-\eta_{PVSTC}))}{T_{cell}-T_a}\right) \quad (2)$$

Where U is the thermal loss factor; α is the absorption coefficient of solar irradiation. The default value for the absorption coefficient (α) is 0.9; T_{cell} and T_a are the module and the ambient temperatures (in °C) respectively; G is the irradiance incident on the plane of the module or array (W/m^2) and η_{PVSTC} is the module efficiency at STC.

B. B. PVsyst cell temperature model

Also, PVsyst, implements a cell temperature model based on the Faiman module temperature model given by [25] as;

$$T_{cell} = T_a + \left(\frac{\alpha(G)(1-\eta_{PVSTC})}{U_0 + U_1\,(V_{wind})}\right) \quad (3)$$

where T_{cell} 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_{PVSTC} is the efficiency of the PV module (PVsyst default is 0.1) ; V_{wind} is wind speed (m/s) ; U_0 is the constant heat transfer component (W/ m^{2}K) and U_1 is the convective heat transfer component (W/m^{2}K).

PVsyst does not provide enough information on how to select the value of U_0 andU_1 for different situations or PV sites. The current default values assume no dependence on wind speed , henceU_1 = 0.

C. The published thermal loss factor settings for $U_0$and U_1

The five set of published thermal loss factor settings for Uo and U1are ;

i. For fully insulated arrays (close roof mount): Uo =15, U1=0 [20,26].

ii. For free-standing arrays the current default: Uo =29, U1 =0 [20,26].

iii. Some PVSyst users proposed, Uo =25, U1=1.2 [20,26].

iv. The default value in the old version of PVsyst Uo=20, U1=6 [20,26].

v. SunEdison (SunEdison, 2015) proposed Uo =26, U1=1.4

D. Development of the Cell temperature and thermal loss factor models for one given PV Module

Let the cell temperature model (Eq 3) in PVSyst be rearranged as follows;

$$T_c - T_a = \left(\frac{\alpha(G)(1-\eta_{PVSTC})}{U_0 + U_1\,(V_{wind})}\right) \quad (4)$$

Now, since in most PV thermal loss factor setting the U_0 is set to zero (0) , then thermal loss factor U can be derived such that the $U_0$and $U_1$are integrated into one denoted as U. In that case, U is given by its components as;

$$U \;=\; U_0 + U_1(V_w) \quad (5)$$

Then from Eq (4) and Eq (5) U is given as,

$$U \;=\; U_0 + U_1(V_w) = \left(\frac{\alpha_{pv}(G)\,(1-\eta_{PV})}{T_c - T_a}\right) \quad (6)$$

For a PV with given α_{pv} and η_{pv} then using Eq (4) the cell temperature, T_c is computed for each of the five (5) different settings of U_0 and U_1 and meteorological dataset with nj different set of values for G, T_a and V_w. The cell temperature for each combination of U_0 and U_1 and meteorological dataset with nj different set of values for G, T_a and V_w is denoted as $T_{c(k,j)}$ and it is given from Eq (3) as;

$$T_{c(k,j)} = T_{a(j)} + \left(\frac{\alpha_{pv}(G_j)(1-\eta_{pv})}{U_{0(k)} + U_{1(k)}\,(V_{w(j)})}\right) \quad (7)$$

In Eq(7), j identifies the meteorological dataset record number, and k identifies the thermal loss factor setting record number, where in this paper k =1,2,3,4,5. The cell temperature is computed for a single PV module with efficiency (η_{pv}) and absorption coefficient (α_{pv}). Based on $T_{c(k,j)}$ in Eq (7) the thermal loss factor for any given k and j is given as;

$$U_{(k,j)} = U_{0(k)} + U_{1(k)}\,(V_{w(j)}) = \left(\frac{\alpha_{pv}(G_j)(1-\eta_{pv})}{T_{c(k,j)} - T_{a(j)}}\right) \quad (8)$$

For each k, the minimum cell temperature (denoted as $T_{cmin(k,j)}$) the maximum cell temperature (denoted as $T_{cmax(k,j)}$) are computed and the percentage difference between the $T_{cmin(k,j)}$ and $T_{cmax(k,j)}$ which is denoted as $T_{cPmminmax(k,j)}$ is also computed as follows;

$$T_{cmin(k,j)} = minimum(T_{c(k,j)}) \text{for k = 1,2, 5.} \quad (9)$$

$$T_{cmin(k,j)} = minimum\left(T_{a(j)} + \left(\frac{\alpha_{pv}(G_j)(1-\eta_{pv})}{U_{0(k)} + U_{1(k)}(V_{w(j)})}\right)\right) \text{for k = 1,2, 5.} \quad (10)$$

$$T_{cmax(k,j)} = maximum\left(T_{a(j)} + \left(\frac{\alpha_{pv}(G_j)(1-\eta_{pv})}{U_{0(k)} + U_{1(k)}(V_{w(j)})}\right)\right) \text{for k = 1,2, 5.} \quad (11)$$

$$T_{cPminmax(k,j)} = \left(\frac{T_{cmax(k,j)} - T_{cmin(k,j)}}{T_{cmin(k,j)}}\right) 100\,\% \text{for k = 1,2, 5.} \quad (12)$$

Next, all the meteorological data records, namely G_j, $T_{a(j)}$ and $V_{w(j)}$ in which the value obtained for $T_{cPminmax(k,j)}$is within ± 5% for all k = 1,2, 5 are selected and the mean cell temperature $T_{cmean(j)}$ computed from each of the selected meteorological data records is computed as follows;

$$T_{cmean(j)} = \left(\frac{1}{5}\right)\left(\sum_{k=1}^{k=5}(T_{c(k,j)})\right) \quad \text{where} \quad -5\% \le T_{cPminmax(k,j)} \le +5\% \quad (13)$$

As stated is Eq 13, $T_{cmean(j)}$ is computed only for those meteorological data records where $-5\% \leq T_{cPminmax(k,j)} \leq +5\%$.
Assuming there are nxj meteorological data records where $-5\% \leq T_{cPminmax(k,j)} \leq +5\%$, then in Eq 13 j = 1,2,3,…njx. Then, a table of $T_{a(j)}, G_j, V_{w(j)}$ and $T_{cmean(j)}$ is created for j = 1,2,3,…njx. From the table, a multiple linear regression model is developed for T_c as function of T_a, G and V_w in which

$$T_c = A(G) + B(T_a) + C(V_w) \quad (14)$$

Where A, B and C are the regression coefficients. The values of A, B and C are obtained from the multiple regression model that is developed from the table of $T_{a(j)}, G_j, V_{w(j)}$ and $T_{cmean(j)}$. Furthermore, the thermal loss U is given from Equation 3.5 as;

$$U = \left(\frac{\alpha_{pv}(G)\,(1-\eta_{PV})}{T_c - T_a}\right) \quad (15)$$

Essentially, where the values of A, B, and C are known, Eq 14 can be used to determine the cell temperature(T_c) and Eq 15 can be used to determine the thermal loss factor (U) for a given PV module with known efficiency η_{pv} and absorption coefficient α_{pv} along with any given metrological parameters, namely, T_a, G and V_w.

III. RESULTS AND DISCUSSIONS

A. The meteorological data used in the study

This study was conducted with dataset consisting of 4307 meteorological data records obtained from PVsyst at latitude 14.48°N and longitude -17.01°W and altitude of 5m. The key meteorological data used are the global irradiance on the horizontal plane (G given in W/m²) plotted in Figure 1, ambient temperature (Ta given in °C) plotted in Figure 2, and wind speed (Vw given in m/s) plotted in Figure 3. Also, the study used a PV panel with absorption coefficient of solar irradiation, α_{pv} =0.9 and the solar panel efficiency, η_{pv} =18.4 %.

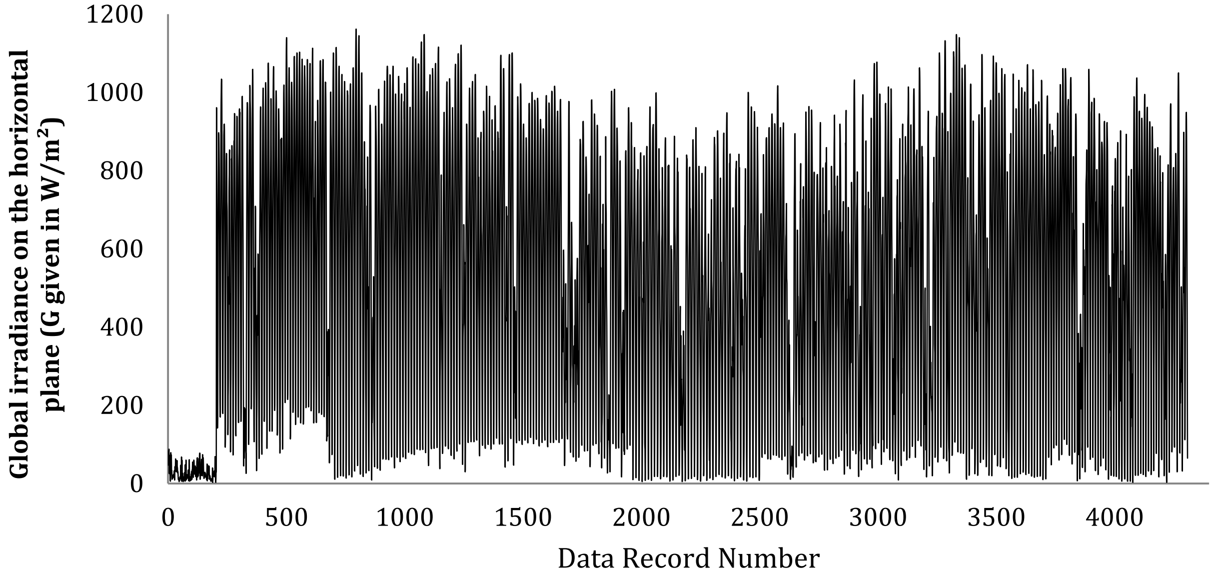

Figure 1: Global irradiance on the horizontal plane (G given in W/m²)

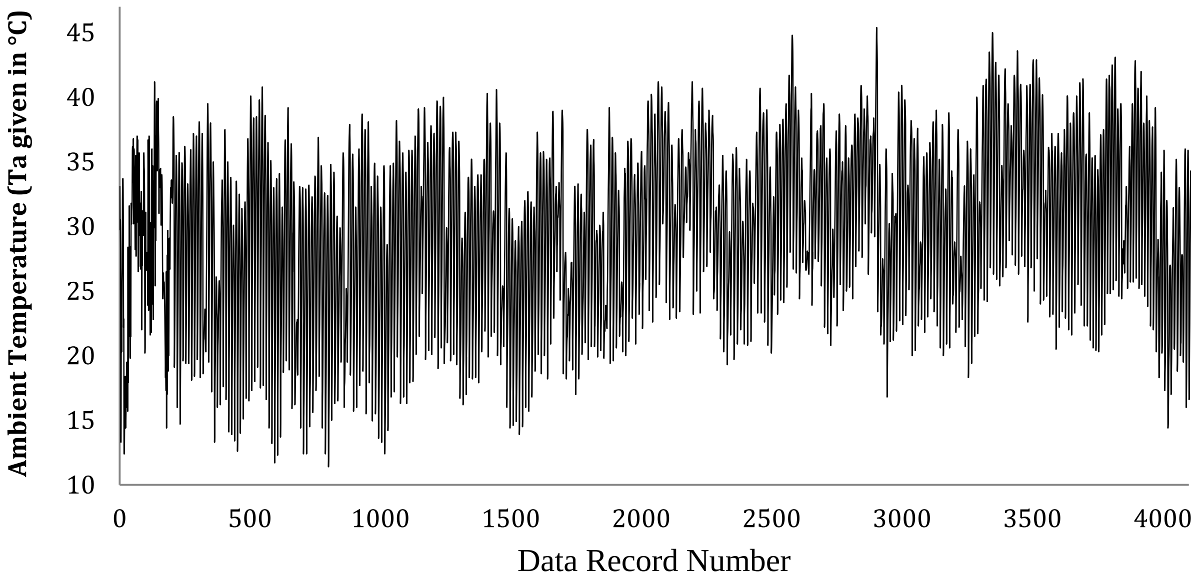

Figure 2 Ambient Temperature (Ta given in °C)

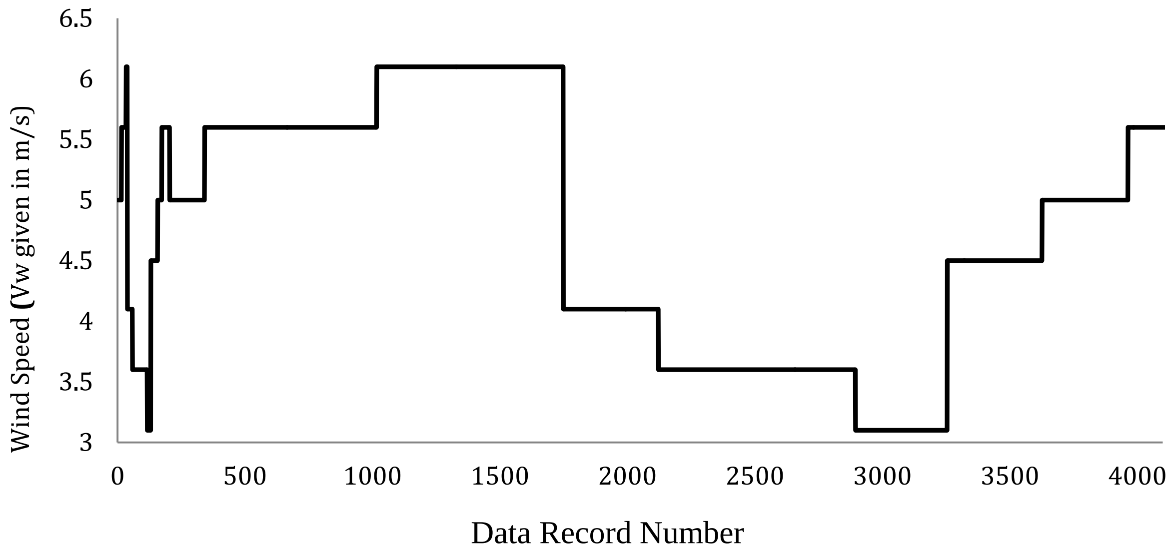

Figure 3Wind Speed (Vw given in m/s).

B. The Cell Temperature Model

Table 1 Sample meteorological data with cell temperature predictions for the five thermal loss factor settings and percentage difference between the minimum cell temperature and the maximum cell temperature whereα_{pv} =0.9 and η_{pv} =18.4%

Data record number	G(j) (W/M²)	Ta(j) (°C)	Vw(j) (m/s)	Tc(j,1) (°C) for Uo = 29 ; U1 =0	Tc(j,2) (°C) for Uo = 15 ; U1 =0	Tc(j,3) (°C) for Uo = 20 ; U1 = 6	Tc(j,4) (°C) for Uo =25 ; U1 = 1.2	Tc(j,5) (°C) for Uo =26 ; U1 = 1.4	$T_{cPminmax(k,j)}$, Percentage difference between the maximum and minimum Tc(j,k) (%) for k =1,2,3,4 and5
j				k=1	k=2	k=3	k=4	k=5	
1	83	33.1	5	35.2	37.2	34.3	35.1	35.0	8.3
2	47	29.8	5	31.0	32.1	30.5	30.9	30.9	5.3
3	60	30.5	5	32.0	33.4	31.4	31.9	31.8	6.6
4	88	28	5	30.2	32.3	29.3	30.1	30.0	10.3
5	26	13.3	5	14.0	14.6	13.7	13.9	13.9	6.5
6	63	20.1	5	21.7	23.2	21.0	21.6	21.5	10.4
7	72	25.4	5	27.2	28.9	26.5	27.1	27.0	9.3
8	23	20.3	5	20.9	21.4	20.6	20.8	20.8	3.8
9	23	25.7	5	26.3	26.8	26.0	26.2	26.2	2.8
10	6	26.8	5	26.9	27.1	26.9	26.9	26.9	0.6
11	36	32	5	32.8	33.5	32.5	32.9	32.8	2.9
12	79	33.7	5	35.5	36.8	34.9	35.6	35.5	5.4
13	53	33.7	5	34.9	35.7	34.5	35.0	34.9	3.4
14	73	30.9	5	32.4	33.5	32.0	32.6	32.5	4.6
15	26	22.2	5	22.7	23.1	22.6	22.8	22.8	2.2
16	33	22.8	5.6	23.5	23.9	23.3	23.6	23.5	2.6
17	11	12.4	5.6	12.6	12.7	12.6	12.7	12.6	1.5
18	16	12.4	5.6	12.7	12.9	12.6	12.8	12.8	2.0
19	20	14.5	5.6	14.9	15.1	14.8	15.0	14.9	2.0
20	19	15.6	5.6	15.9	16.1	15.9	16.0	16.0	1.6
21	14	17.3	5.6	17.6	17.7	17.5	17.6	17.6	1.0
22	22	18.4	5.6	18.8	19.0	18.7	18.9	18.9	1.4

Table 1 shows sample meteorological data with cell temperature predictions for the five thermal loss factor settings (that is k =1,2,3,4 and 5) and percentage difference between the minimum cell temperature and the maximum cell temperature where α_{pv} =0.9 and η_{pv} =18.4%. In Table 1 only the cell temperature predictions for the first 22 data records (that is j =1,2,3,…,22) are shown. According to Table 1, at the row with j = 6, the maximum percentage difference in cell temperature of about 10.4°C is observed from the five different thermal loss factor settings. Also, from Table 1, at the row with j = 10, the minimum percentage difference in cell temperature of about 0.6°C is observed from the five different thermal loss factor settings. The graph of $T_{cPminmax(k,j)}$, the percentage difference between the maximum and minimum cell temperature, Tc(j,k) where k =1,2,3,4 and 5 for all j ≥ 0 is shown in figure 4. In the graph of Figure 4, where results for all the 4307 meteorological data records are plotted , higher maximum percentage difference in cell temperature and lower minimum percentage difference in cell temperature are observed.

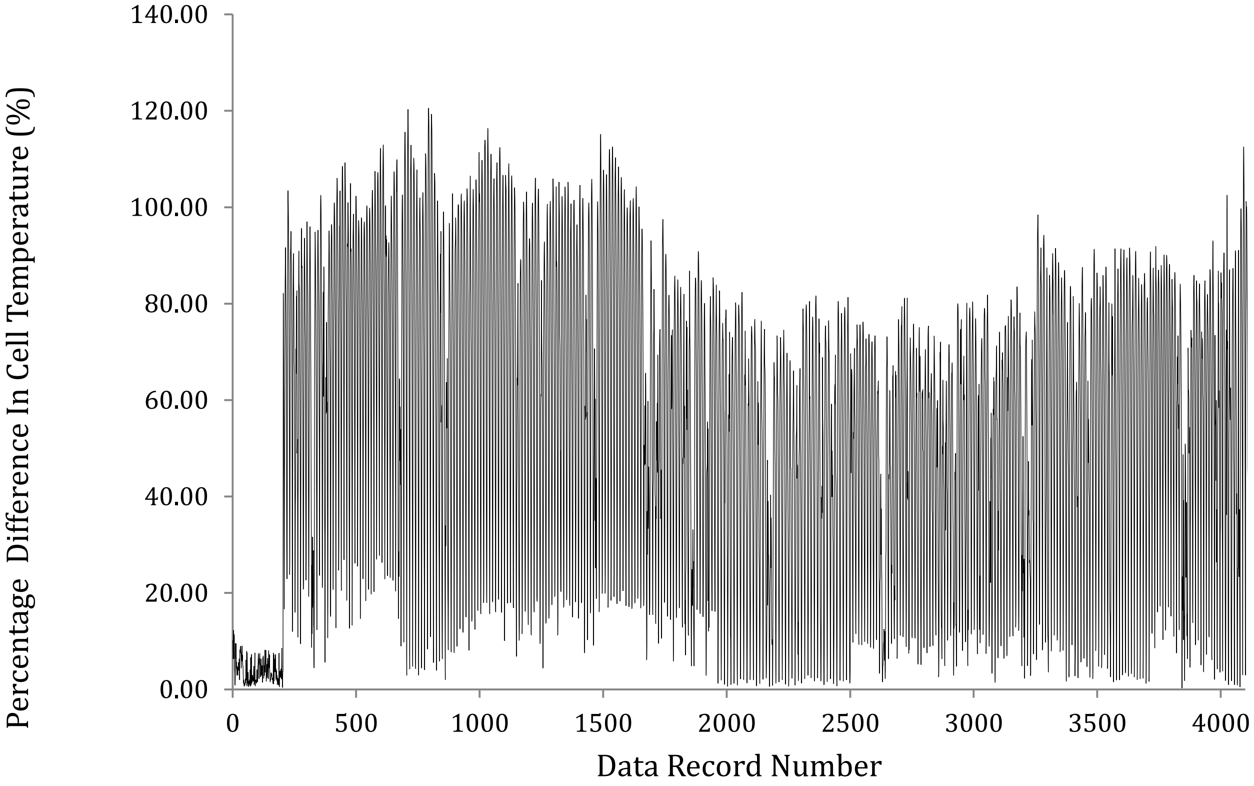

Figure 4: Graph of $T_{cPminmax(k,j)}$, the percentage difference between the maximum and minimum cell temperature, Tc(j,k) where k =1,2,3,4 and5 for all j ≥ 0

Table 2 shows portion of the meteorological data with $T_{cmean(j)}$, the mean cell temperature (°C) per selected meteorological data record whose percentage difference between the minimum cell temperature and the maximum cell temperature is less or equal to ± 5%; where α_{pv} =0.9 and η_{pv} =18.4. Figure 4 show the graph of $T_{cmean(j)}$, the mean cell temperature (°C) per selected meteorological data record for all the data records whose percentage difference between the minimum cell temperature and the maximum cell temperature is less or equal to ± 5%; where α_{pv} =0.9 and η_{pv} =18.4.

Table 2: Sample meteorological data with $T_{cmean(j)}$,the mean cell temperature (°C)per selected meteorological data record whose percentage difference between the minimum cell temperature and the maximum cell temperature is less or equal to ± 5%; where α_{pv} =0.9 and η_{pv} =18.4.

Data record number	G(j) (W/M²)	Ta(j) (°C)	Vw(j) (m/s)	Tc(j,1) (°C) for Uo = 29 ; U1 =0	Tc(j,2) (°C) for Uo = 15 ; U1 =0	Tc(j,3) (°C) for Uo = 20 ; U1 = 6	Tc(j,4) (°C) for Uo =25 ; U1 = 1.2	Tc(j,5) (°C) for Uo =26 ; U1 = 1.4	$T_{cPminmax(k,j)}$, Percentage difference between the maximum and minimum Tc(j,k) (%) for k =1,2.3.4.5	$T_{cmean(j)}$, The Mean Cell Temperature (°C) Per Selected Meteorological Data Records
j				k=1	k=2	k=3	k=4	k=5		
8	23	20.3	5	20.9	21.4	20.6	20.8	20.8	3.8	20.92
9	23	25.7	5	26.3	26.8	26.0	26.2	26.2	2.8	26.302

10	6	26.8	5	26.9	27.1	26.9	26.9	26.9	0.6	26.952
11	36	32	5	32.8	33.5	32.5	32.9	32.8	2.9	32.896
13	53	33.7	5	34.9	35.7	34.5	35.0	34.9	3.4	34.964
14	73	30.9	5	32.4	33.5	32.0	32.6	32.5	4.6	32.6
15	26	22.2	5	22.7	23.1	22.6	22.8	22.8	2.2	22.796
16	33	22.8	5.6	23.5	23.9	23.3	23.6	23.5	2.6	23.528
17	11	12.4	5.6	12.6	12.7	12.6	12.7	12.6	1.5	12.638
18	16	12.4	5.6	12.7	12.9	12.6	12.8	12.8	2.0	12.742
19	20	14.5	5.6	14.9	15.1	14.8	15.0	14.9	2.0	14.92
20	19	15.6	5.6	15.9	16.1	15.9	16.0	16.0	1.6	15.994
21	14	17.3	5.6	17.6	17.7	17.5	17.6	17.6	1.0	17.586
22	22	18.4	5.6	18.8	19.0	18.7	18.9	18.9	1.4	18.846

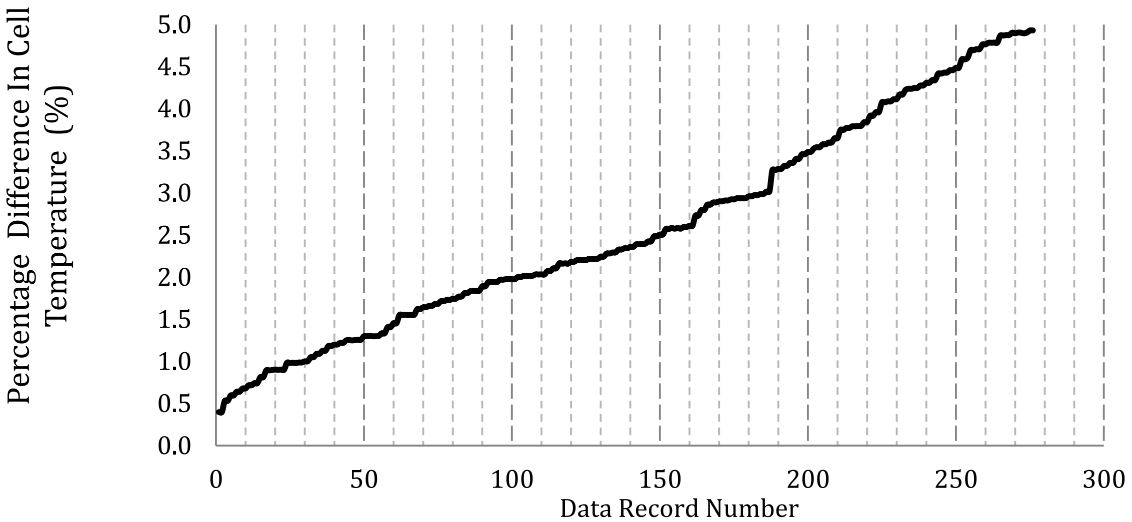

Figure 5: Graph of $T_{cmean(j)}$, the mean cell temperature (°C)per selected meteorological data record for all the data records whose percentage difference between the minimum cell temperature and the maximum cell temperature is less or equal to ± 5%; where α_{pv} =0.9 and η_{pv} =18.4

From Figure 5 it can be seen that less than 280 meteorological data records have percentage difference between the minimum cell temperature and the maximum cell temperature of less or equal to ± 5%. Those are the meteorological data records that are used in developing the multiple linear regression models for computing the cell temperature.

The actual average cell temperatures given in Table 4.4 are generated for the data records that have percentage difference in cell temperature less than 5%. The multiple linear regression model developed from the 276 data records is given as;

$$\mathrm{T_c(°C) = T_a + 0.025021(G) + 0.003(V_w)} \quad (16)$$

where the explanatory variables are G (W/m²), Ta (°C) and Vw (m/s).

Error analysis on the multiple linear regression model of Eq 16 with respect to the selected 276 data records gave Root Mean Square Error (RMSE) of 0.0179184°C with maximum absolute error of 0.064653°C. When the multiple linear regression model (Eq 16) is applied to predict for the entire 4307 data records the RMSE is 0.49622661°C with maximum absolute error of 1.902997°C.

Similarly, when only ambient temperature and solar radiation (G) are considered in the multiple linear regression model developed from the 276 data records, the model becomes;

$$T_c°\mathrm{C} = T_a + 0.0259(\mathrm{G}) \quad (17)$$

Error analysis on the multiple linear regression model of Eq 17 with respect to the selected 276 data records gave Root Mean Square Error (RMSE) of 0.011972225°C with maximum absolute error of 0.040719547°C. When the multiple linear regression model (Eq 17) is applied to predict for the entire 4307 data records the RMSE is 0.438063308°C with maximum absolute error of 1.200625313°C.

Essentially, in terms of RMSE, the second cell temperature model (Eq 17) has better prediction accuracy for the average cell temperature with about 13.27737359% improvement over the RMSE obtained with the first cell temperature model.

In any case, any of the two cell temperature models can be used to estimate the cell temperature which can then be used to determine the thermal loss factor.

C. Thermal Loss Factors For Onshore Meteorological Data

The 4307 meteorological data records used in the study are onshore dataset. As such, the cell temperature and thermal loss factor settings obtained are applicable to the onshore site.

For the given dataset with 4307 data records , the average G, T_a,V_{wind} and T_c are computed. Now average of G = 541.8148492 (W/m²), then given that α_{pv} = 0.9,η_{pv} =18.4 % and then

α(average G) $(1 - \eta_{STC})$ = 0.9(541.8148492)(1-0.184) = 397.90882525248.

Also, average of T_a = 30.00816705°C and average of T_c computed with Eq 16 is T_c =40.51°C. Hence;

$$T_c - T_a = 43.5649163918332 - 30.00816705 = 13.5711402235042$$

Then, the thermal loss factor, U is computed using Eq 15 whereby,

$$U_0 = U = \left(\frac{\alpha_{pv}(G)\,(1-\eta_{PV})}{T_c - T_a}\right) \text{ and } U_1 = 0 = \frac{397.90882525248}{13.5711402235042} = 29.32$$

Onshore cell temperature based on multiple linear regression model of Eq17

Also, average of T_a = 30.00816705 °C and average of T_c computed with Eq 16 is T_c =44.04117164428°C. Hence;

$$T_c - T_a = 44.04117164428 - 30.00816705 = 14.03300459428\ °C$$

Then, the thermal loss factor,

$$U_0 = U = \left(\frac{\alpha_{pv}(G)\,(1-\eta_{PV})}{T_c - T_a}\right) \text{and} U_1 = 0 = \frac{397.90882525248}{14.03300459428} = 28.35521235521236$$

So, the thermal loss factor obtained is U_0 = 29.30 and U_1 = 0 for the model (Eq 16) with G, T_a and V_{wind} whereas the thermal loss factor obtained are U_0 = 28.36 and U_1 = 0 for the model (Eq 17) with only Gand T_a. The two thermal loss factors are very close to the thermal loss factor setting currently used by PVsyst, namely, U_0 = 29 and U_1 =0.

D. Thermal Loss Factors For Offshore Meteorological Data

The 4307 meteorological data records used in the study are onshore dataset. For offshore PV installation the equivalent offshore ambient temperature are determined from the offshore data as follows [27,28,29];

$$T_{as} = 5.0 + 0.75(T_a) \tag{18}$$

Where T_{as} is sea (or offshore) temperature in °C and T_a is air temperature on land (or onshore air temperature) in °C.

Also, for offshore PV installation the equivalent offshore wind speed are determined from the offshore data as follows [27, 30,31];

$$V_{ws} = 1.62 + 1.17\,(V_w) \tag{19}$$

Where V_{ws} = is sea (or offshore) wind speed in m/s andV_w is wind speed on land (or onshore wind speed) in m/s.

A portion of the offshore ambient temperature and offshore wind speed and their corresponding onshore ambient temperature and onshore wind speed are given in Table 3. The graph plot of the onshore ambient temperature and the offshore ambient temperature are given in figure 6 while the graph plot of the onshore ambient temperature and the offshore wind speed are given in figure 7.

Table 3; A portion of the offshore ambient temperature and offshore wind speed and their Corresponding onshore ambient temperature and onshore wind speed.

Onshore data		Offshore data	
Ta (°C)	Vw (m/s)	Ta (°C)	Vw (m/s)
28.85	8.17	26.64	11.18
s28.85	8.17	26.64	11.18
21.58	8.17	21.18	11.18
21.58	8.17	21.18	11.18
29.83	5.83	27.37	8.44
29.83	5.83	27.37	8.44
28.40	6.42	26.30	9.13
28.40	6.42	26.30	9.13
31.40	5.83	28.55	8.44
31.40	5.83	28.55	8.44
29.75	5.83	27.31	8.44
29.75	5.83	27.31	8.44
29.38	6.42	27.03	9.13
29.38	6.42	27.03	9.13
30.58	5.83	27.93	8.44
30.58	5.83	27.93	8.44
31.78	5.83	28.83	8.44

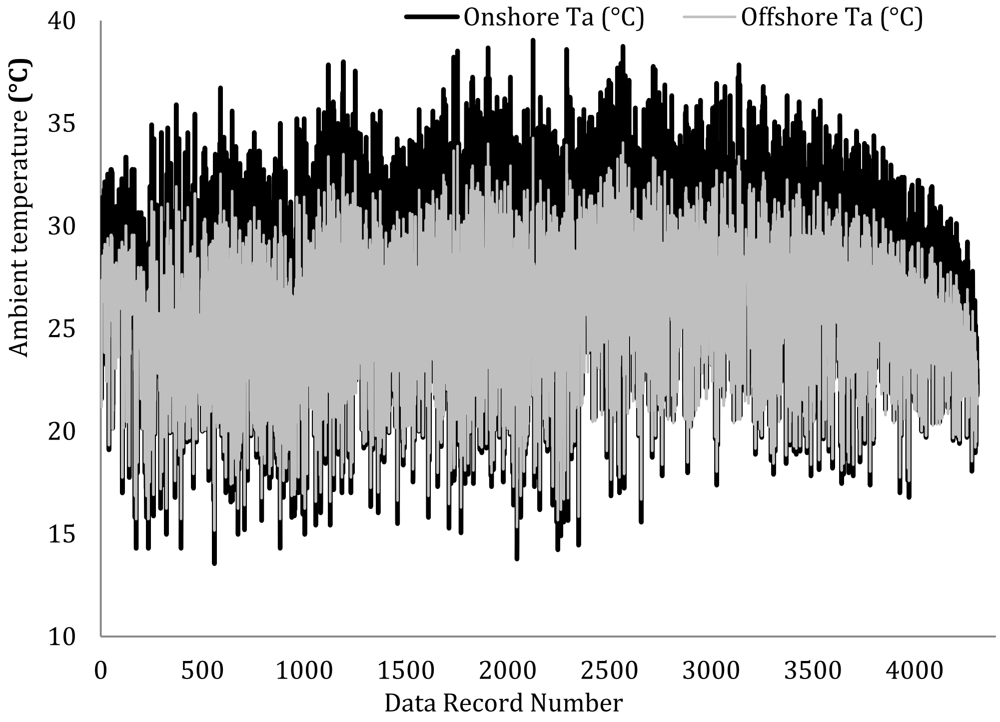

Figure 6; Graph plot of the onshore ambient temperature and the offshore ambient temperature

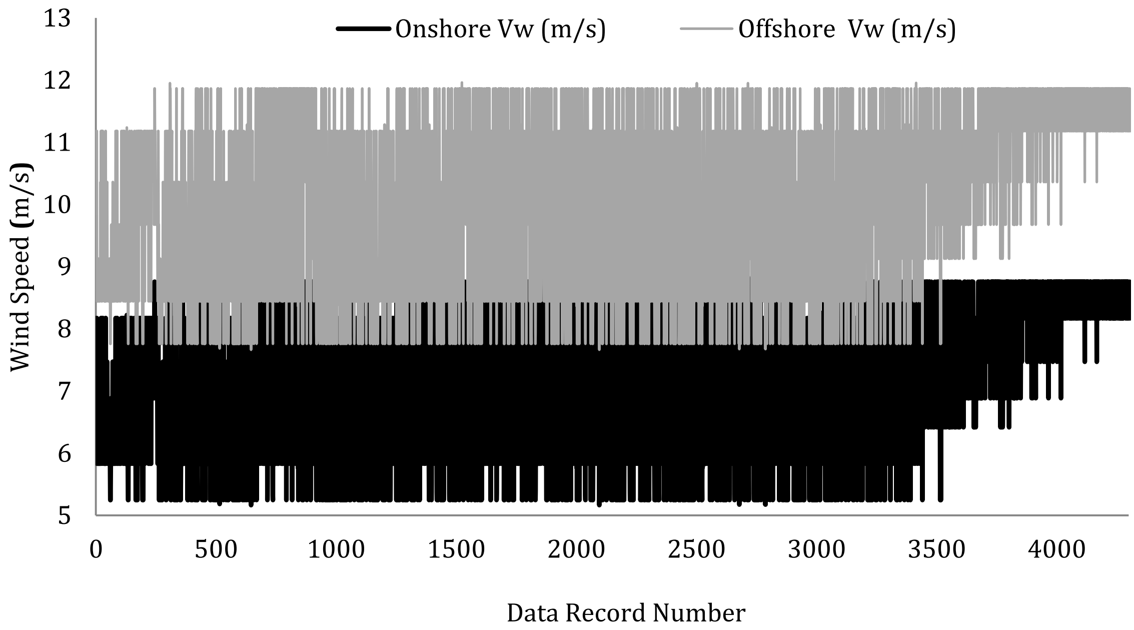

Figure 7; Graph plots of the onshore wind speed and the offshore wind speed

Now cell temperature model of Eq16 and Eq17 are used to estimate the cell temperature for the offshore site for the entire 4307 offshore data records. RMSE of 0.591012111(°C) and maximum absolute prediction error of 1.601085315(°C) are obtained when the cell temperature model of Eq16 is used to estimate the cell temperature for the entire 4307 offshore data records. Similarly, RMSE of 1.054379357 (°C) and maximum absolute prediction error of 2.577628938 (°C) are obtained when the cell temperature model of Eq17 is used to estimate the cell temperature for the entire 4307 offshore data records. Effectively, the cell temperature model of Eq16 gave better cell temperature prediction for the offshore installation.

Essentially, in terms of RMSE, the cell temperature model of Eq 16 has better prediction for the offshore cell temperature with about 78.40232668260837% improvement over the RMSE obtained with the cell temperature model of Eq 17.

Offshore cell temperature based on multiple linear regression model of Eq16

For the given dataset with 4307 data records, the average G, T_a,V_{wind} and T_c are computed. Now, average of G = 541.8148492 (W/m²), then given that α_{pv} = 0.9,η_{pv} =18.4 % gives α(average G) $(1 - \eta_{STC})$ = 0.9(541.8148492)(1-0.184) = 397.90882525248.

Also, average of $T_a = 27.50497$ °C and average of T_c computed with Eq 16 is $T_c = 41.0834107457762$°C. Hence;

$$T_c - T_a = 41.0834107457762 - 27.50497 = 13.5784407457762$$

Then, the thermal loss factor, U is computed using Eq 15 whereby,

$$U_0 = U = \left(\frac{\alpha_{pv}(G)\,(1 - \eta_{PV})}{T_c - T_a}\right) \text{ and } U_1 = 0 = \frac{397.90882525248}{13.5784407457762} = 29.3044564322495$$

Offshore cell temperature based on multiple linear regression model of Eq17

Also, average of $T_a = 27.50497$°C and average of T_c computed with Eq 16 is $T_c = 41.53797459428$ °C. Hence;

$$T_c - T_a = 41.53797459428 - 27.50497 = 14.03300459428\ °C$$

Then, the thermal loss factor,

$$U_0 = U = \left(\frac{\alpha_{pv}(G)\,(1 - \eta_{PV})}{T_c - T_a}\right) \text{ and } U_1 = 0 = \frac{397.90882525248}{14.03300459428} = 28.35521235521236$$

So, the offshore thermal loss factor obtained is U_0 = 29.30 and U_1 = 0 for the model (Eq 16) with G, T_a and V_{wind} whereas the thermal loss factor obtained are U_0 = 28.36 and U_1 = 0 for the model (Eq 17) with only G and T_a. Hence, the two thermal loss factors settings obtained for the offshore installation are similar to the thermal loss factor setting currently used by PVsyst, namely, U_0 = 29 and U_1 =0. It can be concluded that the current thermal loss factor setting of PVSyst is applicable to both onshore and offshore PV sites.

V. Conclusion

Analytical approach for determination of the thermal loss factor settings in PVsyst software for onshore and offshore PV sites is presented. The approach is based on available five different thermal loss factor settings and meteorological data records obtained from PVsyst software. Particularly, the meteorological data used are the ambient temperatures (the ambient temperatures (in °C) respectively; G is the irradiance incident on the plane of the module or array (W/m^2) in °C) , solar irradiance incident on the plane of the module or array (G in W/m^2) and the wind speed (Vw in m/s). In the study two multiple linear regression cell temperature models were developed , model one with G (W/m²), Ta (°C) and Vw (m/s) as the explanatory variables and model two with G (W/m²) and Ta (°C) as the explanatory variables. The results showed that for both the onshore and the offshore sites, the thermal loss factor obtained are similar to the latest thermal loss factor setting in PVsyst software, namely, U_0 = 29 and U_1 =0.The results also showed that the latest thermal loss factor setting in PVsyst software is applicable to both onshore and offshore PV sites.

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