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Comparative Analysis of Three NOCT-Based Cell Temperature Models

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Abstract: In this paper, comparative analyses of three NOCT-based cell temperature models are presented. The models are the HOMER (Hybrid Optimization of Multiple Energy Resources) software cell temperature, Ross cell temperature model and Davis and Rauschenbach cell temperature model. Noticeably, unlike PVSysts software, the three models do not include the effect of wind speed. Three models are analyzed using the meteorological data of a site in Ibeno, Akwa Ibom state, Nigeria. The results showed that among the three NOCT-based cell temperature models, the Ross model has the highest cell temperature for any given ambient temperature and solar irradiance. The HOMER Davis and Rauschenbach models have almost the same cell temperature values but in all the occasions, the HOMER model gives the lowest cell temperature among the three models. Equally, Ross model has the lowest annual energy yield and the highest thermal loss whereas the HOMER model has the highest annual energy yield and the lowest thermal loss.

Keywords: Cell Temperature, Thermal Loss, Energy Yield, Temperature Derating Factor, Photovoltaic, Solar Energy, Renewable Energy

1. Introduction

As the adoption of photovoltaic power system continues to rise across the globe, there is growing concern on the performance and cost of photovoltaic (PV) modules. Meanwhile, photovoltaic (PV) effect is the direct conversion of light into electricity in solar cells [1]. As such, one of the main performance parameter is the energy conversion efficiency of PV array which is defined as the percentage of the solar energy to which the array is exposed that is converted into electrical energy. Generally, the performance of a solar photovoltaic system (SPV) is dependent upon many site-specific factors as well as PV-technology specific factors and installation –specific factors [1, 2]. Site specific factors include among others, solar radiation, ambient temperature, wind speed and direction. These site specific factors greatly affect the cell operating temperature. The panel material composition, temperature coefficient and mounting structure are among the PV-technology and installation –specific factors which in many ways affect the SPV performance. For a typical commercial PV panel, a proportion of the solar radiation is converted into electricity, typically 13% to 20%, and the remainder is converted into heat [3]. Furthermore, more heat is generated by the PV panel due to the photovoltaic action and further heating occurs due to the energy radiated at the infrared wavelength of the solar spectrum [3]. The overall effect is increase in cell temperature which leads to reduction in cell efficiency and corresponding reduction in cell power output.

Presently, there are several mathematical models for relating the ambient climatic parameters to the cell temperature and hence to cell efficiency and power output. Also, different software exists that utilize the models in carrying out performance analysis of solar power systems. In this paper, the focus is on the cell temperature models adopted in the HOMER (Hybrid Optimization of Multiple Energy Resources) software [4, 5, 6]. Noticeably, unlike PVSysts software, HOMER cell temperature model does not include the effect of wind speed around the PV module. As such in this paper, the focus is on such cell temperature models that are based on ambient temperature without accounting for the effect of wind speed. The paper will also consider the operating cell efficiency, operating PV output power, percentage thermal loss and the reduction in efficiency due to cell temperature model employed in HOMER software.

2. Theoretical Background of Cell Temperature Models

Cell temperature is affected by the incident irradiance, weather conditions (such as air temperature and wind speed), and module construction and material properties [7, 8, 9].

2.1. Ross Cell Temperature Model

Most PV manufacturers provide the temperature elements for PV modules based on the nominal operating cell temperature (NOCT). The Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the following conditions: solar irradiance = 800 W/m^2, air temp. = 20°C, wind speed = 1 m/s, mounting = open back side [10, 11]. The NOCT is used to estimate the cell temperature as follows [10, 11, 12, 13, 14, 15]:

$$T_{cell} = T_a + \left(\frac{NOCT-20}{800}\right) G \tag{1}$$

where T_a is in °C, G is irradiance on the plane of array (or Solar irradiance incident on module surface) expressed in W/ m^2, and NOCT stands for nominal operating cell temperature. It is defined as the temperature of a cell at standard reference environment (SRE), i.e. for an ambient temperature of 20°C, an irradiance of 800 W/m^2, a wind speed of 1 m/s and an open rear surface mounting (the module is tilted at 45°). In many literatures, the model is attributed to Ross [16, 17, 18]. Notably, the Ross NOCT based cell temperature model does not include the effect of wind speed on the cell temperature. The NOCT methodology or Ross thermal Model is used in many literature and in solar power simulation software like Pvwatts [19, 20].

2.2. Davis and Rauschenbach Cell Temperature Model

The solar energy that is absorbed by a module is converted partly in to thermal energy and partly into electrical energy, which is removed from the cell through the external circuit [17]. From the energy balance equation on a unit area of a module which is cooled by losses to the surroundings Davis and Rauschenbusch derived the following thermal model for computing cell temperature:

$$\frac{\tau\alpha}{U} = \left(\frac{NOCT-T_{NOCT}}{G_{NOCT}}\right) = \left(\frac{NOCT-20}{800}\right) \tag{2}$$

Where

$\tau\alpha$, is the absorptivity of the module or the effective transmittance-absorbance product of the module.

U is the Loss coefficient

NOCT is the Nominal Operating Cell Temperature. It is given in module specification

T_{NOCT} is the ambient temperature for NOCT conditions. It is 20° Celsius

G_{NOCT} is the irradiation for NOCT conditions. It is 800 W/m^2

Absorptivity of a module is the ratio of total radiation absorbed by a module to the total radiation striking the surface of a module. A module has to absorb at least 90% of the radiation falling on it. So, $\tau\alpha$ is taken to be 0.90. Then, when it is taken that τα/UL is constant, the cell temperature (T_{cell}) of the PV with ambient temperature (T_a) is given as [21, 22, 23, 24];

$$T_{cell} = T_a + \left(G\left(\frac{\tau\alpha}{U}\right)\right)\left(1 - \frac{\eta_{STC}}{\tau\alpha}\right) \tag{3}$$

$$T_{cell} = T_a + \left(1000\left(\frac{\tau\alpha}{U}\right)\right)\left(1 - \frac{\eta_{STC}}{\tau\alpha}\right) \tag{4}$$

Where

T_{cell} is the module temperature

Ta is the corresponding ambient temperature

G is irradiance on the plane of array (or Solar irradiance incident on module surface) expressed in W/m^2,

η_{STC} is the efficiency of the PV Cell.

2.3. Homer PV Cell Temperature Model

HOMER (Hybrid Optimization of Multiple Energy Resource) is a hybrid system modeling tool developed by (NREL) National Renewable Energy Laboratory. [4, 25, 26]. According to the information on Homer help page, the software evaluates the PV cell temperature as follows [27]:

$$T_{cell} = \frac{T_a + (NOCT - T_{NOCT})\left(\frac{(G)}{G_{NOCT})}\right)\left(1 - \frac{\eta_{STC}[1-\beta_{STC}(T_{STC})]}{\tau\alpha}\right)}{1 + (NOCT - T_{NOCT})} \tag{5}$$

$$T_{cell} = \frac{T_a + (NOCT-20)\left(\frac{(G)}{800W/m^2)}\right)\left(1 - \frac{\eta_{STC}[1-\beta_{STC}(T_{STC})]}{\tau\alpha}\right)}{1 + (NOCT-20)\left(\frac{(G)}{800W/m^2)}\right)\left(\frac{\beta_{STC}(\eta_{STC})}{\tau\alpha}\right)} \tag{6}$$

HOMER assumes that the PV cell efficiency varies linearly with temperature according to the following equation:

$$\eta_{mp} = \eta_{STC}[1 + \beta_{STC}(T_{Cell} - T_{STC})] \tag{7}$$

η_{mp} is the efficiency of the PV array at its maximum power point [%]

where:

T_{cell} is the module temperature

η_{STC} is the maximum power point efficiency under standard test conditions [%]

T_a is ambient temperature,

G is irradiance on the plane of array (or Solar irradiance incident on module surface) expressed in W/m^2,

T_{STC} is the cell temperature under standard test conditions [25°C]

T_{NOCT} is the cell temperature at NOCT conditions [20°C]

G_{NOCT} = 800 W/m^2, G_{STC} = 1000 W/m^2, $\tau\alpha = 0.9$

β_{STC} = Power temperature coefficient of module in %/°C and $|\beta_{STC}|$ = absolute value of temperature coefficient of maximal power β_{STC} in %/°C. β_{STC} must be divided by 100 if it is given in %.

2.4. Meteorological Data

The study site is located in Ibeno at latitude of 4.53 and longitude of 7.97. The meteorological data of the study site is obtained from the National Aeronautics and Space Administration Surface meteorology and Solar Energy (NASA SSE) website. Photovoltaic System simulation software, PVSyst (Version 5.06). The 22-year monthly averaged daily meteorological data (temperature, solar irradiation on horizontal plane) is first downloaded into PVSyst software meteorological file. Then, the PVSyst software is used to generate the hourly meteorological data for optimally tilted plane of 7°. The optimal tilt angle computed from the equation [28, 29, 30]:

$$\beta_{opt} = 3.7 + 0.69|\emptyset| = 3.7 + 0.69\ |4.53\ | \quad (8)$$

$$\beta_{opt} = =6.8257 \approx 7$$

Where β_{opt} is the optimal tilt angle and $\emptyset$ is the local latitude of the site (β_{opt}, $\emptyset$ in degrees).

The ENP Sonne High Quality 180 Watt, 24V monocrystalline module is selected in this design. It has short circuit current Isc (A) of 5.38 A, panel efficiency of 14.1%, power temperature coefficient of -0.480 %/ºC and Nominal Operating Cell Temperature (NOCT) of 45.0ºC.

The hourly meteorological (solar irradiance and ambient temperature) data is used to compute the cell temperature for three cell temperature models.

2.5. Power Loss Due to Cell Temperature

The rated power as generally indicated on the module's label is measured at 25°C which is the STC temperature. Any temperature increase above 25°C will result in decrease in PV output power which can be determined from the knowledge of the cell temperature (T_{cell}) and the temperature coefficient β_{STC} (%/°C) of the module and it is given as;

$$\text{Loss}_{thermal}(\%) = |\beta_{STC}|(T_{cell} - T_{STC}) \quad (9)$$

Where

$\text{Loss}_{\text{thermal}}(\%)$ is the percentage thermal loss which is the percentage of the total output power that is lost due to the operating cell temperature, T_{cell} which is different from the STC temperature, T_{STC}.

T_{cell} is the cell temperature.

T_{STC} the standard operating cell temperature STC which is 25 ° C

β_{STC} is the temperature coefficient of the module. β_{STC} = Power temperature coefficient of module in %/°C and $|\beta_{STC}|$ = absolute value of temperature coefficient of maximal power β_{STC} in %/°C. β_{STC} must be divided by 100 if it is given in %.

Example; consider a Schott Power Poly module with nominal power (W_P) =275 W, module efficiency (η_{PV}) = 14.1%, the temperature coefficient of the module (β_{STC}) = -0.45 %/°C, NOCT = 47°C, ambient temperature is 40°C $\tau\alpha = 0.9$ and G_{STC} = 1000 W/m^2, Then, the cell temperature according to Davis and Rauschenbach cell temperature model is given as;

$$\frac{\tau\alpha}{U} = \left(\frac{47-20}{800}\right) = 0.03375 \quad (10)$$

$$T_{cell} = T_a + \left(G_{STC}\left(\frac{\tau\alpha}{U}\right)\right)\left(1 - \frac{\eta_{STC}}{\tau\alpha}\right) \quad (11)$$

$$T_{cell} = 40 + \left(1000\ (0.03375)\right)\left(1 - \frac{(14.1/100)}{0.9}\right) \quad (12)$$

$$T_{cell} = 40 + 28.4625 = 68.4625$$

$$\text{Loss}_{thermal}(\%) = |\beta_{STC}|(T_{cell} - T_{STC}) \quad (13)$$

$$\text{Loss}_{thermal}(\%) = |-0.45|(68.4625 - 25) = 0.45(43.4625) = 19.558125\%$$

HOMER calculates the power output of the PV array as follows [27]:

$$P_o = \left(P_{STC}\left(\frac{G}{G_{STC}}\right)\right)\left[\left(1 - |\beta_{STC}|(T_{cell} - T_{STC})\right)\right]f_{der} \quad (14)$$

Where

G is irradiance on the plane of array (or Solar irradiance incident on module surface) expressed in W/m^2,

P_{STC} is the PV rated power output at STC

β_{STC} = Power temperature coefficient of module in %/°C and $|\beta_{STC}|$ = absolute value of temperature coefficient of maximal power β_{STC} in %/°C. β_{STC} must be divided by 100 if it is given in %.

$$G_{STC} = 1000 \text{ W/m}^2$$

T_{cell} is the module temperature

f_{der} is the PV derating factor (%). The PV derating factor (f_{der}) is a scaling factor used by HOMER account for reduction in output power in real-world operating conditions which are different from the STC conditions under which the PV panel was rated. In this case where temperature effect is explicitly specified, the PV derating factor (f_{der}) does not include temperature effect. However, when the temperature effect is not explicitly specified, the PV derating factor (f_{der}) should include temperature effect.

f_{temp} is the temperature derating factor

$$f_{temp} = \left(1 - |\beta_{STC}|(T_{cell} - T_{STC})\right) \quad (15)$$

HOMER assumes that the PV cell efficiency varies linearly with temperature. In respect of the temperature derating factor, the PV cell efficiency at the operating cell temperature, T_{cell} is given as:

$$\eta_{mp} = \eta_{STC}[1 + \beta_{STC}(T_{Cell} - T_{STC})] \quad (16)$$

$$\eta_{mp} = \eta_{STC}(f_{temp}) \quad (17)$$

3. Results and Discussions

According to Table 1 and figure 1, the peak global irradiance on the tilted plane occurred at about 12 noon, the peak ambient temperature occurred at about 2 pm whereas the peak cell temperature for the three models occurred at about 1 pm. Essential, both global irradiance (G) and ambient temperature (Ta) have significant influence on the cell temperature. Again, in all cases where G =0, the cell temperature of three models are equal to the ambient temperature (Ta). However, when G is above zero, the cell temperature of three models are above the ambient temperature (Ta). Ross cell temperature (T_{cell}) is in most cases above the cell temperature of other two models. HOMER T_{cell} and the Davis and Rauschenbach T_{cell} closely follow one another with Homer T_{cell} always lower than the T_{cell} of Davis and Rauschenbach by a very small margin. In essence, among the three T_{cell} models, the Ross model has the highest T_{cell} whereas Homer model gives the least T_{cell} value.

Based on the meteorological data used in the study, out of the 24 hours in a day, the value of G was zero (0 W/m²) for 13 hours and the value of G was above zero in 11 hours of the first day presented in meteorological data (Table 2). The average ambient temperature and cell temperature for the four models are given in Table 2 and Figure 2. Particularly, the 13 hours of zero value of g did not contribute to the output power. As such, in Table 2, the total value of G for the day over 24 hours is the same as the total G over those 11 hours with none zero value of G. In this paper, only the hours with none zero value of G are used in computing the average cell temperature. Consequently, the average ambient temperature for those none zero output hours is 24.21°C and the corresponding average cell temperatures for the day for the three models are 31.05466°C for Rose model, 29.98247°C and for Davis and Rauschenbach model 29.94282°C for HOMER model. Again, Ross model has the highest average cell temperature for the first day. HOMER model average cell temperature for the day is slightly lower than that obtained from the Davis and Rauschenbach model.

Table 1. *The Ambient Temperature, The Cell Temperature Of The Three Models and The Global Irradiance on The Tilted Plane Versus The Hour of The Day.*

Hour	Global Irradiation On The Tilted Plane (W/m². day)	Ambient Temperature, Ta (°C)	Ross Tcell	Davis and Rauschenbach Tcell	HOMER Tcell
0	0	20.81	20.81	20.81	20.81
1	0	20.01	20.01	20.01	20.01
2	0	20.60	20.60	20.60	20.60
3	0	19.93	19.93	19.93	19.93
4	0	20.04	20.04	20.04	20.04
5	0	20.38	20.38	20.38	20.38
6	0	20.16	20.16	20.16	20.16
7	48	19.60	21.10	20.87	20.87
8	136	20.59	24.84	24.17	24.18
9	198	21.22	27.41	26.44	26.43
10	269	22.64	31.05	29.73	29.70
11	281	23.39	32.17	30.80	30.76
12	441	24.61	38.39	36.23	36.12
13	425	26.72	40.00	37.92	37.79
14	311	28.08	37.80	36.28	36.19
15	202	27.56	33.87	32.88	32.85
16	78	26.55	28.99	28.61	28.60
17	20	25.36	25.99	25.89	25.89
18	0	23.33	23.33	23.33	23.33
19	0	22.72	22.72	22.72	22.72
20	0	21.44	21.44	21.44	21.44
21	0	21.44	21.44	21.44	21.44
22	0	21.07	21.07	21.07	21.07
23	0	21.21	21.21	21.21	21.21

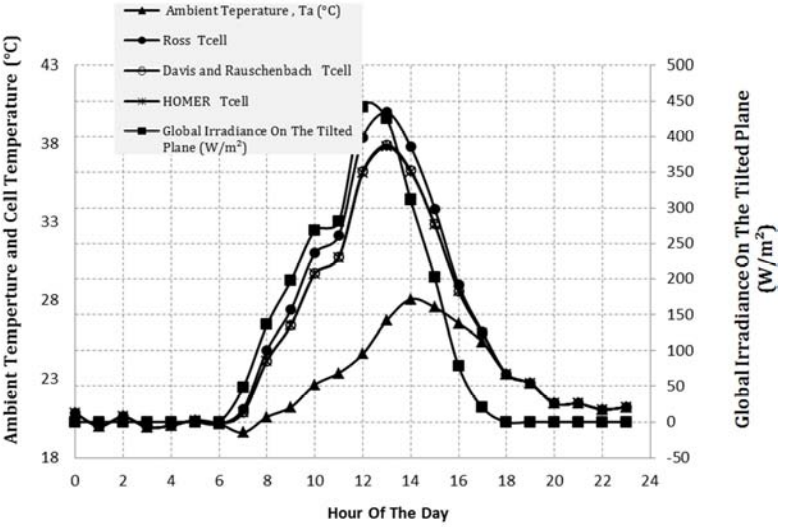

Figure 1. *The Ambient Temperature, the Cell Temperature Of The Three Models and The Global Irradiance on the Tilted Plane Versus The Hour of The Day.*

Table 2. *The Daily Total and Daily Average Values of Ambient Temperature, The Cell Temperature Of The Three Models and The Global Irradiance on The Tilted Plane.*

	Hour	Global Irradiance On The Tilted Plane (W/m²)	Ambient Temperature, Ta (°C)	Ross Tcell	Davis and Rauschenbach Tcell	HOMER Tcell
Total	24	2409	539.46	614.7413	602.9472	602.511
Total	11	2409	266.32	341.6013	329.8072	329.371
Average	24	100.375	22.4775	25.61422	25.1228	25.10463
Average	11	219	24.21091	31.05466	29.98247	29.94282

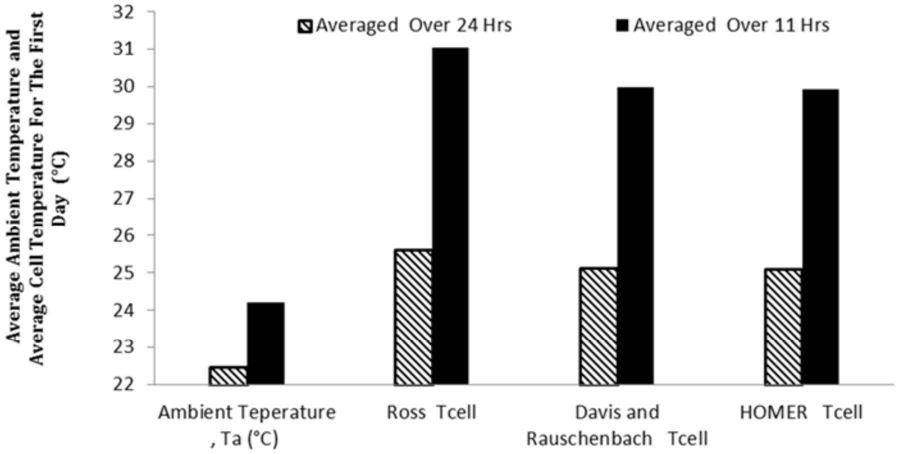

Figure 2. *The Daily Average Values of Ambient Temperature, The Cell Temperature Of The Three Models.*

Based on the meteorological data used in the study, out of the 8760 hours in a year, the value of G was zero (0 W/m²) for 4419 hours and the value of G was above zero in 4341 hours, Table 3 shows that the annual average ambient temperature for those none zero G output hours is 27.59°C and the corresponding annual average cell temperatures for the three models are 38.075°C for Rose model, 37.00°C, for Davis and Rauschenbach model and 36.84°C for HOMER model. Again, Ross model has the highest annual average cell temperature. HOMER model annual average cell temperature is slightly lower than that obtained from the Davis and Rauschenbach model.

According to Table 4, the annual energy output (Wh/year) of HOMER model is the highest followed by that of the Davis and Rauschenbach model. The Ross model has the highest percentage thermal loss whereas the HOMER model has the least percentage thermal loss.

Table 3. *The Annual Total and Daily Average Values of Ambient Temperature, The Cell Temperature Of The Three Models and The Global Irradiance on The Tilted Plane.*

	Hour	Global Irradiance On The Tilted Plane (W/m²)	Ambient Temperature, Ta (°C)	Ross Tcell	Davis and Rauschenbach Tcell	HOMER Tcell
Total over 4341 hours	4341	1551222	119746.7	168222.3	160627.8	159931.8
Averaged over 4341 hours	4341	357.34	27.59	38.75	37.00	36.84

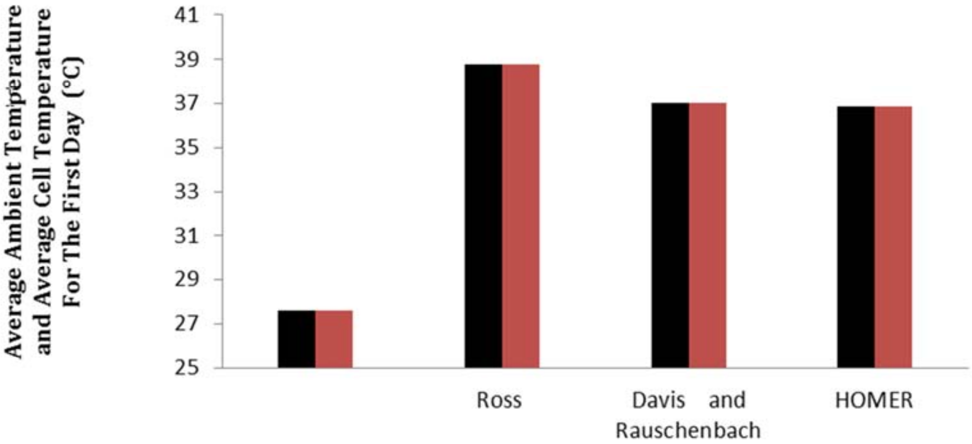

Figure 3. *The annual average values of ambient temperature, the cell temperature of the Three Models.*

Table 4. *The Annual Energy Output and Thermal Loss For Three Models.*

	Ross	**Davis and Rauschenbach**	**HOMER**
Average Ambient Temperature, Ta (°C)	27.58504	27.58504	27.58504
Average Cell Temperature, Tcell (°C)	38.75198	37.00249	36.84216
Annual Output Energy (Wh/year)	264253.4	266598.2	266813.1
Temperature Derating Factor	0.946399	0.954796	0.955566
Annual Thermal Loss (wWh/year)	14966.56	12621.79	12406.91
Percentage Thermal Loss (%)	5.360131	4.520376	4.443418

4. Conclusion

Three NOCT-based cell temperature models are analyzed using the meteorological data of a site in Ibeno, Akwa Ibom state, Nigeria. The cell temperature models are, Ross model, HOMER model and Davis and Rauschenbach model. The results showed that among the three models, the Ross model has the highest cell temperature for any given ambient temperature and solar irradiance. The HOMER Davis and Rauschenbach models have almost the same cell temperature values but the HOMER model gives the lowest cell temperature among the three models. Equally, Ross model has the lowest annual energy yield and the highest thermal loss whereas the HOMER model has the highest annual energy yield and the lowest thermal loss.

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