Validation of Thermal Models for Polycrystalline Photovoltaic Module Under Derna City Climate Conditions

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Abstract: The main objective of the present paper is to compare nine different cell temperature models available in the literature with data measured under real Derna city climatic conditions (a semi arid climate) for month of August. The study focuses on a comparison of nine theoretical models to calculate the cell temperature based on the experimental measurements such as the ambient temperature, irradiance, and wind speed in some of the models. The presently used models are explicit, depending on the easily measurable parameters and of wide applicability. Six statistical quantitative indicators are used to evaluate the cell temperature models analysed, namely, R², RMSE, RRMSE, MAE, MBE and MARE. The cell temperature correlations presently studied, first order linear models depending on the ambient temperature, solar irradiation incident on the panel and voltage output, provide the most accurate cell temperature estimations at Derna city climatic conditions.

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1. INTRODUCTION

There are many factors affecting the performance of a PV module. Amongst these some are meteorological variables such as the incident solar radiation on the module, ambient temperature, module temperature, and wind speed. In the past few decades, with the increasing use of PV systems, several studies were carried out on the impact of meteorological parameters such as temperature, radiation, wind speed etc on the performance of PV systems [1,2]. Rehman and El-Amin studied the effect of module temperature on the performance of the polycrystalline modules and showed the mathematical extent of the dependency of the energy efficiency on the module temperature[3]. Ubertini and Desideri investigated the effect of module temperature on the performance of a 15 kW polycrystalline system installed on a rooftop [4]. The study showed that the efficiency decreased by approximately 0.025% for every 1°C increase in module temperature. In Refs. [5,6] the authors reported that the performance of PV systems is a highly location dependent where the climate and the nature of the installation field affect it relatively significant.

Parretta et al reported that 7% of all energetic losses in PV systems are due to a cell temperature effect [7]. They reported that at an ambient temperature of 25°C PV modules will be operating at temperatures above ambient temperatures. They can lose up to 14% of their energy production. According to Nishioka et al [8], the temperature coefficient dependence of the system performance was analyzed in order to estimate the annual output of the system in an actual operating environment. As a result, it was found that the annual output energy of their PV system increased by about 1% for an improvement of 0.1‰ in the temperature coefficient. The authors in Ref. [9] analysed the influence of varying ambient temperatures on the PV panel temperature and validated models for the prediction of cell temperature based on the measured solar radiation and ambient temperature. Pantic et al evaluated and developed linear and nonlinear models to predict the effect of cell temperature on the output power and efficiency of PV modules using five different models for comparison purpose[10]. The results indicated that the nonlinear model provides the most accurate prediction for the temperature of the PV module.
In Refs. [11-20], the researchers developed various thermal models for PV systems taking into account the wind effect on PV cell/module/array temperature calculations. Amongst these research works, Koehl et al. reported a wind cooling effect of 15-20°C for wind speeds of 10 m/s at a solar irradiance of about 1000 W/m² [19].

In this paper, the main objective is to compare nine different cell temperature models available in the literature with data measured in Derna city. In this regard, the article focuses on the comparison of nine theoretical models to calculate the cell temperature based on the experimental measurements of the ambient temperature, irradiance, and wind speed in some of the models.

1.2. Climate in Derna

Derna is a city in the eastern coast of Libya. In Derna, the monthly average daily irradiation on horizontal surface is 5.27 kWh/m² [21]. The mean monthly values of daily irradiation, temperature, wind speed and relative humidity are illustrated in Figure 1. The maximum average wind speed is 4.8 m/s in February and the minimum value is 3.7 m/s in October. The average maximum temperature in Derna is 26.9 °C in August, while the minimum is 14.4 °C in February. As shown in Figure 1, the relative humidity in April is 54.4% whereas it is 60.9% in July.

![Figure (1). Monthly average ambient temperature, relative humidity, daily solar radiation and wind speed for Derna.](image_url)

2. EXPERIMENTAL SETUP AND METHODOLOGY

The experimental system consists of a polycrystalline type of PV module with 300 WP of nominal power, situated at the top of a building in Derna (32.75 N; 22.63 E), on the eastern coast of Libya. The module is mounted tilted at an angle equal to the latitude (32.7°) of the location, facing due south. Table 1 shows the technical characteristics of the photovoltaic module.
Table (1). Specifications of the PV module presently used

| Electrical specification | Value |
|--------------------------|-------|
| PV model | DS72300 |
| Rated power (Pmax) | 300 W |
| Maximum power voltage (V_{pm}) | 36.5 V |
| Maximum power current (I_{pm}) | 8.22 A |
| Open-circuit voltage (V_{oc}) | 45.3 V |
| Short-circuit current (I_{sc}) | 8.94 A |
| Temperature coefficient for maximum power (P_{max}) | 0.44%/°C |
| Temperature coefficient for open-circuit voltage (V_{oc}) | -0.329 V /°C |
| Temperature coefficient for short-circuit current (I_{sc}) | 0.038 A/°C |
| Cell efficiency | 19.7% |

| Mechanical specification | Value |
|--------------------------|-------|
| Module area | 1.93 m² |
| Weight | 26.7 kg |
| Dimensions LxWxH | 1955x 880 x 990 mm |

| Operating conditions | Value |
|----------------------|-------|
| Ambient operating temperature | -20 °C to 46 °C |
| NOCT | 47.5°C |

The data presented in Table 1 are provided by the manufacturer for Standard Test Conditions (STC) of 1000 W/m² of irradiance level, 25°C of cell temperature, and 1.5 of air mass (AM 1.5). The PV module under study is made up of 72 cells connected in series, each of 0.024 m². Figure 2 shows the photovoltaic module mounted on the roof of a building in Derna, Libya.

Figure (2). Photovoltaic modules mounted at an angle of 32.7° are situated on the top of a building in Derna, Libya
The layout of the experimental system is presented in Figure 3.

![Experimental Setup Diagram](image)

**Figure (3). The layout of the experimental setup**

For the purpose of measuring cell temperature and meteorological variables, the logging interval is set at a one-minute interval using a 3-channel data logger with RS232 & RS485 connector. One temperature sensor (TSA 101 sensor) is installed and fixed on the back surface of the PV module by thermal tape to measure the cell temperature, and another TSA 101 sensor is installed to monitor the ambient temperature. The measurement of solar radiation data is performed with a RK200-03 pyranometer fixed beside the PV module at the same tilt angle as the PV panel. The measurement range for the pyranometer was $0–2000 \text{ W/m}^2$ over the spectral range of 300–3200 nm.

From the literature, a total of nine cell temperature models are chosen to be used in the present study. These models are chosen because they are commonly used in the literature, dependent on easily measurable parameters and widely applicable. The selected models are presented in Table 2. Five days’ worth of PV cell temperature data, collected at the experimental site described above, are used for validating the cell temperature models presently investigated.

**Table (2). Photovoltaic cell temperature models used in the present study.**

| Correlation | Eq. | Comment | Ref. |
|-------------|-----|---------|------|
| $T_{\text{cell}} = 0.943T_a + 0.0195G_t - 1.528V + 0.3529$ | (1) | Linear temperature prediction model | [19] |
| $T_{\text{cell}} = T_a + \frac{G_t}{800}(T_{\text{NOCT}} - 20)$ | (2) | NOCT used in this study is 47.5 °C | [12] |
| $T_{\text{cell}} = 30 + 0.0195(G_t - 300) - 1.14(T_a - 25)$ | (3) | Lasnier 1, for p-Si | [24] |
| $T_{\text{cell}} = T_{\text{ref}} + C_1(G_t - G_{200}) - C_2(T_a - T_{\text{NOCT}})$ | (4) | $C_1 = 0.0175$ and $C_2 = 1.14$ was found by Lasnier | [25] |
| $T_{\text{cell}} = T_a + \frac{G_t(T_{\text{NOCT}} - 20)}{800}[1 - \frac{\eta_{BEC}}{\tau\alpha}] \frac{9.5}{5.7 + 3.8V}$ | (5) | NOCT Dyn 1, use the correlation 1 of McAdams for convection, uses $(\alpha) = 0.81$ | [12] |
| $T_{\text{cell}} = T_a + \frac{G_t(T_{\text{NOCT}} - 20)}{800}[1 - \frac{\eta_{BEC}}{\tau\alpha}] \frac{8.5}{5.7 + 2.8V}$ | (6) | NOCT Dyn 2, use the correlation 1 of Skoplaki for the convection | [13] |
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\[ T_{\text{cell}} = T_a + \frac{1 - \eta_{\text{PVSyst}}}{U_{\text{LO}} + U_{\text{LIV}}} (\tau \alpha) G_T \] (7) PVSyst, \( \eta_{\text{PVSyst}} = 0.1 \), \( U_{\text{LO}} = 29\text{W/m}^2/\text{C} \) and \( U_{\text{L1}} = 0 \text{ W/m}^2/\text{C} \) [20]

\[ T_{\text{cell}} = T_a + k_{\Delta T} G_T \] (8) Skoplaki 2, With \( k_{\Delta T} = 0.02 \cdot 0.04 \text{K.m}^2/\text{W} \) [26]

\[ T_{\text{cell}} = T_a + \frac{S}{U_{\text{LO}} + U_{\text{LIV}}} \] (9) Faiman, use \( S = (\tau \alpha) G_T \), \( U_{\text{LO}} = 30.02\text{W/m}^2/\text{C} \) and \( U_{\text{L1}} = 6.28\text{Ws/m}^2/\text{C} \) [18]

In Table 2, \( T_{\text{NOCT}} \) is the so-called nominal operating cell temperature, which is defined as the temperature of the cell at the conditions of the nominal terrestrial environment, \( I_{\text{NOCT}} = 800 \text{W/m}^2 \), \( T_{\text{a,NOCT}} = 20^\circ\text{C} \), \( T_{\text{ref}} \) is the reference temperature, \( T_a \) is the ambient temperature, \( V \) is the wind speed, \( G_T \) is the intensity of the solar irradiance, \( G_{200} = 200 \text{W/m}^2 \) and \( \eta_{\text{STC}} \) is the module efficiency at STC.

In the related literature, the goodness of different cell temperature models is assessed based on some typical statistical parameters. In the present study, six of such statistical quantitative indicators are used to evaluate the predictive capability of different cell temperature models presently investigated. The quantitative indicators currently used are given as follows:

1. The root mean squared error (RMSE) is also called the root mean square deviation, (RMSD). The RMSE is a frequently used parameter to compare forecasting errors of different models [27]. The lower the RMSE value is, the better the predictive capability of a model in terms of its absolute deviation is. However, presence of some large errors can result in greater values of RMSE. The RMSE is given by,

\[ \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (X_{\text{m},i} - X_{\text{c},i})^2}{n}} \] ................................................................. (10)

where \( X_{\text{m},i} \) is the measured value, \( X_{\text{c},i} \) is the calculated value of cell temperature and \( n \) is the total number of observations.

2. The relative root mean square error (RRMSE) is given by,

\[ \text{RRMSE} = \sqrt{\frac{\frac{1}{n} \sum_{i=1}^{n} (X_{\text{m},i} - X_{\text{c},i})^2}{\sum_{i=1}^{n} X_{\text{m},i}}} \times 100 \] ................................................................. (11)

This indicator is calculated by dividing RMSE by the average value of measured data. According to [28], model accuracy is considered excellent when \( \text{RRMSE} > 10\% \), good if \( 10\% < \text{RRMSE} < 20\% \), fair if \( 20\% < \text{RRMSE} < 30\% \), and poor if \( \text{RRMSE} > 30\% \).

3. The mean absolute error (MAE) is the sum of absolute values of the errors divided by the number of observations. This quantity is often used in statistics to measure how close the calculated values are to the measured values. In [27], the authors pointed out some advantages of MAE over the root mean squared error (RMSE) in dimensioned evaluations and inter-comparisons of average model performance error. It is given by,

\[ \text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |X_{\text{m},i} - X_{\text{c},i}| \] ................................................................. (12)

4. The mean bias error (MBE) [27] is an indicator that expresses a tendency of a model to underestimate (negative value) or overestimate (positive value) a calculated value, while the MBE values closest to zero are...
desirable. The drawback of this test is that it does not show the correct performance when the model presents overestimated and underestimated values at the same time, since overestimation and underestimation values cancel each other. The mean bias error is given by,

$$MBE = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{X_{m,i} - X_{c,i}}{X_{m,i}} \right)$$

5- The mean absolute relative error (MARE). is an indicator that is expressed as average absolute value of relative differences between estimated and measured cell temperature values and is given by,

$$MARE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{X_{m,i} - X_{c,i}}{X_{m,i}} \right|$$

The MARE, when expressed in percentages, is also known as mean absolute percentage error (MAPE) [28].

6- The coefficient of determination (R2) [29] is often used in statistics for estimating the performance of models. It depicts the fraction of the calculated values that are closest to the line of measurement data. While the ideal values of all other statistical indicators used in this study is 0, values of the coefficient of determination close to the unity indicate more efficient models. The coefficient of determination is given by,

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (X_{m,i} - X_{c,i})^2}{\sum_{i=1}^{n} (X_{m,i} - X_{m,avg})^2}$$

$X_{m,avg}$ is the average of the measured data.

3. RESULTS AND DISCUSSION

3.1. Cell Temperature Analysis

The cell temperature of a PV module depends mainly on solar irradiance level incident on the module as well as the ambient temperature. Figure 6 shows the variation of hourly average ambient temperature, cell temperature and the solar irradiance for a particular day in August (2017), measured at the experimental system in Derna city. As seen from the figure, the cell temperature rises from the level of ambient temperature at sunrise to the maximum, which is well above the ambient temperature at around the noon.
As mentioned before, a total of nine cell temperature correlations are being investigated, using five days’ worth of PV cell temperature data collected at the experimental site for validation purposes. The cell temperature values calculated from the correlations are given in Figures 5-13 versus the measured cell temperature values.

Figure (5). The cell temperature calculated by Eq. (1) versus the measured temperatures.

Figure (6). The cell temperature calculated by Eq. (2) versus the measured temperatures.

Figure (7). The cell temperature calculated by Eq. (3) versus the measured temperatures.
Figure (8). The cell temperature calculated by Eq. (4) versus the measured temperatures.

Figure (9). The cell temperature calculated by Eq. (5) versus the measured temperatures.

Figure (10). The cell temperature calculated by Eq. (6) versus the measured temperatures.
An experimental investigation of the performance of a polycrystalline PV module and ...

Figure (11). The cell temperature calculated by Eq. (7) versus the measured temperatures.

Figure (12). The cell temperature calculated by Eq. (8) versus the measured temperatures.

Figure (13). The cell temperature calculated by Eq. (9) versus the measured temperatures.
The statistical parameters presently employed (RMSE, RRMSE, MAE, MBE, MARE and R²) are calculated based on the measured and the estimated cell temperature data for the assessment of the goodness of different cell temperature correlations. The statistical parameters are presented in Table 3. Bold values refer to the most accurate model for the particular indicator. Regarding the statistical parameters presently used, with R² being the only exception, the lower the value is, the more accurate the estimate is. As can be seen from Table 3, the models given by Eqs. 1,3,4,5,6,8 and 9 all return the same R² values. On the other hand, the models given by Eqs. 2 and 7 return R² values of 0.94 and 0.95, respectively. From the table, however, it is interesting to note that the cell temperature correlation given by Eq. 1 provides the most favorable statistical values for the parameters RMSE, RRMSE, MAE, MBE and MARE. It could be safely concluded that the model given by Eq. 1 is by far the most accurate correlation for modeling the cell temperature as far as the presently used data is involved for the city of Derna in Libya.

Table (3). The statistical parameters calculated based on the measured and the estimated cell temperature data

| Correlation (Table 2) | RMSE  | RRMSE | MAE   | MBE   | MARE  | R²  |
|-----------------------|-------|-------|-------|-------|-------|-----|
| 1                     | 1.35  | 0.4   | 1.00  | 0.63  | 0.03  | 0.96|
| 2                     | 9.79  | 2.9   | 9.44  | -9.44 | 0.28  | 0.94|
| 3                     | 3.67  | 1.0   | 3.46  | -3.45 | 0.11  | 0.96|
| 4                     | 6.03  | 1.8   | 5.90  | -5.90 | 0.18  | 0.96|
| 5                     | 4.47  | 1.3   | 4.30  | -4.29 | 0.13  | 0.96|
| 6                     | 4.51  | 1.3   | 4.34  | -4.34 | 0.13  | 0.96|
| 7                     | 6.08  | 1.8   | 5.89  | -5.89 | 0.18  | 0.95|
| 8                     | 4.14  | 1.2   | 3.96  | -3.96 | 0.12  | 0.96|
| 9                     | 3.76  | 1.1   | 3.57  | -3.57 | 0.11  | 0.96|

4. CONCLUSION

The main objective of the present paper is to compare nine different cell temperature models available in the literature with data measured under real Derna city climate conditions for a month of August. Six statistical quantitative indicators (R², RMSE, RRMSE, MAE, MBE and MARE) were used to evaluate the goodness of the cell temperature correlations presently studied. Regarding the statistical indicators, the results show that the correlation given by Eq. (1) provided the most accurate cell temperature estimations for the climatic conditions presently analysed.

5. ACKNOWLEDGMENTS

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6. NOMENCLATURES

Glossary of Symbols & Abbreviations

| Symbol | Description |
|--------|-------------|
| $\tau_a$ | Effective transmittance |
| $\eta_{STC}$ | The module efficiency at STC |
| $G_{stc}$ | Solar radiation for standard test conditions W/m² |
| $I_{sc}$ | Incident solar irradiation Wh/m² |
| $P_{max}$ | Short circuit current of PV module A. |
| $P_{max}$ | The maximum power under standard test conditions W |
| $T_a$ | Ambient temperature °C |
| $T_c$ | Cell temperature °C |
| $T_{ref}$ | Reference temperature °C |
| $V$ | Volt V |
| $V_{mpp}$ | Module's voltage at maximum power V. |
| $V_{oc}$ | Open circuit voltage of PV module V. |
| $X_{ci}$ | Calculated value of cell temperature. |
| $X_{m.avg}$ | Average of the measured data. |
| $X_{m.i}$ | Measure value. |

Abbreviations

| Abbreviation | Definition |
|--------------|------------|
| AC | Alternating Current. |
| AM | Air Mass. |
| DC | Direct Current. |
| MAE | Mean Absolute Error. |
| MBE | Mean Bias Error. |
| MARE | Mean Absolute Relative Error. |
| NOCT | Nominal Operating Cell Temperature. |
| PRMSE | Relative Root Mean Square Error |
| PV | Photovoltaic. |
| $R^2$ | Coefficient of Determination. |
| RMSE | Root Mean Square Error. |
| STC | Standard Test Conditions. |

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