Climate-specific Thermal Model Coefficients for c-Si and Thin-Film PV Modules

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Climate-specific Thermal Model Coefficients for c-Si and Thin-Film PV Modules
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Abstract — The thermal model coefficients (U_c and U_v), similar to the thermal loss factors used in PVsyst for various PV technologies specific to a hot climate are presented in this paper. Minitab, a statistics package was used for the analysis of the data. These coefficients were determined by statistically correlating a year-long data for the modules mounted on free-standing arrays of four PV technologies (crystalline silicon, CdTe, CIGS, a-Si) which experienced hot-desert climate conditions. Various statistical approaches were used to analyze the data. Limiting the wind speed in the one hour interval data showed statistically satisfactory patterns in the model adequacy plots. The U_c and U_v values determined for a-Si module with Tefzel superstrate was higher than the a-Si module with glass superstrate. The lowest U_c and U_v values were observed for CdTe PV technology. For crystalline PV technology, U_v value of 25.46 W/m²°C and U_c value of 4.31 W/m²°C were obtained.

Index Terms — thermal model, thermal loss factors, PVsyst, hot-desert climate

I. INTRODUCTION

Module temperature is influenced by various design, installation and weather factors. The design factors include module technology type, encapsulant type, superstrated type and substrate type. The installation factors include fixed-open rack, rooftop and 1-axis tracking. The weather factors include ambient temperature, irradiance and wind speed. Therefore, predicting the operating temperature of a module in the field is a complex undertaking due to the influence of these interactive factors. Thermal models help to effectively quantify these factors and estimate the module operating temperature by considering their influences. These models help in reducing inherent uncertainty associated with module temperature determination which in turn improve the accuracy of performance models. These accurately determined performance models play an important role to project annual energy production while designing and operating a photovoltaic system.

Various thermal models are being put forward in the photovoltaics (PV) industry based on either theoretical heat transfer approach or the empirical equations using real time field data. And PVsyst is one of the most used commercially available models. PVsyst is a widely-used PC software package for simulation and data analysis of complete PV systems. It defines the thermal loss (for modules) by using thermal model coefficients of U_c and U_v which is further used in predicting the energy output. PVsyst states that thermal behavior is characterized by a thermal loss factor, U which is split into two components: constant U_c component and wind proportional U_v component. PVsyst proposes U_c and U_v values for three different configurations: wind-dependent and wind-independent weather data for modules on free-standing arrays as well as for modules on fully insulated arrays [1]. Based on a year-long field measured data, this study has statistically determined the thermal model coefficients (U_c and U_v) for modules mounted on free-standing arrays of various thin-film and crystalline silicon (c-Si) PV technologies experiencing hot-desert climate conditions. The primary goal of this study is to provide technology-specific and climate-specific thermal coefficients, U_c and U_v, especially for PVsyst.

II. EXPERIMENTAL METHODS

In this study, the data obtained by ASU-PTL in 2000-2002 has been analyzed and presented. The data was collected at Mesa, Arizona on the field installed modules from different manufacturers covering multiple technologies for a long-term field monitoring [2]. Fourteen (14) PV modules that were tested in this test program is shown in Fig. 1.

Fig. 1. Modules installed at ASU-PTL site during 2000-2002. Top: front view, bottom: back view [2]
The technologies are: monocrystalline Si (mono-Si), polycrystalline Si (poly-Si), EFG-polycrystalline Si (EPG-Si), amorphous Si (a-Si), Copper Indium Gallium Diselenide (CIGS) and Cadmium Telluride (CdTe). A set of two modules with same electrical specifications and manufacturers for each PV technology was installed. The modules were installed on an open rack system at the site, which experienced hot desert climate conditions. The modules were maintained at near their P_{max} (maximum power) operating conditions with the help of power resistors. Weather station installed near the test setup monitored the wind speed and direction, ambient temperature, and latitude-tilt global irradiance. All the modules were installed on south facing, latitude-tilt racks with thermocouples attached on the substrate of each module. Table I provides the information about the various PV modules installed on this system along with respective cell technology, front and back sheet material specifications and their manufacturers.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cell Technology</th>
<th>Model Number</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a-Si</td>
<td>US32</td>
<td>USSC</td>
</tr>
<tr>
<td>2</td>
<td>a-Si</td>
<td>US32</td>
<td>USSC</td>
</tr>
<tr>
<td>3</td>
<td>Mono c-Si</td>
<td>SM55</td>
<td>Siemens</td>
</tr>
<tr>
<td>4</td>
<td>Mono c-Si</td>
<td>SM55</td>
<td>Siemens</td>
</tr>
<tr>
<td>5</td>
<td>CIGS</td>
<td>ST40</td>
<td>Siemens</td>
</tr>
<tr>
<td>6</td>
<td>CIGS</td>
<td>ST40</td>
<td>Siemens</td>
</tr>
<tr>
<td>7</td>
<td>EFG-Poly c-Si</td>
<td>50ATF</td>
<td>ASEA</td>
</tr>
<tr>
<td>8</td>
<td>EFG-Poly c-Si</td>
<td>50ATF</td>
<td>ASEA</td>
</tr>
<tr>
<td>9</td>
<td>Poly c-Si</td>
<td>MSX60</td>
<td>Solarex</td>
</tr>
<tr>
<td>10</td>
<td>Poly c-Si</td>
<td>MSX60</td>
<td>Solarex</td>
</tr>
<tr>
<td>11</td>
<td>CdTe</td>
<td>N/A</td>
<td>SCI</td>
</tr>
<tr>
<td>12</td>
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<td>N/A</td>
<td>SCI</td>
</tr>
<tr>
<td>13</td>
<td>a-Si</td>
<td>Millennium</td>
<td>Solarex</td>
</tr>
<tr>
<td>14</td>
<td>a-Si</td>
<td>Millennium</td>
<td>Solarex</td>
</tr>
</tbody>
</table>

The data was stored at every 5-minute interval in the data acquisition system and retrieved periodically. The quality of the collected data was verified periodically by normalized module temperature rise from ambient at 800 W/m² irradiance. Average wind speed measured throughout the year was 1.8 m/s and average ambient temperature was 23.6°C. Average measured plane of array (POA) (annual) during the solar window time was 837 W/m².

III. VALIDATION METHODS

3.1 Thermal models

Various thermal models have been proposed in the industry based on theoretical approach or the empirical equations based on real time data. This paper presents two of those models, which were referred as part of this study.

3.1.1 Faiman module temperature model

David Faiman model uses the simple heat transfer phenomenon to determine module temperature. This approach measured POA irradiance, ambient temperature, wind speed and module temperature for seven module types in order to fit data for heat loss coefficients U_{i} and U_{c} [3]. The equation to determine module temperature is as follows:

\[ T_m = T_a + \frac{a \times EPOA \times (1 - \eta_m)}{U_0 + U_1 \times v} \]  (1)

where

- \( T_m \): module temperature (°C)
- \( T_a \): ambient air temperature (°C)
- \( H \): irradiance incident on the plane of the module or array (W/m²)
- \( U_c \): constant heat transfer component (W/m²°K)
- \( U_1 \): convective heat transfer component (W/m²°K)
- \( v \): wind speed (m/s)

3.1.2 PVsyst thermal model

PVsyst, a PV performance modelling software, have implemented a cell temperature model based on the Faiman module temperature model. The equation to determine the cell temperature is as follows:

\[ T_c = T_a + \frac{a \times EPOA \times (1 - \eta_m)}{U_0 + U_1 \times WS} \]  (2)

where

- \( T_c \): cell temperature (°C)
- \( T_a \): ambient air temperature (°C)
- \( a \): adsorption coefficient of PV module (PVsyst default value = 0.9)
- \( EPOA \): irradiance incident on the plane of the module or array (W/m²)
- \( \eta_m \): PV module efficiency (PVsyst default value = 0.1)
- \( U_c \): constant heat transfer component (W/m²°K)
- \( U_1 \): convective heat transfer component (W/m²°K)
- \( WS \): wind speed (m/s)

3.2 Statistical correlation flowchart

Based on the principles similar to these models, Excel and Minitab were used extensively to statistically correlate the year-long data on a monthly and seasonal basis. The methodology as shown in Fig. 2 was used to correlate the data and determine U_{c} and U_{v} coefficients.

IV. RESULTS AND DISCUSSION

4.1 Determination of \( U_c \) and \( U_v \) values using five-minute interval data for year-long

The five-minute interval data available for one year was used to fit the line and obtain \( U_c \) and \( U_v \) parameters. Even after limiting the y-axis co-ordinate to 120 W/m²°K, the R-square...
Retrieve monthly data with main parameters together: irradiance (W/m²), wind speed (m/s), module temperature (°C) and ambient temperature (°C) at five-minute interval.

- Filter the data for solar window time from 10am to 2pm.
- Calculate the following values: $\Delta T = T_{	ext{mod}} - T_{	ext{amb}}$ and $(\frac{\text{Irradiance}}{\Delta T})$.
- Remove prominent outliers (mainly due to datalogging issues).
- Limit wind speed to 4m/s, which is a maximum feasible limit to keep out the random outliers.
- Plot $(\frac{\text{Irradiance}}{\Delta T})$ versus wind speed.
- Intercept of the line = $U_c$ and Slope of the line = $U_v$.
- Performing model adequacy checking of the residuals to statistically determine the values.
- Average the values for two modules with same model number, cell technology, and manufacturer.

Fig. 2. Flowchart to determine $U_c$ and $U_v$ coefficients.

Determine $U_c$ and $U_v$ values for a year-long data (2001) at five-minute interval for polycrystalline silicon PV technology.

The accuracy of the trend was 0.50 as shown in Fig. 3. Additionally, due to presence of more than 10,000 data points, the residual plot obtained in for a year-long data was difficult to analyze. Therefore, the data for each month for each technology was separately analyzed. The model adequacy plot is shown in Fig. 4. This paper only presents the plots for one module but exact same statistical analysis was performed for all 14 modules of four PV technologies and presented elsewhere [4].

4.2 Determination of $U_c$ and $U_v$ Values using Five Minute Interval Data for Each Month

The five-minute interval data available for about 1 year period was analyzed separately for each month to obtain $U_c$ and $U_v$ values technology-specific for each month and understand the trend. The summer and spring season tend to have higher $U_c$ values as compared to winter and fall seasons. On the other hand, during the summer-spring season, $U_v$ values are lower. Fig. 5 represents $U_c$ and $U_v$ values based on data for each month separately for polycrystalline PV technology.

An average value of the data for all the months was calculated and plotted as per specific technology. Fig. 6. shows the $U_c$ and...
4.3 Determination of $U_c$ and $U_v$ Values using Hourly Interval Data for Year-long

In order to statistically determine the residuals for model-adequacy checking and to remove the outliers causing tailed distribution, the five-minute interval data was converted to hourly interval data for full one year. The regression fit was obtained for a year-long data at one hour interval for polycrystalline Silicon PV technology with an R-square value of 0.69 as shown in Fig. 7.

A random pattern of data points was observed in Fig. 7 for wind speed values of 4 m/s and above. From feasibility point of view, wind speed values greater than 4 m/s affects the energy yield of PV modules and might affect its performance. Therefore, limiting the wind speed to 4 m/s also improved the R-square value and the model adequacy plots followed satisfactory patterns. Fig. 8 represents a sample model-adequacy check plots for PV technology module.

It can be seen that the fitted values follow satisfactory pattern, the mean is normally distributed about zero and follows normal distribution. Therefore, the plots satisfy model adequacy check and the determination of $U_c$ and $U_v$ is statistically correlated. Moreover, the 95% confidence interval was obtained for each of the parameters. Fig. 9 (a) and (b) represents the $U_c$ and $U_v$ values for all replicates of c-Si and thin film PV technology modules respectively.

There is a stark difference between the values for amorphous silicon technology with glass and Tefzel superstrate, because the modules with polymer superstrate operate at lower temperatures than those with glass superstrate. The following trend is observed in amorphous silicon PV modules:

$U_c$ value for a-Si with Tefzel superstrate > $U_c$ value for a-Si with Glass superstrate.

Two ANOVA designs were performed to determine significance of module replicates and PV technology on $U_c$ and $U_v$ values, if any. The p-value for all the cases was obtained to be greater than 0.05 signifying no dominant effect as shown in Table II.

It can be observed from Fig. 10 that the $U_c$ and $U_v$ values for CdTe technology are the lowest. The lowest values for the CdTe modules are attributed to the glass/glass construction type. Considering all the PV technologies, the following trend is observed for the $U_c$ and $U_v$ values:

Polymer-Polymer > Glass-Polymer > Glass-Glass
### ANOVA Design to Determine Significance of Module Replicates (Uc Values)

<table>
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<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
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<tr>
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<td>0.1015</td>
<td>0.1015</td>
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<td>0.762</td>
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<tr>
<td>Error</td>
<td>12</td>
<td>12.7337</td>
<td>1.0611</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
<td>12.8352</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### IV. Summary

This investigation provides the thermal coefficients (Uc and Uv) for thermal models including PVsyst. These coefficients have been developed for both c-Si and thin-film technologies specifically for the hot-desert climatic conditions. It is observed that the values of these coefficients are heavily influenced by the type of construction (glass/glass, glass/polymer, polymer/polymer).

### Acknowledgement

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### References


