Comparative Analysis of Module Temperature Measurements and Estimation Methods for Various Climate Zones Across the Globe

Presented by
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Introduction

- PhotoVoltaic Collaborative to Advance Multi-climate Performance Energy Research (PV CAMPER) [1]
- Network of 12 members with 15 test sites in the major climate zones world-wide formed in 2018

Organizational Objectives:

1. Create a global research platform with common infrastructure to address persistent PV performance challenges.
2. Improve the accuracy of irradiance and other sensor measurements needed for yield comparison and simulations.
3. Identify local environmental contributors to long-term reliability.

Research Projects

- Pyranometer Study
- Albedo Study
- Soiling Study
- Over-Irradiance Study
- Module Temperature Study

[1] Laurie Burnham et al. “Photovoltaic Collaborative to Advance Multi-Climate Performance and Energy Research (PV CAMPER)”, 36th EU PVSEC, Marseille, 2019
## Test Sites

Tab. 1. Description of the test sites.

<table>
<thead>
<tr>
<th>Member Institution</th>
<th>Test Site</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Global POA Irradiance</th>
<th>Back-of-module Temperature</th>
<th>Sensor Fixation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhalt University</td>
<td>GER-BBG</td>
<td>Bernburg, Germany</td>
<td>51.77°N</td>
<td>11.77°E</td>
<td>SMP10-V</td>
<td>PT1000</td>
<td>Double Tape</td>
</tr>
<tr>
<td>CREST</td>
<td>UK-LBOR</td>
<td>Loughborough, United Kingdom</td>
<td>52.76°N</td>
<td>1.24°W</td>
<td>CMP11</td>
<td>PT100</td>
<td>Coooned with gas-flue silicone adhesive sealant</td>
</tr>
<tr>
<td>Sandia National Labs</td>
<td>USA-SNLA</td>
<td>Albuquerque, United States</td>
<td>35.05°N</td>
<td>106.54°W</td>
<td>SMP11</td>
<td>Omega Type T</td>
<td>Tape</td>
</tr>
<tr>
<td></td>
<td>USA-IBMW</td>
<td>Williston, United States</td>
<td>44.27°N</td>
<td>73.68°W</td>
<td>SMP11</td>
<td>Omega Type T</td>
<td>Tape</td>
</tr>
<tr>
<td></td>
<td>USA-FSEC</td>
<td>Cocoa, United States</td>
<td>28.41°N</td>
<td>80.77°W</td>
<td>SMP11</td>
<td>Omega Type T</td>
<td>Tape</td>
</tr>
<tr>
<td></td>
<td>USA-LVRM</td>
<td>Henderson, United States</td>
<td>36.01°N</td>
<td>114.55°W</td>
<td>SMP11</td>
<td>Omega Type T</td>
<td>Tape</td>
</tr>
<tr>
<td>SERIS</td>
<td>SG-SG</td>
<td>Singapore, Singapore</td>
<td>1.28°N</td>
<td>103.87°E</td>
<td>SMP11</td>
<td>PT1000</td>
<td>Double-sided adhesive tape</td>
</tr>
<tr>
<td>UFSC</td>
<td>BRA-BTS</td>
<td>Brotas de Macaúbas, Brazil</td>
<td>12.31°S</td>
<td>42.34°W</td>
<td>CMP11</td>
<td>PT1000</td>
<td>Double-sided adhesive tape</td>
</tr>
<tr>
<td>YU</td>
<td>KOR-GGN</td>
<td>Gyeongsan, South Korea</td>
<td>35.82°N</td>
<td>128.76°E</td>
<td>CMP10</td>
<td>Omega Type T</td>
<td>Tape</td>
</tr>
</tbody>
</table>

![Solar measurement equipment at two of the test sites: BRA-BTS (top) and GER-BBG (bottom).]
Data Analysis

Study goals:

- Comparison between estimated and measured module temperature for different climatic zones and for different PV technologies;
- Comparison between different temperature sensors, measurement techniques, and sensor fixation methods.

**Ross’s model [1]**

\[ T_{Ross} = T_{amb} + kG \]

**Faiman’s model [2]**

\[ T_{Faiman} = T_{amb} + \frac{\alpha G (1-\eta_m)}{U_0 + U_1 WS} \]

Comparison metrics:

- Mean Absolute Error (MAE)
- Root Mean Square Error (RMSE)
- Normalized Root Mean Square Error (nRMSE)
- R-squared (R^2)

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Results

MAE values

Fig. 3. MAE values for the different sites for the two module temperature models analysed.
Results

MAE values

Fig. 3. MAE values for the different sites for the two module temperature models analysed.
Results
UK-LBOR

Fig. 4. Images of the BoM temperature fixation method used at the UK-LBOR test site.

Fig. 5. Measured and modeled module temperatures for September 22nd, 2019 for the mono-Si PV module installed at the UK-LBOR test site.
Results

MAE values

Fig. 3. MAE values for the different sites for the two module temperature models analysed.
Results
BRA-BTS

Fig. 6. MAE values for different levels of irradiance at the BRA-BTS site for the CIGS PV module.

Fig. 7. Correlation between measured and modeled module temperature for the CdTe PV module installed at the BRA-BTS test site.

Fig. 8. Measured and modeled module temperatures for September 22nd, 2018 for the multi-Si PV module installed at the BRA-BTS test site.
Results

MAE values

Fig. 3. MAE values for the different sites for the two module temperature models analysed.
Results
GER-BBG

Fig. 9. Correlation between measured and modeled module temperature for the GER-BBG test site using Ross’s model.

Fig. 10. Correlation between measured and modeled module temperature for the GER-BBG test site using Faiman’s model.
Results

MAE values

Fig. 3. MAE values for the different sites for the two module temperature models analysed.
Fig. 11. Correlation between measured and modeled module temperature for the KOR-GGN test site using Faiman’s model.
Main Findings

- Ross’s and Faiman’s models provide similar results for nearly all sites and PV technologies evaluated, including different climates.
- All sites presented larger errors for high irradiance levels for both models.
- The findings also confirm a correlation between estimation results and the type of module temperature sensor and fixation method employed.

Future work

- Investigate the models’ behaviour according to other parameters: diffuse irradiation, wind speed, fixation method, sensor type and accuracy, ambient temperature and seasonality.
- Analysis of other models for module temperature estimation and other module technologies such as bifacial modules.
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