

Thermal behavior analysis of different solar PV modules via thermographic imaging

Cite as: J. Renewable Sustainable Energy **12**, 013503 (2020); <https://doi.org/10.1063/1.5113763>

Submitted: 07 June 2019 . Accepted: 07 January 2020 . Published Online: 28 January 2020

Divine Kafui Atsu , István Seres, and István Farkas



View Online



Export Citation



CrossMark

ARTICLES YOU MAY BE INTERESTED IN

[Evaluation of solar module equivalent models under real operating conditions—A review](#)

Journal of Renewable and Sustainable Energy **12**, 012701 (2020); <https://doi.org/10.1063/1.5099557>

[Instant hydrogen production using Ga-In-Sn-Bi alloy-activated Al-water reaction for hydrogen fuel cells](#)

Journal of Renewable and Sustainable Energy **12**, 014701 (2020); <https://doi.org/10.1063/1.5124371>

[Multi-objective decision framework for comprehensive assessment of organic Rankine cycle system](#)

Journal of Renewable and Sustainable Energy **12**, 014702 (2020); <https://doi.org/10.1063/1.5129491>

Scilight Highlights of the best new research
in the **physical sciences**

[LEARN MORE!](#)



Thermal behavior analysis of different solar PV modules via thermographic imaging

Cite as: J. Renewable Sustainable Energy **12**, 013503 (2020); doi: 10.1063/1.5113763

Submitted: 7 June 2019 · Accepted: 7 January 2020 ·

Published Online: 28 January 2020



View Online



Export Citation



CrossMark

Divine Kafui Atsu,^{1,2,a)}  István Seres,^{3,b)} and István Farkas^{3,c)}

AFFILIATIONS

¹Mechanical Engineering Doctoral School, Szent István University, Páter K. u. 1, H-2100 Gödöllő, Hungary

²Department of Energy Systems Engineering, Koforidua Technical University, Box 981, Koforidua, Ghana

³Department of Physics and Process Control, Szent István University, Páter K. u. 1, H-2100 Gödöllő, Hungary

^{a)}E-mail: atsud22@yahoo.com. Tel.: +36 308982434.

^{b)}E-mail: Seres.Istvan@gek.szie.hu

^{c)}Author to whom the correspondence should be addressed: farkas.Istvan@gek.szie.hu

ABSTRACT

The temperature of a photovoltaic (PV) system is a critical factor in the photovoltaic conversion process; hence, the practical performance of a PV system significantly depends on its temperature. Several different methods exist for the determination of PV module temperature. In this study, thermography was employed to investigate the thermal behavior of different solar PV modules under outdoor operating conditions. It was observed that the temperature difference across the area of a PV module could reach as high as 12.5–14.8 °C depending on the type of PV module. Hence, the trends for the lowest and highest temperature were not predictable. Glass-to-glass non-frame PV modules exhibited the highest temperature gradients compared to glass-to-Tedlar non-frame modules. The observed temperature gradients demonstrated that measuring the temperature at a single point on the module was not sufficient to accurately represent the temperature over the entirety of the PV module.

Published under license by AIP Publishing. <https://doi.org/10.1063/1.5113763>

I. INTRODUCTION

The temperature of solar modules is a critical factor determining the efficiency of the photovoltaic (PV) conversion process; hence, accurate prediction of the temperature of a solar module is necessary for prediction of the performance of a solar PV system.

In the solar energy conversion process using a PV module, a proportion of the solar radiation is absorbed, and part of it, typically 13%–20%, is converted into electricity, while the remainder is converted into heat.¹ Additionally, heat is generated because of the photovoltaic effect and energy radiated in the infrared region of the solar spectrum.²

The electrical characteristics of a module show a linear relationship with the module's operating temperature. An increase in temperature reduces the bandgap of the solar cell, which results in photons with longer wavelengths being absorbed. Consequently, this leads to a decrease in the open-circuit voltage (V_{oc}), while the increase in the short circuit current (I_{sc}) is insignificant, resulting in an overall reduction in the efficiency of the solar cell.³

Several operating factors affect the temperature of a solar PV module, e.g., solar radiation, ambient temperature, wind speed and

direction, physical properties of the module materials, and the mounting structure. The influence of these factors on the entirety of the module may not be uniform, especially with the effects of 3D wind flow.

Consequently, measuring the temperature of solar modules by placing sensors discretely on the module would neither provide an accurate representation of the thermal behavior of the entire module⁴ nor represent the overall temperature distribution of the module or indicate the average temperature. This temperature value, if used to predict the power output of the system, may result in an over- or under-estimation of the power output. The manufacturer's value of the temperature coefficient for monocrystalline silicon modules is typically around $-0.45\%/^{\circ}\text{C}$. For example, if the measured module temperature value is 8 °C lower, the expected DC output power would have been overestimated by 3.6%, which is a significant value for large PV systems.⁵

The non-homogenous distribution of temperature within the cells in a solar module and within modules in an array could affect the performance of the modules and the system because of the thermal mismatch, which results in differential thermal stress on the solar cells.⁶ The module temperature, apart from being used to predict the

output of a solar module, may also be used to predict its degradation rate.⁷

Uniformity of the module temperature indicates that the module is healthy and does not have any faults. In the case of a defective module, the temperature distribution would be non-uniform because of the effects of the possible defects. An abnormal temperature distribution in a module would aid in finding the location of the defects.⁵

For thermal infrared sensing, detectors that are sensitive to long-wave radiation, generally between 7 and 14 μm , are used. The sensors detect infrared radiation emitted from an object and then transform the infrared energy into a temperature reading. The results are then displayed as infrared images. The infrared signal undergoes detection, scanning, condensing, and amplification before the final image is displayed. The conversion of the radiation into a temperature reading is performed using an algorithm.⁸ Temperature measurements using thermal imaging provide optimal understanding of the temperature distribution of a module under outdoor operation. The pattern and intensity of the infrared radiation emitted by a surface are a function of its temperature. A homogeneous temperature distribution over the surface of a PV module results in a uniform infrared radiation emission pattern.

Irshad *et al.*⁵ measured the temperature of a pc-Si solar module under outdoor conditions via thermal imaging; they employed the color pattern of the IR images to model the temperature of the whole module. The information extracted from the thermal signature of the PV module was used to calculate the temperature of the module. However, this procedure introduced errors because of the imprecise nature of the IR camera. In an attempt to reduce the error introduced by variation in the environmental conditions, all the IR images used were acquired in the time span of two minutes. Hence, the results of these measurements cannot be used to provide a comprehensive explanation of the thermal behavior of the solar module.

Krauter and Preiss⁹ compared four different methods (determination of junction temperature via V_{oc} , cell temperature measurement via cell-attached Pt100 foil-sensors laminated inside the module, surface measurements via attached Pt-100 sensors with and without heat conductive paste, and surface measurements via an attached Pt-100 sensor with different thicknesses of the fixation tape layers to prevent cooling of the sensor from the ambient atmosphere) to determine the operating temperature of a PV module. They concluded that these methods for temperature measurements on the backside of the module were not convincing, and the appropriate method was the V_{oc} method, at least for radiation levels above 200 W/m^2 . Even though this method provides the average junction temperature across the whole module, the disadvantage is that it is an open circuit method and cannot be used under grid-connected conditions in real time.⁵

Maturia *et al.*¹⁰ used thermography for preliminary evaluation of the temperature distribution on the rear of solar PV modules. Measurements were taken during a sunny cloudless day. They used the obtained IR images to show the temperature gradient along a line across the middle of the module; however, the thermal behavior over the entire surface area of the modules was not discussed.

In a study by Fares *et al.*,¹¹ thermography was employed to investigate the effects of temperature on the performance of a pc-Si module. They applied a cooling water jet to modulate the module temperature. However, this process was performed under controlled conditions and would not be feasible for a real system.

Bazilian *et al.*¹² used a qualitative method to interpret the temperature gradients in thermographic images of BiPV modules. They used the output of the infrared camera to study the temperature gradients between the BiPV modules and the metallic roofing.

A literature review of the use of thermography for thermal performance evaluation shows that this method is appropriate for improving the accuracy of temperature measurements. This is because the acquired images directly reduce the error arising from the effects of varying ambient conditions. Thermography approaches have generally been used for single module technology assessments and are mostly qualitative interpretations of the obtained images; hence, they cannot be generalized for other types of PV systems. Because the temperature of the solar cell varies depending on the operating conditions, determining the temperature of the modules requires an approach that considers the whole surface area.

To overcome the observed gaps in the literature, this work focused on studying different categories and orderings of free-standing solar modules under practical outdoor conditions. The captured thermal images obtained using a high-resolution IR camera were quantitatively processed. The proposed new approach, including image filtering, allows for more accurate analysis of the thermal behavior of the modules. Hence, more characteristic temperature profiles can be obtained for the entire module, which can reliably be used for comparison with predictions from theoretical models.

II. EXPERIMENTAL SETUP

The study was conducted in the forecourt of the Solar Energy Laboratory in Szent Istvan University, Godollo, Hungary, which lies at a latitude of $47^{\circ}35'39''$ N and a longitude of $19^{\circ}22'0''$ E on 23 June, 2018. The setup comprised four solar modules with different layers of formation: front glass with a Tedlar back sheet assembly and a front glass back glass assembly. Both module assemblies had similar stack structures with a front glass, an ethylene-vinyl acetate (EVA) encapsulant layer, the electrically active parts, the second encapsulant layer, and finally the back Tedlar sheet or the back glass depending on the configuration. The module specifications are listed in Table I.

The modules were inclined on a fixed support to face south, as shown in Fig. 1.¹³ The measuring equipment and the other materials used for the acquisition of data are shown in Fig. 2. The modules were fixed in proximity to each other to ensure comparable conditions. An infrared (IR) camera with specifications enumerated in Table II was used to capture the IR images. The IR camera was placed perpendicular to the modules and close to the surface. The camera remained fixed at the same position throughout this study. This was to ensure that the images were free from unintended effects such as reflections and shadowing. The emissivity of the modules was assumed to be constant. The solar radiation was measured using a Kimo solarimeter LSL 200 at the level and inclination of the PV modules (resolution 1 W/m^2 , accuracy 5%), while the ambient temperature was measured using an HT-9815 Xintest Pt-100 sensor ($\pm 0.1^{\circ}\text{C}$). An MS6252A-anemometer ($\pm 3\%$) was used for the wind speed measurement. The captured thermographic images of the modules were processed using the Report Generator Lite software. Data collected over three hours (between 11 a.m. and 2 p.m.) were used for the analysis to represent the most critical and more representative period with regard to temperature variation during the day.

TABLE I. Solar module characteristics at STC (25 °C, 1000 W/m², AM 1.5).

Parameter	a-Si (G-G)	mc-Si (G-G)	pc-Si (G-T) (60 Wp)	pc-Si (G-T) (105 Wp)
V _{oc} (V)	62.5	23.4	21.3	29.5
I _{sc} (A)	1.15	9.02	3.8	4.92
V _{mpp} (V)	44.0	19.2	17.1	23.5
I _{mpp} (A)	0.90	8.71	3.5	4.47
P _{mpp} (W _p)	40	165	60	105
Module area/(m ²)	0.791	1.62	0.564	0.826
Temp. coeff. of power	−0.47%/C	−0.40%/°C	−0.47%/°C	−0.47 % /°C
Temp. coeff. of Voc		−0.32%/°C	−0.073% /°C	−0.38 % /°C
Temp. coeff. of Isc		0.05%/°C	0.003% /°C	+0.10 % /°C
Efficiency	5%	10.3%	10.6%	12.6%
Formation of layers	Glass-Glass no frame (G-G)	Glass-Glass no frame (G-G)	Glass-Tedlar with frame (G-T)	Glass-Tedlar with frame (G-T)

III. APPLIED TEMPERATURE MODELS

Different theoretical models were used to compare the predictions with the experimentally acquired and processed module temperature data, which included the maximum, minimum, and average temperatures. The studied models were selected based on how easily obtainable their parameters and variables are, as well as to capture all the factors that affect the temperature of the PV modules.

A. Ross's thermal model

The first is the most common expression for finding the cell temperature of a PV module is Ross's thermal model, which makes use of the nominal operating cell temperature (NOCT) of the module that is given by the manufacturer in the relation expressed by

$$T_c = T_a + \frac{(T_{NOCT} - 20)}{800} \times G_T, \quad (1)$$

**FIG. 1.** Studied solar modules.

where T_c is the cell temperature (°C), T_a is the ambient temperature (°C), and G_T is the measured irradiation (W/m²). This relation is valid only for free-standing PV modules.¹⁴

B. Sandia model for module temperature

The Sandia model to determine the module temperature is

$$T_m = G_T \times (e^{a+b \times WS}) + T_a, \quad (2)$$

where G_T is the solar irradiance incident on the plane of the module (W/m²), T_a is the ambient temperature (°C), WS is the wind speed (m/s), and “a” and “b” are parameters that depend on the module

**FIG. 2.** Data acquisition equipment.

TABLE II. Specifications of the (NEC Avio) IR camera.

Parameter	Specification
Type	H2640
Temperature range	−40 to 500 °C
Spectral range	8–13 μm
Emissivity	0.1–1.00
Basic accuracy	±2% or ±2 °C
A/D resolution	14 bits
Response time	150 ms
Detector	Microbolometer
Focusing range	30 cm to infinity

material and construction as well as the mounting configuration of the module. The values of “a” and “b” for different configurations are listed in Table III.

C. PVsyst temperature model

Faiman presented a module temperature model based on simple heat transfer concepts, which was adapted by PVsyst and is expressed as

$$T_c = T_a + E_{POA} \frac{\alpha(1 - \epsilon_{ta_m})}{U_0 + U_1 \times WS}, \quad (3)$$

where T_c is the module temperature (°C), T_a is the ambient temperature (°C), E_{POA} is the irradiance incident on the plane of the module or array (W/m^2), U_0 is the constant heat transfer component ($W/m^2 K$), U_1 is the convective heat transfer component ($Ws/m^3 K$), α is the adsorption coefficient with a default value fixed at 0.9 in PVsyst, ϵ_{ta_m} is the efficiency of the module, and WS is the wind speed (m/s). For the constant heat transfer component in the expression, the default PVsyst value of $29 W/m^2$ was used for the free-standing mounting. A default value of $U_1 = 0$ was used for the convective heat transfer component.^{10,16}

D. Temperature model used by the Homer software

The equation for determining the module temperature used in the Homer software is given by

$$T_c = \frac{T_a + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{G_T}{G_{T,NOCT}} \right) \left[1 - \frac{\eta_{mp,STC}(1 - \alpha_p T_{c,STC})}{\tau \alpha} \right]}{1 + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{G_T}{G_{T,NOCT}} \right) \left(\frac{\alpha_p \eta_{mp,STC}}{\tau \alpha} \right)}, \quad (4)$$

TABLE III. Parameters of “a” and “b” for different module configurations.¹⁵

Module type	Mount	A	B (s/m)
Glass/cell/glass	Open rack	−3.47	−0.0594
Glass/cell/glass	Close roof mount	−2.98	−0.0471
Glass/cell/polymer sheet	Open rack	−3.56	−0.0750
Glass/cell/polymer sheet	Insulated back	−2.81	−0.0455

where T_c is the module temperature (°C), T_a is the ambient temperature (°C), G_T is the solar irradiance on the plane of the module (W/m^2), $\eta_{mp,STC}$ is the efficiency of the module under standard test conditions (STC), $T_{c,STC}$ is the cell temperature at STC, α_p is the temperature coefficient of power (%/°C), $T_{c,NOCT}$, $G_{T,NOCT}$, and $T_{a,NOCT}$ are the cell temperature (°C), solar irradiance (W/m^2), and ambient temperature (°C) at the operating conditions, respectively. A value of 0.9 was used for $\tau \alpha$ in the equation.¹⁷

IV. RESULTS AND DISCUSSION

In this section, the data are processed and analyzed to characterize the different modules as well as validate the results via comparison with the applied temperature models.

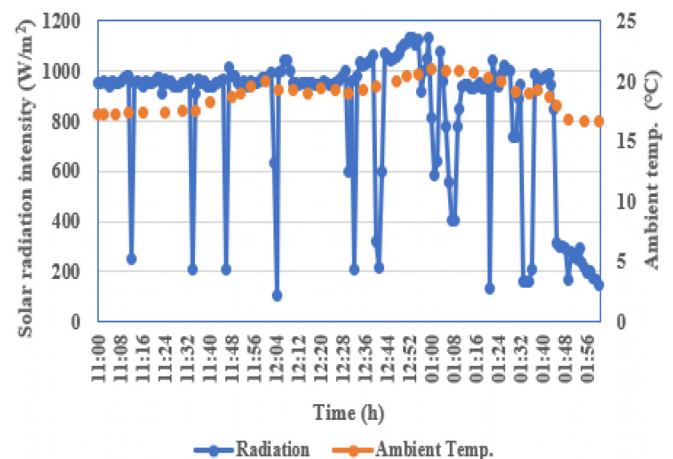
A. Thermal characterization of PV modules

The measured irradiation and ambient temperature for the period of study are plotted against time, as shown in Fig. 3. The maximum, minimum, and average irradiation intensities were $1135 W/m^2$, $107 W/m^2$, and $815 W/m^2$, respectively. The average ambient temperature during the period of the study was $19^\circ C$.

Figure 4 shows samples of the captured and processed thermographic images of the PV modules. The Report Generator Lite software was used to analyze and determine the maximum, minimum, and average temperatures over the aperture area for each module.

The trend for the variation in the temperature of the PV modules is illustrated in Fig. 5. For simplicity, the relative values for the three-hour time period were used instead of the real ones. The trend in the average temperatures of the modules was similar for all the modules studied; however, the a-Si (G-G) non-frame module experienced the highest average module temperatures of $53.32^\circ C$, while the lowest average temperature of $49.35^\circ C$ was recorded for pc-Si (60 Wp), as shown in Fig. 5.

The G-G non-frame modules recorded higher average module temperatures than the G-T frame modules. The lowest minimum temperature of $14.95^\circ C$ was measured for the pc-Si (60 Wp), and the highest of $57.24^\circ C$ was observed for the mc-Si (G-G) modules. The non-frame G-G modules recorded higher maximum temperatures

**FIG. 3.** Plot of irradiation and ambient temperature vs time.

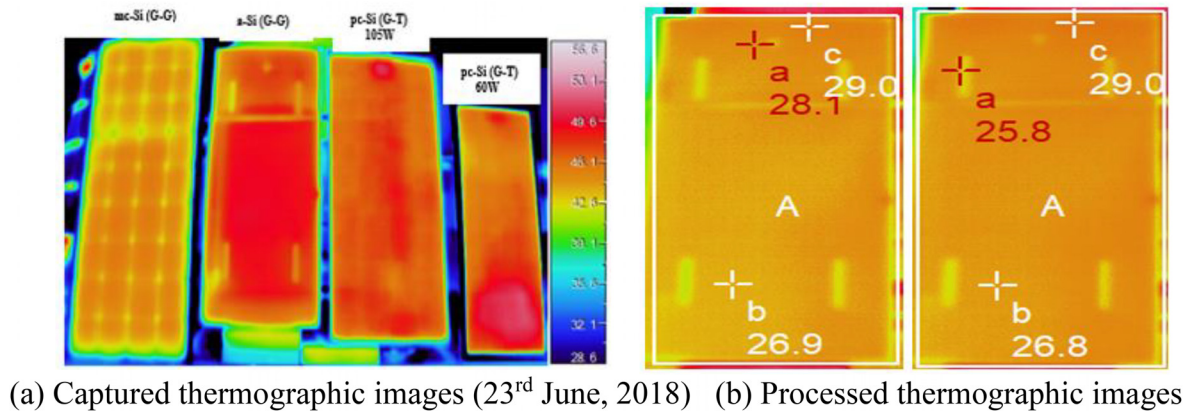


FIG. 4. Thermographic images of the studied PV modules.

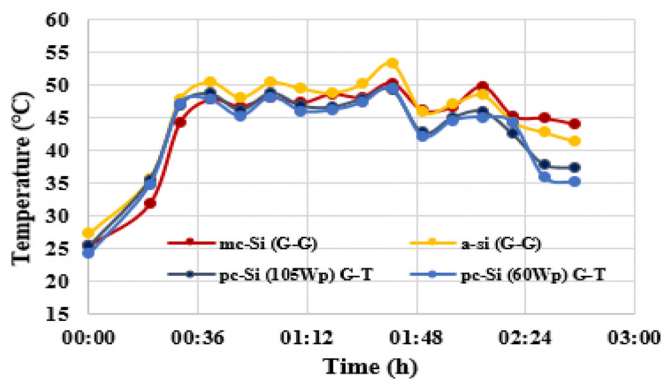


FIG. 5. Variation of the average module temperatures with time.

than the G-T with-frame modules. The average maximum temperature, however, showed a different trend, with pc-Si (105 Wp) G-T recording the highest temperature of 48.31 °C. The variations of the maximum and minimum temperatures from the average temperatures are shown in Tables IV and V, respectively.

Figure 6 shows the temperature gradients of the modules studied. In this case, the temperature gradient was the difference between the maximum and minimum temperature of the modules at a given time t .

The a-Si (G-G) module had the lowest recorded temperature gradient of 4.89 °C among the studied modules. This temperature was recorded at the initial stage when the average temperature was close to

25 °C. Subsequently, 30 min from the end of the process, a-Si (G-G) again recorded the lowest temperature gradient. It was observed that at low average module temperatures, the a-Si (G-G) module maintained a relatively uniform temperature compared to the other modules studied. The a-Si (G-G) module recorded the highest temperature gradient of 14.77 °C during the period of study. This temperature gradient occurred during the period of the highest average recorded module temperature of 53.32 °C. Therefore, it could be determined that the difference between the module temperature and the ambient temperature and the module frame together determine the uniformity of the module's temperature.

Analysis of the processed thermographic images showed that the positions for the maximum and minimum temperature values for each module varied and depended on the conditions at the time the image was captured. In other words, the exact positions of the maximum or minimum temperature over the area of the PV module could not be predetermined.

At high module temperatures, a-Si (G-G) exhibited a large disparity in the cell temperature. The mc-Si (G-G) module demonstrated the highest temperature gradient of 11.38 °C at the start of the study. The pc-Si (G-T) 105 Wp module demonstrated a relatively constant temperature gradient of ~10 °C after 1 h of exposure and up to 40 min before the end of the study. The degree of difference between the maximum and minimum temperatures of the modules over the entire period of the study is shown in Fig. 7.

The results show that the non-frame modules had the highest temperature gradient within the panel (a-Si G-G: 14.8 °C; mc-Si: 14.27 °C) compared to the with-frame modules (pc-Si 105 Wp: 13.93 °C) and (pc-Si 60 Wp: 12.68 °C).

TABLE IV. Deviation of maximum temperature from the average temperature.

	mc-Si (G-G)	a-Si (G-G)	pc-Si (105 Wp) G-T	Pc-Si (60 Wp) G-T
Max.	5.58	4.51	8.35	7.94
Min.	1.81	1.3	1.83	1.31
Ave.	3.30	2.58	5.60	4.10
Stdev.	6.60	6.79	7.00	6.77

TABLE V. Deviation of the minimum temperature from average temperature.

	mc-Si (G-G)	a-Si (G-G)	pc-Si (105 Wp) G-T	pc-Si (60 Wp) G-T
Max.	12.04	10.85	8.71	9.34
Min.	2.45	3.01	2.66	2.34
Ave.	5.81	6.76	4.46	4.64
Stdev.	7.12	6.74	6.67	7.55

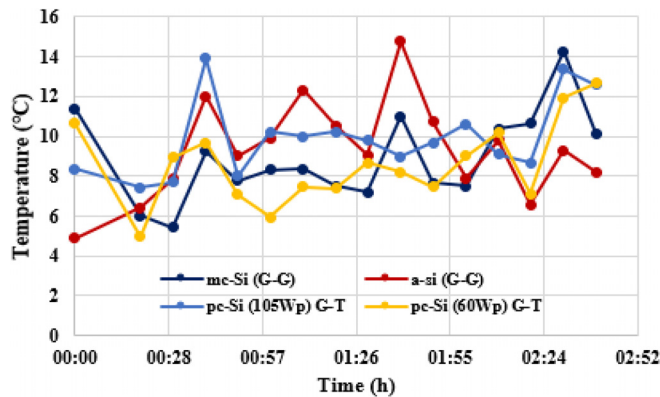


FIG. 6. A plot of the temperature gradient of the PV modules.

The pc-Si (G-T) (60 Wp) module displayed the least temperature difference of 10.1%, while the highest temperature non-uniformity of 11.3% was observed for the pc-Si (G-T) (105 Wp) module. The average difference between the maximum and minimum temperatures for the modules studied was determined to be 10.6%.

B. Evaluation of temperature models

The results of the comparison between the measured module temperatures and the predictions via the theoretical models are presented in Figs. 8–11. It can be observed that each model's prediction is either close to the minimum or the average measured temperatures of the modules. The Ross and Homer models had predictions that were similar and closer to the average temperatures measured for all the PV modules. The prediction of the Sandia model was closer to the measured minimum temperatures for the PV modules. The predictions of the Pvsyst model, however, were between the minimum temperatures and the average temperatures of the PV modules. During the first 20 min of exposure, all the measured temperatures were below the predictions of all four models. The trend changed after 30 min of exposure: at this point, the modules reached a relatively stable temperature. Forty minutes before the end of the study, with decreasing irradiation intensity, all the predicted

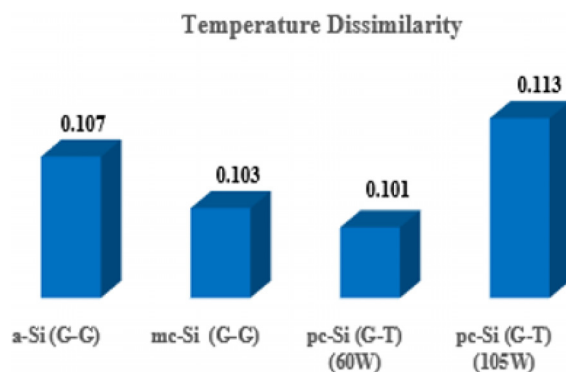


FIG. 7. Difference between the maximum and minimum temperatures of the PV modules.

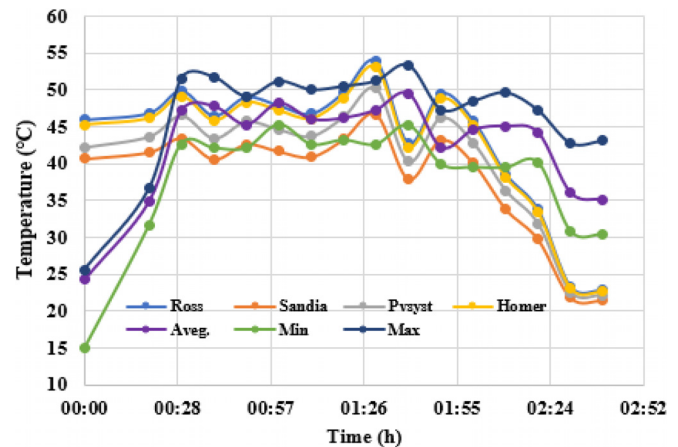


FIG. 8. Comparison of the theoretically predicted temperature with the measured (maximum, minimum, and average) module temperatures for the pc-Si 60Wp (G-T) module.

temperatures were below the measured maximum, minimum, and average temperatures for all the modules. During the periods of high-intensity irradiation, above 1000 W/m^2 , the Ross and Homer models predicted temperatures that were above the measured maximum temperatures for all the modules, except pc-Si 105 Wp (G-T), for which the values were very close but below the maximum temperature.

The root mean square errors (RMSEs) for the temperature predictions of the various models are shown in Tables VI–VIII. The Homer and the Ross models displayed more accurate results for the average temperature for all the modules, with the Sandia model providing relatively good results for the minimum temperatures of the PV modules. The Pvsyst model, however, recorded values that were mostly close to either the minimum or the average temperatures of the modules. The highest errors for the maximum and average temperatures were observed for the Sandia model.

The mean bias error (MBE) was determined for each model to show the precision of the models in relation to the experimental data

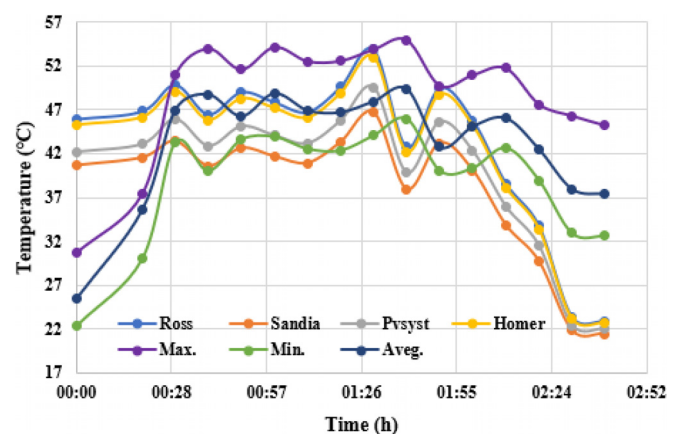


FIG. 9. Comparison of the theoretically predicted temperature with the measured (maximum, minimum, and average) module temperatures for the pc-Si 105Wp (G-T) module.

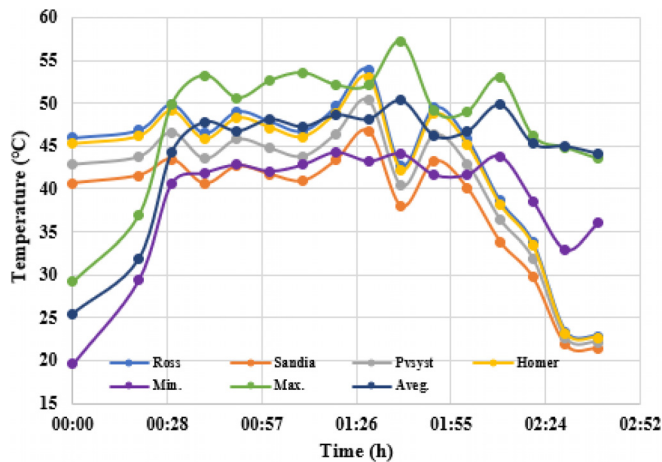


FIG. 10. Comparison of the theoretically predicted temperature with the measured (maximum, minimum, and average) module temperatures for the mc-Si (G-G) module.

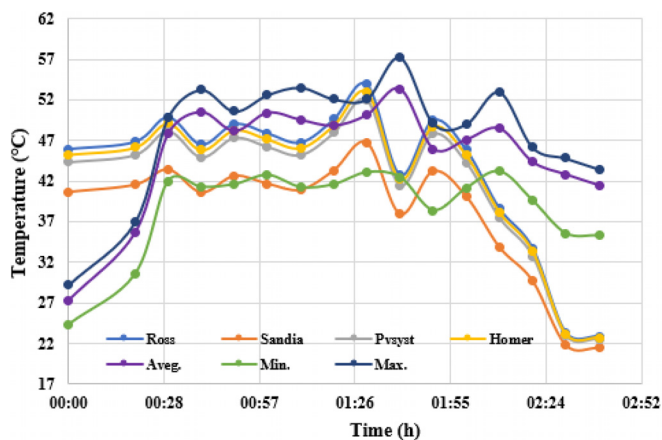


FIG. 11. Comparison of the theoretically predicted temperature with the measured (maximum, minimum, and average) module temperatures for the a-Si (G-G) module.

and whether the predicted module temperatures were overestimated or underestimated. However, because the positive error cancels out the negative error, this process does not indicate the actual deviation from the experimental values but only shows the direction of the resultant

TABLE VI. Comparison of model prediction with maximum module temperature using the RMSE.

Maximum				
Module	Homer	PVsyst	Sandia	Ross
pc-Si (G-T) (60 Wp)	0.0919	0.1047	0.1600	0.0882
pc-Si (G-T) (105 Wp)	0.1090	0.1167	0.1803	0.1015
mc-Si (G-G)	0.1010	0.1058	0.1383	0.0982
a-Si (G-G)	0.0958	0.1025	0.1415	0.0941

TABLE VII. Comparison of model prediction with minimum module temperature.

Minimum				
Module	Homer	PVsyst	Sandia	Ross
pc-Si (G-T) (60 Wp)	0.0948	0.0847	0.0897	0.0998
pc-Si (G-T) (105 Wp)	0.0936	0.0928	0.0895	0.0994
mc-Si (G-G)	0.0936	0.0925	0.0894	0.0994
a-Si (G-G)	0.1030	0.1018	0.0765	0.1057

deviation. The experimental values for the maximum module temperatures for all four modules studied had, on average, higher temperatures than the predicted values for all the four theoretical models. The maximum temperatures were underestimated by the models for all the four PV modules. The highest precision for the predicted maximum temperature values using the MBE was observed for the pc-Si (G-T) (60 Wp) module with the Ross model, displaying an MBE of -3.517 , as shown in Fig. 12(a).

Comparison of the predictions of the theoretical models with the measured minimum module temperatures showed that the Sandia model tended to underestimate the temperature, while the Homer, Ross, and Pvsyst models overestimated the minimum temperatures. The Sandia model displayed the highest precision for the minimum temperatures; MBE values of -0.1448 , -0.9998 , -1.0067 , and -0.8954 were determined for pc-Si (G-T) (60 Wp), pc-Si (G-T) (105 Wp), mc-Si (G-T), and a-Si (G-T), respectively, as shown in Fig. 12(b).

V. CONCLUSIONS

This work studied the thermal behavior and characterized different free-standing solar PV modules via infrared imaging. Analysis of the thermographic images shows that the temperature of the solar modules could deviate from the actual values by as much as 14.8°C , depending on the type of PV module, if accurate measuring methods are not used. This indicates that the DC power output of a module could be over- or under-estimated by a margin of 6.7% based on the temperature coefficient of power.

The non-frame modules displayed a higher temperature difference than the framed modules. The pc-Si (G-T) (60 Wp) module recorded the least temperature difference of 10.1%, while the highest temperature non-uniformity of 11.3% was determined for the pc-Si (G-T) (105 Wp) module.

The Homer model yielded the most accurate prediction for the average module temperatures for all the modules. The RMSEs for the Homer model were 0.07731 for pc-Si (G-T) (60 Wp), 0.07744 for

TABLE VIII. Comparison of model prediction with average module temperature.

Average				
Module	Homer	PVsyst	Sandia	Ross
pc-Si (G-T) (60 Wp)	0.0773	0.0841	0.1210	0.0797
pc-Si (G-T) (105 Wp)	0.0774	0.0824	0.1254	0.0787
mc-Si (G-G)	0.0922	0.0971	0.1178	0.0921
a-Si (G-G)	0.0846	0.0881	0.1198	0.0847

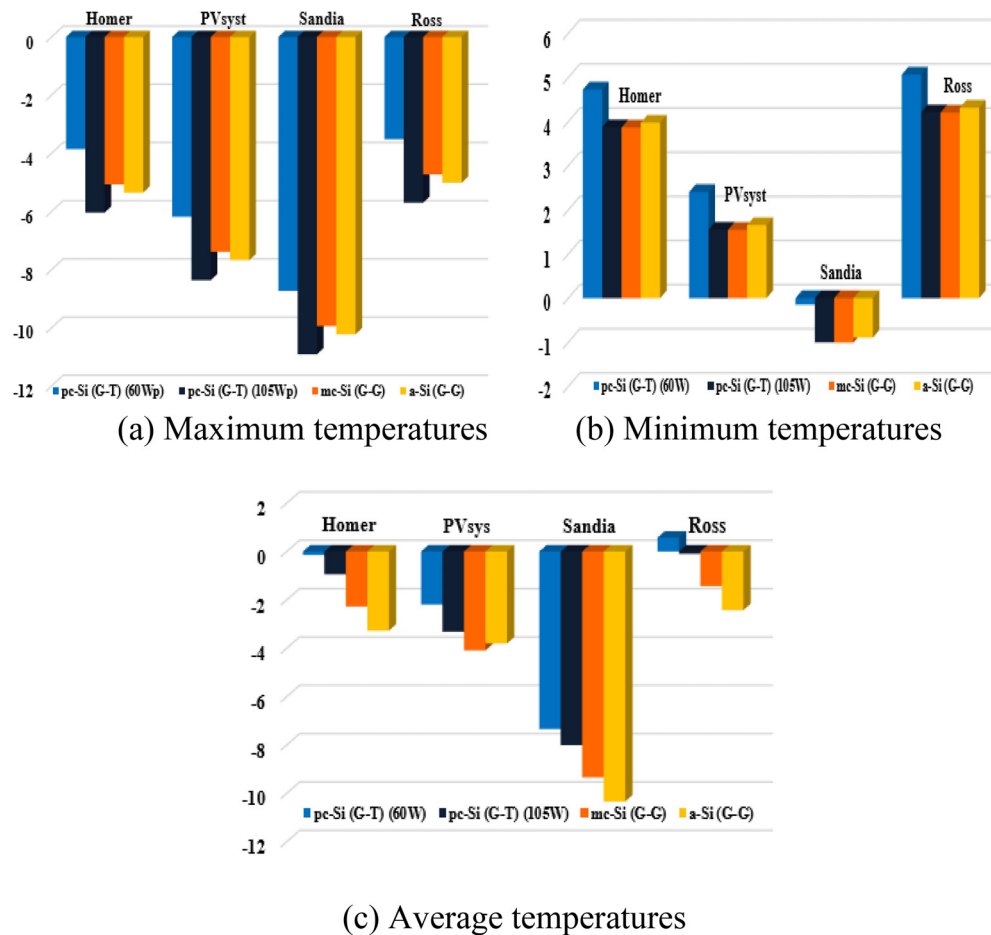


FIG. 12. MBE of predicted module temperatures.

pc-Si (G-T) (105 Wp), 0.09205 for mc-Si (G-T), and 0.08462 for the a-Si (G-T) module. The results showed that 50% of the studied models provided a more accurate prediction for the measured average temperatures: 25% predicted the minimum temperature, while 25% yielded predictions that were close to both the measured minimum and maximum temperatures.

In general, the thermographic approach resulted in more reliable temperature profiles over the entire module. This work demonstrated an improved approach for evaluating the temperature of PV modules; the results can be used for more accurate characterization of the PV module performance, which is reflective of practical application conditions.

ACKNOWLEDGMENTS

This work was supported by the Stipendium Hungaricum Programme and the Mechanical Engineering Doctoral School, Szent István University, Gödöllő, Hungary.

REFERENCES

- ¹J. K. Tonui and V. Tripanagnostopoulos, *Sol. Energy* **81**, 498 (2007).
- ²S. Armstrong and W. G. Hurley, *Appl. Therm. Eng.* **30**, 1488 (2010).
- ³E. L. Meyer and E. E. Van Dyk, *IEEE Trans. Reliab.* **53**, 83 (2004).
- ⁴D. L. King, J. A. Kratochvil, and W. E. Boyson, Technical Report No. 7, USA (2004).
- ⁵Irshad, A. J. Zainul, and H. Ahteshamul, *Infrared Phys. Technol.* **92**, 134 (2018).
- ⁶J. Belmont, thesis, Arizona State University, 2013.
- ⁷R. F. Coelho, F. M. Concer, and D. C. Martins, in Proceedings of the IEEE International Conference on Sustainable Energy Technologies (ICSET '10) (2010), p. 1.
- ⁸P. A. Jacobs, *Proc. SPIE* **TT70**, 79 (2006).
- ⁹S. Krauter and A. Preiss, in 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, USA (2009).
- ¹⁰L. Maturia, G. Belluardoa, D. Moser, and M. D. Buono, *Energy Procedia* **48**, 1311 (2014).
- ¹¹Z. Fares, M. Becherif, M. Emziane, A. Aboubou, and S. M. Azzem, *Smart Innovation Syst. Technol.* **22**, 875 (2013).
- ¹²M. D. Bazilian, H. Kamalanathan, and D. K. Prasad, *Renewable Energy* **26**(3), 449 (2002).
- ¹³A. D. Kafui, I. Seres, and I. Farkas, *Acta Technol. Agric.* **22**, 5 (2019).
- ¹⁴A. Q. Jakhriani, A. K. Othman, A. R. H. Rigit, and S. R. Samo, *World Appl. Sci. J.* **14**, 1 (2011).
- ¹⁵See <https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/module-temperature/sandia-module-temperature-model/> for information about PV performance modeling collaborative - Sandia Module Temperature Model (last accessed November 15, 2018).
- ¹⁶See http://files.pvsyst.com/help/index.html?noct_definition.htm for information about equivalence with the U-factor (last accessed June 12, 2018).
- ¹⁷T. A. Olukan and M. Emziane, *Energy Procedia* **62**, 694 (2014).