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Providing an accurate method for obtaining the efficiency of a photovoltaic solar module

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ABSTRACT

A widely-used correlation to obtain efficiency is considered, and the hypothesis of dividing a photovoltaic module into a number of sub-regions and calculating efficiency of each region employing the temperature of that part to determine the efficiency of the module more precisely is proposed and examined. Experimental data recorded during a year are employed to check the accuracy of the proposed hypothesis and the original method (suggestion of the 61215 standard, where one temperature is considered for the whole module). Comparison of the both hourly and monthly profiles of performance criteria shows that the proposed hypothesis is much more accurate than the original method. It is found that in July, as the sample month for which the hourly profiles are investigated, the average values of the error in prediction of efficiency, produced power, and generated energy are 5.70, 7.72, and 6.07% for the original approach whereas using the proposed hypothesis reduces them to only 1.45, 1.75, and 1.35%, respectively. Moreover, the values of annual average error in prediction of the three aforementioned performance criteria are improved from 4.14, 5.45, and 4.55% in the original method to 1.05, 1.25, and 1.09% for the proposed hypothesis, which is a huge achievement.

1. Introduction

During recent years, using photovoltaic solar modules to utilize solar energy for generating electricity has been significantly grown all around the world. Based on the statistics published by the International Energy Agency [1,2], the installed capacity of the photovoltaic solar modules increased from 256 to 401 GW, only in the range of 2015–2017.

Efficiency is taken into account as one of the most important performance criteria of a photovoltaic solar module (briefly called a solar module) [3–5]. It shows the ratio of the produced electrical power to the received solar irradiance. Efficiency is used for determination of the power, energy, and required area of a PV power generation system [6,7]. As a result, the accurate estimation of this performance criterion is of great importance [8–10].

In the studies that have been conducted in the field of solar modules, two different approaches to calculate the efficiency have been employed. On the one hand, in the experimental studies, obtaining the efficiency has been done by the recorded data for the voltage, current, and radiation, and on the other hand, in the analytical investigations, correlations have been employed for this purpose.

Based on what discussed in several studies such as [11–14], the prediction ability of correlations to calculate efficiency is heavily dependent on the module's temperature (T_{module}), which is one of their inputs. Considering this point, different correlations have been suggested to predict the temperature of a solar module in the literature. Table 1 provides a list of such investigations. As this table shows, despite presenting different functions, all the studies have one point in common; in such investigations, researchers have tried to use a close approximation for "one" value for the temperature of the whole cell or module (T_{module}) to put in the considered correlation for efficiency. Although using one value for the temperature of the whole system gives high accuracy for small cells in the lab scale, for the commercial products, which have much bigger dimensions, considering one value for the temperature of the whole system leads to relatively high errors, as discussed in some references like [15,16].

As a result, considering the mentioned gap of the research, indicated in the previous paragraph, in this study, the hypothesis of

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Nomenclature

A	area (m^2)
G	irradiance ($W.m^{-2}$)
E	generated energy (W.h)
I	current (A)
j	the number assigned to a sub-region
num	number
P	power (W)
t	time (s or h)
T	temperature (°C)
V	voltage (V)
Scripts	
amb	ambient
cal	calculated
center	center
conv	conventional
exp	experimental
end	end
eq	equivalent
hyp	hypothesis
module	module
noct	nominal operating cell temperature
ref	reference condition
sub-regions	sub-regions
start	start
Greek symbols	
β	temperature coefficient for voltage ($\%.(C^{\circ})^{-1}$)
η	efficiency
γ	temperature coefficient for the maximum power ($\%.(C^{\circ})^{-1}$)

dividing a module into some sub-regions and calculating efficiency for each part to enhance the prediction accuracy of efficiency for the whole module is proposed and examined. The most famous correlation in the literature (which is introduced in the section 2.1) is employed to calculate efficiency for each sub-region while the recorded experimental data for the temperature of each part is used as T_{module} for that.

Experiments are conducted for a 60 W polycrystalline solar module during a year. During the experiments, in addition to the data for temperature of each sub-region, more information such as current, voltage, solar irradiance, ambient temperature, and so on is also gathered. The ability of the most frequent method to calculate efficiency (Obtaining “one” value for module’s temperature from the suggested way of 61215 International Standard and putting into the most famous correlation to determine efficiency, which is called the conventional (original) method) and the considered hypothesis is compared together. Moreover, in order to provide an extensive insight, the accuracy of the proposed hypothesis and the original method to predict other key performance criteria of a solar module, including generated power and produced energy is also evaluated. The investigations are done using the hourly profiles for the aforementioned performance criteria on a sample day as well as the monthly profiles throughout the year.

The following structure is considered for this paper. First, the material and methodology part is presented. It contains introducing the employed correlation to obtain efficiency as well as details about the original method and proposed hypothesis. Then, the information about the experimental setup is given. After that, the hourly and monthly results are presented and discussed, respectively, and the ability of the two investigated approaches to predict different performance criteria is compared together. The part described conclusions is also the last section of the paper.

Table 1
A list of the conducted related studies in the field.

Study	A brief description
King [17]	A correlation to determine one value as the operating temperature of a solar module was proposed. Then, the impact of parameters, including outdoor air temperature and irradiance on the performance was investigated through the parametric study.
Skoplaki et al. [18]	A semi-empirical correlation to obtain one value as the operating temperature for the whole module was found. After that, a dimensionless number, called mounting parameter was defined, and the performance of a building-integrated photovoltaic was investigated.
Gottschalg et al. [19]	The performance of six different types of photovoltaic material was compared together by employing the long term recorded data. Comparisons were done from the both energy and environmental aspects.
Segado et al. [20]	This study presented a comparative study among the different models to determine the operating temperature of a solar module. The output for all the models was one temperature for the whole module.
Zhu et al. [21]	Artificial neural network was employed to find a network, which gave one value as the operating temperature of a solar module.
Coskun et al. [22]	A review was conducted on the implicit correlations to find the operating temperature of a solar module. As the study showed, all such correlations predicted one value for the whole module’s surface, which was not realistic.
Gaglia et al. [23]	Using the experimentally measured data for summer and winter, some correlations were found for different performance criteria, including one to predict an operating temperature for the whole module. It was found that the effect of wind velocity is much lower than the outdoor air temperature and irradiance.
Fine et al. [24]	By defining different parameters such as a reduced temperature for the whole module, an approach to predict the performance of a solar module was proposed. The error of the proposed approach was around 4%.
Ma et al. [25]	Using the experimental data, the electrical characteristics for an integrated building photovoltaic system, i.e., current and voltage, were predicted. However, no investigation about the efficiency, power, and current was conducted.
Ba et al. [26]	The experimental data was used to find correlations, by which one value for the operating temperature of a solar module is obtained. Then, the best fit for the distribution of efficiency, power, and produced energy during a year was found.
Gulkowski et al. [27]	A comprehensive comparative study was conducted to find the best photovoltaic system among cadmium telluride, polycrystalline silicon, and copper indium gallium diselenide technologies. For this purpose, an experimental study was carried out in Eastern Poland, which has a moderate climate.
The 61215 International standard [28]	A model, called the nominal operating cell temperature (noct) was provided to estimate one value for the temperature of the whole module. It is taken into account as the most famous way to obtain operating temperature of a module in the literature.

2. Material and methodology

In this section, initially, the correlation employed to obtain efficiency in this study is introduced. Then, the way suggested by the 61215 International Standard to determine the temperature of module, which considers “one” value for the whole module is explained, and after that, the details about the hypothesis of dividing the module into sub-regions and the way to determine other performance criteria are presented. It should be noted that all the input parameters to determine the performance criteria of the solar module in this study are obtained from either the experiments or the catalogue in case they can not be measured.

2.1. The employed correlation to obtain efficiency

As mentioned in the introduction part, the efficiency of a solar module is defined as the ratio of the produced power to the received solar radiation, which means:

$$\eta = \frac{P}{A_{module}\ G} \tag{1}$$

In Eq. (1), η, P, A_{module}, and G are efficiency, produced power, area of module, and irradiance, respectively. As the most popular correlation [29], Eq. (2) is used to obtain the efficiency of a solar module [28]:

$$\eta_{cal} = \eta_{ref}\left\{1 - \beta_{ref}\left(T_{module} - T_{ref}\right) + \gamma \log_{10}(G)\right\} \tag{2}$$

According to Eq. (2), efficiency, which is introduced by η, is calculated as a function of the module's temperature (T_{module}) and irradiance (G). In addition to T_{module} and G, the reference temperature (T_{ref}) and the reference value for efficiency (η_{ref}) as well as β and γ coefficients, which are the characteristics of the investigated solar module, should also be available to determine efficiency from Eq. (2).

2.2. The way to calculate T_{module} in the conventional (original) method

According to what indicated in the introduction part, in the most frequent method to obtain efficiency (which is called the original method here), Eq. (2) is employed to obtain efficiency of a solar module while Eq. (3), which was recommended by 61215 standard [28], is used to predict “one” value for the temperature of the whole module.

$$T_{module,conv} = T_{amb} + \frac{G}{G_{ref}}\left(T_{noct} - T_{ref}\right) \tag{3}$$

, where, G_{ref} and T_{ref} are 800 W m^{-2} and 20 °C, respectively [30]. As mentioned before, since Eq. (3) is the conventional way to calculate T_{module}, here, the conventional (original) method refers to the combination of Eqs. (2) and (3) to determine efficiency.

2.3. The proposed hypothesis

In the proposed hypothesis, a single solar module is divided into some sub-regions. In order to determine number of sub-regions, different methods can be employed. For instance, in the case of the single polycrystalline solar module investigated in this study, as it will be described completely in section 4.1, a thermal imaging camera is used to find number of the parts which have different temperature levels, and each part is considered as a sub-region.

After dividing the single solar module into $num_{sub-regions}$ parts, for each sub-region, Eq. (2) is used to determine efficiency. However, instead of using the introduced correlation (Eq. (3)), the temperature for the center of that sub-region is used to determine the efficiency of that part, and the total efficiency of the solar module is determined by employing the weighted average (Eq. (4)):

$$\eta_{hyp} = \frac{1}{A_{module}} \sum_{j=1}^{num_{sub-regions}} A_j\ \eta_{cal}\left(T_{module} = T_{center,j}\right) \tag{4}$$

in which, $T_{center,j}$ is the temperature for the center of jth sub-region. $T_{center,j}$ can be obtained from a developed numerical method for the heat transfer, a found empirical correlation for that, or other ways. In this study, however, the experimental values for $T_{center,j}$ are employed. The reason is, as mentioned before, all other input parameters to determine the performance are obtained from either experiments or catalogue, and only if the experimental values for $T_{center,j}$ are employed, a fair comparison between the original method and the proposed hypothesis is achieved.

2.4. The way to obtain other performance criteria

This part describes the way to obtain generated power and produced energy of a solar module. As discussed, in addition to the efficiency, generated power and produced energy are other important performance criteria which are investigated here. Moreover, a temperature called equivalent temperature (T_{eq}) is introduced and the way to determine it is given. T_{eq} is another criterion whose values for the original method and the proposed hypothesis are compared.

2.4.1. Generated power

The experimental value of the generated power of a solar module is calculated from multiplying the current by the voltage:

$$P_{\exp} = VI \tag{5}$$

The current and voltage used in Eq. (5) are obtained from experiments. Nevertheless, for the original method and the proposed hypothesis, in which efficiency is directly obtained via a correlation (Eq. (2)), Eq. (6) is employed to compute the generated power:

$$P_{cal} = \eta G A_{module} \tag{6}$$

2.4.2. Produced energy

The trapezoidal rule is employed to determine the produced energy, which is the answer for the following definite integral [31]:

$$E = \int_{t_{start}}^{t_{end}} P\ dt \tag{7}$$

2.4.3. The equivalent temperature of module

For a module, an imaginary temperature called the equivalent temperature (T_{eq}) can be defined. The concept of T_{eq} can be employed for the efficiency values obtained from experiments or the proposed hypothesis. They are indicated as $T_{eq,ex}$ and $T_{eq,hyp}$, respectively.

$T_{eq,ex}$ is a temperature for the whole system at which the efficiency obtained from Eq. (2) will be equal to the recorded value from experiment. When all other parameters except for the temperature of module is fed into Eq. (2), $T_{eq,ex}$ is analytically calculated by solving the obtained linear equation as follows:

$$T_{eq,\exp} = T_{ref} + \frac{1}{\beta_{ref}}\left\{1 - \frac{\eta_{\exp}}{\eta_{ref}} + \gamma \log_{10}(G)\right\} \quad (8)$$

If instead of the experimental value of the efficiency ($\eta_{\exp}$), the one obtained from the proposed hypothesis (η_{hyp}) is replaced, the equivalent temperature for the suggested hypothesis (the modified approach) is obtained:

$$T_{eq,hyp} = T_{ref} + \frac{1}{\beta_{ref}}\left\{1 - \frac{\eta_{hyp}}{\eta_{ref}} + \gamma \log_{10}(G)\right\} \quad (9)$$

3. Experimental study

A 60 W polycrystalline solar module with the specifications given in Table 2, is investigated in this study.

All the experiments were carried out in Tehran, Iran, during a year starting from January to December of 2019. The information on the changes in the average received solar irradiance on the horizontal surface and the average ambient air temperature at the location of experiments, which is obtained from the experimental measurements by the research team, are presented in Fig. 1 and Fig. 2, respectively. Data for current, voltage, irradiance, ambient temperature, and temperature of the module was recorded from 8:00 in the morning to 16:00 in the afternoon. Recording data was done every 10 min. A thermal imaging camera was also employed to find number of sub-regions based on the point mentioned in section 2.3.

Moreover, as Fig. 3 shows, in order to conduct the experiments, a steel frame was designed and built, and the solar module was installed on that. Having installed the module on the frame, facing the south, the data for current, voltage, ambient temperature, as well as temperature on the module's surface was recorded by the measurement devices introduced in Table 3. Moreover, according to the recommendation of several references like [33], the tilt angle was adjusted to the latitude of the location (35.7 °N).

4. Results and discussion

As the name suggests, in this part, the results are presented and discussed. First, in section 4.1, the data recorded by the thermal imaging camera, based on which number of sub-regions is determined for the investigated module, is given. After that, in section 4.2, the hourly profiles of performance criteria for one sample day in July, i.e., July 15, 2019, are employed to compare the values obtained from the proposed hypothesis, original method, and experiments. It is worth mentioning that July is the month with the highest solar irradiation in the site location [37–39]. Moreover, the variation trends are also discussed in section 4.2. Next, in section 4.3, the accuracy of the proposed hypothesis and the original method to predict different performance criteria throughout a year is evaluated by comparison of the monthly error values. Finally, in section 4.4, considering the vital role of error level on the results of a study [40–43], error analysis is done.

4.1. Determination of number of sub-regions

As described earlier, in the current study, number of sub-regions is found by employing a high-resolution thermal imaging camera. It is equal to the number of parts with different temperature levels, which makes a grid pattern.

According to the pictures captured during experiments, 16 sub-regions can be identified for the investigated solar module. Fig. 4 shows one of the captured photos, which was captured on August 15, 2019, at 14:10. Therefore, in order to employ the proposed hypothesis for the 60 W investigated solar module, it is divided into 16 sub-regions.

4.2. Detailed comparison of the hourly profiles of performance criteria for July

Using the experimental data for a sample day in July, as the month with the highest solar irradiation in the site location, the ability of the original (conventional) method and the proposed hypothesis to predict T_{module}, efficiency, and produced power are compared together. The hourly profiles for July 15, 2019, which are shown in Fig. 5 to Fig. 7, are employed for this purpose. In addition, at the end of this part, the accuracy of the conventional and presented approaches to predict generated energy in the investigated period are also compared. The measured experimental data used to obtain the hourly profiles of this part is reported in Appendix A.

4.2.1. Temperature of the module (T_{module})

The previously recommended (The prediction of Eq. (3), indicated as $T_{module,conv}$ in the text), and the equivalent values for temperature of the module ($T_{eq,\exp}$ and $T_{eq,hyp}$) are compared together in different times of the sample day in Fig. 5. This figure shows that $T_{module,conv}$ is significantly higher than $T_{eq,\exp}$ and $T_{eq,hyp}$. The higher the level of irradiance is, the more difference in $T_{module,conv}$ and two other investigated temperatures ($T_{eq,\exp}$ and $T_{eq,hyp}$) is observed. At 9:00, $T_{module,conv}$, $T_{eq,hyp}$, and $T_{eq,\exp}$ are 49.8, 41.3, and 40.8 °C while at 11:30, they reach 69.5, 52.6, and 51.8 °C,

Table 2
Specifications of the studied solar module [32].

Parameter	Value	Unit
Manufacturer	Yingly Company	–
Module type	Polycrystalline Si-based	–
Type of module	YL60P-17b 3/7	–
Dimensions	670×660 × 25	mm × mm × mm
The rated produced power	60	W
The maximum efficiency	13.50	%
Voltage at the maximum produced power point	18.30	V
Current at the maximum produced power point	3.28	A
Open-circuit voltage	22.10	V
Short circuit current	3.66	A
Nominal operating cell temperature (T_{noct})	46	°C
Temperature coefficient for the maximum power (γ)	−0.45	%.(C°)$^{-1}$
Temperature coefficient for voltage (β)	−0.37	%.(C°)$^{-1}$

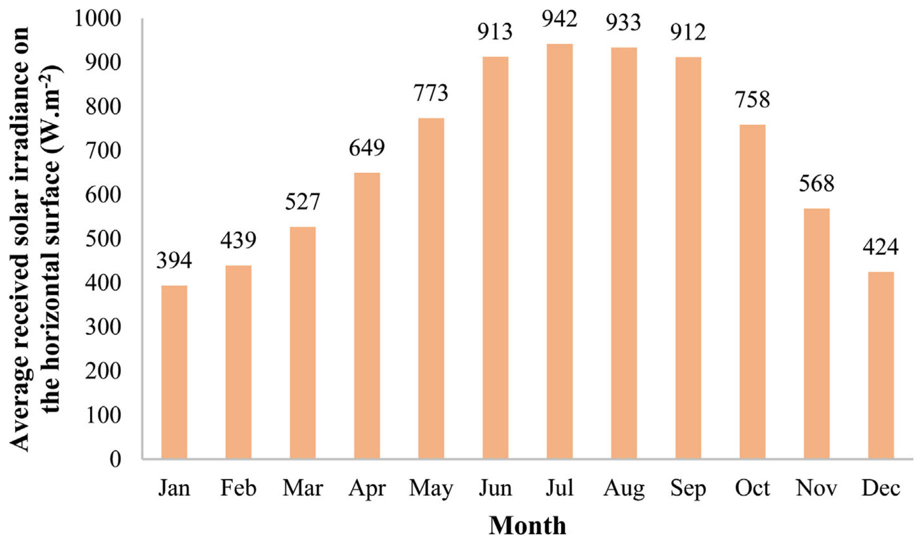

Fig. 1. Changes in the monthly average received solar irradiance on a horizontal surface at the location of experiments, which were obtained from the measurements by the research team.

respectively.

Moreover, according to the obtained results, the values of $T_{eq,\exp}$ and $T_{eq,hyp}$ are close together, which shows that the proposed hypothesis provides higher accuracy for prediction of the efficiency and other related performance criteria. The point is investigated in details in the subsequent sub-sections, i.e., parts 4.2.2, 4.2.3, and 4.2.4.

4.2.2. Efficiency

The values of efficiency obtained from the original (conventional) method, the proposed hypothesis, and the experiments are compared together in Fig. 6.

According to what discussed in part 4.2.1, since the calculated temperature from Eq. (3) is higher than $T_{eq,\exp}$, the efficiency calculated by the conventional method is much lower than the experimental value. The difference becomes more significant at higher levels of irradiance, i.e., around noon. The highest difference is for the peak of solar irradiation, i.e., 12:30, where the calculated efficiency from the conventional approach is 0.7% less than 11.8% determined by measurement. It is a huge difference in efficiency.

On the other hand, the efficiency obtained based on the mentioned hypothesis is so close to the experimental values. Not only the value but also the variation trend is predicted much more accurately than the conventional approach. On the investigated day, i.e., July 15, 2019, the mean absolute error of prediction by the conventional method is 5.70% whilst the corresponding value for the proposed hypothesis is only 1.45%. Therefore, employing the introduced method results in a significant improvement in the estimation of the efficiency, and consequently, the performance of a solar module.

4.2.3. Generated power

The hourly profiles of power generated by the solar module obtained by the experiments, the conventional way, and the

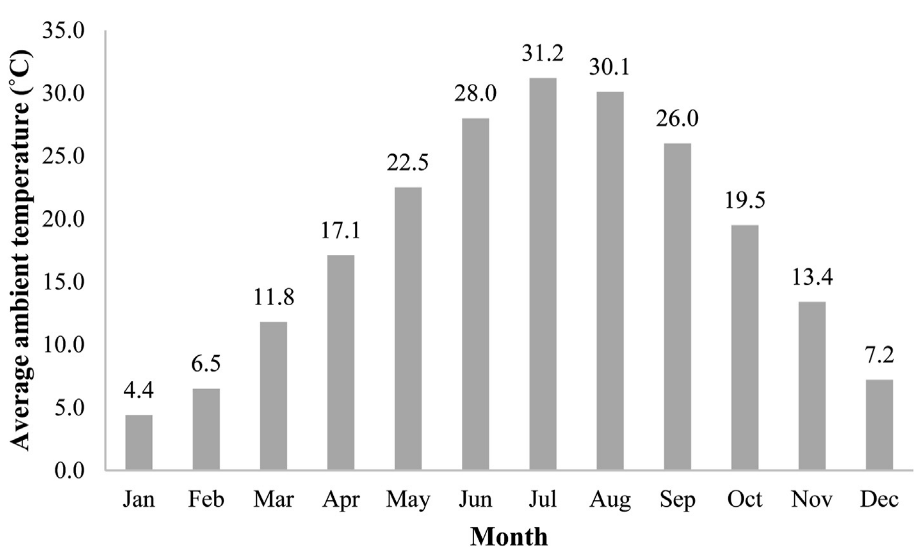

Fig. 2. Changes in the monthly average ambient temperature at the location of experiments, which were obtained from the measurements by the research team.

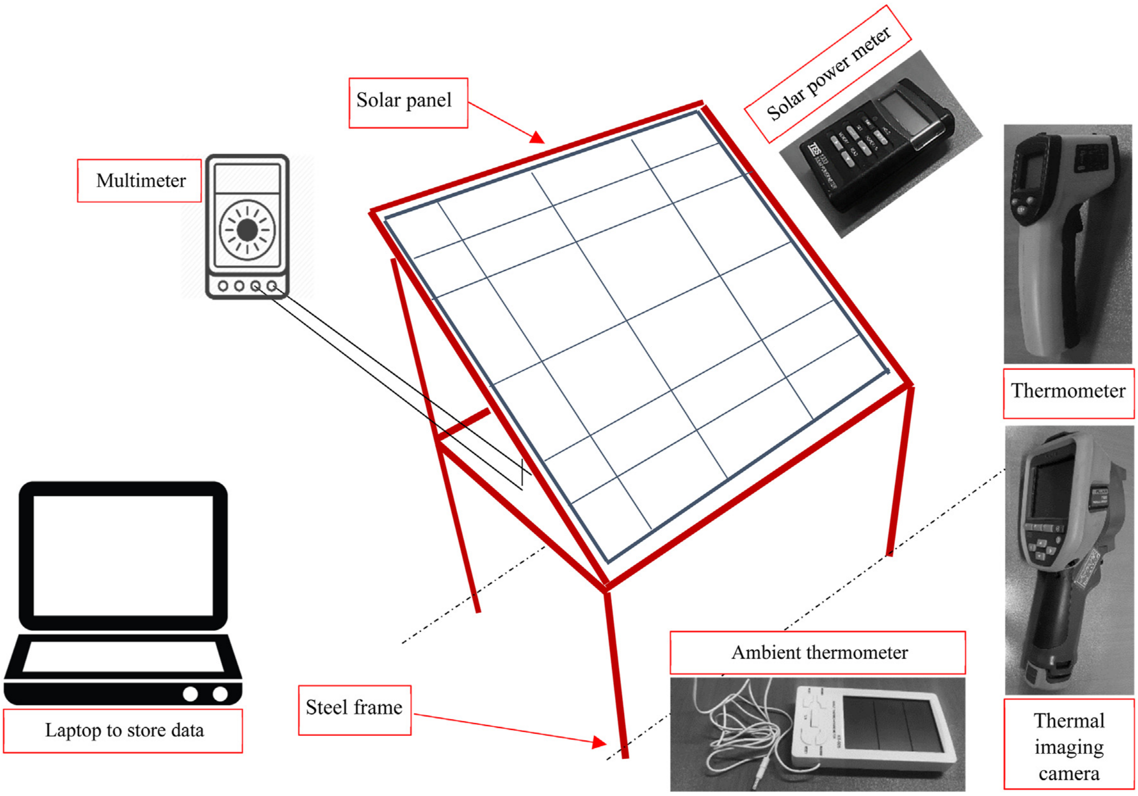

Fig. 3. Schematic of the experimental setup.

proposed hypothesis are shown in Fig. 7. This figure reveals that like the efficiency, the presented approach to divide the module into some sub-regions is able to predict both trend and values much more precisely whereas the conventional method has relatively higher error values; the average error for estimation through the introduced way (7.72%) is 4.4 times bigger than the proposed hypothesis (1.75%).

4.2.4. Produced energy

In Fig. 8, as the main output of a solar module, values of the generated energy during the investigated period, which are obtained from the measurement and the two other ways are compared together. The period is from 8:00 to 16:00 of the investigated day, i.e., July 15, 2019. It should also be mentioned that as indicated before, the produced energy is calculated by employing trapezoidal rule from Eq. (7). As observed, the actual value is 378.70 W h while estimation of the conventional approach and the proposed hypothesis are 355.71 and 373.59 W h, respectively. It means that using the conventional way leads to 22.99 W h underestimation of the produced energy. The difference decreases

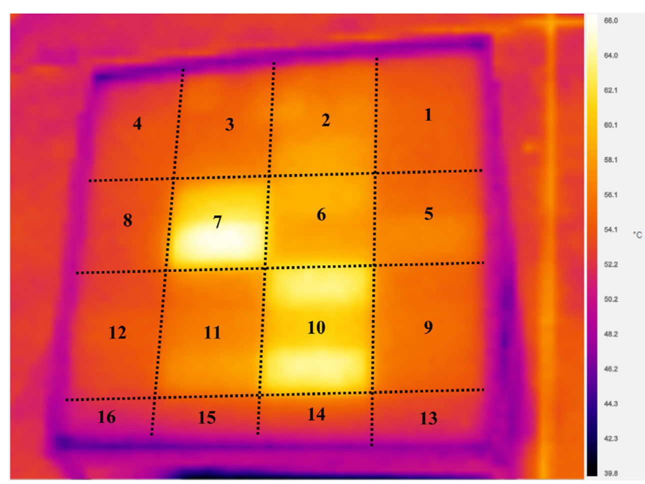

Fig. 4. The photo captured by the thermal imaging camera on August 15, 2019, at 14:10; in this picture, the sub-regions are also shown.

Table 3
List of the devices used to record data [34–36].

Device	Parameters measured by the device	Model	Accuracy	The maximum error (%)
Ambient thermometer	Ambient temperature	KT-905	0.1 °C	2.5
Infrared thermometer	Temperature on the module's surface	Benetech GM 320	0.1 °C	2.5
Solar power meter	Irradiance	TES-1333	10 W m^{-2}	0.5
Multimeter	Voltage	Hytals TS98A	0.1 V	1.0
	Current		0.1 A	2.0
Thermal imaging camera	Temperature distribution on the module's surface	Fluke TiS20	2 °C	2.0

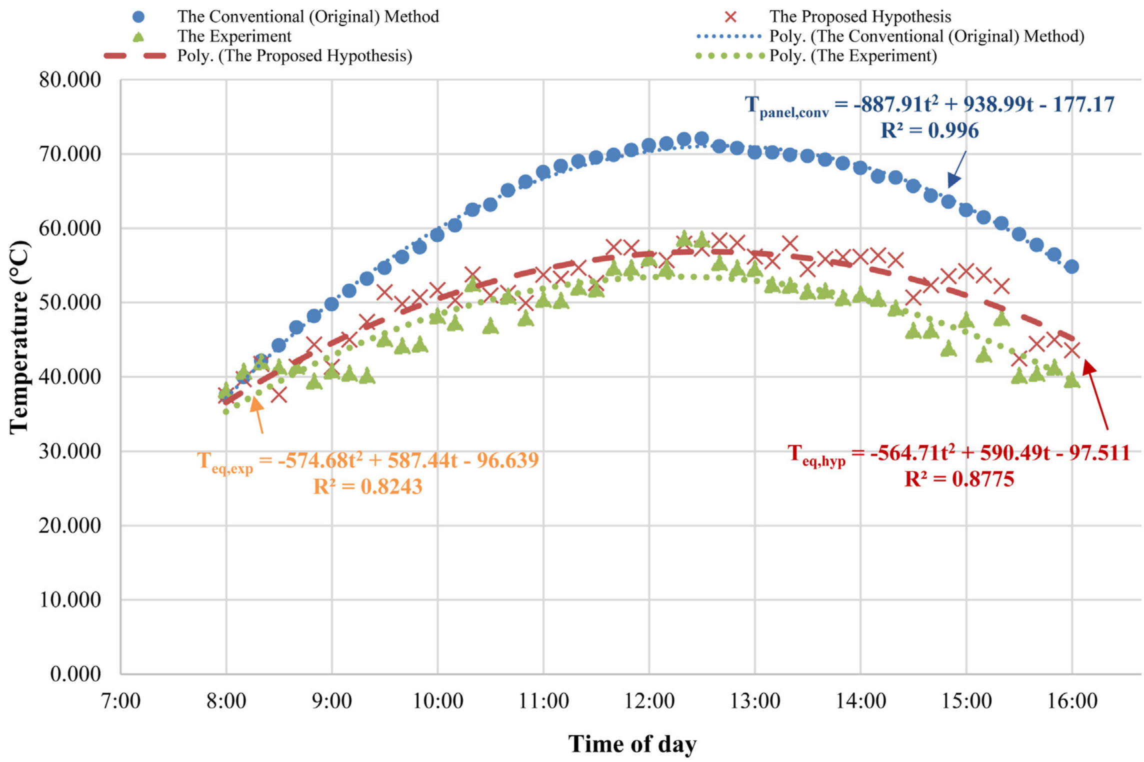

Fig. 5. Comparison of the values of the temperature of module obtained from the conventional (original) method, and the module's equivalent temperature for the proposed hypothesis and the experimental condition on July 15, 2019.

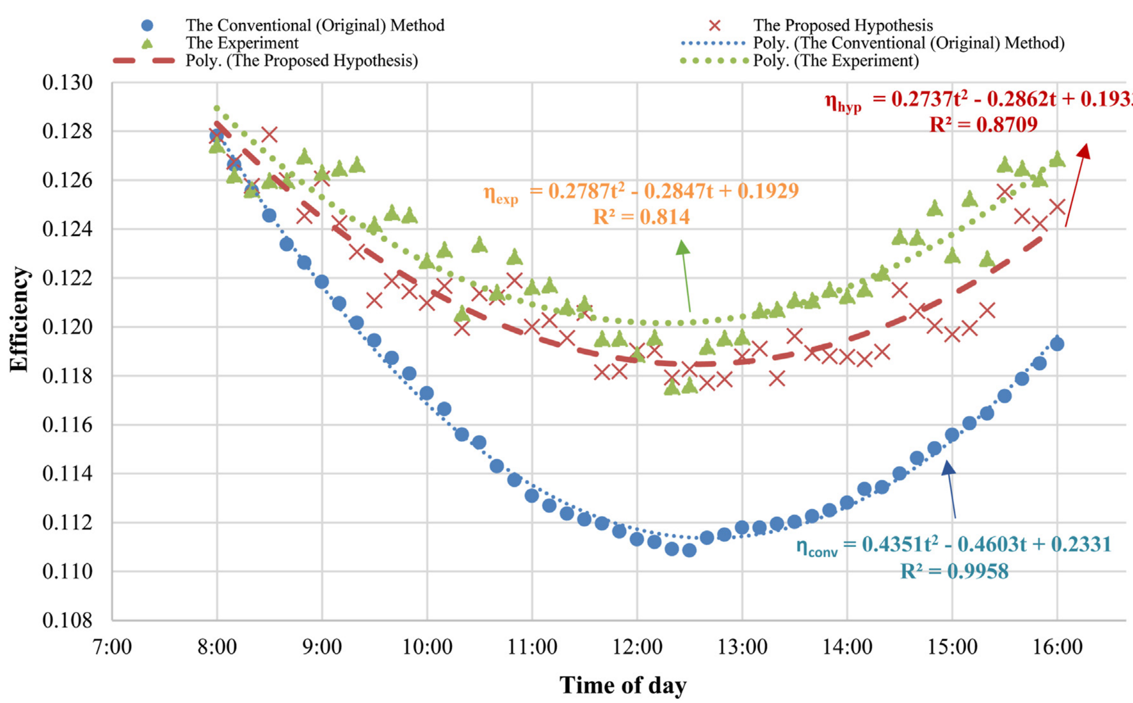

Fig. 6. Comparison of the efficiency of the solar module obtained from the conventional (original) method, the proposed hypothesis, and the experiments on July 15, 2019.

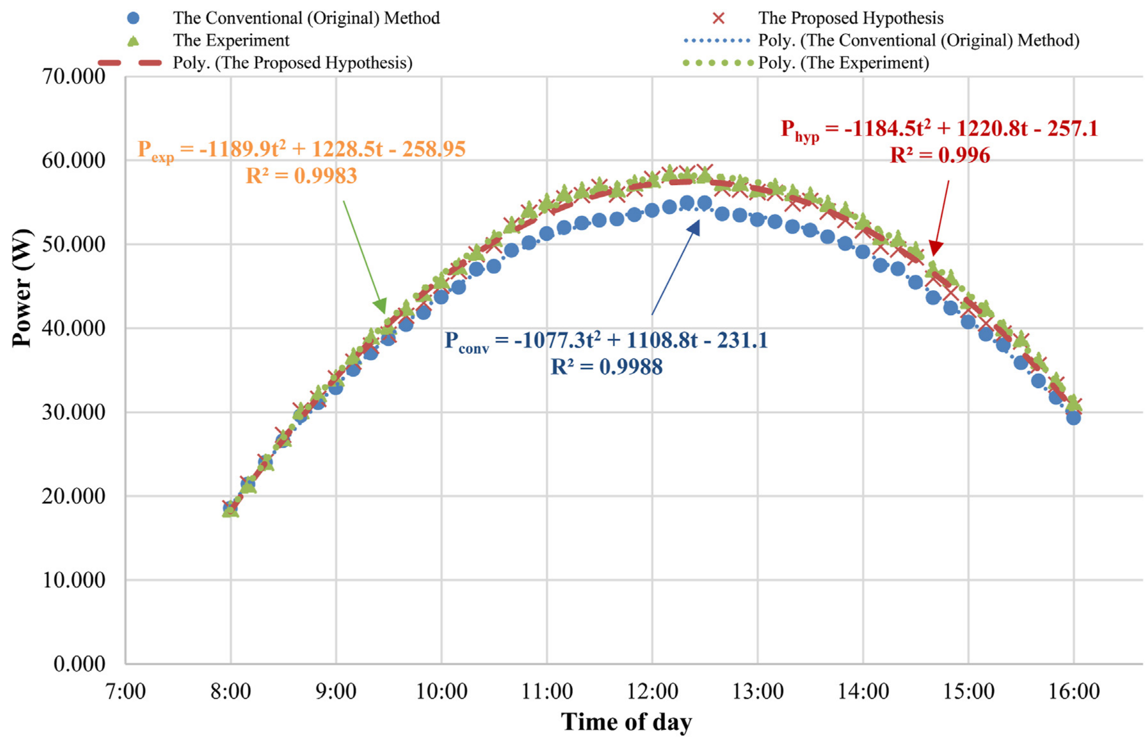

Fig. 7. Comparison of the generated power of the solar module obtained from the conventional (original) method, the proposed hypothesis, and the experiments on July 15, 2019.

significantly and reduces to the two-ninth for the suggested method, in which the prediction is only 5.11 W h lower than the measurement.

More accurate prediction of the produced energy not only helps to get to know the technical performance of a solar module better, but also has economic benefits. When prediction provides a smaller underestimation of the produced energy, constant energy demand is met by a lower area of the solar modules, which means the lower payment for both initial and operating costs.

4.3. Comparison of the prediction ability for monthly profiles of performance criteria

In the previous part, it was shown that the proposed hypothesis has more level of accuracy in comparison with the conventional method to calculate the performance criteria for the studied sample day, i.e., July 15, 2019. Having proven this point, here, the prediction ability of the proposed hypothesis compared to the original method is evaluated during a year.

The results are presented in Fig. 9, Fig. 10, and Fig. 11, which

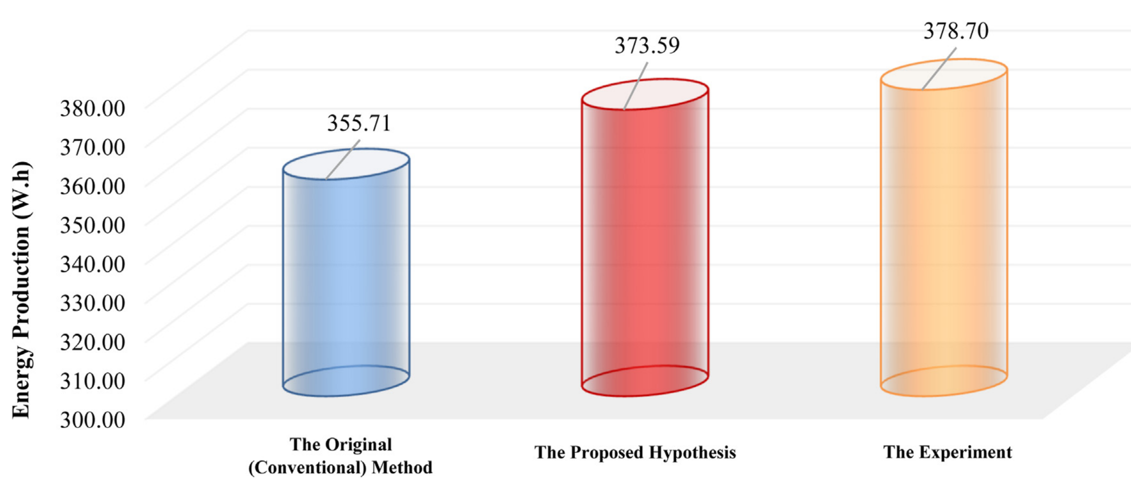

Fig. 8. Comparison of the energy production of the solar module obtained from the conventional (original) method, the proposed hypothesis, and the experiments in the period of 8:00 to 16:00 of the investigated day, i.e., July 15, 2019.

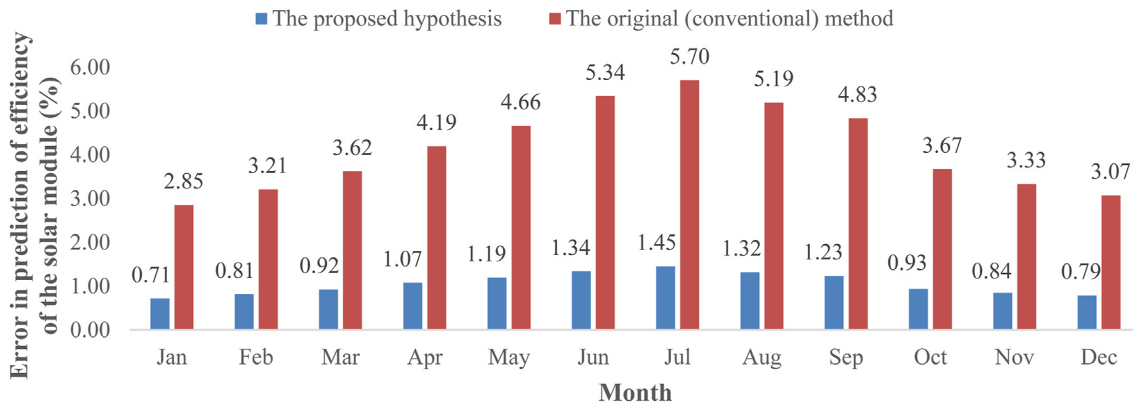

Fig. 9. Comparison of the monthly average error in prediction of efficiency of the solar module obtained from the conventional (original) method and the proposed hypothesis.

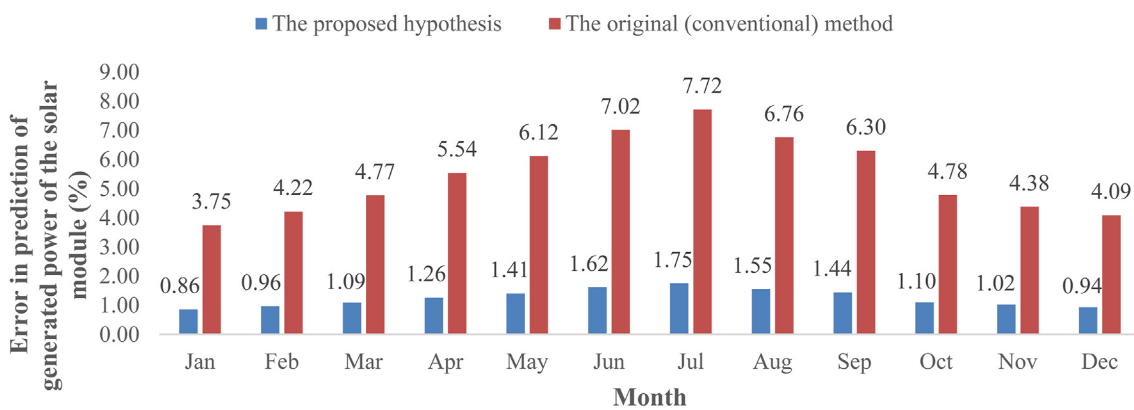

Fig. 10. Comparison of the monthly average error in prediction of generated power of the solar module obtained from the conventional (original) method and the proposed hypothesis.

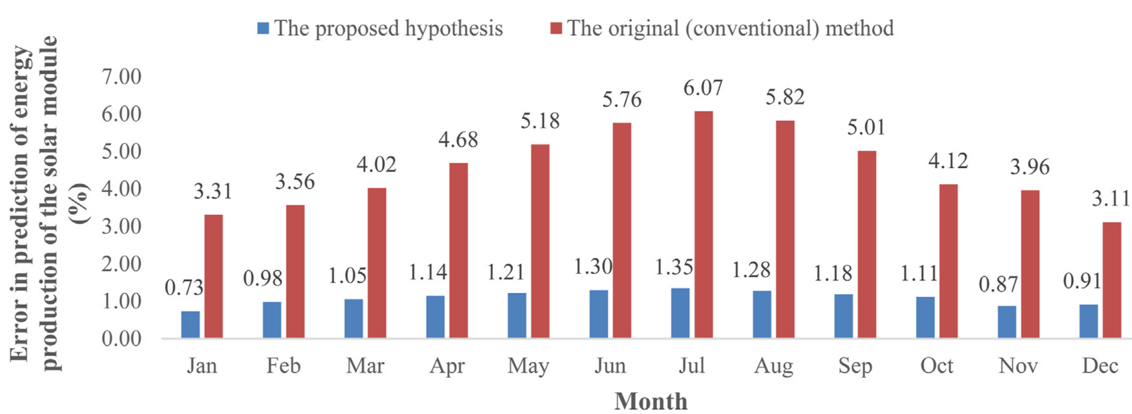

Fig. 11. Comparison of the monthly average error in prediction of energy production of the solar module obtained from the conventional (original) method and the proposed hypothesis.

Table 4
The results of error analysis for the calculated parameters.

Parameter	The maximum error (%)
Produced power	2.2
$T_{eq,\mathrm{exp}}$	1.7
$T_{eq,hyp}$	1.9
Efficiency	2.3
Generated energy	2.2

shows much higher accuracy of the proposed hypothesis compared to the original method in the prediction of all the performance criteria in all months of a year. On average, the error in prediction of efficiency, generated power, and produced energy by the original method are 4.14, 5.45, and 4.55% while the corresponding values for the proposed hypothesis are only 1.05, 1.25, and 1.09%, respectively. Moreover, as observed, the hotter a month is, the more accurate the proposed method to calculate efficiency works compared to the original method.

4.4. Error analysis

In order to conduct error analysis, the method thoroughly discussed in Ref. [44–46] was employed for the calculated parameters (the ones obtained indirectly). The results are given in Table 4.

5. Conclusions

As a solution to predict the efficiency of a solar module more accurately, a well-known correlation in the literature was considered, and the hypothesis of dividing a module into sub-regions was examined. In the proposed hypothesis, instead of considering a constant temperature for the whole module, the module was divided into some parts, and the efficiency was computed for each part by putting the temperature for the center of that sub-region into the correlation. Having obtained the efficiency of each part, the module's efficiency was determined through the weighted average of the efficiency of the sub-regions.

The accuracy of the conventional (original) method and the proposed hypothesis was compared together using the experimental data recorded from the performance of a 60 W polycrystalline solar module during a year in Tehran, Iran. Based on the investigation done for the hourly profiles on a sample day in July, it was found that the conventional approach has a mean absolute error of 5.70% in prediction of the efficiency while the value was enhanced considerably for the examined hypothesis, where the mean absolute error was only 1.45%. Moreover, the mean absolute error of the prediction for the produced power by the proposed hypothesis (1.75%) became 4.4 times lower compared to the conventional method (7.72%). In addition, the difference between actual and estimated values of produced energy throughout a day decreased to the two-ninth in the proposed approach.

Comparison of the annual profiles also showed that the values of the annual average error in prediction of efficiency, produced power, and generated energy for the original method are 4.14, 5.45, and 4.55%. In contrast, the proposed hypothesis had much better magnitudes. It has only 1.05, 1.25, and 1.09% error, respectively. Therefore, the greater ability of the proposed hypothesis to predict the technical performance of a solar module was proven. Using the proposed hypothesis instead of the conventional method also leads to designing solar module systems for power generation more economically viable, as discussed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Ali Sohani: Conceptualization, Methodology, Software, Investigation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Hoseyn Sayyaadi:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Appendix A. The experimental data for July as the sample month

Table A.1 and Table A.2 show the data recorded from the experiments on July 15, 2019. Reporting data is done in two parts. In one part (Table A.1), the information about current and voltage of the module, as well as the ambient air temperature and irradiance is given. Another part (Table A.2) presents the values of the temperature for the center of each sub-region. It should be noted that the experimental setup by which the experimental data of Table A.1 and Table A.2 is obtained, has been introduced in part 3 of the manuscript.

Table A.1
The obtained experimental data on July 15, 2019, including the current and voltage of the module, as well as the ambient air temperature and irradiance

Time	G (W.m^{-2})	V (V)	I (A)	T_{amb} (°C)
8:00	360	19.66	0.94	25.8
8:10	420	19.59	1.09	26.3
8:20	475	19.54	1.23	26.7
8:30	530	19.49	1.38	27.0
8:40	595	19.48	1.55	27.3
8:50	630	19.53	1.65	27.7
9:00	670	19.48	1.75	28.0
9:10	720	19.41	1.89	28.2
9:20	765	19.32	2.02	28.3
9:30	805	19.27	2.09	28.5
9:40	845	19.29	2.20	28.7
9:50	880	19.20	2.30	28.8
10:00	925	19.21	2.38	29.0
10:10	955	19.26	2.46	29.3
10:20	1010	19.16	2.56	29.7
10:30	1020	19.13	2.65	30.0
10:40	1070	19.24	2.72	30.3
10:50	1095	19.22	2.82	30.7
11:00	1125	19.14	2.88	31.0
11:10	1145	19.16	2.93	31.2
11:20	1160	19.14	2.95	31.3
11:30	1170	18.94	3.01	31.5
11:40	1175	18.92	2.99	31.7
11:50	1190	18.91	3.03	31.8
12:00	1205	18.98	3.04	32.0
12:10	1215	19.00	3.08	31.9
12:20	1230	18.91	3.08	32.0
12:30	1230	18.86	3.09	32.1
12:40	1195	18.75	3.06	32.2
12:50	1190	18.85	*3.04*	32.1
13:00	1175	18.93	2.99	32.0
13:10	1170	19.02	2.99	32.2
13:20	1155	18.91	2.97	32.3
13:30	1145	19.00	2.94	32.5
13:40	1125	18.92	2.90	32.7
13:50	1105	18.98	2.85	32.8
14:00	1080	18.91	2.79	33.0
14:10	1040	18.93	2.69	33.2
14:20	1030	18.99	2.67	33.3
14:30	990	18.90	2.61	33.5
14:40	945	18.83	2.50	33.7
14:50	915	18.94	2.43	33.8
15:00	875	18.84	2.30	34.0
15:10	840	18.92	2.24	34.2
15:20	810	18.81	2.13	34.3
15:30	760	19.10	2.03	34.5
15:40	710	19.04	1.90	34.7
15:50	665	18.97	1.78	34.8
16:00	610	19.01	1.64	35.0

Table A.2
The values of temperature for the center of each sub-region determined by experiments on July 15, 2019. Assigning the numbers is done based on Fig. 4. All units for temperature are also °C.

Time	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}
8:00	34.6	35.9	37.4	37.7	37.0	39.2	39.4	37.9	38.3	38.7	39.1	37.5	37.2	36.9	36.7	36.8
8:10	36.8	38.1	39.1	38.7	38.7	40.6	41.1	39.7	40.2	41.6	41.0	40.3	39.8	40.0	40.0	39.8
8:20	41.9	42.2	42.4	42.3	42.5	43.3	43.6	42.0	41.2	43.2	43.0	40.8	39.4	40.0	40.3	39.9
8:30	35.8	35.9	35.3	34.7	38.2	43.1	41.7	35.4	38.2	42.2	41.7	36.1	35.8	35.9	36.0	36.0
8:40	42.2	42.1	40.7	39.4	43.6	44.2	43.1	39.5	42.0	43.6	43.0	39.7	39.0	40.1	40.5	39.8
8:50	43.5	43.6	43.4	43.1	44.4	46.3	46.2	43.9	43.7	46.1	46.5	44.5	42.1	43.5	44.6	44.3
9:00	40.5	41.1	41.2	40.7	41.6	43.4	43.4	40.8	40.5	42.9	43.4	41.1	38.3	39.9	41.4	41.3
9:10	43.7	44.2	45.0	45.3	44.6	46.9	47.7	45.5	43.7	46.8	47.2	44.9	41.9	43.8	45.0	44.2
9:20	45.5	46.0	46.3	46.2	48.1	51.2	51.2	46.8	47.7	51.6	50.9	46.0	44.8	46.0	45.8	44.5
9:30	52.0	52.1	51.9	51.5	52.0	54.1	54.1	51.4	50.4	53.1	52.9	49.9	48.9	49.8	49.7	48.6
9:40	50.0	50.6	50.1	49.1	50.9	52.6	51.9	49.1	50.2	52.0	51.1	47.7	48.6	49.2	48.0	46.2
9:50	49.9	50.0	49.9	49.7	51.7	56.5	56.5	50.0	49.8	56.8	55.5	48.1	46.1	47.7	47.6	45.9
10:00	52.7	52.7	51.6	50.5	53.5	55.5	54.3	49.6	52.6	54.7	53.3	47.9	50.8	50.9	49.1	47.2
10:10	50.3	50.7	50.3	49.4	52.1	55.2	54.2	49.1	51.0	55.1	52.8	46.9	48.0	48.3	46.8	45.0
10:20	54.5	55.1	54.8	53.9	54.9	56.6	56.6	53.4	53.2	55.9	55.4	51.6	51.1	51.8	51.4	50.3
10:30	50.4	50.8	51.3	51.5	52.3	56.0	55.8	50.7	51.1	55.8	54.3	47.1	48.1	48.8	47.0	44.4
10:40	51.2	51.3	50.9	50.5	52.6	55.3	54.1	49.8	52.6	54.7	52.6	47.8	51.3	51.1	48.8	46.6
10:50	48.5	49.1	49.3	48.9	50.9	55.1	54.8	48.9	50.6	55.5	53.5	46.7	48.0	48.3	46.6	44.5
11:00	55.3	55.1	53.5	52.1	56.0	57.0	56.1	52.3	55.1	56.0	54.7	50.6	53.5	53.2	50.8	48.7
11:10	52.6	52.8	53.0	53.0	54.1	57.7	57.2	52.0	53.4	58.2	55.8	49.6	51.3	52.0	50.5	48.2
11:20	54.9	54.9	53.7	52.5	56.1	57.6	56.7	52.2	56.3	57.6	55.9	51.8	55.4	54.8	52.9	51.7
11:30	53.4	53.0	51.4	50.2	54.9	58.2	56.0	49.3	53.9	58.2	54.8	48.3	51.5	51.4	49.7	48.2
11:40	60.5	60.2	57.9	56.0	60.5	60.9	60.2	55.3	58.5	60.2	58.5	51.4	56.6	56.5	54.2	52.1
11:50	57.4	58.0	57.1	55.6	58.7	63.0	61.5	55.6	57.8	63.4	60.2	53.7	55.6	55.7	53.8	51.8
12:00	56.2	56.6	55.6	54.3	57.0	58.6	57.6	54.6	56.5	58.2	56.7	53.6	55.1	55.1	53.7	52.3
12:10	55.5	55.9	55.3	54.3	56.3	60.4	60.0	54.0	55.2	61.4	58.7	52.5	53.3	54.0	53.0	51.4
12:20	59.5	59.5	58.3	57.1	59.9	60.5	60.5	56.6	58.3	60.0	58.7	55.3	56.2	56.4	55.6	54.6
12:30	57.9	58.0	57.3	56.5	58.7	62.3	62.0	55.9	56.7	63.4	60.1	53.6	54.0	54.5	53.5	51.9
12:40	58.8	59.5	59.1	58.0	58.8	62.2	62.1	57.8	57.4	61.5	60.6	56.1	56.1	56.1	55.3	54.5
12:50	58.7	60.1	60.2	58.9	58.9	62.7	62.8	57.7	56.8	62.4	60.3	54.4	54.5	54.7	53.6	52.2
13:00	57.6	57.9	57.0	55.9	57.8	58.5	58.5	55.3	56.0	58.5	57.4	53.8	54.1	54.3	53.7	52.9
13:10	55.4	55.5	54.7	53.8	57.0	60.4	60.3	52.9	56.3	61.3	58.2	51.5	54.0	54.1	52.6	51.1
13:20	60.0	59.9	58.0	56.2	60.1	61.3	61.1	55.5	58.5	60.7	58.3	54.6	56.9	56.8	55.5	54.3
13:30	54.2	54.8	54.4	53.3	55.5	59.0	58.7	52.4	54.5	59.3	57.0	51.4	52.1	52.4	52.0	51.2
13:40	57.3	57.4	56.1	54.6	57.7	58.9	58.7	54.0	56.5	58.2	56.5	52.7	55.0	55.0	53.5	52.1
13:50	55.9	56.1	55.9	55.5	56.7	61.7	60.7	54.3	55.4	62.2	59.5	52.5	53.3	53.7	53.0	51.9
14:00	58.0	58.0	57.2	56.4	57.3	59.1	59.2	55.8	55.0	58.6	57.3	53.8	53.3	54.1	53.6	52.4
14:10	54.5	55.5	56.3	56.1	55.1	59.9	60.4	60.2	54.3	60.4	58.8	58.2	52.8	53.7	53.4	52.2
14:20	56.6	57.0	56.1	54.9	56.7	57.9	57.8	55.1	55.3	57.7	56.7	54.4	53.7	54.4	54.3	53.5
14:30	47.9	48.7	49.0	48.5	48.5	54.1	53.5	47.7	47.5	54.8	52.8	46.7	51.9	53.2	53.4	52.4
14:40	57.7	52.9	52.2	51.2	52.8	52.7	52.2	50.6	51.6	53.1	53.3	50.0	50.4	51.0	50.8	54.9
14:50	51.7	53.0	54.4	54.5	52.4	57.5	57.6	53.4	51.6	58.3	56.4	51.8	50.1	51.1	51.8	51.4
15:00	54.7	54.9	54.7	54.4	54.8	56.3	56.5	54.2	53.3	56.4	55.6	52.9	51.7	52.7	52.8	51.9
15:10	52.4	53.3	54.1	54.0	53.6	57.3	57.1	52.5	53.5	57.7	56.0	50.9	52.2	52.3	51.6	50.8
15:20	49.4	52.1	53.5	53.1	53.5	55.0	55.1	52.0	52.6	54.7	50.4	49.5	51.6	51.0	50.5	51.1
15:30	42.3	43.0	43.6	43.5	42.6	44.7	44.9	42.5	41.8	44.9	43.1	40.7	40.7	40.9	40.5	40.0
15:40	45.4	45.4	45.5	45.6	45.3	47.1	46.8	44.2	43.7	46.8	44.4	42.2	42.2	42.4	42.2	41.7
15:50	46.8	46.6	45.6	44.7	46.0	47.7	46.8	43.7	44.4	46.9	45.8	42.5	43.7	43.7	43.1	42.4
16:00	41.1	41.4	42.3	42.9	42.4	45.1	45.6	43.4	43.6	45.7	45.1	43.8	43.4	43.9	44.1	43.8

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