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THE EFFECT OF DIFFERENT SKY TEMPERATURE MODELS ON THE ACCURACY IN THE ESTIMATION OF THE PERFORMANCE OF A PHOTOVOLTAIC MODULE

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ABSTRACT

This paper considers the effect of different sky temperature models on the accuracy in the estimation of the performance of an open-rack-mounted photovoltaic (PV) module. It is found that, for the same ambient conditions, the temperatures of the PV module calculated using individual sky temperature models deviate, on average, by about 4 °C from the measured one. Further, this causes an error in the estimation of the power output of the PV module that can not be ignored when a precise performance analysis is required. The effect of different sky temperature models is estimated using a heat balance equation of the PV module, where the term related to long-wave radiation heat exchange between the sky and the PV module's upper surface is significantly affected by the sky temperature. Based on comparisons between the calculated and measured temperatures of the PV module considered, sky temperature models, providing the best results, are singled out. Furthermore, it is pointed out which models have the largest deviations.

INTRODUCTION

The most important feature of a PV module is its conversion efficiency, i.e. electrical power that can be generated by the PV module under certain conditions. Although not directly related to the material from which PV cells are produced, the PV module's temperature is a parameter that mostly affects the conversion efficiency. The PV module's temperature depends on a number of environmental, spatial, structural and other conditions and, therefore, there is a great possibility of error in the estimation of this parameter.

In the literature, there are many steady-state models for estimating the temperature of the PV module [1-3]. The most accurate models are based on the law of conservation of energy, i.e. the balance between the energy that a PV module receives from sunlight, on one side, and the released heat from its two surfaces and the amount of electricity generated in it, on the other [1,4]. For these models, assuming that the view factor equals one, the amount of heat radiated from the PV module's upper surface can be calculated using the following formula [1,5]:

$$q_r = \varepsilon_f \cdot \sigma_{SB} \cdot \left(T_{PV}^2 + T_{sky}^2\right) \cdot \left(T_{PV} + T_{sky}\right) \tag{1}$$

where ε_f is the thermal emissivity of the PV module's upper surface, σ_{SB}=5.67·10^{-8} W/(m^2·K^4) is the Stefan-Boltzmann constant, T_{PV} is the PV module's temperature in K, and T_{sky} is the sky temperature in K.

The sky temperature T_{sky} can be determined directly or using the atmospheric emissivity ε_{sky}, i.e.

$$T_{sky} = \varepsilon_{sky}^{0.25} \cdot T_a \tag{2}$$

where T_a is the ambient temperature in K. There are several correlations for the atmospheric emissivity which have been used in order to estimate the effective sky temperature. Some of the most common correlations for ε_{sky} are listed in Table 1.

The sky temperature T_{sky} depends on many factors, such as the ambient temperature, dew point, amount of clouds, and site conditions [6]. In the literature, there are a large number of models used to estimate this temperature. It is clear that the application of different models gives different values for q_r, which consequently results in obtaining different values for the PV module's temperature. Wrong estimation of the PV module's temperature inevitably leads to an erroneous value for its power.

In this paper, the temperatures of one PV module of the type BISOL BMO-255 are calculated using different sky temperature models and compared to the temperature of this PV module measured under the same conditions of operation. It is found that a larger number of models yield similar results, but also there are models that are generating large deviations in the temperature of the PV module. To the best knowledge of the authors, the effect of different sky temperature models on the accuracy in the estimation of the performance of the PV module has not yet been considered in any research paper. This is the main purpose of this paper.

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SKY TEMPERATURE MODELS AND THERMAL MODEL USED FOR ESTIMATING THE PV MODULE'S TEMPERATURE

There are a large number of research papers dealing with models for the estimation of the sky temperature. Most of these models apply to clear sky conditions. Other models use correction factors to account for the average cloud cover. Algarni and Nutter [6] provided a comprehensive review of existing sky temperature models, for both clear and cloudy sky conditions. Table 1 outlines some of the models that provide the best agreement between the calculated and measured values of the PV module's temperature, as well as those that provide the largest deviations. The estimation of the PV module's temperatures is carried out using the model described in detail in [1], but with difference that the correlations (3) and (4) are used for modeling the heat transfer coefficients due to convection from the PV module's upper and lower surfaces [7], respectively. The correlations (3) and (4) are as follows:

$$h_{c,f} = 3.72 + 1.16 \cdot v_w \tag{3}$$

$$h_{c,b} = 1.8 + 1.93 \cdot v_w \tag{4}$$

where v_w is the wind velocity in m/s. In addition, it is assumed that the view factors between the PV module's upper surface and the sky, as well as between the PV module's lower surface and the ground, are equal to one. These assumptions are introduced to simplify the model, i.e. neglect the effect of the inclination angle of the PV module on the heat transfer by convection and radiation, which is negligible in accordance with [1].

Table 1. *Clear sky atmospheric emissivity models and direct temperature models*

Atmospheric emissivity models			
Model	Author	Eq.	Ref.
ε_{sky}=0.8004+0.00396·T_{dp}	Bliss	(5)	[6]
ε_{sky}=0.711+0.56·(T_{dp}/100)+0.73·(T_{dp}/100)^2	Berdahl and Martin	(6)	[6]
ε_{sky}=0.741+0.0062·T_{dp}	Berdahl and Fromberg	(7)	[6]
ε_{sky}=0.77+0.0038·T_{dp}	Berger et al.	(8)	[6]
ε_{sky}=0.787+0.764·log((T_{dp}+273.157)/273)	Clarc and Allen	(9)	[6]
ε_{sky}=0.34+0.11·$P_v^{0.5}$	Robitzsch	(10)	[6]
ε_{sky}=0.48+0.058·$P_v^{0.5}$	Angstorm (Algeria)	(11)	[6]
ε_{sky}=0.5+0.032·$P_v^{0.5}$	Angstorm (USA)	(12)	[6]
Direct temperature models			
T_{sky}=0.6·T_a	Alnaser	(13)	[8]
T_{sky}=0.0552·$T_a^{1.5}$	Swinbank	(14)	[6]
T_{sky}=T_a-20	Garg	(15)	[6]

In Table 1, the dew point temperature Tdp is defined by the Magnus formula [9]:

$$T_{dp} = \frac{243.04 \cdot \left[ln\left(\frac{RH}{100}\right) + \frac{17.625 \cdot T_a}{243.04 + T_a} \right]}{17.625 - ln\left(\frac{RH}{100}\right) - \frac{17.625 \cdot T_a}{243.04 + T_a}} \text{ in } ^{o}\text{C}, \tag{16}$$

while the vapor pressure Pv is indicated by the Antoine equation [10]:

$$P_v = 1.333 \cdot 10^{8.07131 - \frac{1730.63}{233.426 + T_a}} \text{ in mbar}, \tag{17}$$

where T_a is the ambient temperature in ^{o}C, and RH is the relative humidity in %.

DESCRIPTION OF THE EXPERIMENTAL SETUP

Although the main purpose of this paper is to calculate the differences between the PV module's temperatures obtained using different correlations/models for the sky temperature, the temperature of the considered PV module was measured under actual ambient conditions; so that, based on comparisons between the calculated and measured temperatures, correlations providing the best results can be singled out. Along with the temperature of the PV module, the values of the meteorological parameters relevant to the temperature calculation using the model described in the previous section were also measured. Namely, these parameters are the solar irradiance, wind velocity and ambient temperature.

Table 2. *Technical and optical characteristics of the PV module used*

Characteristics of PV module[a]	**BISOL BMO255**
Length	1.649 m
Width	0.991 m
Nominal power	255 W
Maximal power voltage/open-circuit voltage	30.7 V / 38.1 V
Maximal power circuit current/short-circuit current	8.30 A / 8.90 A
Solar cell efficiency	17.5 %
Power temperature coefficient	-0.4 %/°C
Thermal emissivity for the PV module's upper surface	0.91
Thermal emissivity for the PV module's lower surface	0.9

[a] PV module's characteristics at solar irradiance of G=1000 W/m^2 and T_a=25 °C

The measurements of the PV module's temperature and meteorological parameters were performed in the village of Prelez (the municipality of Zubin Potok, Serbia). The experimental setup was composed of one BISOL BMO255 mono-crystalline PV module with a nominal power output of 255 W, a KIMO SL100 portable solarimeter, a TFA sinus weather station for measuring the ambient temperature and wind velocity, and an Agilent 34970a data acquisition/switch unit with three thermocouples of the J-type for measuring the PV module's temperature. The data acquisition was repeated every 33 seconds. The thermocouples were attached directly to the lower surface of the PV module at three points (top, middle, and bottom) using the adhesive tape.

The PV module's temperature is then treated as the average value of three temperatures measured on the PV module's lower surface. A schematic depiction of the experimental setup is presented in Figure 1, while a photograph of this setup is shown in Figure 2. The PV module was south oriented and fixed at an angle of 43°, which represents the latitude of the village of Prelez. The PV module was operated in the full-load mode (a 400 W halogen lamp). The second PV module appearing in Figure 2 was not used for the purpose of this study. Temperature measurements were performed on 11/07/2018. The variations of the three meteorological parameters (i.e. ambient temperature, solar irradiance, and wind velocity) are shown in Figure 3. All the technical information about the PV module used, as well as the optical characteristics of the PV module's upper and lower surfaces are given in Table 2.

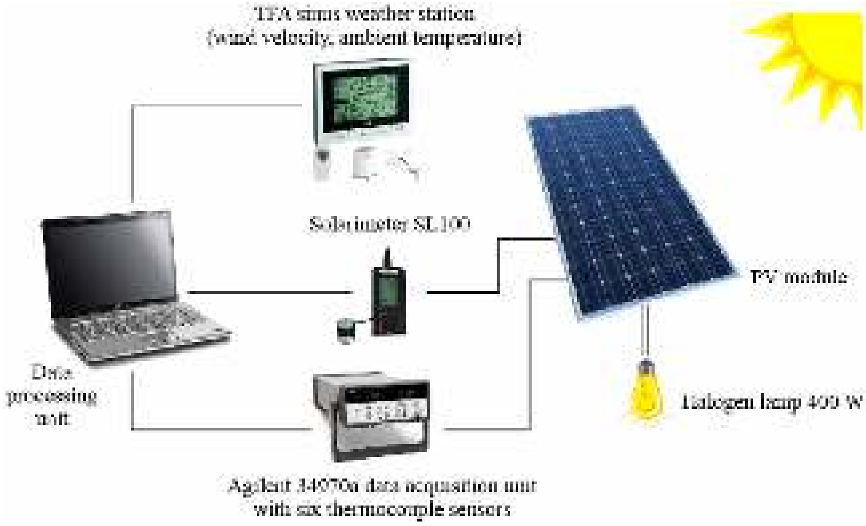

Fig. 1. Simplified schematic of the experimental measurement equipment used

Fig. 2. Photograph of the experimental setup

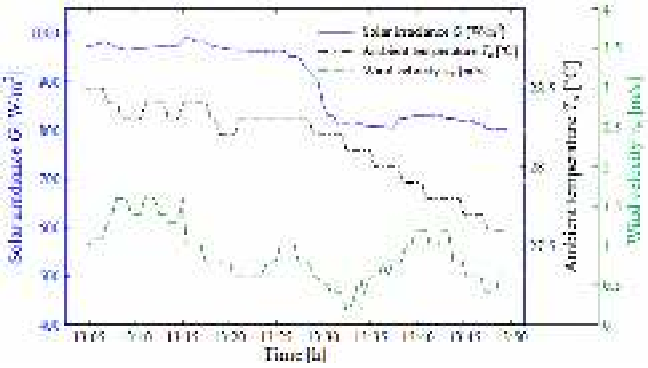

Fig. 3. Data on solar irradiance, ambient temperature, and wind velocity during the day 11/07/18 (RH for this day was 60 %)

RESULTS AND DISCUSSION

Figure 4 shows the temperature of the PV module measured under the ambient conditions from Figure 3. This figure also shows the temperature curves of the PV module calculated using the sky temperature models from Table 1 for the same ambient conditions.

From Figure 4, it is evident that calculated curves best match the measured one. It is obvious that the correlations (5)-(9), (11), (13) and (14) yield similar results and that the values of the PV module's temperature obtained using these correlations are well-matched with the measured values. This can not be said for the correlations (10), (12), and (15). In a greater part of the measuring period, the correlation (10) overestimates the measured values by about 4 °C, while the correlations (12) and (15) underestimate the measured values by about 3.5 °C and 2.5 °C, respectively. With respect to the standard formula for calculating the power output of a PV module

$$P_{el} = \eta_{T_{ref}} \cdot \varepsilon_f \cdot A \cdot G \cdot \left(1 - \beta_{ref} \cdot \left(T_{PV} - T_{ref}\right)\right), \qquad (18)$$

the errors in the estimation of the PV module's temperature surely lead to an error in the estimation of the corresponding power output.

The parameters which have not been defined earlier have the following meanings: η_{Tref} is the conversion efficiency of the PV module at the reference temperature T_{ref} and the global solar irradiance G=1000 W/m^2, β_{ref} is the temperature coefficient of the PV module in 1/K, A is the area of the PV module's upper or lower surface in m^2, and

T_{ref} is the temperature at which the PV module's efficiency equals η_{Tref} in K.

Generally, the simulated PV module's temperatures change sharply, while the measured one changes gradually. This is caused by ignoring the thermal capacities of the PV module's materials in the thermal model considered, i.e. the thermal model does not include the factor characterizing the thermal lag of the PV module.

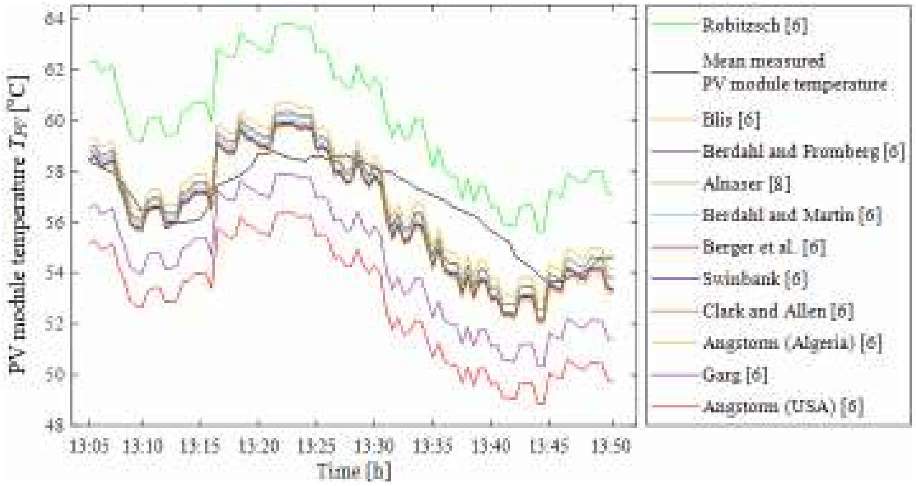

Fig. 4. Comparison between the PV module's temperatures calculated using correlations from Table 1 and meteorological parameters from Figure 3 and that measured on the day 11/07/18

In Figure 4, correlations yielding similar results are very close to each other, so it is difficult to notice the curve that belongs to each individual correlation (i.e. to the author). Therefore, in the legend on the right side of this figure, the correlations are aligned in such a manner that the first and last correlations match those which are displayed at the top and bottom on the left side of the figure, respectively. This does not apply to the curve that represents the measured temperature, because it cuts most of the correlations. The same principle is applied to Figure 5.

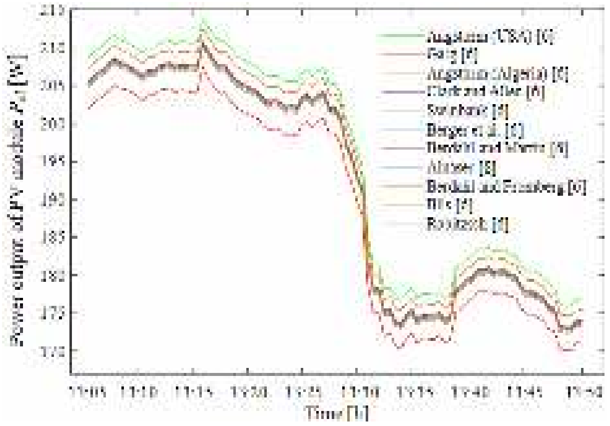

Fig. 5. Power outputs of the PV module of the type BISOL BMO255 (Table 2) calculated using equation (18) for the values of TPV taken from Figure 4

The power outputs of the considered PV module corresponding to the temperature curves from Figure 4 are presented in Figure 5. In regards to the correlation (14) which proved to be satisfactorily accurate and widely used [1,3-5], it is evident that, according to Figure 5, the error in the PV module's power output equals about -3 W when it is estimated using the correlation (10). It is also evident that, in regards to the correlation (14), the errors relating to the same parameter equal about 3 W and 2 W when they are estimated using the correlations (12) and (15), respectively.

An error of a few watts in the estimated power output of a single PV module is not critical. However, based on the fact that the efficiency of the best commercial PV modules does not exceed 20 %, this error is especially significant in case of larger numbers of PV modules (such as in case of PV arrays). An error in the estimated power output, that would be made in case of the application of the correlation (10), (12) or (15), could also affect the decision-making process that is not in line with the actual situation. For instance, in the planning process, if these correlations are used in models for estimating the potential power output of a PV system, a power output which is smaller or greater than the actual one would be obtained (depending on the correlation used). In addition to this, the calculated power output represents the initial information for the proper sizing of the whole PV system and related accessories.

In the models for the selection of the optimal configuration of renewable energy sources (which are often used by consumers of electricity which are not connected to a power supply network), the aforementioned error will affect the obtained solution to a certain extent. On the basis of the above facts, it can be concluded that the error in the estimated PV module's temperature, which is caused by the use of correlation (10), (12) or (15), can certainly not be ignored in the case when the exact analysis of the PV module's performance is required. Accordingly, it is recommended that the correlation (14) or any other correlation giving similar result can be used for the purpose of approximation of the sky temperature in the models which are based on the law of conservation of energy.

CONCLUSION

This paper has provided the background for proper selection of the sky temperature model/correlation for the purposes of the models which are based on the law of conservation of energy. In addition, it has been shown that most of the existing correlations provide results similar to those obtained by means of the most widely used Swinbank correlation (14), and that, in comparison with the Swinbank correlation, some of the correlations lead to an error in the estimated PV module's temperature of about 4 °C. The simulation results confirmed the initial assumption that the error in the estimated PV module's temperature is transferred further to the conversion efficiency, which also, for actual conditions of operation, results in the wrong estimation of the PV module's power output. On the basis of the analysis carried out here, it has been concluded that a sufficiently precise estimation of the PV module's performance can be performed using correlations (5)-(9), (11), (13) and (14), as well as that the correlations (10), (12) and (15) should not be used as sky temperature models. The Swinbank and Alnaser correlations proved to be the simplest correlations that provide good results, as well as an easy way to calculate the effective sky temperature because they depend only on the ambient temperature.

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