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Efficiency improvement of PV module using an electrical thermal model

Photovoltaic (PV) cells lose in their efficiency when operating under high temperatures. Proposing a new system of cells cooling is considered an overriding necessity. For this purpose, the main objective of this paper is the development of a suitable mathematical model that can calculate the internal temperature of the PV module as a function of ambient temperature, wind speed, and total irradiance. This paper presents an electrical and thermal model that analyses the heat transfer mechanisms in PV modules such as conduction, convection, and radiation. An air forced cooling is introduced principally to improve the performance of our studied system and reducing the internal temperature. This work demonstrates a good relevant result obtained through the comparison between the PV module with and without the air-cooling system.

Keywords: Photovoltaic cells, efficiency, module temperature, electrical thermal model, heat transfer mechanisms, air cooling system.

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1. Introduction

Nowadays, photovoltaics represents an important stake in energies and more generally in renewable energies. The photovoltaic solar energy is a clean energy source that allows a direct conversion of solar radiation into electricity by the photovoltaic effect. Besides, the conversion by photovoltaic effect does not present any noise nuisance and has no negative impact on the ecosystem. However, under strong solar irradiation, the efficiency of solar cells decreases because of the high operating temperature, which can reach 70 ° C [1, 2]. Power losses of 0.2% to 0.5% per Kelvin difference to 25°C (standard testing conditions STC) are the typical and nominal module operating temperature (NMOT) [3]. Therefore, power losses of which due to the rise in temperature can be predicted in module temperature [4].

Water-based cooling systems are designed to cool cells. Unfortunately, these systems are not durable, costly, and sometimes cannot be integrated into solar cells [5, 6]. In order to reduce the internal temperature of the photovoltaic cell, an external temperature is forced into the cell by using an air-cooling system. Therefore, in the present work, we introduce a new study based on an electrical and thermal model for photovoltaic in terms of reduction of internal temperature. An electrical model is used to analyse the electrical behaviour and found that the higher is the temperature, the lower is the PV module production. In this study, the other conditions (e.g., solar irradiance, wind, humidity, etc.) are constant. Then, a flexible thermal model is, therefore, necessary to analyze the heat transfer mechanisms in PV modules such as conduction, convection, and radiation and their effects on the encapsulant curing. We present such a model and show results regarding the calculation of module temperatures after the resolution of the heat balance equation.

For validation, we compare the electrical performance of the PV cell with and without a cooling system. In this context, we have selected the "SPR- 455J-WHT-D "of SunPower

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Manufacturer to elaborate the influence of the forced external air on the electrical efficiency by using the heat balance equation. Finally, we carried out a simple model with MATLAB/SIMULINK to simulate the electrical behaviour with the thermal circuit that represents the heat transfer with forced convection of air cooling.

2. Electrical model

2.1. Equivalent circuit of the electrical model of photovoltaic cell

The conversion of solar energy into electrical energy is based on the photoelectric effect, i.e. the ability of photons to create charge carriers (electrons and holes) in a material. The energy of the absorbed photons allows electronic transitions from the valence band to the conduction band of the semiconductor. In fact, generating electron-hole pairs, which can contribute to the transport of current (photoconductivity) by the material when it is polarizing [7,8]. If the PN junction is maintained under solar lighting, the electron-hole pairs that are created in the space charge zone of the junction are immediately separated by the electric field. This one prevails in this region, and entrained in the neutral zones of each side of the junction. A PV module consists of many PV cells connected in series ns or in parallel np. Therefore, an equivalent circuit of the PV cell, which can be expressed as a photodiode with a large p-n junction, shown in figure1, can express PV arrays and modules. The equivalent circuit is used together with the following set of circuit equations to express a typical current-voltage I-V and P-V curves of the PV module.

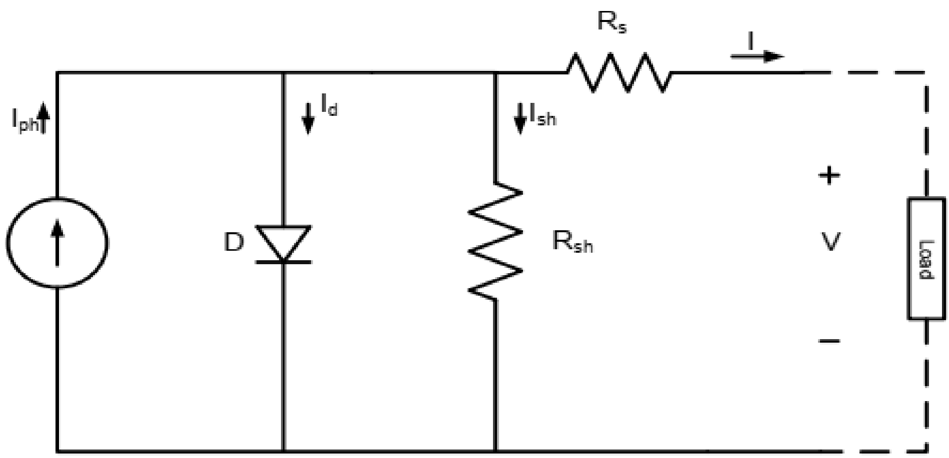


Fig. 1. Equivalent circuit of PV cell

$$I = n_p I_{ph} - n_p I_0 \left[exp\left\{\frac{q}{AKT}\left(\frac{V}{n_s} + IR_s\right)\right\} - 1\right] - \frac{V-n_s}{R_{sh}} \quad (1)$$

Where

$$I_{ph} = \left\{I_{sc} + K_{sc}\left(T - T_{ref}\right)\right\}\frac{q_{rad}}{1000} \quad (2)$$

$$I_0 = I_r\left(\frac{T}{T_r}\right)^3 exp\left\{\frac{qE_{gap}}{KA}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right\} \quad (3)$$

In equation (1), q is the electron charge (1.602×10-19, C); k represents the Boltzmann constant (1.38×10-23 J/◦K), T is the surface temperature of module, A is the ideality factor (A =1–5), ns is the number of cells connected in series, and np is the number of cells parallelly connected so $= n_s n_p$. I_{sc} is the short-circuit current, ksc is the temperature coefficient of the short-circuit current, and q_{rad} is the solar radiation in W/m2. The module reverse saturation current I_0 is expressed in (3), where E_{gap} is the energy of the band gap for silicon (E_{gap}=1.1 eV) and T_{ref} is the reference temperature of PV module.

2.2. Temperature effect on the solar cell

When the temperature increases due to the strong solar irradiations and the encapsulation that causes the greenhouse effect, the output power of the photovoltaic cells decreases, and consequently there is a loss of efficiency. Figures 3 (a) and 3 (b) illustrate the characteristics I (V) and P (V) of a solar cell under different operating temperatures. The two below figures show that when the operating temperature of the cell increases, the delivered electric power decreases. This reduction in the output power of the cell generates the reduction in its efficiency, which is defined by the equation (4),

$$\eta = \frac{P_m}{P_i} \quad (4)$$

$$\eta_m = \eta_{ref}[1 + P_{coef}(T_m - T_{ref})] \quad (5)$$

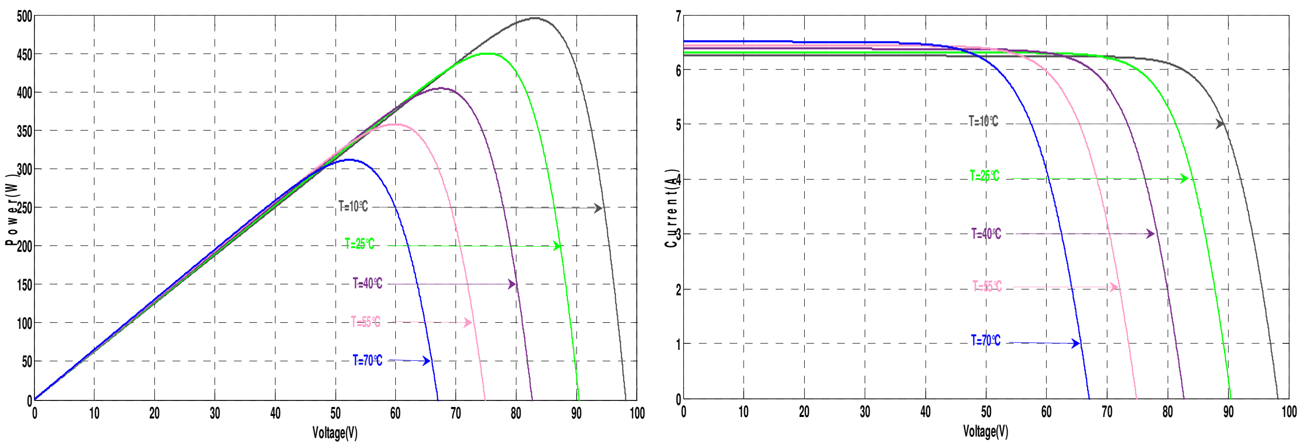
where, Pm, represents the maximum produced power. It is given by, η_{ref} and T_{ref} are the module's electrical efficiency and temperature at the reference condition at solar radiation of 1000W/m². The temperature coefficient, P_{coef} , is normally given by the PV manufacturer. η_{ref} is given in the equation bellow:

$$\eta_{ref} = V_{co} I_{cc} FF \quad (6)$$

Vco : Open circuit voltage; Icc : Short circuit current, FF, Form factor. Pi, Power of solar radiation, it is given by,

$$P_i = E.S \quad (7)$$

with, S is the cell surface; E is illumination in W/m²



(a) (b)

Fig. 2. (a) - I (V) Characteristic of a PV module for different temperatures
(b) - P (V) Characteristic of a PV module for different temperatures

3. Thermal model of PV module

To determine the PV cell temperature, it is necessary to study carefully the thermal behaviour of the PV module. This study has been carried out from considering the PV modules made of three layers (Figure 3), for each of them a thermal balance has been performed.

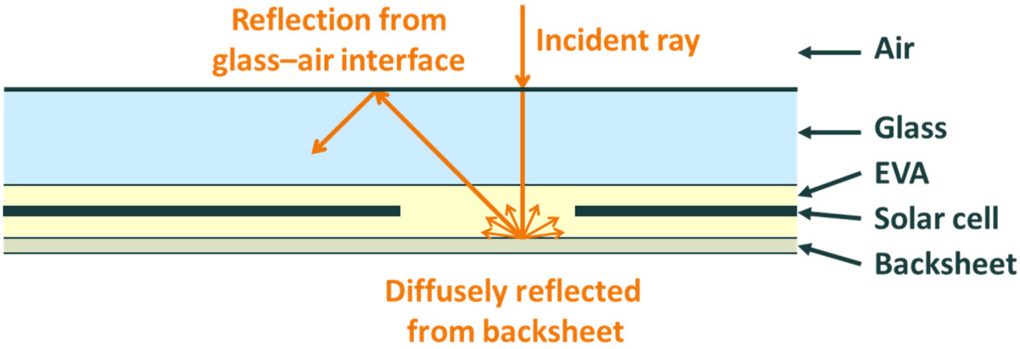


Fig. 3. Photovoltaic module section

In our proposed model two main assumptions are taken into account:

1) the temperature has been supposed uniform in each layer and it varies along the y-axis (figure.4).

2) the thermal capacitances of the layers have been supposed negligible (steady state study) [10].

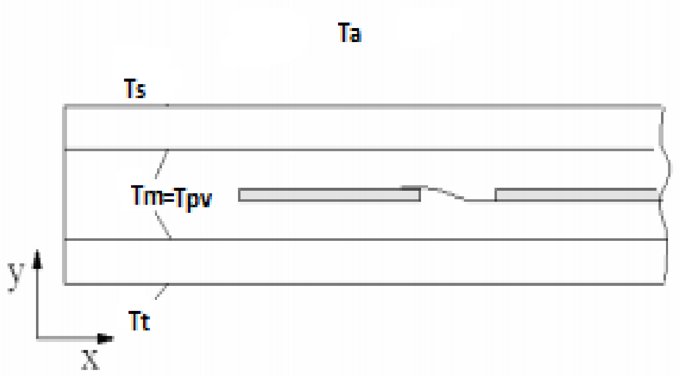


Fig. 4. PV module temperature in differents layers

3.1. Module heat transfer

Therefore, the thermal model is based on the analysis of three heat transfer mechanisms in PV modules, such as conduction, convection, and radiation. The radiation appears in temperature difference between the PV module and the surroundings, as shown in figure 5. Otherwise, heat transfer helps us in the prediction of the PV module temperature Tm, when considering the steady-state condition.

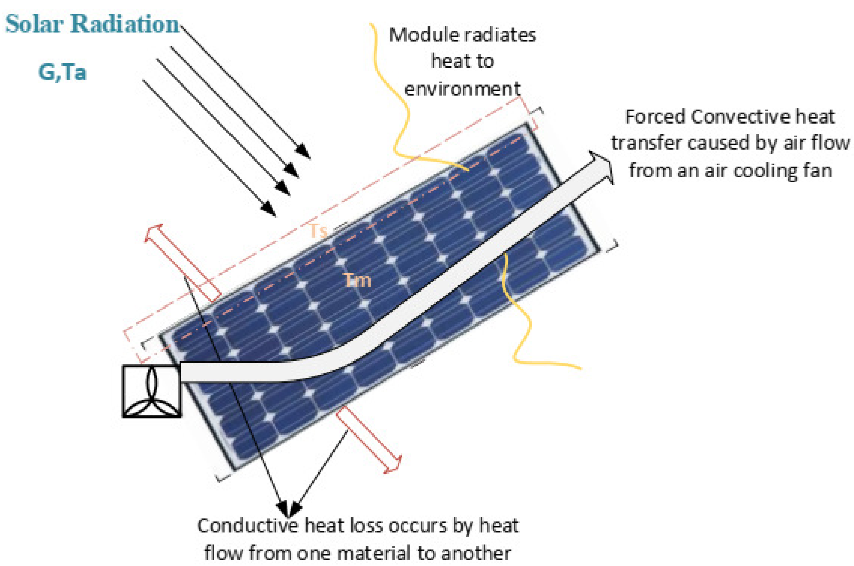


Fig. 5. Heat transfer schema with an air-cooling system of PV module.

a. Convective heat transfer

When the heat transfer is accompanied by a mass transfer, this mode of heat exchange exists within the fluid media (air/water, etc.) or when a fluid circulates around a solid. The transfer is governed by the Newton law of cooling and is directly proportional to the convection heat transfer coefficient, surface area, and the temperature difference [11].

Two heat transfer coefficients need to be established: The forced convection heat transfer coefficient, due to the wind flowing over the surface of the PV panel, h_{forced}, and the coefficient of the free convective heat transfer, h_{free}, which is considered negligible.

$$q_{conv} = h_{forced}\, A(T_s - T_a) \tag{8}$$

Where T_a is the ambient temperature, h_{forced} is the heat transfer coefficient by forced convection with flow and it is related to Nusselt number via the following equations [11], The plan flow regime of a fluid (air in our case) may be laminar or turbulent as shown in Figure 5:

$$h_{forced} = \frac{N_u k}{L} \tag{9}$$

$$\begin{pmatrix} N_u = 0.66 Pr^{1/3} Re^{1/2} & if\ Re < 3.10^5 \\ N_u = 0.036 Pr^{1/3} Re^{4/5} & if\ Re > 3.10^5 \end{pmatrix} \tag{10}$$

The transition from one regime to another is characterized by Reynolds number:

$$R_e = \frac{V\rho\, L}{\mu} \tag{11}$$

Where L is the height of PV Panel, K is the air conductivity up to 0.027, V is the wind velocity origin of air-cooling system, μ is the dynamic viscosity of air (N s/m2) and ρ is the density of the material (kg/m3).

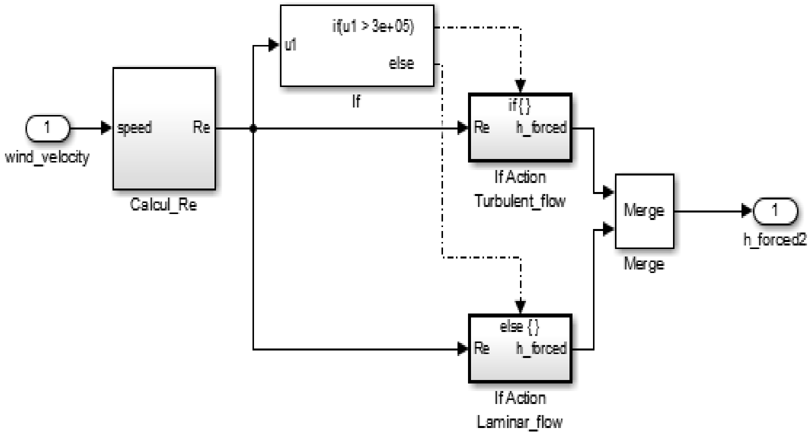


Fig. 6. Forced heat transfer coefficient calculation

b. Conductive heat transfer

Through a material layer, the transfer is governed by the Fourier law and is directly proportional to the material thermal conductivity, area normal to the heat flow direction, and temperature difference. It is inversely proportional to the thickness of the layer [9].

$$q_{cond} = \frac{Ak}{l}(T_s - T_m) \tag{12}$$

Here, A is the module area (m²), k is the thermal conductivity of air (W/ (m K)) and l is the thickness of material (m), Ts is the apparent sky temperature (related to ambient temperature) [11].

$$T_s = 0.32\, T_a + 0.037536\, T_a\, 1.5$$

c. Radiative heat transfer:

It is called also thermal radiation. It describes the heat transfer caused by electromagnetic waves between two surfaces. In our case, power radiative heat transfer includes the difference between the heat emitted from the surrounding through sunlight to the module and the heat emitted from the PV module to the surrounding [12]. The transfer is governed by the Stefan-Boltzmann law and is directly proportional to the area, the radiation coefficient, and the difference of the fourth power of absolute temperature. The radiation coefficient depends on the configuration properties and emissivity of interacting bodies.

$$q_{rad} = \sigma\, \varepsilon\, A({T_a}^4 - {T_m}^4) \tag{13}$$

Where the constant of proportionality σ is Stefan-Boltzmann constant, and ε is the emissivity of PV panel of value 0.91 on its front surface [13].

Finally, the principal of energy conservation can be implemented using:

$$q_{cond} = q_{conv} + q_{rad} \tag{14}$$

$$A_k(T_s - T_m) = h_{forced}\, A(T_s - T_a) + \sigma\, \varepsilon\, A({T_a}^4 - {T_m}^4) \tag{15}$$

The thermal model is based principally on the resolution of the equation (15) of the energy conservation to find the influence of air velocity to the internal temperature of PV cell.

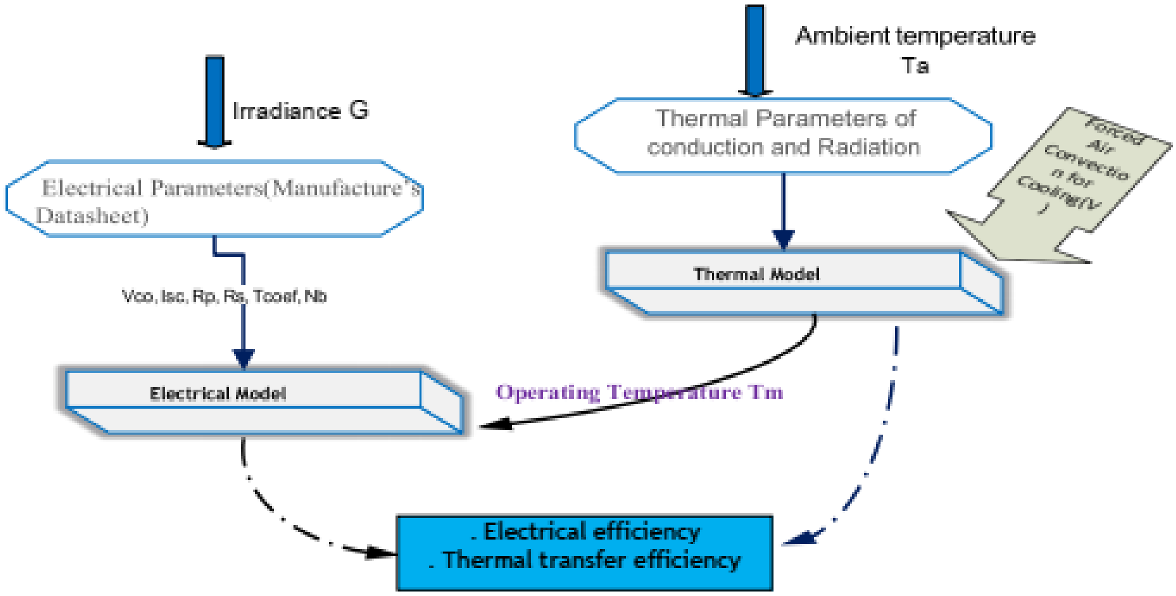


Fig. 7. A complete description model of our studied system

4. Results and discussion

Our proposed model was tested using a polycrystalline photovoltaic module type "SPR-455J-WHT-D "of SunPower Manufacturer, with parameters as reported in Table 1. These parameters are based upon Standard Test Condition (STC). The STC is defined with cell temperature 25°C and, irradiance level 1000 W/m2 at the spectral distribution of air Mass 1.5 solar spectral content. Figure 7 describes the complete architecture of our studied system composed of an electrical and thermal model of the PV module. The latter takes as input the profile of the ambient temperature and the solar irradiance of the region of Sfax. Here, the weather is reported at the site of the Sfax region.

The, figure 9 shows the profile of ambient temperature and solar irradiance on 7th June of the Sfax region site. The maximum solar radiation occurs at 13:00 which is 955 Wh/m² and with maximum ambient temperature was 301 K. The dependence of module surface temperature, electrical efficiency, and air velocity is investigated in the thermal model. All simulations are completed and performed by using the commercial software MATLAB® (Simulink) which validates the following described model, as shown in Figure 8.

Table 1: Value of "SPR- 455J-WHT-D "parameters

	Parameters	Value
Pnom	Nominal Power at STC (manufacturer)	455Wc
	Technology	Si-mono
Nb	Number of cells	128
Tref	Reference temperature	298K
G	Reference irradiance	1000 W/m²
Vco	Open circuit voltage	90.5V
Isc	Short circuit current	6.32 A
T_coef	Temperature coefficient at Isc	3.5 mA/°C
Rp	Parallel resistance	4591ohm
Rs	Series resistance	0.58 ohm
ɳ	Efficiency (/surf. Module)	21.1%

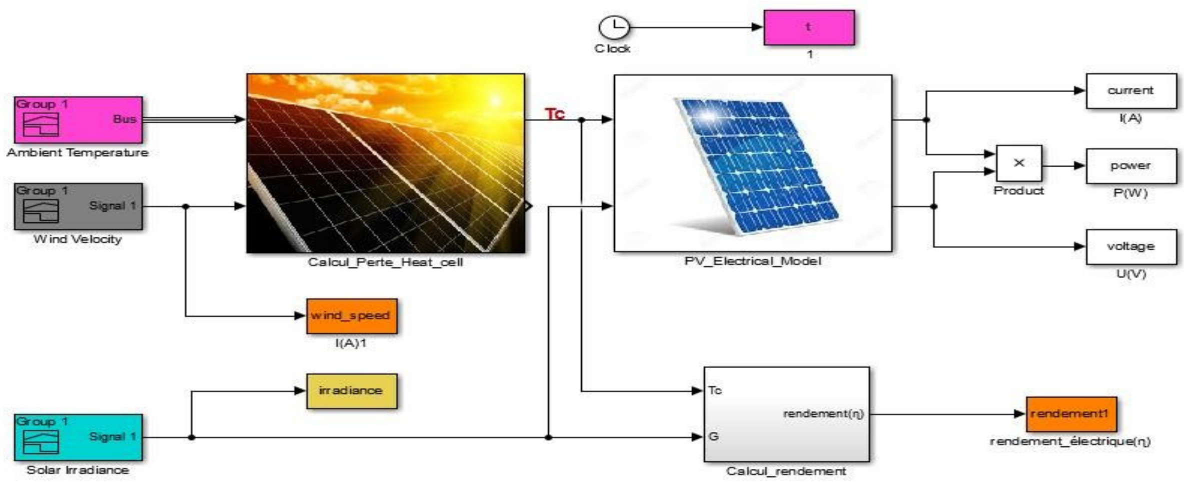


Fig. 8. Complete electrical-thermal model for improving PV performance

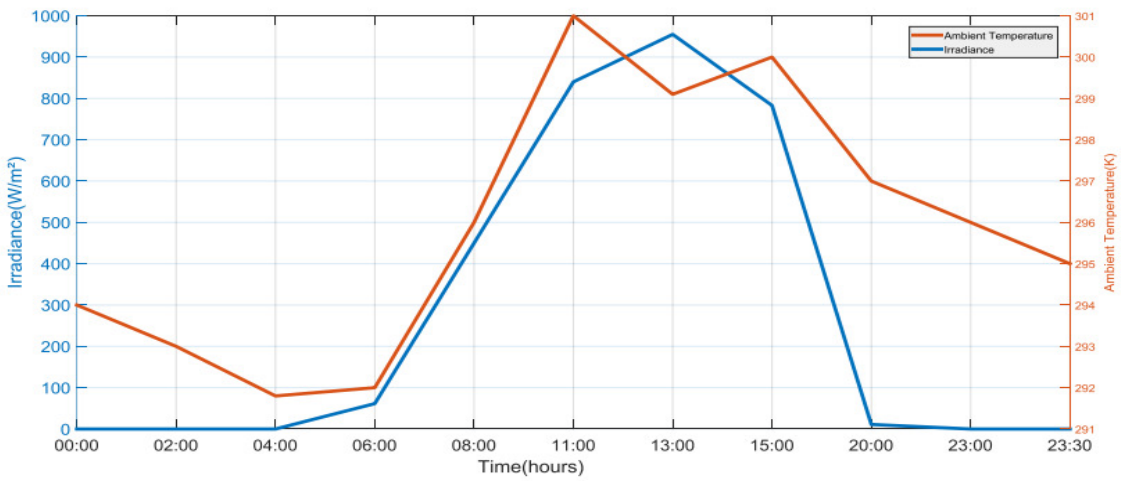


Fig. 9. Profile of temperature and solar irradiance on Sfax site

The simulation results describe and clearly demonstrate the physical phenomenon that must have appeared. As shown in figure 10, the internal temperature of the photovoltaic module reacts well with the evolution of the air velocity. Indeed, when the air speed increases, the average internal temperature decreases, which is the case for the cooling phenomenon of such system. In the same vein, the higher the air velocity is, the higher the removing heat from the PV module to the surrounding.

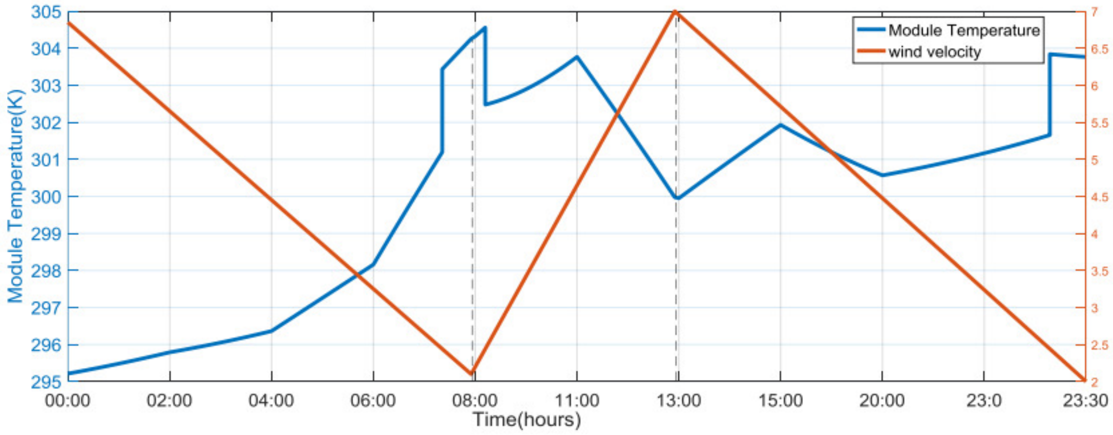


Fig. 10. Module temperature evolution as a function of air-cooling wind velocity

In the term of showing the efficiency of the model developed, we have cleared the evolution of the temperature of the PV module with and without forced air cooling system identified in the model by a forced air speed. Therefore, we calculate a margin of error between 1K and 9 K of temperature below the value obtained in the basic case, as depicted in figure 11. As a result, to perform the electrical efficiency, we need to increase the air velocity by forced convection and the electrical efficiency goes down as the module temperature rises as shown in Figure 12.

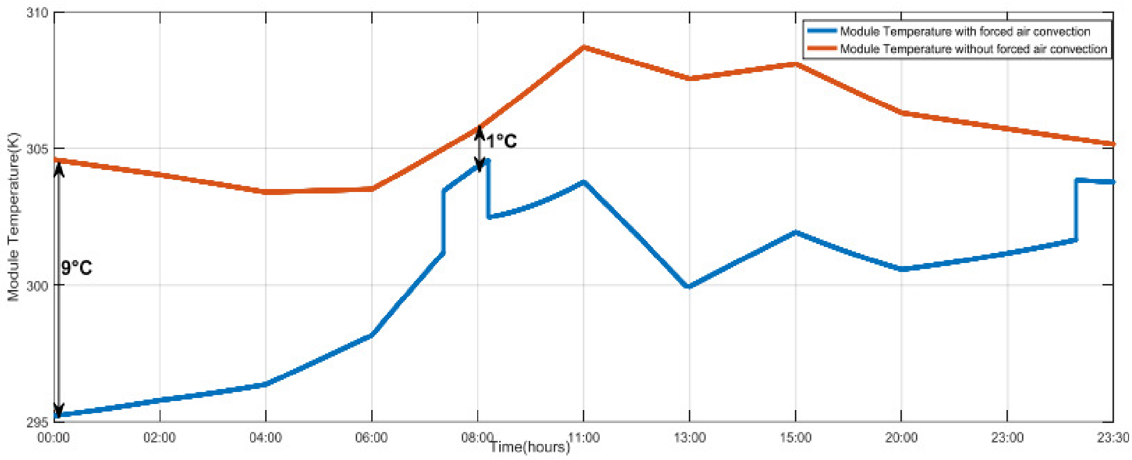


Fig. 11. Module temperature with and without air forced convection

The conversion efficiency of a photovoltaic (PV) cell, or conversion rate, refers to how much of the incoming solar energy is converted into electrical power. Improving this conversion efficiency is a key goal of research and helps make PV technologies costcompetitive with conventional sources of energy. As well as lowering of temperature after integrating a cooling system, the second primary goal is to improve the efficiency of the PV module in order to maximize power generation. For this reason, and after using the equation (5), we approach the two figures which demonstrate the improvement in terms of yield, Figure 11, efficiency as a function of temperature and efficiency as a function of speed. the air. When the temperature decreases due to increases in air velocity, the module efficiency increases. This proves that the increase in environmental temperature increases also the absorption of generated heat, which also decreases energy production. Finally, results simulation and measurement are in good agreement, but it remains also to validate these works with an experimental test bench.

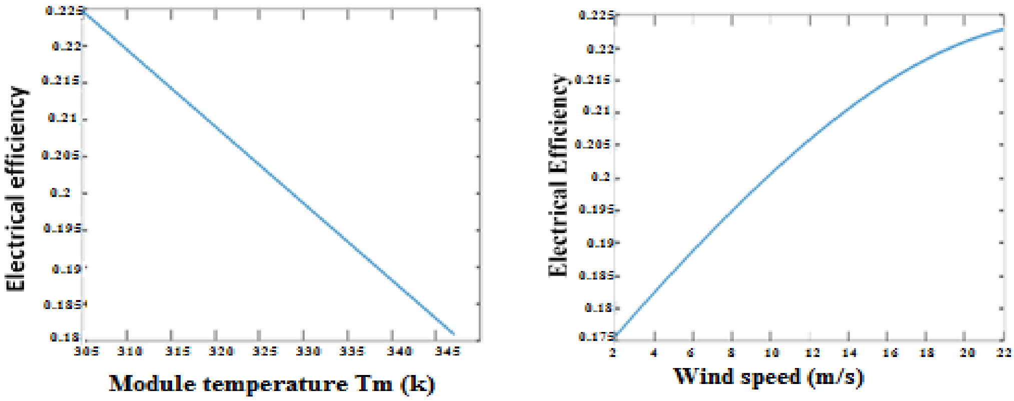


Fig. 12. Electrical efficiency as a function of Module temperature and wind velocity

5. Conclusion

In this work, we presented a new methodology to improve the performance of the photovoltaic system. This methodology makes it possible to develop an electrical thermal model of a PV module based on the integration of air velocity generated by the air cooling system. The electrical efficiency is inversely influenced by the operating temperature because of increase of the generated heat caused by receiving more solar radiation. Indeed, this work highlights good results, when reducing the module temperature, obtained through the comparison between the PV module with and without the air-cooling system. The proposed model allows sensitivity analysis of the effect of meteorology to the performance of the model.

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