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Comparison of Predictive Models for Photovoltaic Module Performance under Tropical Climate

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Abstrak

Makalah ini membahas empat model yang digunakan untuk mengestimasi kinerja modul photovoltaic (PV) ketika iradian dan suhu sel PV diketahui. Model disimulasikan, suhu operasi dan iradian yang bergantung dari efisiensi listrik PV dan keluaran daya dipelajari. Keakuratan model diperoleh dengan membandingkan model dan pengukuran daya maksimum pada modul polycrystalline typical MXS 60 PV pada iklim tropis. Model yang dievaluasi untuk mengestimasi daya maksimum adalah model dioda tunggal, sistem informasi geografis Photovoltaic (PVGIS), Borowy dan Salameh, dan model Hatziargyriou. Analisis kurva kesalahan menunjukkan bahwa model dioda tunggal dan Hatziargyriou memiliki akurasi yang lebih baik. Pendekatan PVGIS dan Borowy tidak tepat sebagai prediksi kinerja modul dalam iklim Sahel Sudan.

***Kata kunci**: iklim tropis, pemodelan, pendekatan Borowy, photovoltaic, PVGIS*

Abstract

This paper examines four models which are used to estimate the performance of photovoltaic (PV) modules when the irradiances and PV cell temperatures are known. The models were simulated and the operating temperature and irradiance dependence of PV electrical efficiency and power output were studied. The models accuracy was obtained by comparing the models and the measurements of maximum power for a polycrystalline typical MXS 60 PV module under tropical climate. The evaluated models for estimating the maximum power are the single diode, the Photovoltaic geographical information system (PVGIS), the Borowy and Salameh, and the Hatziargyriou model. The analysis of the error curves shows that the single diode and Hatziargyriou model have better accuracy. The PVGIS and Borowy approach are not appropriate as the module performance prediction in Sudanese sahelian climate.

***Keywords**: Borowy approach, modeling, photovoltaic, PVGIS, tropical climate*

Abbreviations

V_{oc} *Open-circuit voltage V*	Rs *Cell series resistance Ω*
V_{mp} *Voltage at maximum-power point V*	R_p *The cell (shunt) resistance Ω*
P_m *Power at maximum-power point W*	A *The diode quality factor*
k *Boltzmann's constant,1,38x10^{-23}J/K*	α_0 *Temperature coefficient of open-circuit voltage V/°C*
q *Electronic charge, 1,6x10^{-19} C*	β_0 *Temperature coefficient of short-circuit current %/°C*
T_M *Cell temperature inside module °C*	μ_{pmax} *Temperature coefficient of power %/°C*
I_{ph} *The photo-generated current A*	G_i *Solar radiation W/m²*
I_R *Current owing in the shunt resistance A*	G_0 *Solar radiation in standard conditions (1000 W/m²)*
I_o *The dark saturation current A*	**PVGIS** *photovoltaic geographical information system*
I_{s1} *Saturation current due to diffusion A*	
I_{s2} *The saturation current due to recombination A*	

1. Introduction

Distributed generation offers great potential in meeting future global energy needs [1]. The dwindling supplies of crude oil and natural gas and the global challenges of climatic change and other environmental concerns have resulted in rapid growth of alternative energy sources. Many governments have provided the much needed incentives to promote the utilization of

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renewable energies, encouraging a more decentralized approach to power delivery systems [2]. Currently, photovoltaic (PV) generation systems are actively being promoted in order to mitigate environmental issues such as the green house effect and air pollution.

Recent technological advances in small generators, power electronics, and energy storage devices have provided a new opportunity for distributed energy resources that are located closer to loads [3]. The future of the Photovoltaic industry is promising as the efficiency of the cell and sub-modules continues to increase [4]. In spite of their relatively high cost, there has been very remarkable growth in installed Photovoltaic systems. However the sizing and the optimization of photovoltaic system is a difficult stage for the engineer because of the huge influence of meteorological conditions on the characteristics and performance of a photovoltaic module [5]. A number of studies have been made to determine how the efficiency varies for different PV technologies [6-7]. Availability of accurate models that must quantify how these meteorological factors individually influence the performance of all components of PV module is therefore essential in system sizing, cost analysis and monitoring.

The review of literature presents some background knowledge on the modeling of PV module [8,9]. Models that use constant parameters have been proposed [10] but these models are inaccurate as they do not account for temperature variation. Recently, a lot of researchers have developed single exponential models that neglect the shunt resistance [11,12]. Other researchers have developed models that take account of temperature and irradiance based on datasheet information [13]. Depending on the a priori knowledge of the system structure three different classes of models of the system can be produced as shown in figure 1 [14].

However, many mathematical models and PC software applications for photovoltaic sizing are only appropriate for non tropical region where they are built in. it is important to avoid mistake to make some validations under tropical climate which is not well know.

The aim of the present work is to examine four models among the most used to estimate the performance of photovoltaic (PV) modules under a Sudanese sahelian climate. The operating temperature and irradiance dependence of PV electrical efficiency and power output is simulated. The models accuracy is also computed by comparing modeled and measured maximum power under real conditions. This will help local engineers and technicians working on PV system to choose the most appropriate model for system sizing.

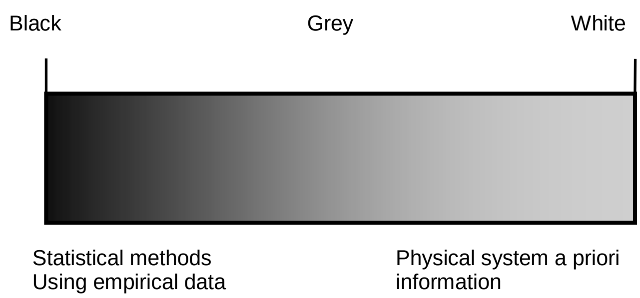


Figure 1. Modeling conceptual sketch

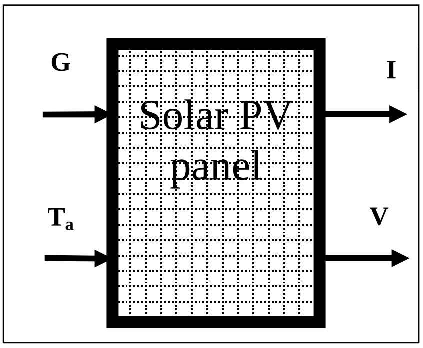
2. Research Method

2.1. Experimental Setup

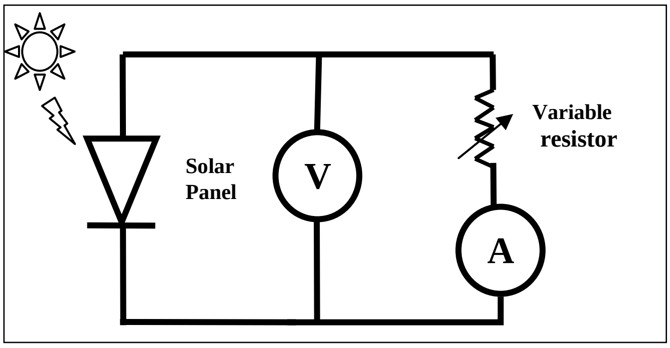
The experiment was performed using a commercial solar cell Solarex MSX60 [15]. The MSX 60 module provides 60 watt of nominal maximum power, and has 36 series connected polycrystalline silicon cells (see table 1). The basic equipment needed for this experiment is an ammeter, a voltmeter and a decade box of resistors (Figure 2). It is important to choose a high impedance voltmeter and low impedance ammeter to prevent loading the circuit. Measurements of global and diffuse incident solar irradiations were carried out using Eppley PSP pyranometers. For temperature measurement, an Universal temperature probe Model EI-1034 is used in association with LABJACK U3 module Transmitter.

The experimental prototype is set up at Garoua **(9°20' N; 13°23' E; altitude 241 m)** a tropical region characterized by a Sudanese-Sahelian climate, located at the north of

Cameroon. The data obtained from the meteorological station shows a mean annual solar irradiation of 5,5 kWh/m^2 per day and the direct sunshine is over 3000 h per year [16]. The site selected for the experimentation is then propitious to implementation and use of PV systems.



(a)



(b)

Figure 2. (a) Schematic diagram of the experimental set up; (b) Schematic circuit diagram for determining I and V of a solar cell.

Table 1. Typical electrical characteristics MSX-60 [15]

MSX-60	
Maximum power (P_{max})	60W
Voltage at Pmax (V_{mp})	17.1V
Current at Pmax (I_{mp})	3.5A
Guaranteed minimum P_{max}	58W
Short-circuit current (I_{sc})	3.8A
Open-circuit voltage (V_{oc})	21.1V
Temperature coefficient of open-circuit voltage	–(80±10)mV/℃ .
Temperature coefficient of short-circuit current . . .	(0.065±0.015)%/℃
Temperature coefficient of power . . .	(0.5±0.05)%/℃ . .
NOCT	47±2℃ . . . .

2.2. Model for Estimation of Maximum Power Output from a Photovoltaic Module
2.2.1. First Approach: Single Diode Model [17]

This single diode model assumes that the dark current of a solar cell can be described by a single exponential dependence modified by a diode quality factor as depicted in nonlinear and implicit Equation (1)[18]. The values of the parameters I_{ph}, I_{s1}, R_s, R_{sh} and A in the equation must be determined to reproduce the IV curve. This requires five equations that will be solved simultaneously to obtain the parameter values [19].

$$I = I_{ph} - I_0\left\{exp\left[\frac{q(V+IR_s}{AkT}\right] - 1\right\} - \frac{V+IR_s}{R_p} \tag{1}$$

At the open-circuit point on the IV curve, V = Voc and I = 0. After substituting these values in (1) the first needed equation is obtained:

$$0 = I_{ph} - I_0\left\{exp\left[\frac{qV_{OC}}{AkT}\right] - 1\right\} - \frac{V_{OC}}{R_p} \tag{2}$$

At the short-circuit point on the IV curve, I = Isc and V = 0. After substituting these values in (1) the second needed equation is:

$$I_{SC} = I_{ph} - I_0\left\{exp\left[\frac{qI_{SC}R_s}{AkT}\right] - 1\right\} - \frac{I_{SC}R_s}{R_p} \tag{3}$$

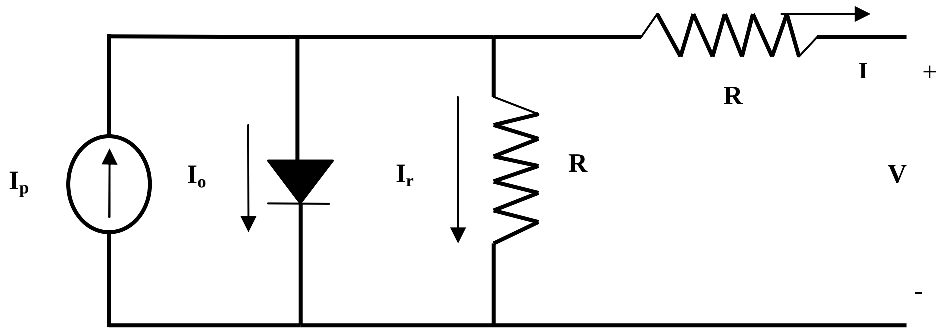


Figure 3. The single exponential model of photovoltaic cell

At the maximum-power point on the IV curve, $I = I_{mp}$ and $V = V_{mp}$. After substituting these values in (1), a third needed equation is obtained:

$$I_{mp} = I_{ph} - I_0\left\{exp\left[\frac{q(V_{mp}+I_{mp}R_s)}{AkT}\right] - 1\right\} - \frac{V_{mp}+I_{mp}R_s}{R_p} \tag{4}$$

More equations can be obtained by obtaining the derivative of (1) with respect to V:

$$\frac{dI}{dV} = -I_0\left\{\frac{q}{AkT}\left(1+\frac{dI}{dV}R_s\right)exp\left[\frac{q(V+IR_s)}{AkT}\right]\right\} - \frac{1}{R_p}\left(1+\frac{dI}{dV}R_s\right) \tag{5}$$

At the open-circuit point again, on the IV curve V = Voc and I = 0 therefore,

$$\frac{dI}{dV} = \frac{dI}{dV}|_{I=0} \tag{6}$$

Substituting in (6) the following results:

$$\frac{dI}{dV}|_{I=0} = -I_0\left\{\frac{q}{AkT}\left(1+\frac{dI}{dV}|_{I=0}R_s\right)exp\left[\frac{qV_{OC}}{AkT}\right]\right\} - \frac{1}{R_p}\left(1+\frac{dI}{dV}|_{I=0}R_s\right) \tag{7}$$

Again at the short-circuit point on the IV curve, I = Isc and V = 0.

$$\frac{dI}{dV} = \frac{dI}{dV}|_{V=0}$$

$$\frac{dI}{dV}|_{V=0} = -I_0\left\{\frac{q}{AkT}\left(1+\frac{dI}{dV}|_{V=0}R_s\right)exp\left[\frac{qI_{SC}R_s}{AkT}\right]\right\} - \frac{1}{R_p}\left(1+\frac{dI}{dV}|_{V=0}R_s\right) \tag{8}$$

The power transferred from the PV at any point is given by:

$$P = IV \tag{9}$$

The power equation (9) can be differentiated with respect to the voltage, V:

$$\frac{dP}{dV} = \left(\frac{dI}{dV}\right)V + I$$
(10)

To find the value of voltage that gives the maximum power the derivative is equated to 0.

$$\frac{dP}{dV} = 0 \tag{11}$$

Substituting in equation (10)

$$\frac{dI}{dV} = -\frac{I_{mp}}{V_{mp}} \tag{12}$$

Substituting in (6) the following equation is obtained

$$-\frac{I_{mp}}{V_{mp}} = -I_0\left\{\frac{q}{AkT}\left(1-\frac{I_{mp}}{V_{mp}}R_s\right)exp\left[\frac{qI_{SC}R_s}{AkT}\right]\right\} - \frac{1}{R_p}\left(1-\frac{I_{mp}}{V_{mp}}R_s\right) \tag{13}$$

Among the equations obtained, equations (2) (3) (7) (8) (13) are the five equations we have choose for numerical resolution using the Newton Raphson method. The initial values of I_{ph}, I_{s1}, R_s, R_{sh} and A used in the algorithm are similar to analytical expressions obtained from [20], [21].

2.2.2. Second Approach: Model of Borowy and Salameh [22]

The mathematical model (22) was developed by Borowy and Salameh in 1996. The model derived from the single diode model that uses the PV cell characteristic specify by the manufacturers. It gives a simple relation to compute the maximum power delivered from a PV array.

$$I = I_{SC}\left\{1-\left[D_1 exp\left(\frac{V_m}{D_2 V_{OC}}\right)-1\right]\right\} + \Delta I \tag{22}$$

D_1, D_2 are two parameters computed from the relations (23) and (24).

$$D_1 = \left(1-\frac{I_{mp}}{I_{SC}}\right) exp\left(-\frac{V_{mp}}{D_2 V_{OC}}\right) \tag{23}$$

$$D_2 = \left(\frac{V_{mp}}{V_{OC}}-1\right)/ln\left(1-\frac{I_{mp}}{I_{SC}}\right) \tag{24}$$

ΔI is a parameter which depends on temperature and solar radiation and compute from the relation (25).

$$\Delta I = \alpha_0\left(\frac{G}{G_0}\right)\Delta T + \left(\frac{G}{G_0}-1\right)I_{SC} \tag{25}$$

$$\Delta T = T_M - T_0 \tag{26}$$

The tension V_m of module is given by the relation (27):

$$V = V_{mp}\left[1+0,0539 log\left(\frac{G}{G_0}\right)\right] + \beta_0\Delta T - R_S\Delta I \tag{27}$$

The power output from the module is:

$$P = I \times V \tag{28}$$

2.2.3. Third Approach: Model of Hatziargyriou [23]

Knowing the technical characteristic provided by the module supplier and local meteorological conditions, only one empirical equation is needed to compute the power output from a module [23].

$$P = \frac{G}{G_0}\left[P_m + \mu_{pmax}(T_M - T_0)\right] \tag{29}$$

Since the module temperature T_M is not known a priori, the following approximate relation between T_M, the ambient temperature T_{amb} and the nominal operating cell temperature NOCT, provided by the module supplier, has been employed [24,25]:

$$T_M = T_{amb} + G\frac{NOCT-20}{800} \tag{30}$$

2.2.4. Fourth Approach : PVGIS Method [26-27]

PVGIS approach provides analysis and assessment of in-site solar energy resources and predicts with good accuracy the potential of PV systems in term of electricity production. The starting point for performing this calculation is the set of semi-empirical formulas for the voltage V and current I of PV modules at maximum power point, given in [7] and used in modified form in [28]. From these we can calculate the relative conversion efficiency of the module (η_{rel}), i.e. the efficiency relative to the efficiency η_0 measured at STC:

$$\boldsymbol{\eta_{rel}(G_i, T_M) = \frac{G_i}{G_0}[1 + a_i(T_M - T_0)] \times [1 + C_1 ln\frac{G_i}{G_0} + C_2(ln\frac{G_i}{G_0})^2 + b_v(T_M - T_0)]} \quad (31)$$

The parameters $\boldsymbol{a_i}$, $\boldsymbol{b_v}$, $\mathbf{C_1}$, $\mathbf{C_2}$ are empirical and were already determined experimentally in reference [28]. Given these relationships between PV module performance and meteorological conditions, we can calculate the power output of a given grid-connected crystalline silicon PV system with nominal peak power P_m as:

$$\boldsymbol{P(G_i, T_m) = P_m \eta_{rel}(G_i, T_m)\frac{G_i}{G_0}} \quad (32)$$

3. Results and Analysis

Firstly, only the single diode model of the PV module was implemented using a Matlab program to simulate the effect of temperature and irradiance on the performance of module. The data points used are taken directly from the manufacturer's published curves. Secondly all the models described above are used to simulate the power output from the module at the month of May in Garoua **(9°20 ' N; 13°23' E; altitude 241 m)** and the result are compared to experimental data.

3.1. Local Meteorological Conditions

The measured hourly variation of global solar radiation G_i and temperature T_{amb} is shown in figure 4**.** In the same figure the temperature of module compute from relation (27) is also depicted.

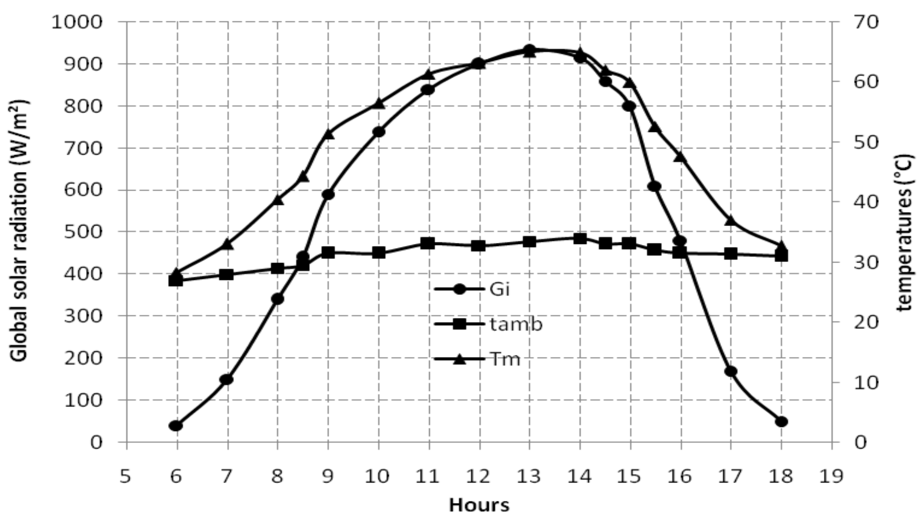


Figure 4. Mean hourly variation of global solar radiation and temperature for the month of may in Garoua (9°20' N; 13°23' E; altitude 241 m)

3.2. Variation of characteristic with temperature and irradiance using single diode model

Figure 5 provides a clear view on how the curves vary with temperature. The discrete data points shown are taken directly from the manufacturer's published curves and show excellent correspondence to the single diode model.

There is significant reduction in the power output of the photovoltaic system as cell temperature increases. This relationship is clearly depicted in Figure 6 where the power is plotted as a function of voltage for 4 different temperatures.

To show the effect of irradiance on the performance of a module the temperature is kept fixed at 25 ℃ and the values of irradiance are cha nged to different values. The variation of the current-voltage characteristics with irradiance are shown in Figure 7. It is quite clear that irradiance has a major effect on the short circuit current and indeed the relationship between irradiance and the short circuit current is a linear one.

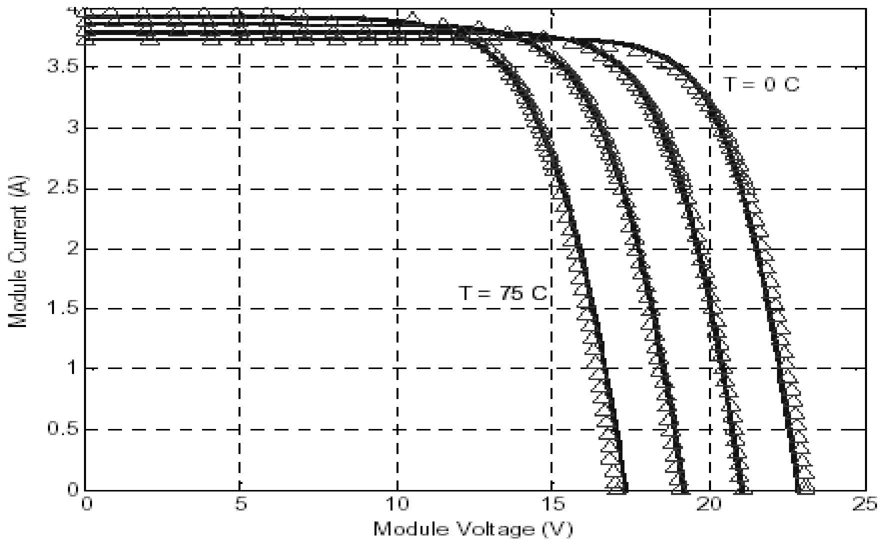


Figure 5. Curves for a photovoltaic module at different temperatures

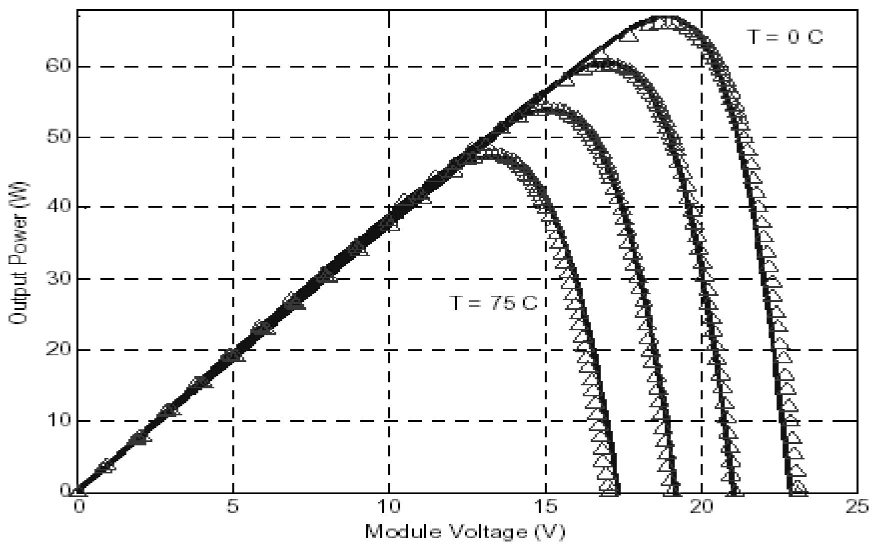


Figure 6. Variation of power output with temperature for a photovoltaic module

To show the effect of irradiance on the performance of a module the temperature is kept fixed at 25 ℃ and the values of irradiance are cha nged to different values. The variation of the current-voltage characteristics with irradiance are shown in Figure 7. It is quite clear that irradiance has a major effect on the short circuit current and indeed the relationship between irradiance and the short circuit current is a linear one.

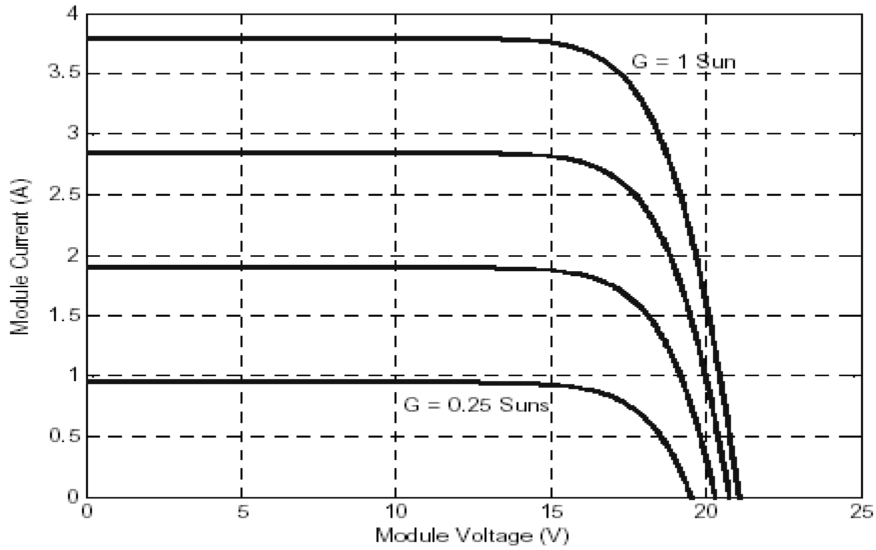


Figure 7. Variation of current and voltage with irradiance.

3.3. Variation of Output Power with Temperature

The study is made for values of solar radiation varying from 300 W/m² to 900 W/m². The models tested are PVGIS, Borowy and Hatziargyriou. The result is depicted in figure 8, 9, 10. Globally, it turns out that the power output depend linearly on the operating temperature, decreasing substantially with T_M as the thermally excited electrons begin to dominate the electrical properties of the semi-conductor. In contrast to others tested models the PVGIS approach reveals that there is no significant variation of output power with temperature. For low values of temperature (5℃ - 25℃) we denote a non linear variation of power wit h T_M with the model of Borowy. In other hand, it is quite clear that the power output increase with the irradiance.

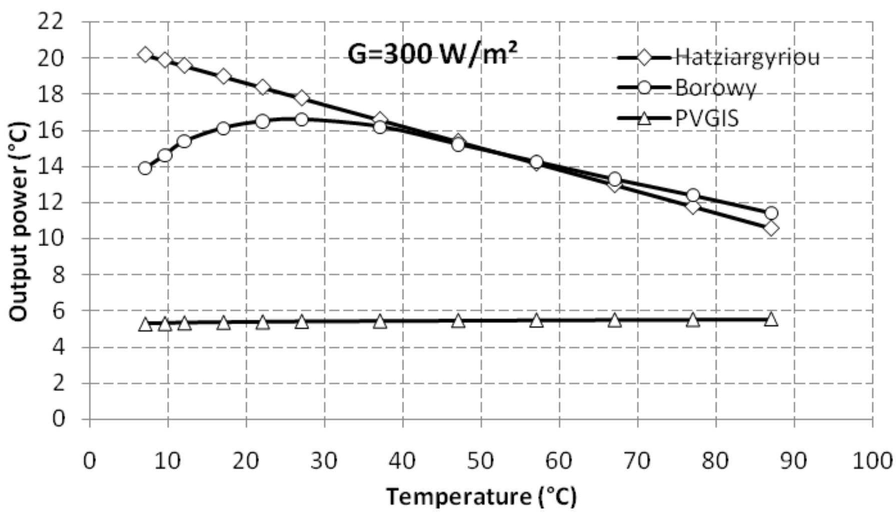


Figure 8. Variation of Power output with temperature (G = 300 W/m²)

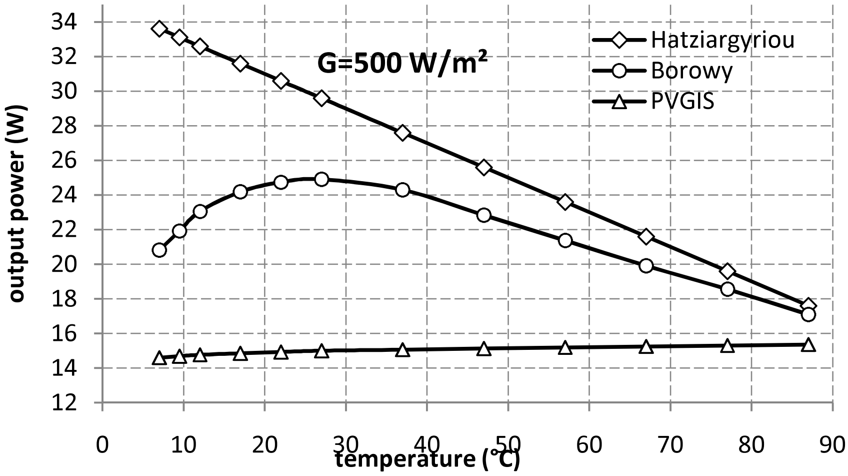


Figure 9. Variation of Power output with temperature (G = 500 W/m²)

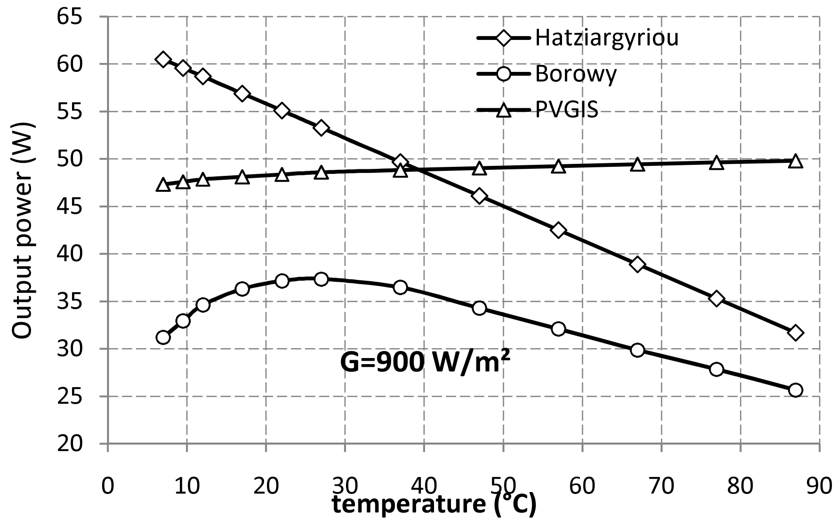


Figure 10. Variation of Power output with temperature (G = 900 W/m²)

3.4. Comparison of Power Output from Solar Panel in Real Meteorological Conditions

The power output from the solar panel using different models described above is computed in real meteorological conditions (see figure 7). Experimental and compute data are depicted in figure 11. The accuracy of different models in real conditions is study by using the relative error from formula (33).

$$\boldsymbol{error} = \frac{|P_{measured} - P_{model}|}{P_{measured}} \quad (33)$$

In figure 11 and 12, we denote that for low values of solar radiation (< 600 W/m²) and temperature observed from 6AM to 9AM and from 4 PM to 6 PM, the single diode model and Hatziargiriou model are the more accurate. In reverse, for high values of solar radiation (600≤G≤950 W/m²) observed from 10AM to 3 PM, the PVGIS and Borowy model are more accurate. In general, at the morning and at the evening the mathematical models are not in good accordance with the experience. Even at the midday despite the high value of solar radiation, there is significant reduction in the experimental and the computed power output from the photovoltaic system due to high value of cell temperature under tropical climate which affect substantially the PV efficiency. The positive effect of high solar radiation in tropical region is compensated by the temperature increasing.

From the error curve shown in figure 12 and in table 2 we can conclude that the single diode model and Hatziargyriou model are appropriate for PV module performance in tropical sahelian region. The PVGIS model and Borowy approach are inaccurate due to the fact they do not well account for temperature variation. The single diode despite it better accuracy is difficult to use and solve in the mathematical form describe above. It can be easily use through the PC software package PVSIST [29] for the study and the sizing of complete PV under Sudanese sahelian climate.

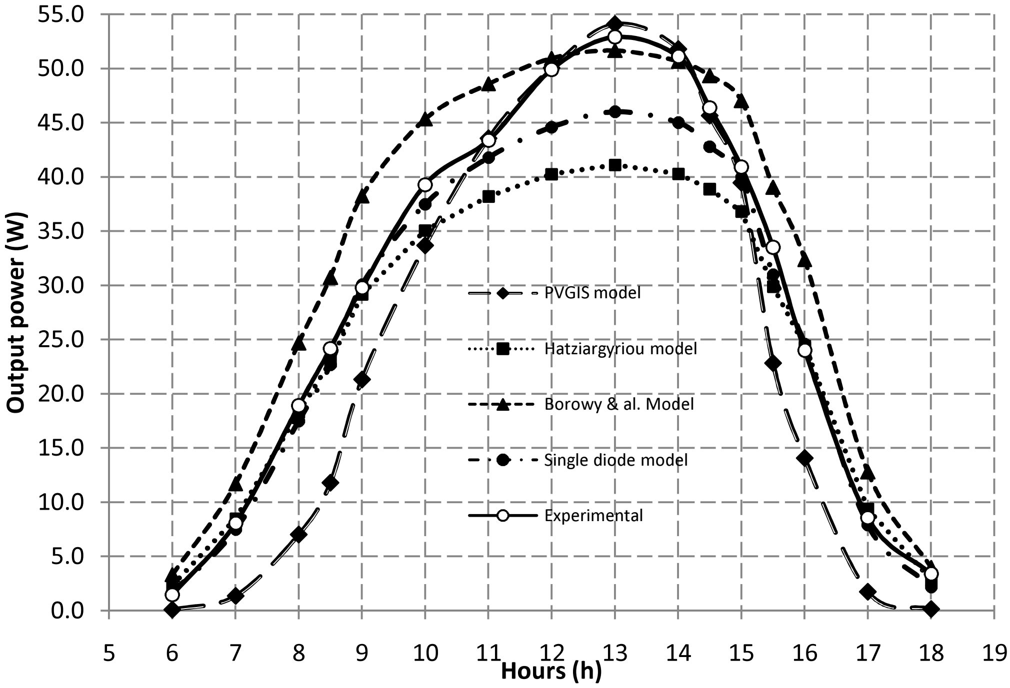


Figure 11. Computed and experimental value of power output from solar panel for the month of May in Garoua (9°20' N; 13°23' E; altitude 241 m)

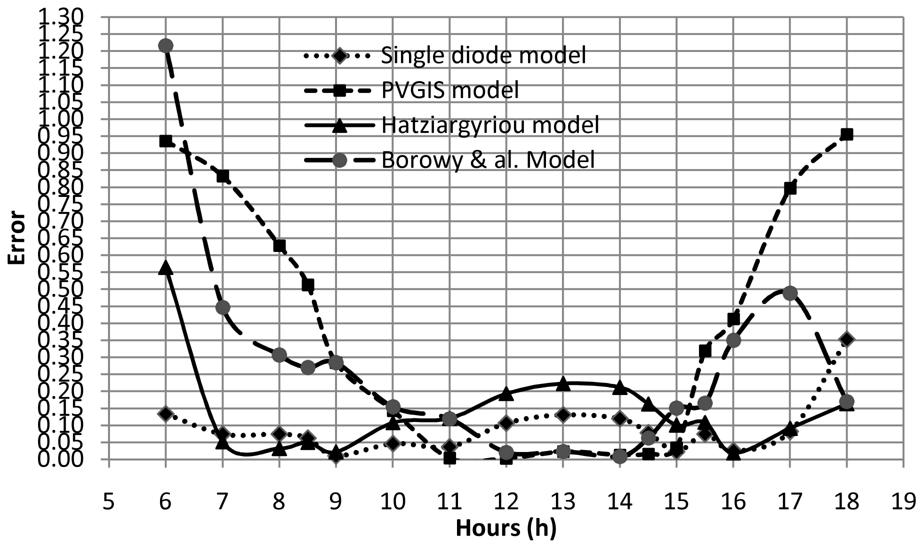


Figure 12. Error generated by different model

Table 2. Mean error by different model

	Mean error generated (%)			
Model	6 AM to 9 AM	10 AM to 4 PM	4 PM to 6 PM	Daily
Single diode model	8,9%	6,5%	15,3%	10,2%
PVGIS model	36,9%	12,5%	72,2%	40,5%
Borowy & al. Model	26,5%	13,4%	33,6%	24,5%
Hatziargiriou model	13,9%	12,7%	9,1%	11,9%

4. Conclusion

A comparison of four models based on the output power from photovoltaic module was done under real tropical meteorological conditions to determine their accuracy. The single diode model, the PVGIS model, the Borowy and Salameh model, and the Hatziargiriou model were implemented using a numerical program to simulate the effect of temperature and irradiance on the performance of the tested module. A comparison was done between the power obtained from experimental set-up and from simulated models. The analysis of the curves shows that the single diode model has the better accuracy whereas the PVGIS approach seems to be not appropriate for the tropical region. This work is the first attempt to make some validation on predictive models for PV module performance under Sudanese sahelian climate and will later be extended to other models and PV technologies.

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