A novel model of photovoltaic modules for parameter estimation and thermodynamic assessment

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Abstract

This paper presents a novel model to evaluate the electrical performance of a silicon photovoltaic (PV) module with respect to changes in main environmental parameters such as temperature and illumination intensity. A simple one-diode model is proposed to estimate the electrical parameters of PV module considering the series resistance and shunt conductance. Effects of PV module parameters on current–voltage characteristic curve are investigated. The proposed model also makes a thermodynamic assessment concerning the effects of environmental and electrical parameters on efficiency and maximum power output of the PV module. Kyocera KD205GH-2P 205-W high-efficiency multi-crystal PV module is used for model evaluation. Model results are compared with the manufacturer's data report and an excellent agreement is observed.

Keywords: photovoltaic module; mathematical model; parameter estimation

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1 INTRODUCTION

Renewable energy resources will be a significant part of power generation in the upcoming future. Within a variety of renewable and sustainable energy technologies in progress, photovoltaic (PV) technology appears to be one of the most promising ways meeting the future energy demands as well as environmental issues [1]. Besides contributing to the CO_2 emission reduction, PV systems are silent and free of moving parts. Therefore, operation and maintenance costs of these systems are very low. Intensive efforts are made to reduce the cost per peak power obtained from PV cells. These efforts aim at narrowing the gap between PV and conventional power sources. Besides the importance of developing new manufacturing processes related to PVs, it is quite significant to provide the most appropriate operating condition for a PV system [2]. Performance parameters of a PV module strongly depend on the environmental parameters such as temperature, illumination intensity level and wind speed. An accurate knowledge of these parameters is of vital importance for the quality control and the performance evaluations of PV modules. Several methods are proposed for extracting the performance parameters that describe the nonlinear electrical model of PVs [3–7].

Gonzalez-Longatt [8] presents a circuit-based simulation model in order to determine the electrical behavior of a typical 60-W PV module with to respect changes in environmental parameters. The model is based on the Shockley diode equation and it calculates the current for a given voltage. The model results indicate that the series resistance of the PV module has a notable impact on the slope of the current–voltage characteristic at V_{oc}. Adamo *et al.* [9] describes a simple one-diode model to evaluate the electrical performances of PV modules. The model is implemented as a MATLAB script which yields the current–voltage and power–voltage characteristics of the PV module under test. It estimates the series and shunt resistances of the PV module obtaining the best fit of the measured current–voltage characteristic. Tsai [10] presents an insolation-oriented model which is implemented and analyzed using MATLAB/Simulink software package. Taking into the effect of illumination intensity level on the cell temperature, the model simulates and analyzes the output current and power characteristics of a PV module. Kim and Choi [11] propose a novel parameter extraction method for the one-diode solar cell model. The method enables to determine the ideality factor using characteristics of the diode obtained from the current–voltage characteristic of a solar cell.

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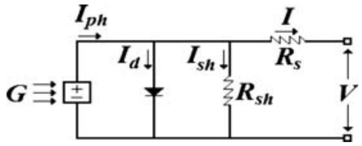

Figure 1. *General equivalent circuit model.*

The goal of this study is to present a model for estimating the electrical parameters of silicon PV modules considering the effects of series and shunt resistance. The proposed study also aims at presenting a thermodynamic assessment which evaluates the parameter effects on energy conversion in a PV module.

2 MATHEMATICAL MODEL

The simplest equivalent circuit of a PV cell/module is a current source in parallel with a diode as shown in Figure 1. The output of this current source is called as photocurrent and is directly proportional to the incident radiation (G). The current–voltage relation of a PV module can be expressed as follows:

$$I = I_{ph} - I_s\left\{\exp\left(\frac{\beta}{Nn}(V + IR_s)\right) - 1\right\} - G_{sh}(V + IR_s) \quad (1)$$

where I_{ph} is the light-generated current or photocurrent, I_s is the diode saturation current, N is the number of cells in series, n is the ideality factor, R_s is the series resistance and G_{sh} $(=1/R_{sh})$ is the shunt conductance. $\beta = q/kT$ is the usual inverse thermal voltage. Equation (1) is implicit and it cannot be solved analytically. Therefore, a suitable numerical method is needed in order to obtain the current–voltage characteristic of the PV module. Manufacturer's data report includes only open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum voltage (V_m), maximum current (I_m) and maximum power output (P_m) measured at the standard test conditions (STC, $T_c = 25°C$, $G = 1000$ W/m^2 and AM = 1.5). In order to establish a model, R_s, R_{sh}, I_s and n must be extracted using the data provided by the manufacturer.

I_{ph} of the PV module for the cell temperature of T can be determined as follows:

$$I_{ph}|_T = I_{ph}|_{T_1} + \zeta(T - T_1) \quad (2)$$

where

$$\zeta = \frac{I_{sc}|_T - I_{sc}|_{T_1}}{T - T_1} \quad (3)$$

In Equation (3), ζ is the temperature coefficient of I_{sc}. V_{oc} of the PV module for the cell temperature of T can be given by

$$V_{oc}|_T = \mu\,(T - T_1) + V_{oc}|_{T_1} \quad (4)$$

In Equation (4), μ is the temperature coefficient of V_{oc}. Diode saturation current (I_s) of the PV module for the cell temperature of T can be determined by

$$I_s|_T = \frac{I_{sc}|_{T_1}}{\exp\left(\dfrac{q\,V_{oc}|_{T_1}}{nkT_1}\right) - 1} I_s|_{T_1}\left(\frac{T}{T_1}\right)^3 \exp\left(\frac{qE_g}{nk\left(\dfrac{1}{T} - \dfrac{1}{T_1}\right)}\right) \quad (5)$$

where E_g is the bang gap of silicon. Series and shunt resistances of the PV module are given by:

$$R_s = \left.\frac{dV}{dI}\right|_{V=V_{oc}} \quad (6)$$

$$R_{sh} = \left.\frac{dI}{dV}\right|_{I=I_{sc}} \quad (7)$$

Ideality factor highly depends on the PV technology as it is illustrated in Table 1. It takes a value between 1 and 2 for silicon PV technology. In the model, n is an unknown parameter and its value has to be estimated. A value of 1.1 may be used initially until a more accurate value is estimated later through curve fitting. For the illumination intensity levels up to 1 sun (1000 W/m^2), photocurrent (I_{ph}) is approximately equal to the short-circuit current (I_{sc}), thus $I_{ph} = I_{sc}$ is considered in the proposed model. Equation (1) is implicit and not solvable analytically. Therefore, an iterative approach is used in the study in order to determine the current, I, for a given voltage, V. Newton–Raphson method is preferred in the model since it provides a more rapid convergence.

Kyocera KD205GH-2P 205-W high-efficiency multi-crystal PV module is utilized for model evaluation. The PV module consists of 54 multi-crystal PV cells connected in series.

Table 1. *Ideality factor for various PV technologies.*

PV technology	n
Si-mono	1.2
Si-poly	1.3
a-Si:H	1.8
a-Si:H tandem	3.3
a-Si:H triple	5.0
CdTe	1.5
CIS	1.5
GaAs	1.3

Table 2. *Electrical characteristics of Kyocera KD205GH-2P PV module.*

Parameter	Variable	Value
Maximum power	P_m	205
Maximum current	I_m	7.71
Maximum voltage	V_m	26.6
Short-circuit current	I_{sc}	8.36
Open-circuit voltage	V_{oc}	33.2
Temperature coefficient of short-circuit current	ζ	5.02×10^{-3}
Temperature coefficient of open-circuit voltage	μ	-1.20×10^{-1}
Temperature coefficient of maximum power	ζ	-9.43×10^{-1}

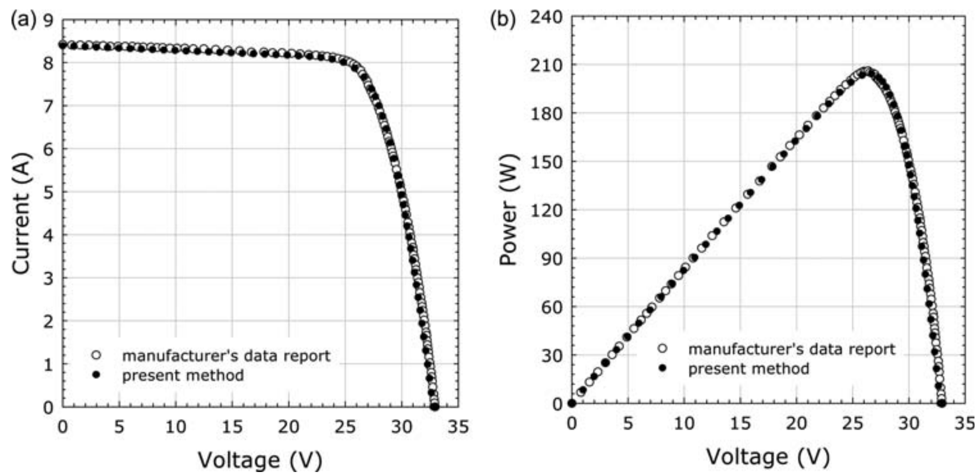

Figure 2. *Accuracy of the proposed model: (a)* I–V *and (b)* P–V *characteristics for STC.*

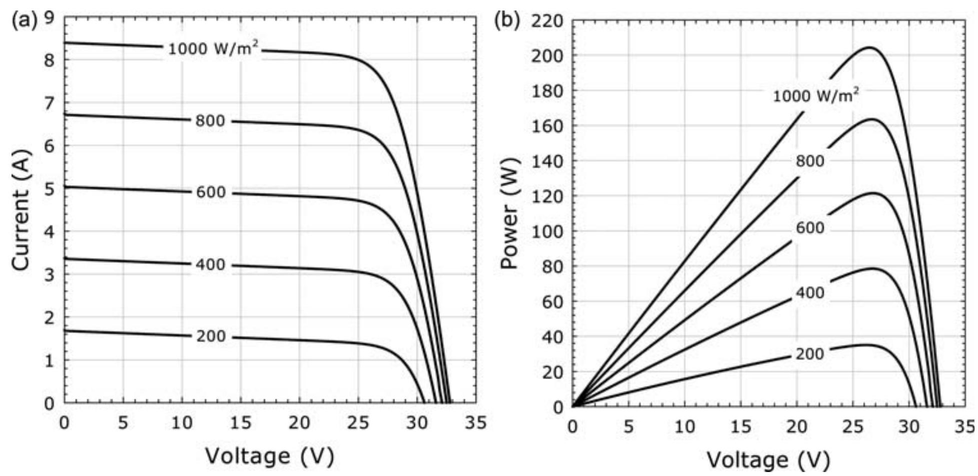

Figure 3. *(a)* I–V *and (b)* P–V *characteristics for different illumination intensity levels.*

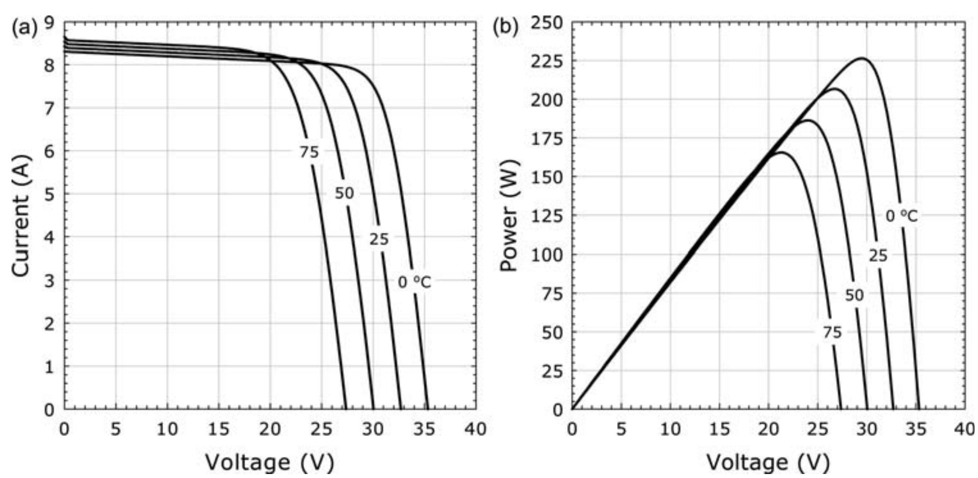

Figure 4. *(a)* I–V *and (b)* P–V *characteristics for different cell temperatures.*

Typical electrical characteristics of the PV module for STCs are shown in Table 2.

3 THERMODYNAMIC ANALYSIS

Efficiency for a PV cell measures the ability to convert radiative energy into electrical energy. As reported by Riffat and Cuce [12], there are three main efficiency expressions which characterize the performance evaluation of PV cells. These are called as energy, exergy and power conversion efficiencies. Energy efficiency is determined by the ratio of theoretical electrical power output of a PV cell divided by the input illumination intensity.

$$\eta_{\mathrm{e}} = \frac{I_{\mathrm{sc}} V_{\mathrm{oc}}}{G A_{\mathrm{c}}} \tag{8}$$

Power conversion efficiency is determined by the ratio of the area under the current-voltage characteristic curve of a PV cell divided by the input illumination intensity.

$$\eta_{\mathrm{pce}} = \frac{\int_0^{V_{\mathrm{oc}}} I(V)\mathrm{d}V}{G A_{\mathrm{c}}} \tag{9}$$

Exergy efficiency is calculated as the maximum useful energy produced by a PV cell divided by the input exergy of illumination intensity.

$$\eta_{\mathrm{ex}} = \frac{I_{\mathrm{m}} V_{\mathrm{m}}}{G_{\mathrm{ex}} A_{\mathrm{c}}} \tag{10}$$

The exergy efficiency can also be written in terms of fill factor (FF) as follow:

$$\eta_{\mathrm{ex}} = \frac{I_{\mathrm{sc}} V_{\mathrm{oc}}}{G_{\mathrm{ex}} A_{\mathrm{c}}} \mathrm{FF} \tag{11}$$

The exergy content of thermal radiation was presented by Petela [13] with the following equation:

$$G_{\mathrm{ex}} = \left[1 + \frac{1}{3}\left(\frac{T_{\mathrm{amb}}}{T_{\mathrm{sun}}}\right)^4 - \frac{4}{3}\left(\frac{T_{\mathrm{amb}}}{T_{\mathrm{sun}}}\right)\right] G \tag{12}$$

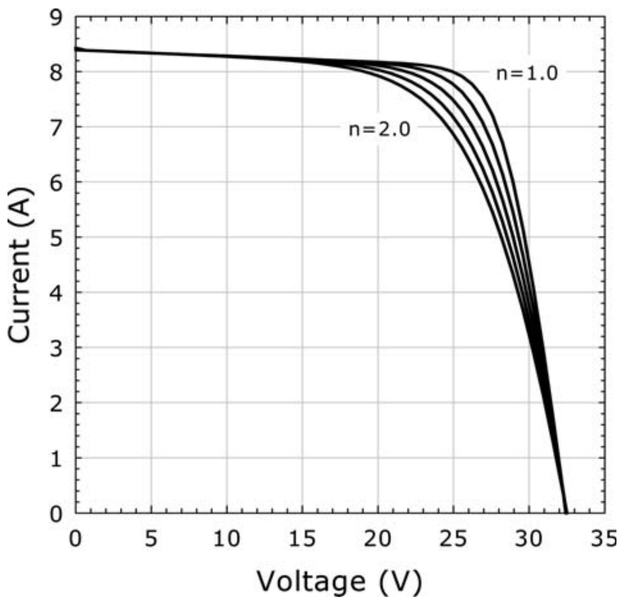

Figure 5. I–V *characteristics for different ideality factors.*

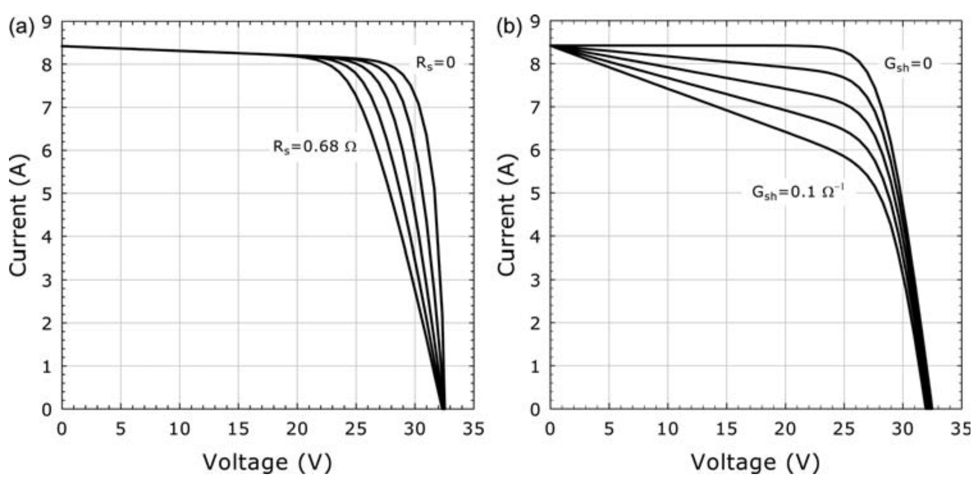

Figure 6. I–V *characteristics for different (a)* R_s *and (b)* R_{sh}.

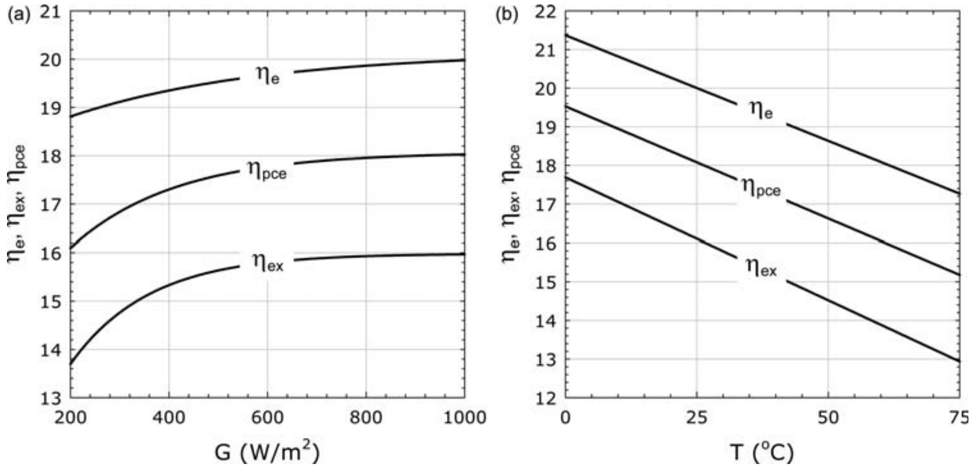

Figure 7. *η_e, η_{pce} and η_{ex} for different (a)* G *and (b)* T.

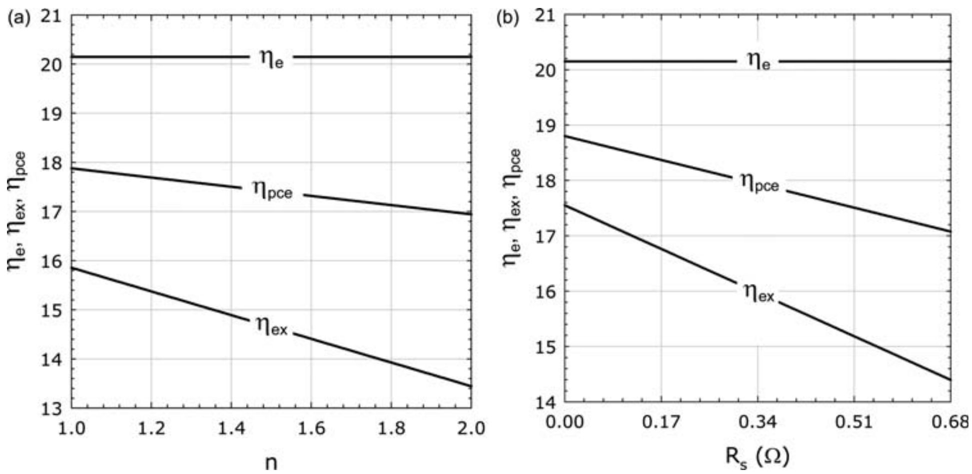

Figure 8. *η_e, η_{pce} and η_{ex} for different (a)* n *and (b)* R_s.

4 RESULTS AND DISCUSSION

4.1 Validation of the model

Before starting the analysis, the proposed model is evaluated in terms of accuracy. For STC, model results are compared with the manufacturer's data report and an excellent agreement is observed as it is shown in Figure 2.

4.2 Results for different illumination intensity levels

Effects of illumination intensity on performance parameters of the PV module are investigated in the range of 200–1000 W/m^2 and the results are shown in Figure 3. As it is clear, current parameters are highly dependant on the radiation intensity level. On the contrary, voltage parameters are less affected by the radiation conditions. Maximum power output of the PV module notably increases with increasing illumination intensity corresponding to the increase in both the current and voltage parameters. P_m is determined to be 204.3, 163.5, 121.5, 78.5 and 35.1 W for the illumination intensity levels of 1000, 800, 600, 400 and 200 W/m^2, respectively.

4.3 Results for different cell temperatures

Effects of cell temperature on performance parameters of the PV module are investigated in the range of 0–75°C and the results are shown in Figure 4. It is observed that I_{sc} slightly increases with increasing cell temperature. Model results indicate that cell temperature is of vital importance for performance of PV module. The maximum power output of the PV module considerably decreases with increasing cell temperature. This decrease arises from the drop in voltage parameters. P_m is determined to be 226.3, 204.3, 186.2 and 165.5 W for the cell temperatures of 0, 25, 50 and 75°C, respectively.

4.4 Results for different ideality factors

Effects of ideality factor on $I-V$ characteristics are illustrated in Figure 5. It is well known in the literature that n has a value between 1 and 2 for silicon PV technology. Therefore, the analysis is carried out for five different ideality factors in the range of 1–2. The results indicate that the higher values of n soften the $I-V$ characteristic curve. It is also noted from the model results that the ideality factor of the PV module is around the initial value ($n \approx 1$).

4.5 Results for different series resistances

The series resistance of the PV module is determined to be 0.34 Ω for STC. R_s of a PV module is almost independent of illumination intensity level. On the other hand, it is affected by the variation in cell temperature. In the model, variation in R_s with cell temperature is neglected since a narrow range of cell temperature is considered in the study. As shown in Figure 6a, a slope of the line between maximum power point (mpp) and V_{oc} decreases with increasing R_s and thus the maximum power output of the PV module reduces.

4.6 Results for different shunt resistances

The shunt resistance, R_{sh}, represents any parallel high-conductivity paths (shunts) across the solar cell p–n junction or on the cell edges [14]. In the model, shunt conductance (G_{sh}) is used instead of R_{sh} ($G_{sh} = 1/R_{sh}$) and G_{sh} of the PV module for STC is determined to be 0.009. As it is illustrated in Figure 6b, a slope of the line between mpp and I_{sc} increases with decreasing R_{sh} and thus the maximum power output of the PV module reduces.

4.7 Results for performance assessment

Energy efficiency (η_e), power conversion efficiency (η_{pce}) and exergy efficiency (η_{ex}) of the PV module for different illumination intensity levels and cell temperatures are shown in Figure 7a and b, respectively.

It is observed from the model results that performance parameters of the PV module increase exponentially with increasing illumination intensity level. On the other hand, they dramatically decrease with increasing cell temperature. From this point of view, maximizing illumination intensity level as minimizing the increase in cell temperature may be suggested in order to enhance the energy conversion of the PV module.

Effects of n on performance parameters are illustrated in Figure 8a. η_{pce} and η_{ex} of the PV module decrease linearly with increasing n. Because increase in n softens the $I-V$ characteristic curve. η_e of the PV module remains constant for different values of n since I_{sc} and V_{oc} does not change. Similarly, η_{pce} and η_{ex} of the PV module show a linear decrease with increasing R_s as shown in Figure 8b.

For an ideal PV cell, R_{sh} is infinite but it is not valid for a commercial PV module. If R_{sh} of the PV module decreases ($R_{sh} = 1/G_{sh}$) η_{pce} and η_{ex} of the PV module notably decreases as shown in Figure 9. On the other hand, η_e of the PV module is not affected by the variation in R_{sh} since I_{sc} and V_{oc} does not change.

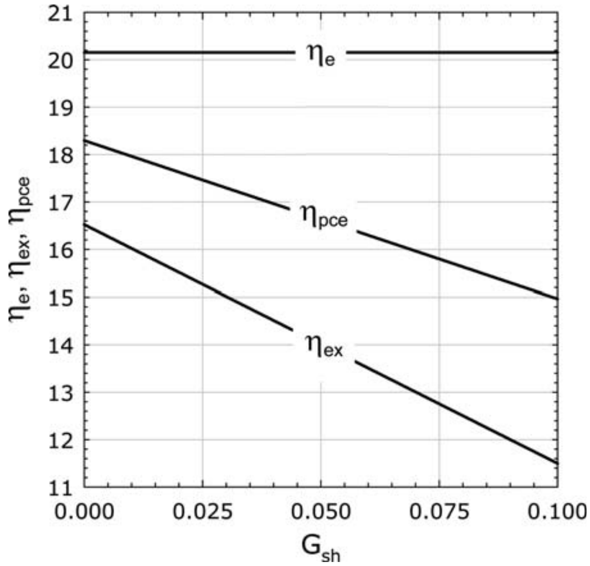

Figure 9. *η_e, η_{pce} and η_{ex} for different* G_{sh}.

5 CONCLUSION

In this paper, a simple one-diode model is proposed in order to evaluate the electrical performance of a silicon PV module with respect to changes in main environmental parameters such as temperature and illumination intensity. The proposed model also enables to make a thermodynamic assessment of energy conversion in a PV module for the various values of performance parameters. The whole model is implemented using MATLAB and an excellent agreement is observed between the model results and the data provided by manufacturer. Specific findings of the study can be given as follows:

- Photocurrent of the PV module increases linearly with increasing illumination intensity. The current parameters are highly dependent on the radiation level. On the other hand, open-circuit voltage shows a slight increase even if a considerable increase in intensity level exists.
- Maximum power output of the PV module dramatically decreases with increasing cell temperature.
- The higher values of ideality factor soften the $I-V$ characteristic curve.
- Maximum power output of the PV module reduces by the increase in series resistance and decrease in shunt resistance.
- Energy efficiency, power conversion efficiency and exergy efficiency of the PV module exponentially increases with increasing illumination intensity level. On the contrary, they linearly decrease with increase in cell temperature.

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