



Modelization and Simulation of a Low Cost Concentrated Photovoltaic Solar Cell: Parametric and Sensitivity Study under MATLAB

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ABSTRACT

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The concentrated photovoltaic solar cells are the most efficient among photovoltaic technologies. This paper studies a low-cost concentrated photovoltaic solar cell made of silicon that is cheap, available, and easy to manufacture coupled to a concentrator. The novelty of this work consists on replacing the expensive triple-junction solar cell with a Silicon cell. A modelization of the electronic equivalent circuit of the low cost concentrated photovoltaic solar cell is given. The equations describing the current, voltage, and power of the CPV cell are presented. Subsequently, the computation program of the implemented MATLAB code is shown. Afterward, the I-V curves and P-V curves of the CPV cell are plotted under different temperatures of the cell, irradiances, and concentration ratios. It is demonstrated that the increase of the temperature of the cell decreases the voltage/power and increases the current produced by a CPV cell. Furthermore, raising the concentration ratio/irradiance enhances the power/current produced by a CPV cell. Finally, a sensitivity analysis is performed to find high leverage variables and shows that the concentration ratio is the most sensitive parameter among the criteria studied. This study can be used as a base case study to the experimental projects ongoing about low-cost concentrated photovoltaic solar cells.

1. INTRODUCTION

With the increase of energetic needs during the actual expansion of using electrical cars and devices, solar energy is the best electrical source as it fulfills the double objective of producing energy and protecting the environment. Solar energy is one of the most abundant renewable energies [1, 2]. Besides, the concentrated photovoltaics CPV have excellent efficiency and environmental impact.

Many studies detail the study of the electronic equivalent circuit of the concentrated photovoltaic solar cell. One can cite Segev et al. [3] who have studied one and two diode models of triple junction CPV cells. They showed that the two diode model fit better with the experimental result of the modeled triple junction CPV cell. Another interesting study was released by Rezk et al. [4] who proposed a model of concentrated triple-junction solar cell with a simulation under the Simulink tool. They proposed a method to track the MPPT that they compared to the classical P&O and show that the P&O gives better results. Aqachmar et al. [5] studied large scale CPV power plants in the six climatic zones of Morocco and estimated that CPV is more competitive than PV in some Moroccan regions. Besides, Burhan et al. [6] designed a strategy for the optimization of the management of the CPV-Hydrogen systems with real weather data of Singapore. Furthermore, Das et al. [7] modeled a multi-junction

photovoltaic cell using MATLAB, they showed that two junctions solar cells deliver 3 times more power than mono-junction solar cells. Moreover, Nieto-Nieto et al. [8] made a setup to characterize multi-junction solar cells up to 1500 suns of irradiance. For instance, Dimroth et al. [9] discussed the promises of multi-junction solar cells for use in CPV systems. Moreover, González-Longatt et al. [10] presented a model of a photovoltaic system in MATLAB. The last study of this literature review was conducted by Famoso et al. [11] compared a low concentrated installation using monocrystalline silicon to a classical photovoltaic device without a concentrator.

Usually, the concentrated photovoltaic solar cells use triple-junction solar cells which costs are high, and which manufacturing requires very high expertise [12]. Using Silicon instead of triple-junction solar cells can be advantageous as Silicon is cheap, available, and easy to manufacture. Hence, this study undertakes the study of the behavior of low-cost concentrated photovoltaic solar cells under different parameters and highlights the high leverage variables. In this paper, a mathematical model is presented to describe the behavior of low cost concentrated solar cells; a computation program is given to calculate the current, voltage, and power produced by a CPV cell under MATLAB environment. The I-V curves and P-V curves of mono-junction CPV cells are exclusively plotted in this paper under different parameters

and the most impacting parameter is found.

2. METHOD DETAILS

2.1 Material used

We study a concentrated silicon solar cell [13] (situated in column IV from the periodic table of Mendeleev) with the datasheet of A-300 solar cell manufactured by Sunpower, which specifications are summarized in the following Table 1. Subsequently, we add the effect of the concentrator. An illustration of the studied device is given in Figure 1.

Table 1. Specifications of the CPV solar cell used for the study

Physical characteristic	Value	Reference
Open circuit voltage	0.665 V	A-300 Sunpower solar cell [14]
Short circuit current	5.75 A	A-300 Sunpower solar cell [14]
Voltage of the crystalline Silicon	1.12 eV	[15]
Diode quality factor of the diode	1.2	[15]
Current/Temperature coefficient [A/K]	3.5/1000	Sunpower A-300 panel [16]
dV/dI coefficient at V_{oc} ($dV/dI_{V_{oc}}$)	-0.00985	A-300 Sunpower solar cell (from the I-V characteristic curve of the cell, we extract dV/dI at V_{oc})

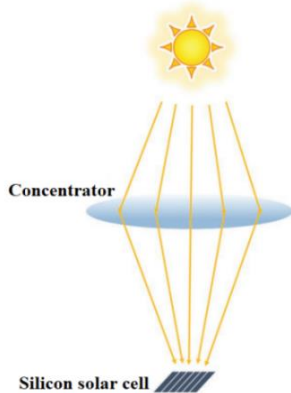


Figure 1. The concentrated solar cell device studied [14, 17]

2.2 Mathematical model

As it is well known, the easiest equivalent electronic circuit of a photovoltaic solar cell is a source of current in parallel with a diode and a shunt resistance. Furthermore, the internal losses caused by the flow of current are represented by a series resistance [10]. This electronic equivalent model is represented in Figure 2.

According to the theory presented by Segev et al. [18], adding a concentrator to a photovoltaic solar junction is represented in the equations describing the equivalent electronic circuit by multiplying the short circuit current by a factor C corresponding to the concentration ratio. Moreover, by considering the shunt resistances very big, the shunt currents are neglected. Therefore, the equations describing the behavior of a concentrated junction solar cell are shown in what follows [10, 19].

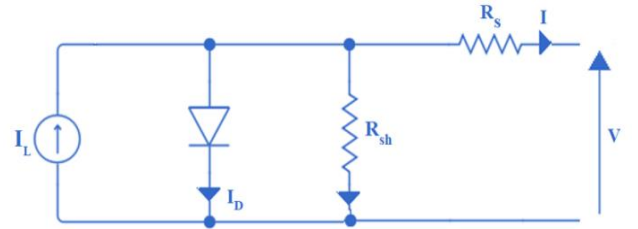


Figure 2. Electronic equivalent circuit of a CPV solar cell

The power p at the output of the concentrated junction solar cell is given by the following Eq. (1):

$$P = I \cdot V \quad (1)$$

From the electrical circuit exhibited in Figure 2, the equation of I can be found and expressed in Eq. (2):

$$I = I_L - I_D \quad (2)$$

where, I_D is the diode dark current which is expressed by the following [10]:

$$I_D = I_0 \cdot \left(\exp \frac{q(V + IR_s)}{nK_B T} - 1 \right) \quad (3)$$

$$I_0 = I_0(T_{r1}) \cdot \left(\frac{T}{T_{r1}} \right)^{\frac{3}{n}} \cdot \exp \frac{-qV_g(T_{r1})}{nK_B \left(\frac{1}{T} - \frac{1}{T_{r1}} \right)} \quad (4)$$

$$I_0(T_{r1}) = I_{sc}(T_{r1}) \cdot \left(\exp \frac{qV_{oc}(T_{r1})}{nK_B T_{r1}} - 1 \right) \quad (5)$$

where, I_0 is the saturation current of the diode, q is the charge of an electron, R_s is the series resistance, T_{r1} is 25°C , n is the diode ideality factor, V_g is the band voltage, I_{sc} is the short circuit current, and V_{oc} is the open-circuit voltage.

The subcell photocurrent I_L is described in the following Eqns. (6), (7) [10, 18]:

$$I_L = I_L(T_{r1}) + K_0 \cdot (T - T_{r1}) \quad (6)$$

$$I_L(T_{r1}) = \frac{E C}{1000} \cdot I_{sc} \quad (7)$$

where, K_0 is the current-temperature coefficient from Table 1, E is the received irradiance (W/m^2), and C is the concentration ratio.

The expression of the series resistance R_s is given by the following Eqns. (8), (9) [10]:

$$R_s = - \frac{dV}{dI_{V_{oc}}} - \frac{1}{X_v} \quad (8)$$

$$X_v = \frac{q I_0(T_{r1})}{nK_B T_{r1}} \cdot \exp \frac{qV_{oc}(T_{r1})}{nK_B T_{r1}} - \frac{1}{X_v} \quad (9)$$

2.3 Computation program

The computation algorithm for calculating the current and the maximal power produced are presented in Figure 3. We first begin by providing the technical specifications of the silicon solar junction. Then, the mathematical model for

calculating the current and the power of a concentrated photovoltaic solar cell is implemented under MATLAB environment. Newton-Raphson numerical method is used to solve the complex equations. Besides, the effect of changing the concentration ratio, the temperature of the cell, and the irradiance is studied. Finally, I-V curves and P-V curves are plotted using MATLAB, and a sensitivity study is conducted by exporting results to Excel spreadsheets.

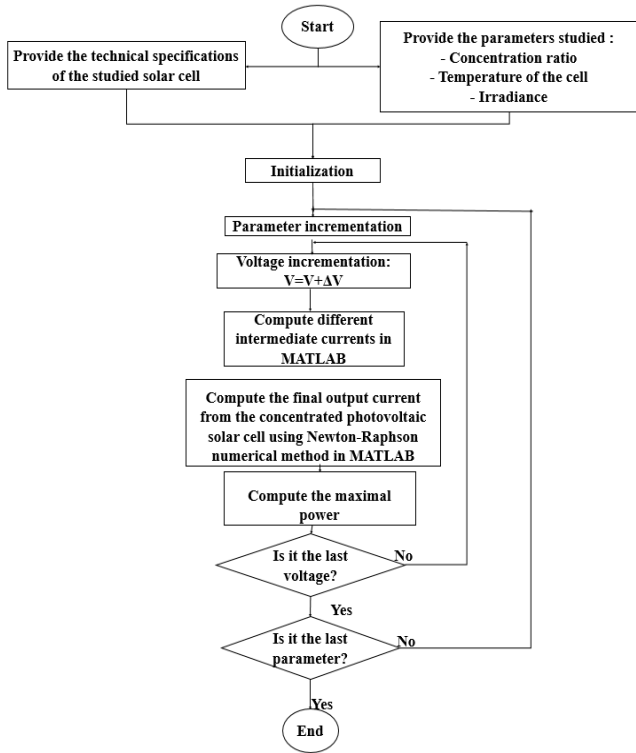


Figure 3. Computation program for the study of the CPV cell

3. RESULTS AND DISCUSSION

3.1 Parametric study

Figure 4 shows the effect of the cell's temperature on the I-V curve and the P-V curve of a concentrated photovoltaic solar cell with a concentrator of 3 as concentration ratio, and 1000 W/m² of irradiance.

It is observed from the I-V curves that while increasing the cell's temperature, the voltage decreases, and the current increases. Moreover, the P-V curves show that there is an inverse relationship between the temperature of the cell and the maximal power produced. In fact, the increase of the temperature of the cell from 20°C to 90°C decreases the maximal power produced from 8.89 W to 6.79 W. Therefore, adding a passive or active cooling technology to the concentrated junction solar cells should be considered while optimizing the power of such efficient solar cells.

Figure 5 shows the effect of the concentration ratio on the concentrated junction solar cell. The initial assumptions are a temperature of the cell of 30°C, and an irradiance of 1kW/m².

It is exhibited that the increase of the concentration ratio makes the current rising. Moreover, the power of the cell is empowered strongly with the increase of the concentration ratio. The maximal power produced by a concentrated junction

solar cell goes from 2.95 W with a concentration ratio of 1 to 1073 W with a concentration ratio of 350. Therefore, studying in an in-depth and experimental way the best materials at the most affordable prices for the conception of the optical concentrators should be undertaken carefully during the conception of concentrated solar cells.

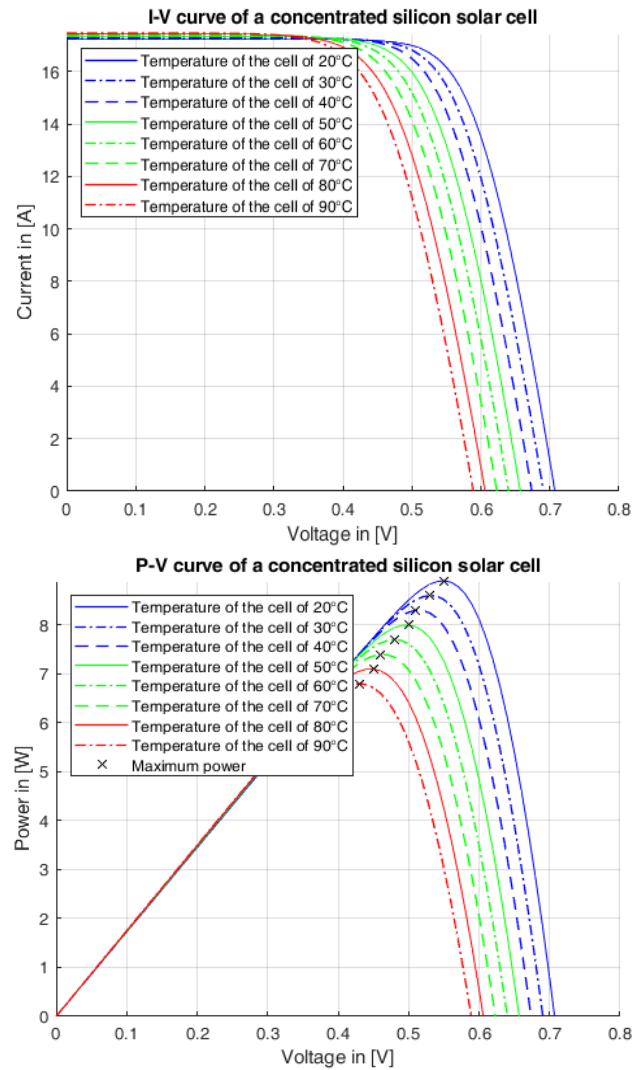
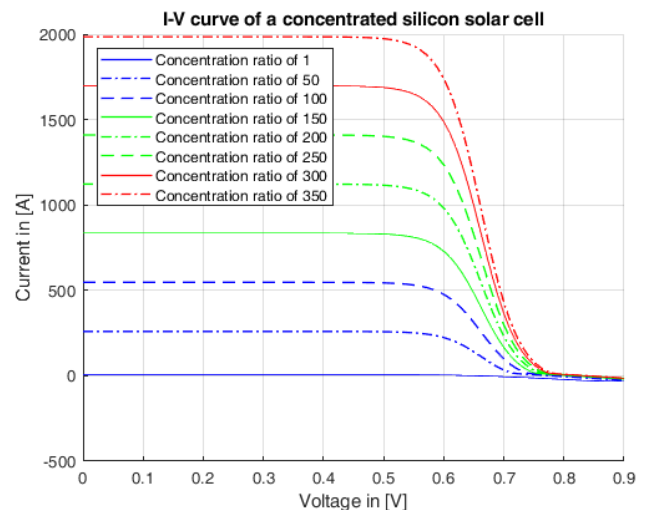


Figure 4. I-V and P-V curves of the CPV cell under different cell temperatures



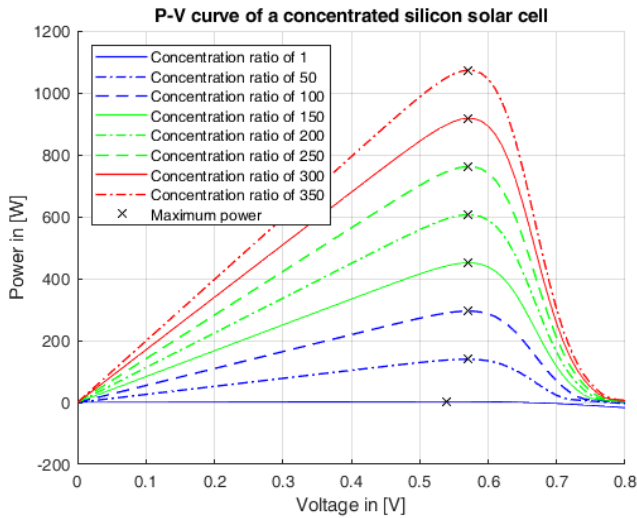


Figure 5. I-V and P-V curves of the CPV cell under different concentration ratios

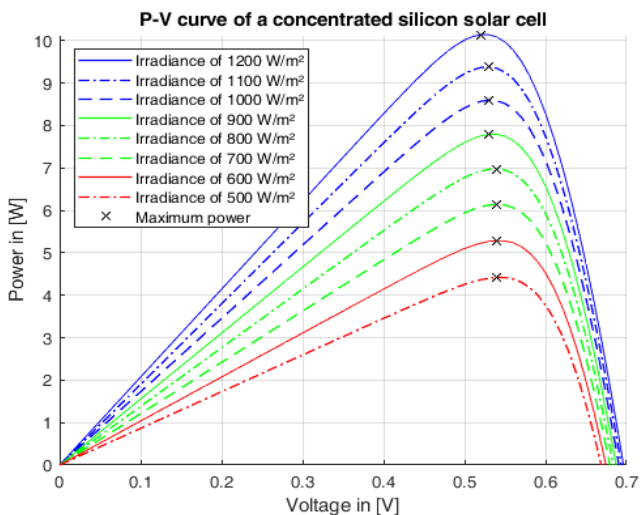
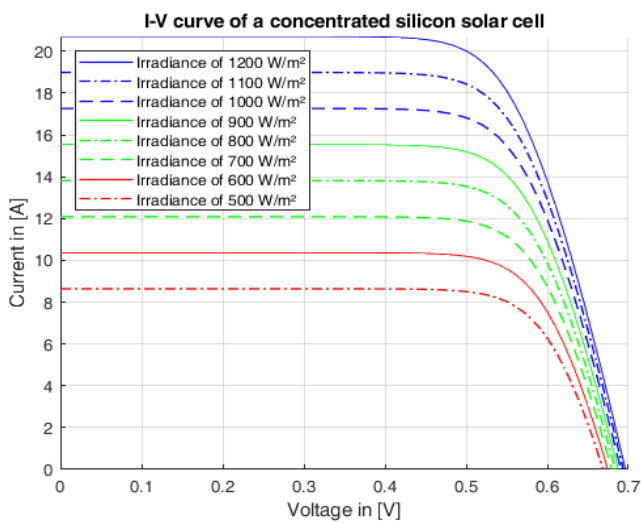


Figure 6. I-V and P-V curves of the CPV cell under different irradiances

The effect of the irradiance on the voltage/current/power produced by a concentrated solar cell is shown in Figure 6. The studied concentrated solar cell has a concentration ratio of 3, and a temperature of the cell of 30°C. It is observed that the current produced rises with the increase of the irradiance.

Besides, the maximal power produced increases from 4.42 W at an irradiance of 500 W/m² to 10.14 W at an irradiance of 1200 W/m². Therefore, installing the concentrated solar cells in the zones with the maximal irradiances should be studied in an in-depth way before the establishment of such devices during the engineering phase. As described in Eq. (7), there is a direct correlation between enhancing the irradiance and maximizing the current produced, and therefore, the power produced. This is why, while studying the installed CPV power plants worldwide, it is noticed that they are installed in high irradiances places in China, the USA, or South Africa [20].

3.2 Sensitivity study

Figure 7 emphasizes the effect of the temperature of the cell on the maximal power produced by the concentrated solar cell described in the part "Material used". One can observe that the maximal power produced by a concentrated solar cell increases linearly with the decrease of the temperature of the cell. Furthermore, a decrease of 10% of the temperature of the cell makes the maximal power increase by an average of 0.06 W.

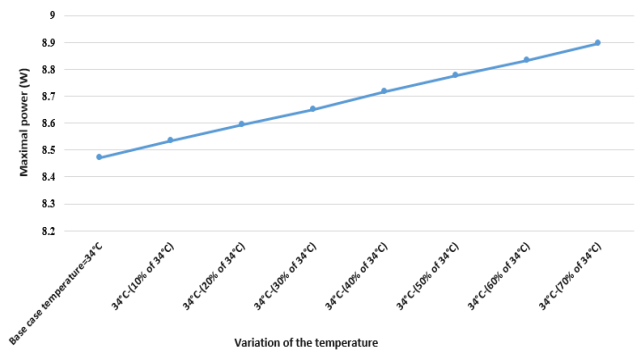


Figure 7. Sensitivity of the maximal power produced by the CPV cell to the variation of the cell temperature

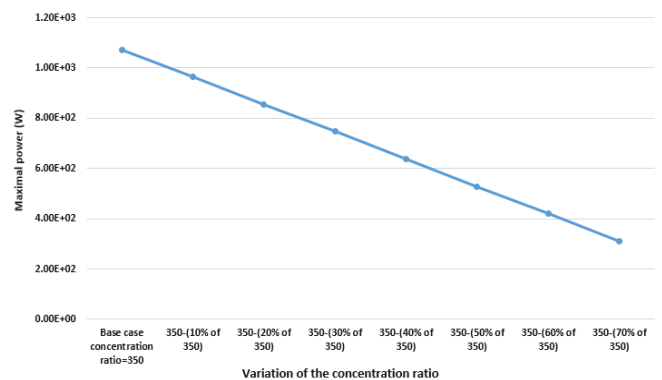


Figure 8. Sensitivity of the maximal power produced by the CPV cell to the variation of the concentration ratio

Another important parameter is the concentration ratio. Figure 8 identifies the influence of the variation of the concentration ratio on the maximal power produced by a concentrated solar cell. It is evident from the figure that the maximal power is very sensitive to the concentration ratio. The maximal power decreases linearly with the decrease of the concentration ratio. Moreover, a decrease of 10% of the concentration ratio makes the maximal produced decrease by an average value of 134 W.

The last important criterion studied is the irradiance. In fact, the effect of the variation of the irradiance on the maximal power produced by a concentrated solar cell is shown in Figure 9. It is exhibited that a decrease of 10% of the irradiance makes the maximal power produced decrease by an average of 1.27 W.

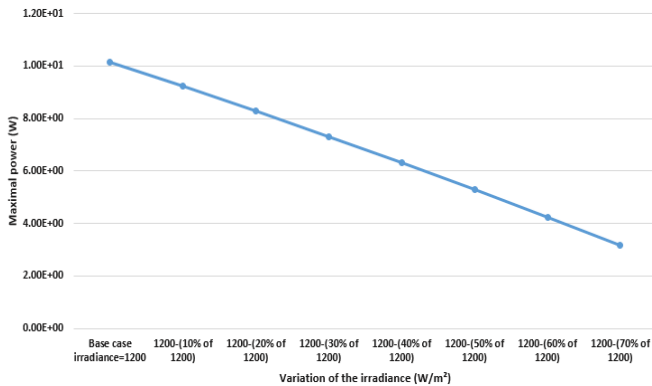


Figure 9. Sensitivity of the maximal power produced by the CPV cell to the variation of the irradiance

4. CONCLUSIONS

This paper studies exclusively a low-cost concentrated photovoltaic solar cell to serve as a simulation study for the ongoing projects about experimental low-cost concentrated photovoltaic solar cells. Mathematical equations used for modeling a CPV solar cell are proposed and a computation program for the implementation of the equations under MATLAB environment is exhibited. The I-V curves and P-V curves of the CPV solar cell are plotted. The main conclusions of the study can be stated as: (a) the increase of the temperature of the CPV cell decreases both voltage and power of the cell while increases the current produced. (b) the increase of the concentration ratio or the irradiance increases the current and the power produced by a cell. (c) the most impacting parameter from the studied parameters is the concentration ratio.

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