INTRODUCTION

Lack of energy as one of the environmental issues caused to look for economically effective energy alternatives with less pollution. At present, the coal and oil are the most popular sources of energy in the world, however, they are also the main reasons for CO₂ depletion and other hazardous effluent emissions. So the limits of these energy sources turned the world’s attention toward the renewable energy resources. The increasing of clean energy demands in the world and on the other hand by considering the source availability, the sun will be the most reliable alternative energy due to easy maintenance, zero emission, and noise. Furthermore, it can be a suitable option for distributed electrification to reduce the high cost of power grid extension.

Among the renewable energy resources, it seems that photovoltaic (PV) energy can be known as the most important energy alternative and it seems an effective choice to decrease harmful environmental impacts such as CO₂ emission. The PV cells can convert light into electricity directly. Also, they are known as an environmental choice to generate power near the load centers. At present, PV systems are very important to generate electrical power and their application is growing rapidly. Crystalline silicon, thin-film silicon,
amorphous silicon, Cu(InGa)Se₂, cadmium telluride, dye-sensitized, organic, and multi-junction solar cells are common types of solar cells. These cells use different materials and technologies which will result in different costs, efficiencies, and environmental impacts. Also, a number of different approaches have been developed to enhance the efficiency of PV systems by changing the materials, improving light trapping, using quantum dots and making multiple excitation generation cells, making multiple-junction structures, and using plasmonic carrier cells.

Financial factors, environmental impacts, and net accessible energy are the important aspects to determine the PV systems’ performance. It is noteworthy, only a few parts of the solar radiation reach the earth’s surface and others will be lost due to reflecting and absorbing by the atmosphere. But it is estimated that the accessible solar energy on the earth’s surface is about 10 000 times the world’s energy consumption. It can be said that irradiance and temperature alongside the physical structure are considered as the important factors to model the PV cells. Also, the important output variables of a PV cell are current, voltage, and power. Generally, the I-V or P-V curves are used to investigate the efficiency of the PV cell. Based on the structure and construction of the systems, it is obvious that changing of inputs immediately causes changes in outputs. Increasing the efficiency of PV cells can be done in laboratories with expensive methods or it can also be simulated using different models. However, modeling a new PV cell and simulating its behavior can be a very useful approach before making samples in the laboratory. So it seems that modeling of the solar cells is very important before making and using them.

In this study, it was tried to describe the behavior of the electric current as one of the most important output factors in solar cells as all other electrical devices. PV systems are different in structures and constructions and there are three main generations of them. By considering the combination of PV cells and from a large-scale point of view, PV systems are categorized into two main branches that include array and concentrated systems. Finally, by explaining the electrical models of each generation and category, the models used to predict the electric current were described and analyzed.

## 2 | MODELS

One of the serious challenges to model the PV systems is to extract the parameters for the models. Although the current models are used as electrical circuits and can analyze mathematically, the identification of parameters is not just as simple because the structure of PV cells is described with the concepts of solid-state physics. The PV technologies depend on various factors such as efficiency conversion and availability of solar radiation. One of the most important requirements in maximizing the capacity of PV systems is to extract parameters of a solar cell/module. It seems that the most effective parameters of the efficiency of PV systems are physical parameters. Based on many published works, the P-V and I-V curves, which are based on the diode model, can be used as direct indicators of performance of solar cell and modules. There are two different types of models for a PV cell. The first type of model is a structural model that describes its mechanism based on the photovoltaic effect. This sort of model investigates some physical concepts such as the distribution of charges, efficient depth of the cell, and few others. The other type of model is used to investigate the current, voltage, and power of a solar cell due to determining the electrical efficiency. Therefore, this sort of model is usually like an electrical circuit whose outputs can be measured. Although there are different types of PV cells (with some of them named in the previous part) with many different physical structures and functions, almost any PV cells can be modeled as an electrical circuit. In the following, some popular electrical models for PV cells are represented with their important formulae and behaviors. Also, it is noteworthy to say that it has been concluded that nonlinear electrical models have been known as an accurate approach to extract the effective parameters of solar cells after making sure its operating conditions. Extracting the parameters of PV cells is mainly related to the used different technologies, their size, illumination, and the operating conditions of temperature. Generally, by considering the diode model, five key parameters were extracted for PV cells/modules as basic indicators including short-circuit current $I_{sc}$, the ideality factor of diode $A$, the open-circuit voltage $V_{oc}$, the shunt resistance $R_s$, and the series resistance $R_p$. On the other hand, it seems that there are some other effective factors other than the above-mentioned ones including the photocurrent generated in Standard Test Conditions (STC) $I_{ph}$, the dark (or leakage) saturation current $I_0$, and the cell temperature $T$.

Also, because of using an electrical model, two other parameters will be used in the models including the unit of electrical charge $q$ ($1.6 \times 10^{-19}$ C) and the Boltzmann constant $\kappa$ ($1.38 \times 10^{-23}$ J/K) and it seems that the number of extracted key parameters of the models can change to improve the accuracy in different generations. Although some of the parameters can be extracted analytically, some others such as $I_{ph}$ and $A$ need the experimental data.

## 3 | FIRST STRATEGY: GENERATIONS

### 3.1 | Models for first generation

The solar cell structure consists of two layers of different semiconductor materials that are doped differently. The construction of a simple silicon solar cell is shown in Figure 1. The solar
cell is like a p-n junction diode. Silicon with embedded metal elements is used on the upper side of the electrode to avoid penetration of direct solar irradiation. Solar cells are designed in different sizes and shapes to maximize the effective surface area and reduce the losses because of contact resistance. There are many types of solar cells, but the wafer-based crystalline silicon is used to build about 90% of the total solar cells, which were described with a single diode model until 2013.

Existing data of solar cells that come from experiments are very important to design new effective solar cells. Each technology leads to build PV cells using the physics variables such as the power-voltage and current-voltage relationships. Although the irradiance is an important factor in the efficiency of a solar cell, the behavior of different types of solar cells is similar in different irradiances (Figure 2). Thus, electrical equivalent circuits are used as the models to describe their electrical behavior in most simulation studies.

Generally, the Shockley diode equation is used to determine the characteristics of the solar cells. So a solar cell is modeled as a light sensor that absorbs the photons of irradiation and converts them into current. Also, an anti-parallel connected diode to the light sensor manages the current’s direction (Figure 3). Based on the described model, a mathematical equation shows the implicit and nonlinear current-voltage relationship of a solar cell, then this equation is investigated to evaluate the effective extracted parameters. Finally, numerical and analytical methods with a series of simplifications and approximations are used to solve the implicit nonlinear equation of I-V relation.

In the above model, $I$ is the output current and obtained by the Kirchhoff law:

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{V}{AT} \right) - 1 \right]$$ (1)

where $V$ is the voltage imposed on the diode, $I_0$ is the leakage current or the reverse saturation current of the diode, and $I_{ph}$ is the photocurrent. $A$ is the ideality factor of diode and $V_T$ is called the thermal voltage of diode because of its exclusive dependency on the temperature. The ideality factor of diode depends on solar cell structures and can be approximately determined as in Table 1. The second part of Equation 1 is called the output current of diode $I_D = I_0 \left[ \exp \left( \frac{V}{AT} \right) - 1 \right]$.

This model is dependent on the solar cell technology and the structure of semiconductors. Hence, by changing the irradiance and temperature, the parameters of a PV cell can be determined. It means that the I-V characteristic for any type of PV cells can be defined by using this model under any new conditions of irradiance and temperature. As it can be seen, the thermal voltage in Equation 1 can be calculated by Equation 2.

$$V_T = \frac{kT}{q}$$ (2)

where $q$ is the unit of electrical charge ($1.6021 \times 10^{-19}$ Coulombs), $k$ is the Boltzmann constant ($1.3806 \times 10^{-23}$ m$^2$ kg.s$^{-2}$ K$^{-1}$), and $T$ is the temperature of the cell in Kelvin. Equation 1 shows the I-V relationship of a PV cell and it can be presented as a graph in Figure 4.
As it can be seen from Figure 4, there is an optimum point of \((I_p, V_p)\) where both the current and voltage have the maximum amount at the same time. Also, there are two other characteristics for a PV cell which depend on its physical structure, including \(I_{sc}\) as the current of the short-circuit state that is related to 0 V of the voltage (Equation 3) and \(V_{oc}\) as the voltage of open-circuit state which is related to 0 A of the current (Equation 4). Finally based on these characteristics, it can be resulted in another important factor named the Fill Factor (FF), which is defined by Equation 5.

\[
I_{sc} = I_{ph} - I_0 \left[ \exp \left( \frac{I_{ph}R_s}{AV_T} \right) - 1 \right], \quad V = 0 
\]  

(3)

\[
V_{oc} = AV_T \ln \left( 1 + \frac{I_{SC}}{I_0} \right), \quad I = 0
\]  

(4)

\[
FF = \frac{A_{I_pV_p}}{A_{I_{sc}V_{oc}}}
\]  

(5)

It is clearly obvious that the area of the rectangle \((I_p, V_p)\) is equal to \(A_{I_pV_p}\) and the area of the rectangle \((I_{sc}, V_{oc})\) is equal to \(A_{I_{sc}V_{oc}}\). So the higher value of FF means the PV cell has more efficiency. Also, the relationship for the power of a PV cell based on the voltage is represented in Figure 4. Hence, the maximum value of power is also related to the maximum value of \(V_p\) and consequently to point \((I_p, V_p)\). From Figures 2 and 4, it seems that the single diode model is suitable to describe the behavior of solar cells made of the
crystalline silicon. Experimental studies show that the average conversion coefficient of crystalline silicon PV systems is about 12%.36

Although Equation 1 represents a general model for PV cells, there are some other factors that affect the electric current. These factors are divided into two major parts. The first factor includes all those that have an internal effect on current such as bypass current between p-n junctions. This effect causes to reduce the circuit electric current and can be modeled as a resistor called Shunt resistance ($R_{sh}$). Shunt resistance is caused because of malformation in a p-n junction and anomalies in the semiconductor structure. Solar cell with the higher value of $R_{sh}$ has the higher resistance against the bypass current inside the semiconductors and is more effective. The other factor that affects the final current is all-external (or load) resistance that leads to reduce the electric current because of connections between the solar cell(s) and other parts of the electrical system. This resistance is represented by $R_s$ and is called the series resistance. There are many efforts taken to reduce it. So, by considering the series and shunt resistance, the modified I-V relationship is represented in Equation 6.37 Also, see Figure 5.

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{V}{AV_T} \right) - 1 \right] - \left( \frac{V + IR_s}{R_{sh}} \right) \quad (6)$$

The above single diode model was investigated computationally and the given results were compared to the experimental data of the PV cells in the STC. The obtained results show a suitable matching between the experimental data provided by the industry and the model data,38 and see Figure 6.

One important issue of this model is that the time does not have any effect on the current. In the real world, the current of a diode will decrease by time because of its joule heating. Based on Equation 2, the temperature of cell affects the voltage and by considering Equations 1 and 4 it will affect the fill factor (FF) of the cell. However, in the existing models, such as the above model and also most of other models, the time is ignored and the efficiency of cell is considered as a fixed value during the time.

3.2 Models for second generation

Figure 3 shows the electrical behavior of a crystalline silicon solar cell by a typical ideal single diode equivalent circuit. Some researchers believe that this model is not valid for solar cells because it considers ideal conditions and it needs many modifications to fit better on experimental data.39 One of the enhanced models for the crystalline silicon solar cell is a simple two-diode model. In this model, in addition to modeling the diffusion current in a solar cell ($I_{D1}$), it has been tried to model the recombination current ($I_{D2}$) too. Figure 7 shows this model as an electrical circuit. Diffusion current is arising from the propagation of charge carriers including holes or electrons or both of them inside a semiconductor. This current is related to recombination of mobile charge carriers and leads to decrease the output current.40

The current-voltage relationship in a two-diode model is represented as Equation 7. Also, in this model, the diode saturation current ($I_0$) that is related to temperature can be shown as Equation 8.

$$I = I_{ph} - I_{01} \left[ \exp \left( \frac{V + R_s I}{AV_T} \right) - 1 \right] - I_{02} \left[ \exp \left( \frac{V + RI}{AV_T} \right) - 1 \right] - \left( \frac{V + IR_s}{R_{sh}} \right) \quad (7)$$

$$I_0 = I_{0,n} \left( \frac{T_n}{T} \right)^3 \exp \left[ \frac{qE_g}{AK \left( \frac{1}{T_n} - \frac{1}{T} \right)} \right] \quad (8)$$

$$I_{0,n} = \frac{I_{sc,n}}{\exp \left( \frac{V_{oc,n}}{AV_{oc,n}} \right) - 1} \quad (9)$$
In the above relations, $I_{0,n}$ is the nominal saturation current expressed by Equation 9 in the STC and $E_g$ is the band-gap energy of the semiconductor ($E_g = 1.12$ eV for the polycrystalline silicon at 25°C).38,41

The first generation of solar cells contains crystalline silicon cells. These cells are hard to build and they need sophisticated technologies.42 As the second generation of solar cells, there are some other PV cells that can build easier but their efficiency might not be greater than or even equal to the first-generation PV cells. Organic photovoltaic cells (OPVs), as one type of second-generation solar cell, are known for the long lifetimes and their theoretical power conversion efficiency which is about 13%.42 Despite crystalline silicon (c-Si) cells, the OPVs do not develop by using the same technology and there are various methods using the different structures and materials.17

The single diode model or simple two-diode model is not suitable for modeling the OPVs. For example in organic solar cells and copper-indium-gallium-selenide (CIGS) solar cells, the current-voltage curves sometimes represent a kink (S-shape)33 that cannot be modeled by the circuit in Figures 3 and 7.39 The circuit of Figure 8 will be like that to Figure 3 for a small amount of current through a reverse second diode. Within a limited voltage range, the reverse second-diode model can match the experimental data well, but it will strongly be dependent on computation time and it will also cause to increase the current after the S-shape in forwarding bias. Garcia-Sanchez et al.44 developed an extension of this model by replacing the $R_{sh2}$ resistance by a third diode that shunts the reverse 2-diode (Figure 9). The I-V relationship for a reverse-diode model (Figure 8) can be expressed as Equations 10 and 11.

$$I = \frac{V + I_{02}R_{sh2} - A_2V_T \left( \frac{I_{02}R_{sh2}}{A_2V_T} \exp \left( \frac{-A_2V}{A_2V_T} \right) \right) + I_01 \Gamma \left[ \exp \left( \frac{V + I_{02}R_{sh2} - (R_s + R_{sh2}) I - A_2V_T W \left( \frac{I_{02}R_{sh2}}{A_2V_T} \exp \left( \frac{-A_2V}{A_2V_T} \right) \right)}{A_1V_T} \right) - 1 \right] - I_{sh}}{\Gamma}$$

$$\Gamma = \left( 1 + \frac{R_s + R_{sh2}}{R_{sh1}} \right)$$

where $W$ is the Lambert function.45 Figure 9 represents a reverse-2-diode model and can solve the equivalent equation precisely for some limited cases in a larger voltage range. So it can fit to the full range of experimental S-shaped I-V curve.44 Also, it can be modified by considering a shunt resistance between $D_2$ and $D_3$ (Figure 10). This 3-diode model can give an appropriate model for the I-V curve in an organic solar cell. The I-V relationship for modified 3-diode model is represented in Equation 12.17 Theoretically, the efficiency of an organic photovoltaic cell (OPV) is about 6%-8%46,47

$$I = \frac{V + I_{02}R_{sh2} - A_2V_T \left( \frac{I_{02}R_{sh2}}{A_2V_T} \exp \left( \frac{-A_2V}{A_2V_T} \right) \right) + I_01 \Gamma \left[ \exp \left( \frac{V + I_{02}R_{sh2} - (R_s + R_{sh2}) I - A_2V_T W \left( \frac{I_{02}R_{sh2}}{A_2V_T} \exp \left( \frac{-A_2V}{A_2V_T} \right) \right)}{A_1V_T} \right) - 1 \right] - I_{sh}}{\Gamma}$$

$$\Gamma = \left( 1 + \frac{R_s + R_{sh2}}{R_{sh1}} \right)$$

![FIGURE 7](image_url) **FIGURE 7** The two-diode model as an equivalent electrical circuit. Adopted from Pillai et al.3 Copyright (2018), with permission from Elsevier

![FIGURE 8](image_url) **FIGURE 8** The reverse 2-diode model. Adopted from De Castro et al.128 Copyright (2018), with permission from Elsevier

![FIGURE 9](image_url) **FIGURE 9** The reverse 3-diode model. Adopted from De Castro et al.128 Copyright (2018), with permission from Elsevier
Another major type of the second generation of solar cells is amorphous silicon solar cell. It is more difficult to analyze the I-V curve of an amorphous silicon solar cell than a crystalline silicon cell. The behavior of curves depends on the module temperature and the level of irradiation and it also depends on the degradation state that strongly hinges on the light exposure duration.  

Despite crystalline silicon solar cells, it cannot be possible to extract the parameters of the I-V curve directly for amorphous solar cells. Also, the resistance (including series and shunt) cannot be investigated in the open-circuit region and the short circuit of the I-V curve. Therefore, the series resistance is distinguished by the material parameters and the shunt resistance is determined by using a dark I-V curve. On the other hand, the fill factor (FF) was oversized because of a constant photocurrent. Also, a constant photocurrent does not lead to a realistic and feasible model because of a constant photocurrent. So a second diode is placed into the model to prepare a two-diode model of crystalline amorphous silicon solar modules. So a second diode is placed into the model to prepare a two-diode model of crystalline amorphous silicon solar modules. Consequently, amorphous silicon solar cells can be modeled by using a recombination model of crystalline solar cells. Consequently, amorphous silicon solar cells can be modeled by using a recombination model of crystalline solar cells.  

As it was described, the recombination current causes to reduce the photocurrent \( I_{\text{ph}} \) (Equation 14).  

\[
I_{\text{rec}} = \frac{I_{\text{ph}}}{\left(\frac{\mu}{d^2}\right)\left(V_{\text{bi}} - (V - IR_s)\right)}
\]  

The recombination current in the \( i \)-layer is \( I_{\text{rec}} \) and \( V_{\text{bi}} \) that represents the voltage over the \( i \)-layer is theoretically about 0.9V for each cell. \( \mu \) is the mobility of the charge carriers, \( d \) is the thickness of the \( i \)-layer, and \( \tau \) is the charge carrier lifetime.  

Also, the dark I-V curve can be affected by the degradation of amorphous silicon solar cells. By considering the one-diode model and let the photocurrent \( I_{\text{ph}} \) be equal to zero, the dark current will be determined generally. Hence, the resultant equation can be equal to the Shockley equation of the I-V curve for one diode, this relation cannot give any detailed information to explain the SWE in the dark environment for amorphous silicon solar modules. So a second diode is placed into the model to prepare a two-diode model of crystalline solar cells. Consequently, amorphous silicon solar cells can be modeled by using a recombination model of crystalline solar cells. Consequently, amorphous silicon solar cells can be modeled by using a recombination model of crystalline solar cells.

\[
I = I_{\text{ph}} \left(1 - \frac{1}{\left(V + IR_s\right)^{-1}}\right) - I_0 \left[\exp\left(V + IR_s\right) A V_T - 1\right] - \frac{V + IR_s}{R_n}
\]  

where \( I_{\text{int}} \) represents the interface recombination current and \( I_{\text{bulk}} \) shows the bulk recombination saturation current.
Although the described model in this section has improved and gives a better result than the models in section 3.1, there are still some issues. One issue is to detect how many diodes are the best choice for the model and it seems answering this question is not easy theoretically and needs experimental data. Another issue is to consider the characteristic of each diode. So it needs to answer this question that if all used diodes are the same or not? And if they are not, what are the differences between them? Also, as in previous section, the time is not considered as an effective factor in this model as well.

3.3 | Models for third generation

In recent years, the multi-junction solar cells have been attracted because of their very high conversion efficiency.\textsuperscript{51} PV systems that are using these solar cells have a high concentration ratio due to reducing the absorbing area. These types of solar cells are very expensive.\textsuperscript{52} One of the super-high-efficiency triple-junction solar cells that is known as a common III-V type is InGaP/InGaAs/Ge that was grown on a p-type Ge substrate by using a metalorganic process called the chemical vapor deposition.\textsuperscript{53} Figure 13 shows the construction of the InGaP/InGaAs/Ge triple-junction solar cell and Figure 14 represents a 3D equivalent electrical circuit model of a typical triple-junction solar cell. In this equivalent model, a grid of the same number of units connected to each other with the lateral resistances is installed for each electrode.\textsuperscript{54}

The in-plane distribution of the photocurrent of each subcell is represented in Figure 15. By considering the optics model without a homogenizer, there is a distribution that is intensively concentrated at the center of subcell to generate photocurrent in the top subcell. Also, the peak intensity of the photocurrent of the bottom subcell can decrease due to chromatic aberration. Hence, it can be concluded that the current between subcells was mismatched. This un-uniformity (current mismatch) leads to a decrease in FF. So the FF and module efficiency decrease because of the mismatch of photocurrent but the optical efficiency still remains high. Also, for the optics model with a homogenizer, the balance of photocurrent is good and the distribution is uniform and maximum power could be increased.\textsuperscript{53,55-59}

In this model, the ideal diode equation was used to investigate the light current-voltage (LIV), see Equation 16.\textsuperscript{60}

\[
I_L = I_0 \left( \frac{qV}{kT} - 1 \right) - I_L
\]  
(16)

where \(I_L\) is related to the thickness and absorption profile of used materials in the solar cell. The current per unit area that has been generated by the light \(I_L\) is known as the number of absorbed photons across the entire thickness of the solar cell. See Equation 17.\textsuperscript{61}

\[
I_L = \int_{\lambda_1}^{\lambda_2} qP_{\lambda} \left( 1 - e^{-\alpha_{\lambda}x} \right) d\lambda
\]  
(17)

In the above equation, \(P_{\lambda}\) is the photon flux incident on a solar cell that was calculated by using Equation 18 and \(P_0\) represents the power (Wm\(^{-2}\)nm\(^{-1}\)) of the AM1.5 Direct Solar spectrum at wavelength \(\lambda\) (nm).\textsuperscript{62}
**FIGURE 14** The 3D equivalent electrical circuit model for the triple-junction solar cells. Adopted from Ota and Nishioka\textsuperscript{76} Copyright (2018), with permission from Elsevier

**FIGURE 15** In-plane distribution of photocurrent for each subcell in the InGaP/InGaAs/Ge solar cell (triple junction). Adopted from Ota and Nishioka\textsuperscript{76} Copyright (2018), with permission from Elsevier
\[
PF_i = \frac{P_0}{\hbar c/\lambda} \Delta \lambda
\] (18)

Also \(I_e\) is the spectrum incident on the \(n\)th material junction (Equation 19), where \(d_{n-1}\) is the thickness of the used material (cm) and \(I_{n-1}\) is the intensity incident of the illumination on the previous junction \(I_n = I_0\) for the top junction. So, as the sum of the contribution of the n- and p-type layers and by assuming uniform doping in each layer, the reverse saturation current per unit area \((I_0)\) is determined as Equation 20.

\[
I_n = I_{n-1} e^{-\alpha d_{n-1}}
\] (19)

\[
I_0 = qn_i^2 \left( \frac{D_e}{N_A L_e} + \frac{D_h}{N_D L_h} \right)
\] (20)

The electron and hole minority carrier diffusion constants \((D_e, D_h)\), the electron and hole minority carrier diffusion lengths \((L_e, L_h)\), and the intrinsic carrier concentration \((n_i)\) are calculated in the general state. Also, the electron and hole minority carrier lifetime \((\tau_e, \tau_h)\) and the electron and hole minority carrier mobility \((\mu_e, \mu_h)\) are defined based on the semiconductor structures and materials.

For a number of junctions that are series connected, the current matching condition was determined by using an iterative process dependent on the thickness of each junction in which the contribution from each layer assumes to be equal and maximized. In this case, the light-generated current \((I_L)\) is supposed to be constant to improve the accuracy of the model. For a series connected multi-junction solar cell with \(n\) layers, the LIV characteristics are calculated by adding the voltages of each junction matched with its current. See Equation 21.

\[
V = \sum_{i=1}^{n} \frac{kT}{q} \left[ \ln \left( \frac{I_i + I_L}{I_0} \right) + 1 \right]
\] (21)

By calculating the derivative of the power output function of a solar cell and calculating the root of the obtained equation, the maximum power output per unit area of a solar cell is determined by Equation 22. Solar cells are connected together in a parallel mechanical stack configuration that is leading to separate load control of each cell. Hence, summing up the maximum power output per unit area of the each solar cell leads to determine the maximum power output per unit area of the stack. Results of studies show that the best gain efficiency of third-generation solar cells can go up to 40%.

\[
P_{\text{max}} = \frac{d(V)I}{dI} = 0
\] (22)

This model was much better than the others because it considered the wavelength, although this model has ignored the time. As it was said before, time will affect the efficiency during operation and all these models cannot predict the current during the operation as precisely as at the initial time. But because all these models have ignored the time, they can be used as indicators to compare the efficiency of models in the same condition.

4 | SECOND STRATEGY: COMBINATION

4.1 | Models for solar cell combination

Solar energy is a kind of clean and renewable energy source (RES) and because of some problems such as shortage and pollution of fossil fuels, it has been and will be more and more suitable for the electricity generation. Flat photovoltaic systems such as PV arrays and concentration photovoltaic systems (CPVs) are producing a large proportion of the solar electricity.

The PV modules are composed of a number of PV cells that are series and/or parallel connected and the PV arrays are the same but made of PV modules instead of PV cells. Based on the equivalent circuit diagram of a single diode model, it can be concluded that the PV modules also can be modeled by the same way. Therefore, the equivalent electrical circuit of a PV array will be similar to Figure 16. By considering \(N_e\) and \(N_p\) as the number of series and parallel cells or modules, respectively, the output current and voltage of the PV array or module can be calculated as Equations 23 and 24.

\[
V_{\text{total}} = N_e V
\] (23)

\[
I_{\text{total}} = N_p I
\] (24)

Concentration photovoltaic systems (CPVs) have two important advantages including lower system cost and higher efficiency than flat PV systems. An optical concentrating system causes the solar beams to focus on the smaller surface and consequently, the solar cell can be designed much smaller than an equivalent structure in the flat PV systems.
And because the solar cells are the most expensive components of a photovoltaic system, the cost of the system will be decreased by using the concentration technologies.\textsuperscript{72–74}

Another important problem of the CPV systems is to increase cell temperature because of a direct irradiation of light.\textsuperscript{75} Compared to the common CPV systems,\textsuperscript{76} this problem is easy to be resolved by using the two-stage CPV systems as in Figure 17. Also, the heat load of the solar cell can be decreased by using a cold mirror for the second reflector.\textsuperscript{77–79}

In Figure 18, four-square solar cells are connected together to form a bigger square.\textsuperscript{77} This structure can prepare the same radiant energy for each cell due to radial symmetry of the irradiance distribution. Therefore, the output power and current of the system will be four times higher than each single solar cell. Bishop developed an equivalent electrical model to calculate the I-V relation of this system\textsuperscript{80,81} as Equation 25.\textsuperscript{77,82}

\[
I = I_{ph} - I_0 \left[ \exp \left( \frac{V + IR}{n_k T} \right) - 1 \right] - \left( \frac{V + IR}{n_k T} \right) \left[ 1 + \alpha \left( 1 - \frac{V + IR}{V_b} \right)^{-\beta} \right]
\]  

where $\alpha$ and $\beta$ are the constants ($\alpha = 2 \times 10^3$ and $\beta = 4$) and $V_b$ is the breakdown voltage. Based on the results of experimental and theoretical studies, it is concluded that combined and concentrated solar cells have the largest value of efficiency up to 80%.\textsuperscript{83,84}

5 | TEMPERATURE EFFECT

Photovoltaic systems are sensitive to temperature and climate conditions. Snow and ice, as dust, can accumulate on the panels and prevent the light from reaching the cells and consequently cause to reduce the produced power.\textsuperscript{85–88} Obstruction of light is a serious concern for photovoltaic systems, so studying and understanding its effective factors such as temperature is very important. Sulaiman \textit{et al} performed a study in 2014 to investigate the effect of light obstruction materials on the efficiency of a solar cell. They mentioned that these materials will affect the PV cells as external resistance. Generally, more resistance will increase the joule heating in the system and the temperature of system will increase consequently. Also, they found that the performance of the solar system will reduce up to 85% because of the light obstruction materials.\textsuperscript{39}

The effect of temperature on the solar cells was modeled by considering different aspects. One of the most popular aspects is the dependency on band gap. In semiconductors, it can be modeled as Varshni relation as Equation 26.\textsuperscript{90}

\[
E_g(T) = E_0(T) - \frac{\alpha T^2}{T + \beta}
\]

where $\alpha$ and $\beta$ are constants, $E_0(T)$ is the band gap of semiconductor at $T \approx 0$ K, and $E_g(T)$ is its value at any temperature $T$. On the other hand, by combining Equations 3 and 4, that represent the short-circuit current and open-circuit voltage, respectively, and then by differentiating the result, it can be concluded that the relation between open-circuit voltage and temperature will be modeled as Equation 27.\textsuperscript{91}

\[
\frac{dV_{oc}}{dT} = \left( \frac{V_{oc}}{T} \right) + \frac{kT}{q} \left( \frac{1}{\frac{dI_{oc}}{dT}} - \frac{1}{I_0} \frac{dI_0}{dT} \right)
\]

where $I_0$ is the current that corresponds to $E_0(T)$. Also $I_0$ is highly sensitive to the temperature changes, and for a p-n junction the solar cell can be modeled as Equation 28.\textsuperscript{92}
\[ I_0 = q \left( \frac{D_n}{L_n N_a} + \frac{D_p}{L_p N_d} \right) n_t^2 \]  

(28)

where \( D_p \) and \( D_n \) are diffusion constants of minority carriers in \( p \) and \( n \) regions, \( N_d \) and \( N_a \) are densities of donor and acceptor atoms, \( n_t \) is the intrinsic carrier density, and \( L_p \) and \( L_n \) are diffusion lengths of minority carriers in \( p \) and \( n \) regions. As it can be seen from Equation 28, \( I_0 \) is strongly dependent on the \( n_t \) that is declared as Equation 29.91

\[ n_t^2 = N_cN_v \exp \left( -\frac{E_g(T)}{kT} \right) \]  

(29)

where \( N_c \) and \( N_v \) are effective densities of majority charges in valence band and conduction band, respectively. Green combined the above equations and modeled the relation between \( I_0 \) and \( T \) as Equation 30.93

\[ I_0 = A. \exp \left( -\frac{qE_g(T)}{kT} \right) \]  

(30)

where \( A = 1.5 \times 10^8 \) mA cm\(^{-2} \) is a constant.94 So the differentiation of the above relation to the temperature can be represented as Equation 31.

\[ \frac{1}{I_0} \frac{dI_0}{dT} = -\frac{q}{kT} \left( \frac{E_g(T)}{T} + \frac{dE_g(T)}{dT} \right) \]  

(31)

Finally, by considering Equation 31, Equation 27 will be modified as Equation 32.

\[ \frac{dV_{oc}}{dT} = \left( \frac{V_{oc}}{T} \right) + \frac{kT}{q} \frac{1}{I_{sc}} \frac{dI_{sc}}{dT} - \frac{E_g(0)}{T} + \frac{aT^2}{T + b} \]  

(32)

In recent years, some researchers have focused on investigating new approaches to cool PV panels due to increasing operational efficiency.95–98 On the other hand, high temperature causes to reduce the generated power because of increasing internal resistance of solar cells.99 Also, temperature plays an important role in the designing and sizing of PV systems, especially where the operating conditions dictate the panel size.100,101 So any technologies or events that can change the temperature of the surface will cause to change efficiency and generated power consequently (see Figure 19).

Some researches show that the output power and electrical efficiency of a PV system depend linearly on the operating temperature.102,103 The used material of PV cells primarily influences the electrical performance. Various correlations between the temperature of a PV cell and its used materials have appeared in the literature.104–108 Also, it is concluded that the geographical location is influencing the efficiency of PV cells due to changing gained irradiance and therefore changing the temperature of the cell.109,110 The results of some researches show that the PV panels are less sensitive to the temperature than individual PV cells.110,111 This result comes from the concept that the sum of parallel resistors will be less than each resistor. So because a PV panel is an array of PV cells, and by considering the joule heating as a resistor for each cell, then it can be concluded that a PV panel can be modeled as an array of parallel resistors considering its thermal behavior. Therefore, the sum of parallel thermal resistors in a PV panel that causes the changes in the temperature is less than its individual PV cells.112–114

**FIGURE 19** Effects of solar radiation and wind speed on photovoltaic PV efficiency, power, and temperature. Adopted from Al-Nimr et al.130 with permission from Elsevier.
6 | FINANCIAL ANALYSIS

One of the most popular indicators to evaluate the efficiency of PV systems is the Energy Payback Time (EPBT) that is related to the environmental performance of renewable energies. It can be defined as the total required time for a renewable energy system to produce the same amount of energy that was consumed to produce the system and it can be defined as Equation 33 for a PV system.$^{2,115,116}$

$$\text{EPBT} = \frac{E_{\text{input}}}{(E_{\text{PV}}/\alpha)}$$  (33)

where $E_{\text{PV}}$ is the annual electricity produced by the PV system, $E_{\text{input}}$ is the primary energy demand to produce the PV systems, and $\alpha$ is the electrical energy conversion factor. Also, another important factor to investigate the efficiency of a PV system is the Greenhouse Gas Emission (GHG) indicator and it is defined as the greenhouse gases emitted due to producing 1 kWh of electricity.$^{2,117-119}$ The EPBT is about 1.11 years and the GHG is about 30.2 g/kWh of CO$_2$-equivalent for the silicon-wafer based cells as the first PV cell generation. The EPBT and GHG are about 1.08 years and 29.2 g/kWh of CO$_2$-equivalent for the third PV cell generation, respectively.$^{120}$

Energy demand will be faced by an upward trend in the second decade of this century and developing countries will consume more energy than developed countries because of socioeconomic parameters.$^{121-123}$ On the other hand, using the PV systems causes many advantages and these advantages will be more for the PV systems as distributed systems and integrated with buildings due to reduction of energy loss of transition, and it is providing larger volumes of electricity at times of peak demand.$^{124,125}$

Also, the decrease of about 99.6% in the unit cost of PV silicon cells has been seen since 1977 in Europe (Figure 20) and it will cause a competition in developing PV systems. It seems that this trend is a result of public policy incentives, investment in relevant technologies, and investment in researches that focus on increasing the efficiency of PV systems.$^{34,124}$

As a financial cost analysis, it seems that an integrated indicator can be determined based on energy intensity, technology, efficiency, and balance of system. This indicator is named the Electrical Energy Return On Investment (EROI) to compare the efficiency of different PV systems (Figure 21) and it can be defined as Equation 34.$^{126}$

$$\text{EROI} = \frac{\text{Electrical Energy Output}}{\text{Electrical Energy Inputs}} = \frac{\kappa L}{\text{CED}}$$  (34)

where $L$ is the standard system lifetime in hours and $\kappa$ is the capacity factor. Zhou and Carbajales-Dale studied on this concept for two different states based on the Balance of System (BOS) energetic cost. The BOS energetic cost was considered 206 kWh m$^{-2}$ for the first state and 37 kWh m$^{-2}$ for the second state.$^8,9$ Their results are represented in Figure 22. In Figure 22, the dots are representing the real data, the ovals are showing the standard deviation of real data, the dot-lines are indicating the theoretical range, and EROI are representing as black curves. It can be seen from the results that the crystalline silicon (red oval and dots) has a higher efficiency but its EROI is less than the others. Also, OPV (purple oval and dots) has less efficiency related to higher EROI than crystalline silicon solar cells. It seems thin-film PV systems (blue oval and dots) are optimal due to efficiency and EROI but they are built by using some technologies that are environmentally harmful.$^9$

---

**FIGURE 20** The price changes of silicon photovoltaic (PV) cells in US$ per watt. Adopted from Ferreira et al.,$^{124}$ with permission from Elsevier

**FIGURE 21** The Electrical Energy Return On Investment (EROI) indicator
Modeling is to simplify a system to understand and predict its behavior. Although it can be found in many different types of models for solar cells, it seems electrical models can be more useful and appropriate to investigate the efficiency of solar cells. In this paper, it was tried to get a brief review of electric current relations between different types of solar cells based on their structure and construction. Also, these relations were discussed based on the combination of solar cells as arrays and CPV systems. Simple and modified single diode, multi-diodes, and diode network models were considered for different generations and combinations of solar cells and expressed their P-V and I-V relations. The results of these studies can be used to understand and model the functionality of solar cells and they are used to assess the efficiency of the new generation before building them. As it was described before, in this study, it was tried to investigate the behavior of the different solar cells due to their current by considering two strategies.

In the first strategy, for the first generation of solar cells made of one-layer crystalline silicon, the popular known model is the single diode model that determined a general model as Equation 6. This model can have an appropriate accuracy by considering shunt and series resistances. The model shows a single diode-like behavior such as an electrical circuit. The current of the circuit is related to the voltage directly and has an optimum point to gain the most efficiency that nominated as the Fill Factor (FF) (Equations 3-5). Although this model is appropriate in a specific range it cannot have a good prediction in different conditions and the predicted current is not matching well to the results of the experiments out of the specified range. For the second generation including the amorphous silicon and dye-synthesized organic cells, the single diode model did not show a good behavior. So the general diode model was modified by using multi-series and/or parallel diodes. These models can describe a better behavior of solar cells in the various conditions. The solar cells of this generation have lower built cost and also lower output current and efficiency, but the models can describe their behavior more precisely, especially in a wider range of conditions. In the third generation, which are multi-junction solar cells, a network of diodes is the best model and the current-voltage relations can be calculated by determining the number of series and/or parallel junctions. The parallel connected diodes are increasing the final current and the series connected diodes can increase the final voltage as well. So by considering this type of solar cell as a unique cell, it can have more efficiency and higher Fill Factor especially due to occupying space but the cost might represent an increase because of using complex technology. In these types of PV cells, the gain irradiation in each layer of the network is different from the others, so the output current from each
layer has a different amount. But as it was said, by considering the occupied space of whole solar cell, the efficiency is increasing based on the total volume.

In the second strategy and by investigating the combination of solar cells, a solar module or array was considered as an extended solar cell. Array as a flat PV system causes to increase both current and voltage, but it occupies more space. For a concentrated PV system, it is assumed some solar cells as ones which can absorb more irradiation due to focusing the light spectrum into a smaller area. The models show this type of combination has a high efficiency, especially in a lower occupied space.

By summing up the results of two scenarios, it seems that a diode model is an appropriate approach for modeling the solar cell behavior. The reason might be that both of them have been built of semiconductors and have similar electrical behavior consequently.

Changing temperature can directly or indirectly affect the efficiency of PV cells. In low temperature, precipitation including rain or snow can remain on the surface of cells. Frozen water, snow, and ice cause obstruction of light and consequently decrease the generated power. On the other hand, high temperature can affect the efficiency of PV cells due to increasing internal resistance of the material in cells. Most of the studies show that the type of materials and the location of setting up the PV systems are two important factors relating to temperature. Also, it has been investigated that the PV panel is less sensitive to the temperature than individual PV cells.

There are some popular indicators to analyze the financial behaviors of PV systems. The EBPT defines as the required time for a PV system to generate the same amount of energy that has been used to build itself. Some studies show that the minimum value of this indicator is related to the third generation of PV cells. Another useful indicator is the GHG that can directly or indirectly change the financial behavior of cells. Like the previous indicator, it is minimum for the third generation too. On the other hand, by investigating the trend of using the PV systems in the last decade and predicting the trend for the next two decades, it is concluded that PV cells, especially silicon-based PV cells, will be facing the less cost per watts. Finally, it was concluded that silicon-based PV cells have less amount of EROI but they have higher efficiency, simultaneously. As a conclusion, by considering the output current, voltage, power, temperature effect, and financial analysis, it seems third-generation PV systems and concentrated PV systems will cause more efficiency and reliability than the other ones.

REFERENCES

1. Sudhakar Babu T, Rajasekar N, Sangeetha K. Modified particle swarm optimization technique based maximum power point tracking for uniform and under partial shading condition. Appl Soft Comput. 2014;36, 12-13.
2. Luo W, Khoo YS, Kumar A, et al. A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies. Sol Energy Mater Sol Cells. 2018;174:157-162.
3. Pfenak IMS, Kim HC. Photovoltaics: life-cycle analyses. Sol Energy. 2011;85(8):1609-1628.
4. Hofer J, Groenewold A, Jayathissa P, Nagy Z, Schlueter A. Parametric analysis and systems design of dynamic photovoltaic shading modules. Energy Sci Eng. 2016;4(2):134-152.
5. Pillai DS, Sahoo B, Ram JP, Laudani A, Rajasekar N, Sudhakar N. Modelling of organic photovoltaic cells based on an improved reverse double diode model. Energy Procedia. 2017;117:1054-1061.
6. Sudhakar Babu T, Prasanth Ram J, Sangeetha K, Laudani A, Rajasekar N. Parameter extraction of two diode solar PV model using fireworks algorithm. Sol Energy. 2016;140:265-276.
7. PVPS I. A Snapshot of Global PV. Report IEA PVPS T1-29. 2016.
8. Ahmad MH, Ghazvini M, et al. Solar power technology for electricity generation: a critical review. Energy Sci Eng. 2018;6(5):340-361.
9. Zhou Z, Carbajales-Dale M. Assessing the photovoltaic technology landscape: efficiency and energy return on investment (EROI). Energy Environ Sci. 2018;11(3):603-608.
10. Solangi KH, Islam MR, Saidur R, Rahim NA, Fayaz H. A review on global solar energy policy. Renew Sustain Energy Rev. 2011;15(4):2149-2163.
11. Bellia H, Youcef R, Fatima M. A detailed modeling of photovoltaic module using MATLAB. NRIAG J Astron Geophys. 2014;3(1):53-61.
12. Chin VJ, Salam Z, Ishaque K. Cell modelling and model parameters estimation techniques for photovoltaic simulator application: a review. Appl Energy. 2015;154:500-519.
13. Zhang Y, Zhang Y, Zheng J, et al. Theoretical analysis of improved efficiency of silicon-wafer solar cells with textured nano-triangular grating structure. Opt Commun. 2018;410:369-375.
14. Konagai M, Sugimoto M, Takahashi K. High efficiency GaAs thin film solar cells by peeled film technology. J Cryst Growth. 1978;45:277-280.
15. Garnett E, Yang P. Light trapping in silicon Nanowire solar cells. Nano Lett. 2010;10(3):1082-1087.
16. Nozik A. Quantum dot solar cells. Phys E Low-dimensional Syst Nanostruct. 2002;14(1-2):115-120.
17. Gilot J, Wienk MM, Janssen RAJ. Double and triple junction polymer solar cells processed from solution. Appl Phys Lett. 2007;90(14):143512.
19. Abbassi R, Abbassi A, Jemli M, Chebbi S. Identification of unknown parameters of solar cell models: a comprehensive overview of available approaches. Renew Sustain Energy Rev. 2018;90:453-474.
18. Macabebe EQB, Sheppard CJ, van Dyk EE. Parameter extraction from I-V characteristics of PV devices. Sol Energy. 2011;85(1):12-18.
20. Gomes RCM, Vitorino MA, deRossiiter Corea MB, Fernandes DA, Wang R. Shuffled complex evolution on photovoltaic parameter extraction: a comparative analysis. IEEE Trans Sustain Energy. 2017;8(2):805-815.

ORCID

Mohammad Hossein Ahmadi
https://orcid.org/0000-0002-0097-2534
21. Humada AM, Hojabri M, Mekhilef S, Hamada HM. Solar cell parameters extraction based on single and double-diode models: a review. Renew Sustain Energy Rev. 2016;56(1):494-509.

22. Jordehi AR. Parameter estimation of solar photovoltaic (PV) cells: a review. Renew Sustain Energy Rev. 2016;61(1):354-371.

23. Ishaque K, Salam Z, Mekhilef S, Shamsudin A. Parameter extraction of solar photovoltaic modules using penalty-based differential evolution. Appl Energy. 2012;99(1):297-308.

24. Derick M, Rani C, Rajesh M, Farrag ME, Wang Y, Busawon K. An improved optimization technique for estimation of solar photovoltaic parameters. Sol Energy. 2017;157(15):116-124.

25. Zhou W, Yang H, Fang Z. A novel model for photovoltaic array performance prediction. Appl Energy. 2017;84(1):1187-1198.

26. Ishaque K, Salam Z. An improved modeling method to determine the model parameters of photovoltaic (PV) modules using differential evolution (DE). Sol Energy. 2011;85(9):2349-2359.

27. Siddiqui MU, Abido M. Parameter estimation for five- and seven-parameter photovoltaic electrical models using evolutionary algorithms. Appl Soft Computing. 2013;13(12):4608-4621.

28. Lun SX, Wang S, Yang GH, Guo TT. A new explicit double-diode modeling method based on Lambert-W function for photovoltaic arrays. Sol Energy. 2015;116(1):69-82.

29. Muhsen DH, Ghazali AB, Khatib T, Abed IA. Parameters extraction of double diode photovoltaic module’s model based on hybrid evolutionary algorithm. Energy Convers Manage. 2015;105(15):552-561.

30. Niu Q, Zhang L, Li K. A biogeography-based optimization algorithm with mutation strategies for model parameter estimation of solar and fuel cells. Energy Convers Manage. 2014;86(1):1173-1185.

31. Clavero C. Plasmon-induced hot-electron generation at nanoparticle/metal-oxide interfaces for photovoltaic and photocatalytic devices. Nat Photonics. 2014;8(2):95-103.

32. Ohtake H, Uno F, Oozeki T, Yamada Y, Takenaka H, Nakajima TY. Estimation of satellite-derived regional photovoltaic power generation using a satellite-estimated solar radiation data. Energy Sci Eng. 2018;6(5):570-583.

33. Raugei M, Leccisi E. A comprehensive assessment of the energy performance of the full range of electricity generation technologies deployed in the United Kingdom. Energy Pol. 2016;90:46-59.

34. "Bloomberg New Energy Finance (BNEF) | EnergyTrend." [Online]. Available: https://www.energytrend.com/taxonomy/term/5748. [Accessed: 25-May-2018].

35. Green MA, Emery K, Hishikawa Y, Warra W, Dunlop ED. Solar cell efficiency tables (version 47). Prog Photovoltaics Res Appl. 2016;24(1):3-11.

36. Zhang H, Shan L, Ren J, Cheng B, Zhang H. Study on photovoltaic grid-connected inverter control system, In: Power Electronics and Drive Systems (PEDS), 2009. International Conference on 2009. IEEE. 2009:210-212.

37. Bonkoungou D, Koalaga Z, Njomo D. Modelling and Simulation of photovoltaic module considering single-diode equivalent circuit model in MATLAB – Semantic Scholar. Int J Emerg Technol Adv Eng. 2013;3(3):493-502.

38. Carbajales-Dale M, Barnhart CJ, Brandt AR, Benson SM. A better currency for investing in a sustainable future. Nat Clim Chang. 2014;4(7):524-527.

39. Rajasekar N, Krishna Kumar N, Venugopalan R. Bacterial foraging algorithm based solar PV parameter estimation. Sol Energy 2013;97:255-265.

40. Rasool F, Drieberg M, Badruddin N, Mahinder Singh BS. PV panel modeling with improved parameter extraction technique. Sol Energy 2017;153:519-530.

41. Sulyok G, Summhammer J. Extraction of a photovoltaic cell’s double-diode model parameters from data sheet values. Energy Sci Eng. 2018;6(5):424-436.

42. Labouret A, Villoz M. Solar Photovoltaic Energy. Stevenage: Institution of Engineering and Technology; 2010.

43. Mohammed SS. Modeling and simulation of photovoltaic module using MATLAB/Simulink. Proceed World Congr Eng Comput Sci. 2008;2008:1-6.

44. Romero B, del Pozo G, Arredondo B. Exact analytical solution of a two diode circuit model for organic solar cells showing S-shape using Lambert W-functions. Sol Energy. 2018;2(10):3026-3029.

45. Silvestre S, Boronat A, Chouder A. Study of bypass diodes configuration on PV modules. Appl Energy. 2009;86(9):1632-1640.

46. Dale M, Benson SM. Energy balance of the global photovoltaic (PV) industry – is the PV industry a net electricity producer? Environ Sci Technol. 2013;47(7):3482-3489.

47. Shockley W. The theory of p-n junctions in semiconductors and p-n junction transistors. Bell Syst Tech J. 1949;28(3):435-489.

48. Bonkoungou D, Koalaga Z, Njomo D, Zoungmore F. An improved numerical approach for photovoltaic module parameters acquisition based on single-diode model. Int J Curr Eng Technol. 2015;5:3735-3742.

49. Kety K, Komis Amou A, Sagna K, Lare Y, Napo K. Simulation and prediction of the power output and the photocurrent for photovoltaic systems. Am J Energy Res. 2017;5(2):41-50.

50. Kong J, Song S, Yoo M, et al. Long-term stable polymer solar cells with significantly reduced burn-in loss. Nat Commun. 2014;5(1):5688.

51. Wagenpfahl A, Rauh D, Binder M, Deibel C, Dyakonov V. S-shaped current-voltage characteristics of organic solar devices. May 2010.

52. García-Sánchez FJ, Lugo-Muñoz D, Muci J, Ortiz-Conde A. Lumped parameter Modeling of organic solar cells’ S-shaped I-V characteristics. IEEE J Photovoltaics. 2013;3(1):330-335.

53. Grassman TJ, Brenner MR, Gonzalez M, et al. Characterization of metamorphic GaAsP/Si materials and devices for photovoltaic applications. IEEE Trans Elect Dev. 2010;57(12):3361-3369.

54. Kang RR, Law DC, Edmondson KM, et al. 40% efficient metamorphic GaAsP/Si materials and devices for photovoltaic applications. IEEE Trans Elect Dev. 2010;57(12):3361-3369.

55. Kong J, Song S, Yoo M, et al. Long-term stable polymer solar cells with significantly reduced burn-in loss. Nat Commun. 2014;5(1):5688.

56. Wagenpfahl A, Rauh D, Binder M, Deibel C, Dyakonov V. S-shaped current-voltage characteristics of organic solar devices. May 2010.

57. García-Sánchez FJ, Lugo-Muñoz D, Muci J, Ortiz-Conde A. Lumped parameter Modeling of organic solar cells’ S-shaped I-V characteristics. IEEE J Photovoltaics. 2013;3(1):330-335.
two-stage dish-style concentration system. *Energy Convers. Manag.* 2013;76:177–184.

60. Corless RM, Gonnet GH, Hare DEG, Jeffrey DJ, Knuth DE. On the LambertW function. *Adv Comput Math.* 1996;5(1):329–359.

61. Voswinckel S, Wesselak V, Lustermann B. Behaviour of amorphous silicon solar modules: a parameter study. *Sol Energy. 2013;92:206–213.

62. Mertens J, Assensi JM, Voz C, Shah AV, Platz R, Andreu J. Improved equivalent circuit and analytical model for amorphous silicon solar cells and modules. *IEEE Trans Electron Devices.* 1998;45(2):423–429.

63. Andreev VM, Grilikhes VA, Khvostikov VP, et al. Concentrator PV modules and solar cells for TPV systems. *Sol Energy Mater Sol Cells.* 2004;84(1–4):3–17.

64. Staebler DL, Wronski CR. Reversible conductivity changes in discharge-produced amorphous Si. *Appl Phys Lett.* 1977;33(4):292–294.

65. Yuan Y, Reece TJ, Sharma P, et al. Efficiency enhancement in organic solar cells with ferroelectric polymers. *Nat Mater.* 2011;10(4):296–302.

66. Yamaguchi M. III–V compound multi-junction solar cells: present and future. *Sol Energy Mater Sol Cells.* 2003;75(1–2):261–269.

67. Wang J, Yang S, Jiang C, Zhang Y, Lund PD. Status and future strategies for Concentrating Solar Power in China. *Energy Sci Eng.* 2017;5(2):100–109.

68. Araki K, Hiramatsumi M, Ito H, Kemmoku Y, Yamaguchi M. 22nd European Photovoltaic Solar Energy Conference : Proceedings of the International Conference Held in Milan, Italy, 3–7 September 2007. München: WIP-Renewable Energies; 2007.

69. Molina MG, Mercado PE. Modeling and control of grid-connected photovoltaic energy conversion system used as a dispersed generator, in. *IEEE/PES Trans Distribut Conf Exp Latin America.* 2008;2008:1–8.

70. Bosi M, Pelosi C. The potential of III-V semiconductors as terrestrial photovoltaic devices. *Prog Photovoltaics Res Appl.* 2007;15(1):51–68.

71. Victoria M, Domínguez C, Antón I, Sala G. Comparative analysis of different secondary optical elements for aspheric primary lenses. *Opt Express.* 2009;17(8):6487–6492.

72. Nishioi K, Takamoto T, Nagai T, Kaneiwa M, Uraoka Y, Fuyuki T. Evaluation of InGaP/InGaAs/Ge triple-junction solar cell and optimization of solar cell’s structure focusing on series resistance for high-efficiency concentrator photovoltaic systems. *Sol Energy Mater Sol Cells.* 2006;90(9):1308–1321.

73. Desideri U, Zepparelli F, Morettini V, Garroni E. Comparative analysis of concentrating solar power and photovoltaic technologies: technical and environmental evaluations. *Appl Energy.* 2013;102:765–784.

74. Du B, Hu E, Kolhe M. Performance analysis of water cooled concentrated photovoltaic (CPV) system. *Renew Sustain Energy Rev.* 2012;16(9):6732–6736.

75. Bett A, Burger B, Dimroth F, Siefer G, Lerchenmüller H. High-Concentration PV using III-V Solar Cells. 2006 *IEEE 4th World Conference on Photovoltaic Energy Conference,* 2006, 615–620.

76. Ota Y, Nishioi K. Three-dimensional simulating of concentrator photovoltaic modules using ray trace and equivalent circuit simulators. *Sol Energy.* 2012;86(1):476–481.

77. Mathews I, O’Mahony D, Corbett B, Morrison AP. Theoretical performance of multi-junction solar cells combining III-V and Si materials. *Opt Express.* 2012;20(Suppl 5):A754–A764.

78. Luque A, Sala G, Luque-Heredia I. Photovoltaic concentration at the onset of its commercial deployment. *Prog Photovoltaics Res Appl.* 2006;14(5):413–428.

79. Lv H, Zheng Y, Wang J, et al. Tracking control and output power optimization of a concentrator photovoltaic system with polar axis. *Opt – Int J Light Electron Opt.* 2016;127(8):3840–3843.

80. Adachi S. Physical Properties of III-V Semiconductor Compounds : InP, InAs, GaAs, GaP, InGaAs, and InGaAsP. New York: John Wiley & Sons; 1992.

81. Bishop JW. Computer simulation of the effects of electrical mismatches in photovoltaic cell interconnection circuits. *Sol Cells.* 1988;25(1):73–89.

82. Shabzendezeh M, Movla H, Shojaei IA. Light concentration effects on the performance of the p-i-n quantum dot solar cells: a simulation study. *Opt – Int J Light Electron Opt.* 2014;125(22):6691–6695.

83. Sze SM, Ng KK. *Physics of Semiconductor Devices.* Hoboken, NJ: Wiley-Interscience; 2007.

84. Bentaher H, Kaich H, Ayadi N, Ben Hmouda M, Maelje A, Lemmer U. A simple tracking system to monitor solar PV panels. *Energy Convers. Manag.* 2014;78:872–875.

85. Andenas E, Jelle BP, Ramlo K, Kolás T, Selj J, Foss SE. The influence of snow and ice coverage on the energy generation from photovoltaic solar cells. *Sol Energy.* 2018;159:318–328.

86. Jelle BP. The challenge of removing snow downfall on photovoltaic solar cell roofs in order to maximize solar energy efficiency—Research opportunities for the future. *Energy Build.* 2013;67:334–351.

87. Deline C. Partially shaded operation of a grid-tied PV system. In: *2009 34th IEEE Photovoltaic Specialists Conference (PVSC),* 2009, 001268–001273.

88. Tabet I, Touafek K, Bellel N, Bouarroudj N, Khelifa A, Adouane M. Optimization of angle of inclination of the hybrid photovoltaic-thermal solar collector using particle swarm optimization algorithm. *J Renew Sustain Energy.* 2014;6(5):053116.

89. Sulaiman S, Singh AK, Mokhtar MM, Bou-Rabee MA, et al. Influence of dirt accumulation on performance of PV panels. *Energy Procedia.* 2014;50:50–56.

90. Varshni YP. Temperature dependence of the energy gap in semiconductors. *Physica.* 1967;34:149–154.

91. Singh P, Ravindra NM. Temperature dependence of solar cell performance—an analysis. *Sol Energy Mater Sol Cells.* 2012;101:36–45.

92. Hu C, White RM. *Solar Cells.* New York: McGraw-Hill; 1983, p. 21.

93. Nell ME, Barnett AM. The spectral p–n junction model for tandem solar-cell design. *IEEE Trans Electron Devices.* 1987;24:257–266.

94. Green MA. *Solar Cells.* Englewood Cliffs, NJ: Prentice-Hall; 1982, p. 88.

95. Al-Nimr MA, Kiwan S, Sharadga H. Simulation of a novel hybrid solar photovoltaic/wind system to maintain the cell surface temperature and to generate electricity. *Int J Energy Res.* 2018;42(3):985–998.

96. Willars-Rodríguez FJ, Chávez-Urbiola EA, Vorobiev P, Vorobiev YV. Investigation of solar hybrid system with concentrating Fresnel lens, photovoltaic and thermoelectric generators. *Int J Energy Res.* 2017;41(3):377–388.
322 | Energy Science & Engineering

97. Al-Waeli AHA, Sopian K, Chaichan MT, Kazem HA, Hasan HA, Al-Shamani AN. An experimental investigation of SiC nanofluid as a base-fluid for a photovoltaic thermal PV/T system. *Energy Convers Manag*. 2017;142:547-558.

98. Saeedi F, Sarchaddi F, Behzadmehr A. Optimization of a PV/T (photovoltaic/thermal) active solar still. *Energy*. 2015;87:142-152.

99. Xing Y, Han P, Wang S, et al. A review of concentrator silicon solar cells. *Renew Sustain Energy Rev*. 2015;51:1697-1708.

100. Gaiduk A, Yorulmaz M, Ruijgrok PV, Orrit M. Room-temperature detection of a single molecule’s absorption by photothermal contrast. *Science*. 2010;330(6002):353-356.

101. King DL, Kratochvil JA, Boyson WE. Temperature coefficients for PV modules and arrays: measurement methods, difficulties, and results. In: *Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference* – 1997, 1183-1186.

102. Hu Y, Yao Y. Optical analysis and output evaluation for a two-stage concentration photovoltaic system by using Monte Carlo ray-tracing method. *Opt - Int J Light Electron Opt*. 2017;131:713-723.

103. Whitaker CM, Townsend TU, Wenger HJ, Iliceto A, Chimento G, Paletta F. Effects of irradiance and other factors on PV temperature coefficients. In: *The Conference Record of the Twenty-Second IEEE Photovoltaic Specialists Conference* – 1991, 608-613.

104. Naveed AT, Kang EC, Lee EJ. Effect of unglazed transpired collector on the performance of a polycrystalline silicon photovoltaic module. *J Sol Energy Eng*. 2006;128(3):349.

105. Zondag HA. Flat-plate PV-thermal collectors and systems: a review. *Renew Sustain Energy Rev*. 2008;12(4):891-959.

106. Evans DL. Simplified method for predicting photovoltaic array output. *Sol Energy*. 1981;27(6):555-560.

107. Barra L, Cotante D. Annual energy production and room temperature effect in siting flat plate photovoltaic systems. *Sol Energy*. 1993;51(5):383-389.

108. Kawajiri K, Oozeki T, Gench Y. Effect of temperature on PV potential in the world. *Environ Sci Technol*. 2011;45(20):9030-9035.

109. Dubey S, Sarvaiya JN, Seshadri B. Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the World – a review. *Energy Procedia*. 2013;33:311-321.

110. Skoplaki E, Palyvos JA. On the temperature dependence of photovoltaic module electrical performance: a review of efficiency/power correlations. *Sol Energy*. 2009;83(5):614-624.

111. Durisch W, Urban J, Smestad G. Characterisation of solar cells and modules under actual operating conditions. *Renew Energy*. 1996;8(1-4):359-366.

112. Mani M, Pillai R. Impact of dust on solar photovoltaic (PV) performance: research status, challenges and recommendations. *Renew Sustain Energy Rev*. 2010;14(9):3124-3131.

113. Armstrong S, Hurley WG. A thermal model for photovoltaic panels under varying atmospheric conditions. *Appl Therm Eng*. 2010;30(11-12):1488-1495.

114. A. G173-03(2012). Standard tables for reference solar spectral irradiances: direct normal and hemispherical on 37° tilted surface. *ASTM Int*. 2012;1:250-254.

115. Frischknecht R, Ilett R, Sinha P, et al., Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems. 2015.

116. (Antonio) Luque A, Hegedus S. *Handbook of Photovoltaic Science and Engineering*. London: Wiley; 2003.

117. Paris Agreement. United Nations Treaty Collection, 2016.

118. Bye G, Ceccaroli B. Solar grade silicon: technology status and industrial trends. *Sol Energy Mater Sol Cells*. 2014;130:634-646.

119. Zhuang YF, Zhong SH, Huang ZG, Shen WZ. Versatile strategies for improving the performance of diamond wire sawn mc-Si solar cells. *Sol Energy Mater Sol Cells*. 2016;153:18-24.

120. Kumar Natarajan S, Katz M, Kumar Mallick T. Thermal model for an early prototype of concentrating photovoltaic for active solar panel initiative system. *J Renew Sustain Energy*. 2012;4(1):011601.

121. “Thin film solar cell,” Apr. 2007.

122. Schaeffer R, Szklo AS, de Lucena AF, et al. Energy sector vulnerability to climate change: a review. *Energy*. 2012;38(1):1-12.

123. Barca S. Energy, property, and the industrial revolution narrative. *Ecol Econ*. 2011;70(7):1309-1315.

124. Ferreira A, Kunh SS, Fagnani KC, et al. Economic overview of the use and production of photovoltaic solar energy in brazil. *Renew Sustain Energy Rev*. 2018;81:181-191.

125. Rüther R, Zilles R. Making the case for grid-connected photovoltaics in Brazil. *Energy Pol*. 2011;39(3):1027-1030.

126. Xie WT, Dai YJ, Wang RZ, Sumathy K. Concentrated solar energy applications using Fresnel lenses: a review. *Renew Sustain Energy Rev*. 2011;15(6):2588-2606.

127. Guo L, Meng Zh, Sun Y, Wang L. Parameter identification and sensitivity analysis of solar cell models with cat swarm optimization algorithm. *Energy Convers Manage*. 2016;108:520-528.

128. De Castro F, Laudani A, Riganti Fulginei F, Salvini A. An in-depth analysis of the modelling of organic solar cells using multiple-diode circuits. *Sol Energy*. 2016;135:590-597.

129. Xu Y, Jin W. Improvement of parameter identification method for the photovoltaic cell. *Opt – Int J Light Electron Opt*. 2017;132:134-141.

130. Al-Nimr M, Kiwan S, Sharagda H. Simulation of a novel hybrid solar photovoltaic/wind system to maintain the cell surface temperature and to generate electricity. *Int J Energy Res*. 2017;42(3):1-14.

How to cite this article: Khatibi A, Razi Astaraei F, Ahmadi MH. Generation and combination of the solar cells: A current model review. *Energy Sci Eng*. 2019;7:305–322. [https://doi.org/10.1002/ese3.292](https://doi.org/10.1002/ese3.292)