A new theoretical formulation of electrical parameters related to photovoltaic cell maximum power output

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Abstract

This work deals with a new theoretical analysis and formulation of electrical parameters lasts to a derivation of a satisfied simple maximum power output equation of photovoltaic (pv) cells. Essentially, this work concentrates on useful parameters in characterizing the maximum power output cannot be expressed explicitly in terms of other parameter. These are such as: the maximum voltage, maximum current and, hence, the maximum power output. An air mass radiation (AM1.5) is used throughout this work. First, referring to AM1.5 sunlight power versus wavelength, all the electrical parameters of wide range pv cells having band gaps ranged (0.4887 ev to 3.815 ev) are calculated by conventional way in order to compare their values with approach values. Second; instead of using the conventional way of modeling each pv cell independently, this approach introduces a method through which the modeling of several pv cells dependently is possible for the determination of the unknown electrical parameters. As a result of this analytical formulation, a satisfied derived equations of electrical parameters are obtained and satisfied up to around 100 % with no interpolation methods or other technique used.

Keywords: PV cells, PV cell electrical parameters.

Introduction

Photovoltaic cells differ from each other according to their different band gap energy and , accordingly, their electrical output parameters differ in their values from pv cell to another according to the semiconducting material from which these photovoltaic cells are fabricated provided that the surface area of these photovoltaic cells, sunlight irradiance, and temperature under which all these different pv cell types are operated, both are identical [17, 4]. The pv cell performance is determined by its related parameters such as; the reverse saturation current (I_0), short circuit current (I_{SC}), open circuit voltage (V_{OC}), fill factor (FF), maximum power (P_m), and conversion efficiency (η). As a material dependent parameter depends on the band gap (E_g) of the material, reverse saturation current is the critical parameter affecting the power output and, hence, the efficiency of pv cells [14, 3]. Electrical parameters are irradiance, temperature dependent parameters and, as a result, their values varies accordingly [1, 16]. Since pv cells are a major element of pv power systems, this accounts for the necessity to study the current-voltage and power-voltage characteristics of pv cells in order to obtain the maximum power output when there are changes, both, in the pv modules themselves and in the environment where they operate [13].
Relationships referring to electrical parameter, some of them cannot be expressed explicitly in terms of other parameters like maximum voltage, maximum current, and maximum power output, while some of them can be solved directly by direct substitutions into their related equations such as the short circuit current, open circuit voltage, reverse saturation current. Electrical parameters cannot be explicitly expressed in terms of other related parameters utilizing techniques such as interpolations, Newton and Raphson method in order to solve for.

Some approximate expressions are putdown for determining some electrical parameters of pv cells, such relations are the open circuit voltage as a function of band gap energy [2]. In addition, although the fill factor of a solar cell is a useful parameter in characterizing the cell performance, it cannot be expressed explicitly in terms of other parameters. An approximate empirical expression of fill factor, is introduced, applicable for ideal cases where no parasitic resistance losses are considered and it is accurate to about one digit in the fourth decimal place for these cases, it is an expression of fill factor as a function only of the open circuit voltag [5, 6].

Because of the difficulty of finding out some parameters, such as V_m, in addition to approximate relations, many modeling methods and techniques have been used such as the computer simulation modeling and algorithms, Newton & Raphson method, math-cad software package for the estimation of electrical parameters under different irradiance and temperature situations [13, 11, 12, 9, 7, 8]. A classical single diode modeling, using Mathcad software packages, are used to model the electrical characteristics of pv cells such that a pv cell current (I) is calculated as a function of the pv cell voltage (V) and solar radiation power (P_{in}) [13]. Laplace integral transform technique is also applied to estimate the efficiency of pv cell as a function of temperature [11]. A new approach for estimating the one-diode model parameters of a pv cell according to the irradiance and temperature is introduced, these parameters are given at known irradiance and temperature from the knowledge of I_{SC} , V_{OC} , and P_m, using Newton and Raphson method to calculate the model parameters [12]. A formula that describes the I-V characteristics is found, based on the information gathered, and the values of I and P are determined according to different values of V, afterwards, the natural cubic spline interpolation method is used to build a mathematical model that can approximate those values and finally a bisection is used as an optimization method in determining the value of V that can produce the maximum power [9]. A simplified algorithm predicts the average steady-state temperature of pv cells has been developed [7]. A simple silicon pv cell has been simulated, using MATLAB, for estimating the pv cell performance [8].

Regardless each of the techniques and methods mentioned above, this work introduces a simple excellent approximate electrical parameter derived equations (direct-solvable equations) by analytically modeling a wide range of pv cells such that any unknown electrical parameter can easily be obtained from the known parameters certain photovoltaic cells group net (covering this wide range of pv cells) provides. This is the only way of overcoming utilizing interpolations and complex software packages. This is achieved by modeling and expressing (dependently) the unknown parameter as a function of several other known parameters for the unknown electrical parameter to be determined rather than conventionally (independently) expressed. As a result, this work presents many important equations such as the one that solves (in inverse way) for the short circuit from the open circuit voltage equation and hence the photon flux is determined. This is achieved knowing only the band gap of the considered pv cell; also the one that solves for the temperature required to equate two maximum voltages of two wide band gap different pv cells, etc.

Conventional calculations of electrical parameters of pv cell

The conventional calculations are conducted referring to the pv cell electrical parameter equations given below:

1- The input sunlight power (P_{in}), in mW cm^{-2}, integrated over all wavelengths comprising the intensity spectrum of the light incident upon the pv cell is given by [10, 8 , 15]:

$$P_{in} = \int_0^\infty P_{in}(\lambda)\ d\lambda \qquad (1)$$

where, the relation connecting the photon flux ($\int N_{ph}$), in cm^{-2}s^{-1}, with input sunlight power is given by:

$$(q/hc)\int_0^\infty P_{in}(\lambda)\lambda\ d\lambda = q\int_0^\infty N_{ph}(\lambda)\ d\lambda \qquad (2)$$

Where "h" is the plank's constant, "q" is the electron charge, and "c" is the velocity of light.

2- The short circuit current density (J_{SC}) in mA cm^{-2}and short circuit current (I_{SC}) in mA, generated when photons energy greater or equal the pv cell band gap energy (i.e, $h\nu \geq E_g$) are given by [10, 4]:

$$J_{SC}(E) = qN_{ph}(E)\ \text{, and;}\ \ I_{SC}(E) = qAN_{ph}(E) \qquad (3)$$

Where "A" is the cross-sectional area of the pv cell.

3- The reverse saturation current (I_0) is expressed as [4, 14, 8], where " k " is the Boltzmann constant, " T " is the pv cell temperature:

$$I_0 = CT^3 e^{-\left(\frac{q}{k}\right)(E_g/T)} \qquad (4)$$

Where, C is a material constant in mA /cm^2/ K^3 , and hence $I_0 = 6.03\times10^9\ e^{-(q/k)(Eg/T)}$ mA [4, 14]:

4- The I-V characteristic equation that relates pv cell current (I) and voltage (V) with each other is given by:

$$I = I_0\left(e^{qV/kT} - 1\right) - I_L \qquad (5a)$$

Such that; when in eq.(5a) V = 0, then I = -I_L referred to " short -circuited condition, where "I_L" is the light-generated current, thus:

$$I = I_{SC} = -I_L \qquad (5b)$$

On the other hand, when in eq.(5a), I = 0, then this case is referred to " the open- circuit condition, and therefore, the open circuit voltage is expressed by:

$$V_{OC} = \frac{KT}{q}\ln\{(I_{SC} + I_0)/I_0\} \qquad (5c)$$

5- The maximum voltage (V_m) is expressed as given below:

$$e^{(q/k)(V_m/T)}\{1 + (qV_m/kT)\} = \{(I_{SC} + I_0)/I_0\} \qquad (6)$$

6- The maximum current (V_m) is related to the maximum voltage, by:

$$I_m = \left\{\frac{\left(\frac{qV_m}{kT}\right)}{\left\{1+\left(\frac{qV_m}{kT}\right)\right\}}\right\}\{I_{SC} + I_0\} \qquad (7)$$

7- The maximum power (P_m) is the product of V_m and I_m , i.e:

$$P_m = (V_m)(I_m) \qquad (8)$$

8- The fill factor (FF) is expressed by:

$$FF = P_m/(V_{OC}\, I_{SC}) = (V_m)(I_m)/(V_{OC}\, I_{SC}) \qquad (9a)$$

9- The voltage factor (VF) is expressed by:

$$VF = V_{OC}/E_g \qquad (9b)$$

10- Finally, the conversion efficiency (η) is given by:

$$P_m/P_{in} = \frac{(V_m)(I_m)}{P_{in}} = \{(V_{OC}\, I_{SC})(FF)\}/P_{in} \qquad (10)$$

Figure (1) shows, according to priority, the steps of calculating the electrical parameters of pv cells.

Approach theoretical modeling and formulation analysis

Throughout this work, it is assumed that the pv cell band, covered by the wide number of pv cells, is divided into two groups; first, the group of N-pv unknown parameter pv cells: $cell_{Ui}$ = [$cell_{U1}$, $cell_{U2}$, $cell_{U3}$, ….., $cell_{UN}$] their referred related electrical parameters are ($I_{0,ui}$,$I_{SC,ui}$, $V_{m,ui}$, $P_{m,ui}$, etc); second, the group of M-pv known (reference) parameters pv cells: $cell_{Ri}$ = [$cell_{R1}$, $cell_{R2}$, $cell_{R3}$,…, $cell_{RM}$] their referred related electrical parameters are ($I_{0,Ri}$,$I_{SC,Ri}$, $V_{m,Ri}$, $P_{m,Ri}$, etc), where " i " is an integer , from 1 to N and from 1 to M that indicates the pv cell number $cell_{Ui}$ and $cell_{Ri}$, respectively.

Pv cells ($cell_{Ui}$ and $cell_{Ri}$), both, forming a net so that any unknown parameter of any $cell_{Ui}$ can be determined as a function of one or several $cell_{Ri}$ for the same parameter whatever is the sunlight irradiance or the thermal conditions. This approach, general pv cells-net structure of both groups ($cell_{Ui}$ and $cell_{Ri}$) is shown in Figure (2).

Approach calculations are conducted referring to the pv cell electrical parameter equations derived as given below:

Formulation of reverse saturation current (I_0)and band gap energy (E_g)

Referring to eq.(4), a system of reverse saturation current representing, both: $cell_{Ui}$ and $cell_{Ri}$, can then be written as:

$$I_{0,u1} = CT^3\ e^{-\left(\frac{q}{k}\right)(E_{g,u1}/T_{,u1})} \qquad (11)$$

$$I_{0,R1} = CT^3\ e^{-\left(\frac{q}{k}\right)(E_{g,R1}/T_{,R1})} \qquad (12)$$

$$I_{0,u2} = CT^3 e^{-\left(\frac{q}{k}\right)(E_{g,u2}/T_{,u2})} \tag{13}$$

$$I_{0,R2} = CT^3\ e^{-\left(\frac{q}{k}\right)(E_{g,R2}/T_{,R2})} \tag{14}$$

. . . . .

$$I_{0,uN} = CT^3 e^{-\left(\frac{q}{k}\right)(E_{g,uN}/T_{,uN})} \tag{15}$$

$$I_{0,RM} = CT^3 e^{-\left(\frac{q}{k}\right)(E_{g,RM}/T_{,RM})} \tag{16}$$

Multiplying eqs.(11 through 16) in themselves, results into:

$$(I_{0,u1}\, I_{0,u2}\ \dots\dots\dots\dots..\, I_{0,N})(I_{0,R1}\, I_{0,R2}\ \dots\dots\dots\dots..\, I_{0,M}) =$$

$$CT^{3^{(N+M)}}\ e^{-(q/k)[(E_{g,u1}/T_{u1})+(E_{gR1}/T_{R1})+(E_{gu2}/T_{u2})+(E_{gR2}/T_{R2})+\cdots+(E_{gRM}/T_{RM})+\cdots+(E_{guN}/T_{uN})]} \tag{17}$$

Taking natural logarithm for both sides of eq.(17), gives:

$$[(E_{gu1}/T_{u1}) + (E_{gR1}/T_{R1}) + (E_{gu2}/T_{u2}) + (E_{gR2}/T_{R2}) + \cdots \dots\dots \quad \dots + (E_{guN}/T_{uN}) + \cdots + (E_{gRM}/T_{RM})] = -(k/q)\ln\left\{(I_{0,u1}\, I_{0,u2}\ \dots\dots\dots\dots..\, I_{0,N})(I_{0,R1}\, I_{0,R2}\ \dots\dots\dots\dots..\, I_{0,M})/\left(CT^{3^{(N+M)}}\right)\right\} \tag{18}$$

Arranging eq.(18):

$$\sum_{i=1}^{N}\{(E_{gui}/T_{ui})\} + \sum_{i=1}^{M}\{(E_{gRi}/T_{Ri})\} = \left(\frac{k}{q}\right)\ln\left\{\frac{\left(CT^{3^{(N+M)}}\right)}{[(\prod_{i=1}^{N} I_{0ui})(\prod_{i=1}^{M} I_{0Ri})]}\right\} \tag{19}$$

Multiplying both sides of eq.(18) by T_{u1} and separate $E_{g,u1}$ to one side, gives:

$$E_{g,u1} = \left(\frac{kT_{,u1}}{q}\right)\ln\left\{\frac{\left(CT^{3^{(N+M)}}\right)}{[(\prod_{i=1}^{N} I_{0ui})(\prod_{i=1}^{M} I_{0Ri})]}\right\} - \{[(E_{g,R1})/(T_{,u1}/T_{,R1})] + [(E_{g,u2})/(T_{,u1}/T_{,u2})] + [(E_{g,R2})/(T_{,u1}/T_{,R2})] + \ \dots..+[(E_{g,uN})/(T_{,u1}/T_{,uN})] + \ \dots + [(E_{g,RM})/(T_{,u1}/T_{,RM})]\} \tag{20}$$

Assume a single pv cell, (cell_{u1}) out of the whole N-cell_{Ui} should communicates, photovoltaically, with all the M-cell_{Ri}. Then eq.(20) becomes:

$$E_{g,u1} = \left(\frac{kT_{,u1}}{q}\right)\ln\left\{\frac{\left(CT^{3^{(1+M)}}\right)}{[(I_{0,u1})(\prod_{i=1}^{M} I_{0,Ri})]}\right\} - \{[(E_{g,R1})/(T_{,u1}/T_{,R1})] + +[(E_{g,R2})/(T_{,u1}/T_{,R2})] + \dots..+\dots+\ \dots + [(E_{g,RM})/(T_{,u1}/T_{,RM})]\}$$

$$= \left(\frac{kT_{,u1}}{q}\right)\ln\left\{\frac{\left(CT^{3^{(1+M)}}\right)}{[(I_{0,u1})(\prod_{i=1}^{M} I_{0,Ri})]}\right\} - \sum_{i=1}^{M}[(E_{g,Ri})/(T_{,u1}/T_{,Ri})] \tag{21}$$

Any pair out of (cell_{Ui} and cell_{Ri}) can satisfy the case. Let the pair be (cell_{U1} and cell_{R1}), then eq.(21) can be written as:

$$E_{g,u1} = \left(\frac{kT_{,u1}}{q}\right)\ln\left\{\frac{\left(CT^{3^{(2)}}\right)}{[(I_{0,u1})(I_{0,R1})]}\right\} - \{[(E_{g,R1})/(T_{,u1}/T_{,R1})]\} \tag{22}$$

Also, it can be proved that:

$$E_{g,u} = E_{g,R}\,(T_{,u}/T_{,R}) + (kT_{,u}/q)\ \ln\{I_{0,R})/I_{0,u}\} \tag{23}$$

FORMULATION OF THE OPEN CIRCUIT VOLTAGE (V_{OC})

The open circuit voltage and its negative (to use later) for cell_{Ui} and cell_{RI} pv cells electrical parameters are, respectively, given by:

$$V_{OC,ui} = \frac{kT_{u,i}}{q}\ln\{(I_{SC,ui} + I_{0,ui})/I_{0,ui}\} \tag{24}$$

$$-V_{OC,ui} = \frac{kT_{u,i}}{q}\ln\{I_{0,ui}/(I_{SC,ui} + I_{0,ui})\} \tag{25}$$

$$V_{OC,Ri} = \frac{kT_{R,i}}{q}\ln\{(I_{SC,Ri} + I_{0,Ri})/I_{0,Ri}\} \tag{26}$$

$$-V_{OC,Ri} = \frac{kT_{R,i}}{q}\ln\{I_{0,Ri}/(I_{SC,Ri} + I_{0,Ri})\} \tag{27}$$

Same as previous analysis procedure, multiplying eqs.(24 and 26), the formulation of the open circuit voltage results into:

$$V_{OC,u1}\,V_{OC,R1}\,V_{OC,u2}\,V_{OC,R2}\,\ldots.\,V_{OC,uN}\,\cdots\,V_{OC,RM}\;=$$
$$\left\{\prod_{i=1}^{N}\frac{kT_{u,i}}{q}\ln\{(\,I_{SC,ui}\;+I_{0,ui}\,)/\,I_{0,ui}\,\}\right\}\left\{\prod_{i=1}^{M}\frac{kT_{R,i}}{q}\ln\{(\,I_{SC,Ri}\;+I_{0,Ri}\,)/\,I_{0,Ri}\,\}\right\} \qquad (\,28\,)$$

FORMULATION OF THE MAXIMUM VOLTAGE (V_m)

The maximum voltage (V_m) is expressed as:

$$e^{(q/k)(V_m/T)}\{1+(qV_m/kT)\}=\{(I_{SC}+I_0)/I_0\} \qquad (\,29\,)$$

Re-arranging eq(29), yields :

$$e^{(q/k)(V_m/T)}=\left\{\frac{\left[\left(\frac{KT}{q}\right)+(V_m)\right]}{\left(\frac{KT}{q}\right)}\right\}\{(I_{SC}+I_0)/I_0\} \qquad (\,30\,)$$

A system of maximum voltage equations, including N-pv cell$_{Ui}$ and M-pv cell$_{Ui}$ can then be written as follows:

$$e^{(q/k)(V_{m,u1}/T_{u1})}=\left\{\frac{\left[\left(\frac{KT_{,u1}}{q}\right)+(V_{m,u1})\right]}{\left(\frac{KT_{,u1}}{q}\right)}\right\}\{(I_{SC,u1}+I_{0,u1})/I_{0,u1}\} \qquad (\,31\,)$$

$$e^{(q/k)(V_{m,R1}/T_{,R1})}=\left\{\frac{\left[\left(\frac{KT_{,R1}}{q}\right)+(V_{m,R1})\right]}{\left(\frac{KT_{,R1}}{q}\right)}\right\}\{(I_{SC,R1}+I_{0,R1})/I_{0,R1}\} \qquad (\,32\,)$$

$$e^{(q/k)(V_{m,u2}/T_{,u2})}=\left\{\frac{\left[\left(\frac{KT_{,u2}}{q}\right)+(V_{m,u2})\right]}{\left(\frac{KT_{,u2}}{q}\right)}\right\}\{(I_{SC,u2}+I_{0,u2})/I_{0,u2}\} \qquad (\,33\,)$$

$$e^{(q/k)(V_{m,R2}/T_{R2})}=\left\{\frac{\left[\left(\frac{KT_{,R2}}{q}\right)+(V_{m,R2})\right]}{\left(\frac{KT_{,R2}}{q}\right)}\right\}\{(I_{SC,R2}+I_{0,R2})/I_{0,R2}\} \qquad (\,34\,)$$

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$$e^{(q/k)(V_{m,uN}/T_{uN})}=\left\{\frac{\left[\left(\frac{KT_{,uN}}{q}\right)+(V_{m,uN})\right]}{\left(\frac{KT_{,uN}}{q}\right)}\right\}\{(I_{SC,uN}+I_{0,uN})/I_{0,uN}\} \qquad (\,35\,)$$

$$e^{(q/k)(V_{m,RM}/T_{,RM})}=\left\{\frac{\left[\left(\frac{KT_{,RM}}{q}\right)+(V_{m,RM})\right]}{\left(\frac{KT_{,RM}}{q}\right)}\right\}\{(I_{SC,RM}+I_{0,RM})/I_{0,RM}\} \qquad (\,36\,)$$

Dividing eqs.(31 through 36), gives:

$$e^{\left(\frac{q}{k}\right)\left[\frac{V_{m,u1}}{T_{,u1}}-\frac{V_{m,R1}}{T_{,R1}}-\frac{V_{m,u2}}{T_{,u2}}-\frac{V_{m,R2}}{T_{,R2}}-\ldots\ldots-\frac{V_{m,uN}}{T_{,uN}}-\ldots\;\frac{V_{m,RM}}{T_{,RM}}\right]}=$$

$$\left\{\{(I_{SC,u1}+I_{0,u1})/I_{0,u1}\}\left\{\frac{\left(\frac{KT_{,u1}}{q}\right)}{(V_{m,u1})+\left(\frac{KT_{,u1}}{q}\right)}\right\}\right\}\Bigg\{\{(I_{0,R1})/$$

$$(I_{SC,R1}+I_{0,R1})\}\left\{\frac{\left[\left(\frac{KT_{,R1}}{q}\right)+(V_{m,R1})\right]}{\left(\frac{KT_{,R1}}{q}\right)}\right\}\Bigg\}\left\{\{(I_{0,u2})/(I_{SC,u2}+I_{0,u2})\}\left\{\frac{\left[\left(\frac{KT_{,u2}}{q}\right)+(V_{m,u2})\right]}{\left(\frac{KT_{,u2}}{q}\right)}\right\}\right\}\Bigg\{\{(I_{0,R2})/$$

$$(I_{SC,R2}+I_{0,R2})\}\left\{\frac{\left[\left(\frac{KT_{,R2}}{q}\right)+(V_{m,R2})\right]}{\left(\frac{KT_{,R2}}{q}\right)}\right\}\Bigg\}\ldots\ldots\ldots\Bigg\{\{(I_{0,uN})/$$

$$(I_{SC,uN}+I_{0,uN})\}\left\{\frac{\left[\left(\frac{KT_{,uN}}{q}\right)+(V_{m,uN})\right]}{\left(\frac{KT_{,uN}}{q}\right)}\right\}\Bigg\}\ldots\left\{\{(I_{0,RM})/(I_{SC,RM}+I_{0,RM})\}\left\{\frac{\left[\left(\frac{KT_{,RM}}{q}\right)+(V_{m,RM})\right]}{\left(\frac{KT_{,RM}}{q}\right)}\right\}\right\} \qquad (\,37\,)$$

Since the ratio $\left[\left(\left(\frac{KT}{q}\right)+(V_m)\right)/\left(\left(\frac{KT}{q}\right)+(V_{OC})\right)\right]$ referring to pv cells is tested to be up to a large degree of extent nearer to unity so it is valid to substitute V_{OC} for V_m in eq.(37), and after taking ln for both its sides, eq.(37) become:

$$\frac{V_{m,u1}}{T_{,u1}} - \frac{V_{m,R1}}{T_{,R1}} - \frac{V_{m,u2}}{T_{,u2}} - \frac{V_{m,R2}}{T_{,R2}} - \ldots.. - \frac{V_{m,uN}}{T_{,uN}} - \ldots - \frac{V_{m,RM}}{T_{,RM}} = \left(\frac{k}{q}\right)\ln\left\{\left\{\left(I_{SC,u1}+I_{0,u1}\right)/I_{0,u1}\right\}\left\{\frac{\left(\frac{KT_{,u1}}{q}\right)}{\left(V_{OC,u1}\right)+\left(\frac{KT_{,u1}}{q}\right)}\right\}\right\}\left\{\left\{\left(I_{0,R1}\right)/\left(I_{SC,R1}+I_{0,R1}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,R1}}{q}\right)+\left(V_{OC,R1}\right)\right]}{\left(\frac{KT_{,R1}}{q}\right)}\right\}\right\}\left\{\left\{\left(I_{0,u2}\right)/\left(I_{SC,u2}+I_{0,u2}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,u2}}{q}\right)+\left(V_{OC,u2}\right)\right]}{\left(\frac{KT_{,u2}}{q}\right)}\right\}\right\}\left\{\left\{\left(I_{0,R2}\right)/\left(I_{SC,R2}+I_{0,R2}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,R2}}{q}\right)+\left(V_{OC,R2}\right)\right]}{\left(\frac{KT_{,R2}}{q}\right)}\right\}\right\}\ldots\ldots\left\{\left\{\left(I_{0,uN}\right)/\left(I_{SC,uN}+I_{0,uN}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,uN}}{q}\right)+\left(V_{OC,uN}\right)\right]}{\left(\frac{KT_{,uN}}{q}\right)}\right\}\right\}\cdot\cdot\left\{\left\{\left(I_{0,RM}\right)/\left(I_{SC,RM}+I_{0,RM}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,RM}}{q}\right)+\left(V_{OC,RM}\right)\right]}{\left(\frac{KT_{,RM}}{q}\right)}\right\}\right\} \quad (38)$$

Simplifying eq.(38) by naming its R.H.S terms by " an electronic parameter constants ", such that:

$$K_{u1} = \left\{\left\{\left(I_{SC,u1}+I_{0,u1}\right)/I_{0,u1}\right\}\left\{\frac{\left(\frac{KT_{,u1}}{q}\right)}{\left(V_{OC,u1}\right)+\left(\frac{KT_{,u1}}{q}\right)}\right\}\right\} \quad (39)$$

$$K_{R1} = \left\{\left\{\left(I_{0,R1}\right)/\left(I_{SC,R1}+I_{0,R1}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,R1}}{q}\right)+\left(V_{OC,R1}\right)\right]}{\left(\frac{KT_{,R1}}{q}\right)}\right\}\right\} \quad (40)$$

$$K_{u2} = \left\{\left\{\left(I_{0,u2}\right)/\left(I_{SC,u2}+I_{0,u2}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,u2}}{q}\right)+\left(V_{OC,u2}\right)\right]}{\left(\frac{KT_{,u2}}{q}\right)}\right\}\right\} \quad (41)$$

$$K_{R2} = \left\{\left\{\left(I_{0,R2}\right)/\left(I_{SC,R2}+I_{0,R2}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,R2}}{q}\right)+\left(V_{OC,R2}\right)\right]}{\left(\frac{KT_{,R2}}{q}\right)}\right\}\right\} \quad (42)$$

. . .

$$K_{uN} = \left\{\left\{\left(I_{0,uN}\right)/\left(I_{SC,uN}+I_{0,uN}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,uN}}{q}\right)+\left(V_{OC,uN}\right)\right]}{\left(\frac{KT_{,uN}}{q}\right)}\right\}\right\} \quad (43)$$

$$K_{RM} = \left\{\left\{\left(I_{0,RM}\right)/\left(I_{SC,RM}+I_{0,RM}\right)\right\}\left\{\frac{\left[\left(\frac{KT_{,RM}}{q}\right)+\left(V_{OC,RM}\right)\right]}{\left(\frac{KT_{,RM}}{q}\right)}\right\}\right\} \quad (44)$$

So that eq.(38) becomes:

$$\frac{V_{m,u1}}{T_{,u1}} - \frac{V_{m,R1}}{T_{,R1}} - \frac{V_{m,u2}}{T_{,u2}} - \frac{V_{m,R2}}{T_{,R2}} - \ldots.. - \frac{V_{m,uN}}{T_{,uN}} - \ldots - \frac{V_{m,RM}}{T_{,RM}} = \left(\frac{k}{q}\right)\ln\{\, K_{u1}\, K_{R1}\, K_{u2}\, K_{R2}\, K_{u3}\, K_{R3}\, \ldots.K_{uN} \ldots\ K_{RM}\,\} \quad (45)$$

Eq.(45) can be simplified to become:

$$\frac{V_{m,u1}}{T_{,u1}} - \sum_{i=2}^{N}\{(V_{m,ui}/T_{,ui})\} - \sum_{i=1}^{M}\{(V_{m,Ri}/T_{,Ri})\} = \left(\frac{k}{q}\right)\{(\prod_{i=1}^{N}K_{ui})(\prod_{i=1}^{M}K_{Ri})\} \quad (46)$$

Any out of the N-unknown electric parameter pv cells (cell$_{Ui}$) its electrical parameter (here is the maximum voltage) can be obtained utilizing: single, some, or both the M-known electrical parameter pv cells (cell$_{Ri}$) for the determination of $V_{m,ui}$. for example, If the concerned pv cell (cell$_{Ui}$) = cell$_{U1}$, then the case of utilizing all the M- cell$_{Ri}$ is derived when both sides of eq.(45) are multiplied by $T_{,U1}$, therefore eq.(45) becomes:

$$V_{m,u1} = \left(T_{,u1}/T_{,R1}\right)\left(V_{m,R1}\right) + \left(T_{,u1}/T_{,R2}\right)\left(V_{m,R2}\right) + \cdots + \left(T_{,u1}/T_{,RM}\right)\left(V_{m,RM}\right)\ \left(\frac{kT,u1}{q}\right)\ln\{\ [\ K_{u1}\ ][\ \prod_{i=1}^{M} K_{Ri}\ ]\ \} \tag{47}$$

And hence, generally, the case of when single pv cell out of the N-cell_{Ui} is modeled with all the M-$\text{cell}_{R,i}$ is then expressed as:

$$\left[V_{m,ui}\right] = \left[T_{,ui}\right]\left[V_{m,Ri}\right] + \left(\frac{kT,ui}{q}\right)\{\ [\ K_{ui}\ ][\ \prod_{i=1}^{M} K_{Ri}\ ]\ \} \tag{48}$$

Referring to eq(48), when, for example; i = 1 that means $\text{cell}_{Ui} = \text{cell}_{U1}$ and hence expressed by:

$$\left[V_{m,u1}\right] = \left[T_{,u1}\right]\left[V_{m,Ri}\right] + \left(\frac{kT,ui}{q}\right)\{\ [\ K_{ui1}][\ \prod_{i=1}^{M} K_{Ri}\ ]\ \} \tag{49}$$

Therefore, the general form of maximum voltage referring to any cell_{Ui} in terms of pv cells (cell_{Ri}) under any irradiance and thermal conditions is expressed by:

$$V_{m,u} = \frac{T_{,u}V_{m,R1}}{T_{,R1}} - \frac{T_{,u}V_{m,R2}}{T_{,R2}} - \frac{T_{,u}V_{m,R3}}{T_{,R3}} - \ldots\ldots - \frac{T_{,u}V_{m,RM}}{T_{,RM}} \cdots - \frac{T_{,u}V_{m,RN}}{T_{,RN}} = \left(kT_{,u}/q\right)\ln\{\ [K_u][\ \prod_{i=1}^{M} K_{Ri}\ ] \tag{50}$$

Different optical irradiance and thermal conditions means different K_U and K_R.

Consider the following pair of a single cell_U and a single cell_R , photovoltaically communicated with each other through this approach pv net model structure:

$$V_{m,u} = \frac{T_{,u}V_{m,R}}{T_{,R}} + (kT_{,u}/q)\ \ln\{\ \{\ [\ (\ I_{SC,u} + I_{0,u}\ )/I_{0u}][(kT_{,u}/q)/((kT_{,u}/q) + V_{oc,u}\ )]\ \{\ [\ I_{0,R}/(\ I_{SC,R} + I_{0,R}\ )\ ][\ ((kT_{,R}/q) + V_{oc,R}\ )/(kT_{,R}/q)\ ]\ \}\} \tag{51}$$

If cells (cell_U and cell_R) both are wide band gap pv cells , then, $V_{OC,u,R} >> kT_{,u,R}/q$ and also $I_{SC,u,R} >> I_{0,u,R}$ and as a result eq.(51) becomes:

$$V_{m,u} = \frac{T_{,u}V_{m,R}}{T_{,R}} + \left(kT_{,u}/q\right)\ln\{\ \{\ [\ I_{SC,u}\ /I_{0,u}][T_{,u}/V_{oc,u}\ )]\ \}\ \{\ [\ I_{0,R}/I_{SC,R}\ ][\ V_{oc,R}\ /T_{,R}\ ]\ \}\ \} \tag{52}$$

Further expanding eq.(52), yields:

$$V_{m,u} = \left\{\frac{T_{,u}V_{m,R}}{T_{,R}}\right\} + \left\{\left(kT_{,u}/q\right)\ln[\ I_{0,R}/I_{0,u}]\right\} + \left\{\left(kT_{,u}/q\right)\ln\{[\ I_{SC,u}/I_{SC,R}]\left[T_{,u}/T_{,R}\right]\left[V_{OC,R}/V_{OC,u}\right]\}\right\} \tag{53}$$

Substituting eq.(23), for the term $\left\{\left(kT_{,u}/q\right)\ln[\ I_{0,R}/I_{0,u}]\right\}$, into eq.(53):

$$V_{m,u} = \left\{\frac{T_{,u}V_{m,R}}{T_{,R}}\right\} + \left\{E_{g,u} - \{\ E_{g,R}(T_{,u}\ /T_{,R})\ \}\right\} + \left\{\left(kT_{,u}/q\right)\ln\{[\ I_{SC,u}/I_{SC,R}]\left[T_{,u}/T_{,R}\right]\left[V_{OC,R}/V_{OC,u}\right]\}\right\} \tag{54}$$

Therefore, eq.(54) is a relation of maximum voltages in terms of the band gap energies.

Referring to eqs.(24 through 27) at $T_{,u} = T_{,R}$, a derived equation of maximum voltage as a function of open circuit voltage concerning wide band gap pv cells (cell_{Ui} and cell_{Ri}) is obtained by substituting eqs.(24 through 27) into eq.(52), as follows:

$V_{oc,u} = (kT/q)\ln[\ I_{SC,u}\ /I_{0,u}]$, $-V_{oc,R} = (kT/q)\ln[\ I_{0,R}\ /\ I_{SC,R}\ ]$, $(kT/q)\ln[\ V_{oc,R}\ /V_{oc,u}\ ] = (kT/q)\ \{\ \ln\left(V_{oc,R}\right) - \ln\left(V_{oc,u}\right)\ \}$, therefore eq(52) becomes:

$$V_{m,u} - V_{m,R} = \left\{\left(\frac{kT_{,u}}{q}\right)\ln\left\{\frac{I_{SC,u}}{I_{0,u}}\right\}\right\} + \left\{\left(\frac{kT_{,u}}{q}\right)\ln\left\{\frac{I_{0,R}}{I_{SC,R}}\right\}\right\} + \left\{\left(\frac{kT_{,u}}{q}\right)\ln\left\{\frac{V_{OC,R}}{V_{OC,u}}\right\}\right\} \tag{55}$$

$$V_{m,u} - V_{m,R} = \left\{V_{oc,u} - V_{oc,R}\right\} + \left\{\left(\frac{kT_{,u}}{q}\right)\left\{\ln\left(V_{OC,R}\right) - \ln\left(V_{OC,u}\right)\right\}\right\} \tag{56}$$

Equating eq.(54) and eq.(56) according to the term $V_{m,u} - V_{m,R}$ and by assuming the last R.H.S of eq.(54) negligible (≈ 0) as the case is valid for wide band gap pv cells, therefore:

$$\left\{E_{g,u} - \{\ E_{g,R}(T_{,u}\ /T_{,R})\ \}\right\} = \left\{V_{oc,u} - V_{oc,R}\right\} + \left\{\left(\frac{kT_{,u}}{q}\right)\left\{\ln\left(V_{OC,R}\right) - \ln\left(V_{OC,u}\right)\right\}\right\} \tag{57}$$

And hence:

$$V_{oc,u} = V_{oc,R} + \left\{E_{g,u} - \{\ E_{g,R}(T_{,u}\ /T_{,R})\ \}\right\} + \left\{\left(\frac{kT_{,u}}{q}\right)\ln\left(V_{OC,R}/V_{OC,u}\right)\right\} \tag{58}$$

It is well examined that substituting $E_{g,R}$ for $V_{OC,R}$ and $E_{g,u}$ for $V_{OC,u}$, respectively, shows a very nearly same results obtained from eq.(58). Eq.(58) therefore can be written as:

$$V_{oc,u} = V_{oc,R} + \left\{E_{g,u} - \{\, E_{g,R}(T_{,u} /T_{,R})\, \}\right\} + \left\{\left(\frac{kT_{,u}}{q}\right) \ln\left(E_{g,R}/E_{g,u}\right)\right\} \qquad (59)$$

Eq.(59) is really an important useful equation of finding out, in inverse way, the short circuit current and hence the photon flux (N_{ph}), that is to say, Knowing only $E_{g,u}$ referring to cell_{Ui} and $E_{g,u}, E_{g,R}$, and $V_{OC,R}$ referred to cell_{Ri} , the open circuit voltage ($V_{OC,u}$) can be calculated as a result the light-generated current (the short circuit current) can easily also be calculated by substituting $V_{OC,u}$ into eq.(24) where the reverse saturation current easily is obtained from eq.(4). From this calculated light-generated current therefore the photon flux (N_{ph}) can also be easily calculated using eq.(3).

Achieving equal maximum voltages of different wide band gap pv cells by temperature variation

Regarding any pv cell parametric equation it is impossible, by direct substitution, to determine at which temperature does certain required maximum voltage is. Referring to the pv cell I-V characteristic equation shown below;

$$I = I_0\left(e^{(qV/kT)} - 1\right) - I_{SC} \qquad (60)$$

It is clear, from eq.(60), that it is difficult to find out what the temperature (T) is at certain required voltage (V) and vice verse. This is because the pv current (I) that satisfies the condition is also unknown. Even if current (I) is known, the reverse saturation current (I_0) is still a temperature dependent parameter as is clear from eq.(4).

Referring to eqs.(51, 52, and 23) for two certain pv cells of different wide band gap energy ($E_{g,u}$ and $E_{g,R}$), and since wide band gap energy pv cells makes possible to assume $V_{m,u} >> kT_{,u}/q$, and also $I_{SC,u} >> I_{0,u}$, therefore:

$$V_{m,u} = \left(T_{,u}/T_{,R}\right)\left(V_{m,R}\right) + \{(E_{g,u}) - [(T_{,u}/T_{,R})(E_{g,R})]\} + \left(KT_{,u}/q\right) \ln\{ [(V_{m,R} I_{0,R})/ (I_{SC,R} T_R)][(I_{SC,u} T_u)/(V_{m,u} I_{0,u})]\} \qquad (61)$$

And for the widest band gap energy pv cell ($E_{g,u}$) required to drop its maximum voltage to be equal the maximum voltage of the less-wider pv cell ($E_{g,R}$); that is to say: $V_{m,u} = V_{m,R} = V_{m,T}$, where $V_{m,T}$ is the maximum voltage referred to an equal voltages $V_{m,u}$ and $V_{m,R}$.

$$V_{m,T} = \left(T_{,u}/T_{,R}\right)\left(V_{m,T}\right) + \{(E_{g,u}) - [(T_{,u}/T_{,R})(E_{g,R})]\} + \left(KT_{,u}/q\right) \ln\left\{ [(V_{m,T})/ (V_{m,T})] \left[\left((I_{SC,u})/(I_{SC,R})\right)\right] [(T_{,u}/T_{,R})/(V_{m,u} I_{0,u})]\right\} \qquad (62)$$

The last R.H.S term of equation (62) above is very small so that it can be neglected and hence eq.(62) can be approximated to:

$$V_{m,T} = \left(T_{,u}/T_{,R}\right)\left(V_{m,T}\right) + \{(E_{g,u}) - [(T_{,u}/T_{,R})(E_{g,R})]\} \qquad (63)$$

$$E_{g,u} - V_{m,T} = \left(T_{,u}/T_{,R}\right)\{E_{g,R} - V_{m,T}\} \qquad (64)$$

Therefore, an excellent approximate equation defining the temperature required to make certain wider band gap pv cells maximum voltages equal is given by:

$$T_{,u} = T_{,R}\{(E_{g,u} - V_{m,T})/(E_{g,R} - V_{m,T})\} \qquad (65)$$

Formulation of Maximum Current (I_m)

In general, the maximum current (I_m) of pv cell is expressed by:

$$I_m = \frac{\left(\frac{qV_m}{kT}\right)}{\left(\frac{qV_m}{kT}\right)+1}[\, I_{SC} + I_0\,] \qquad (66)$$

As a general relation, the maximum current of any cell_{Ui} can be written as:

$$I_{m,ui} = \frac{\left(\frac{qV_{m,ui}}{KT_{,ui}}\right)}{\left(\frac{qV_{m,ui}}{KT_{,ui}}\right)+1}\left(I_{SC,ui} + I_{0,i}\right) \qquad (67)$$

Where $V_{m,ui}$ is the unknown maximum voltage obtained referring to this approach analysis equations, eq.(48).

Formulation of maximum power (P_m)

Simply, the maximum power referring to this work approach is expressed as:

$$P_{m,u} = I_{m,u}\, V_{m,u} = \left[\frac{\left(\frac{qV_{m,u}}{kT}\right)}{\left(\frac{qV_{m,u}}{kT}\right)+1}[\, I_{SC,u} + I_{0,u}\,]\right]\left[\left(kT_{,u}/q\right)\ln\{\,[K_u][\,\prod_{i=1}^{M}[\,K_{Ri}\;]\}\right] \qquad (68)$$

As is the case concerned with wide band gap energy pv cells where $\left(\frac{qV_{m,u}}{kT_{,u}}\right) >> 1$ that leads automatically into $I_{SC,u} >> I_{0,u}$, and hence eq.(68) becomes:

$$P_{m,u} \approx [\, I_{SC,u}]\left[\left(kT_{,u}/q\right)\ln\{\,[K_u][\,\prod_{i=1}^{M}[\,K_{Ri}\;]\}\right] \qquad (69)$$

Eq.(68) is a straight forward direct-substitution equation. With given data of K_u and K_R , the maximum power can directly be determined.

Results and discussions

Referring to the given data (the incident sunlight power versus photon wavelengths) of air mass (AM1.5) sunlight spectrum radiation [2, 15], given in Table (1); Table (1) is completed by the conventional way of computations such that to include also all the electrical output parameters referring to a wide pv cell spectrum at working temperature and sunlight irradiance concentration ratio of 300 K, 1 sun, respectively as given by Table (2). The aim is to compare between electric parameters obtained conventionally in Table (2) and those referring to this approach formulation method. The conventional way of determining the electrical parameters, step by step is ordered as shown in Figure (1) as well as eqs.(1 - 10).

Generally, a very excellent matched results of electrical parameters obtained referring to this work approach (V_{mu} , $I_{m,u}$, and $P_{m,u}$) as compared to conventional electrical parameters (V_m , I_m , and P_m) given in Table (2) referring to conventional eqs.(1 - 10).

Both, Table (3) and Figure (3) illustrate the case where several unknown electrical parameters pv cells ($cell_{Ui}$) ranging from 0.4887 ev to 3.815 ev each, utilizing either of the reference cells ($cell_{Ri}$): 0.4887 ev, 0.5838 ev, and 0.9288 ev both at same temperature $T_{,u} = T_{,R} = 300$ K and same concentration ratio $cr_u = cr_R = 1$ sun. As an example, $cell_U$ of $E_{gu} = 1.2588$ ev is used to communicate with cells ($cell_{Ri}$) of $E_{gR} = 0.4887$ ev, 0.5838 ev, and 0.9288 ev leads to an excellent approximate results of maximum power (P_{mu}) of 20.5497 mW, 20.5967 mW, 20.4850 mW as compared with exact values obtained by the conventional way that results into maximum power (P_m) of 20.4456 mW, as an average of $P_m / P_{mu} \times 100\ \% \approx 100\ \%$ is obtained. The pv-net model referring to this case is shown in figure (4).

Table (4), Figure (5), and Figure (6) both are deal with the case of the two pv cell groups ($cell_{Ui}$ and $cell_{Ri}$) both operating under an equal concentration ratios of 1 sun but different temperature of $T_{,u} = 400$ K while $T_{,R} = 300$ K, respectively. Starting from $cell_U = 0.6342$ ev and ending to $cell_U = 3.815$ ev, the maximum power percentage ratios ($P_{m,u}/P_m$) × 100 % obtained are: 78%, 92.04 %, 92.5 %, 99.45 %, 99.485 %, 99.56 %, 99.6 %, 99.7015 %, 99.757 %, 99.7966 %, respectively.

Again Referring to Table (4) for $cell_R$ of 0.4887 ev sharing several reference pv cells; $cell_{Ui}$ = [0.6342 ev up to 3.815 ev], for the pair [$cell_U = 0.6342$, $cell_R = 0.4887$ ev], the electrical parameter percentage ratios of: $V_m = 87.25\%$ of $V_{m,u}$, $I_m = 90.3\%$ of $I_{m,u}$, and $P_m = 78.9\%$ of $P_{m,u}$ are obtained. On the other hand, when this narrow band gap pv cell of 0.6342 ev is replaced by a wide band gap pv cell ($cell_u = 3.815$ ev) such that the considered pair becomes [$cell_U = 3.815$ ev, $cell_R = 0.4887$ ev], the related electrical parameter percentage ratios are of: $V_m = 99.8\%$ of $V_{m,u}$, $I_m = 99.998\%$ of $I_{m,u}$, and $P_m = 99.8\%$ of $P_{m,u}$. In general, temperature increase affects both electrical parameters V_m , I_m , P_m , or, $V_{m,u}$, $I_{m,u}$, $P_{m,u}$. Comparing Tables (3 and 4) in terms of temperature variation, first when $cell_U = 0.9288$ ev that results into $I_m = 40.689$ mA, $V_m = 0.375$ v, and $P_m = 15.275$ mW at 300 K, while when temperature raised to 400 K, this results into $I_m = 37.477$ mA , $V_m = 0.2144$ v, and $P_m = 8.037$ mW . This drop in electrical parameter values at high temperature is mainly because of the increased value of the electrical parameter " I_0 " with temperature increase, especially when considering narrow band gap pv cells that results into a drop in V_{OC} and V_m because of the smaller temperature dependent ratio $(qV_m/kT)/(qV_m/kT + 1)$ that results into a drop in $I_{m,u}$ and $P_{m,u}$ also; second, wider band gap pv cells are less affected by temperature increase, as an example consider $cell_U$ = 3.815 ev at T = 300 K, 400 K, results into electrical parameter values of: I_{mu} = 0.0201 mA , V_{mu} = 3.014 v, P_{mu} = 0.06 mW, and I_{mu} = 0.02006 mA , V_{mu} = 2.759 v, P_{mu} = 0.0553 mW, respectively. In short, referring to Table (4), starting from $cell_{Ui}$ of 0.6342 ev and ending to $cell_{Ui}$ of band gap 3.815 ev the maximum power percentage ratio P_m / $P_{m,u}$ × 100% is growing such as: 78%, 92.04%, 92.5%, 99.45%, 99.485%, 99.56%, 99.6%, 99.7015%, 99.757%, and 99.8%, respectively.

The case that deal with the determination of electrical parameters with keeping unchanged the temperature of both pv cells ($cell_{Ui}$ and $cell_{Ri}$) at 300 K, on the other hand, raising the concentration ratio of $cell_{Ui}$ from 1 sun to 100 suns and keeping unchanged that of $cell_{Ri}$ (i.e, at 1 sun) is shown in Table (5), Figure (7). Pv cells ($cell_{Ui}$): 0.4887 ev, 0.5838 ev, 1.81 ev, and 3.22 ev utilized with pv cells ($cell_{Ri}$) of: 0.4887 ev, 0.5838 ev, and 3.22 ev show ($P_{m,u}/P_m$) × 100 % of 98.49 %, 99.875 %, 99.663 %; and, 98.892 %, 99.504 %, 99.546 %, and 99.743 %; and, 91.705 %, 96.762 %, 99.945 %, 99.9985 %, respectively. In general, concentrating sunlight increases both electrical parameters.

The case concerned with varying both the temperature and the concentration ratio is illustrated by Figure (8) and Table (6). As a whole result average, about 99.9 % referring to ($V_{m,u}/V_m$) ×,100 %, ($I_{m,u}/I_m$) × 100 %, and ($P_{m,u}/P_m$) × 100 % are obtained.

More than one $cell_R$ when referred by (or photovoltaically net-communicated) with $cell_U$ also show the good results the pair [$cell_U$, $cell_R$] shows. This is illustrated in Table (7) and Figure (9) under T = 300 K and cr = 1 sun. From Table (7), it is clear that utilizing $cell_{Ui}$ as wider band gap pv cell as possible as better are growing the results obtained.

Table (8) shows the variations of electrical parameter constants, K_U and K_R , of several band gap energy pv cells at T = 300 K and cr = 1 sun. As the band gap difference ($E_{g,R}$ - $E_{g,u}$) increases positively as the term kT/q ln { [K_U][K_R] } increases negatively. This term becomes zero only when [K_U] = [K_R], provided that both considered pv cells ($cell_U$, $cell_R$) are operating under an identical irradiance and thermal conditions. Figure (10) shows the variations of V_{mu} with kT/q ln { K_U K_R } for several pv cells when $cell_R$ = 3.815 ev, $V_{m,R}$ = 3.0088 v, at T_U = T_R = 300 K, cr_R = cr_u = 1 sun. It is obvious that this term kT/q ln { K_U K_R } decreases negatively until zero where $cell_U$ = $cell_R$ = 3.815 ev and the band gap difference ($E_{g,R}$ - $E_{g,u}$) = 0.

Table (9) shows the calculated temperature concerning two different wide band gap pv cells such that their maximum voltages equal. An excellent average percentage ratio (checked exact $T_{,u}$ / approach approximate $T_{,u}$) of about 99.5%, (see eq. 65). Even the narrower band gap pv cells such as the pairs [0.53448 ev, 0.4887 ev] and [0.7626 ev, 0.5838 ev] give a comparable percentage results of 99.64%, 99.42%, respectively. Figure (11) shows the comparison between the approach and the conventional maximum current calculations at temperature 300 K and 400 K where $cell_R$ of 0.4887 ev is used as a reference cell at cr_R = 1 sun, $T_{,R}$ = 300K. It is obvious how the approach results are very nearly coincide with the conventional results as all curves show and tables illustrate. Figure (12) shows the comparison between the approach and the conventional maximum voltage calculations for several $cell_{Ui}$ at T_{ui} = 300 K, 400 K and cr_u = 1 sun, 100 suns where for all cases the reference cell is, $cell_R$ = 0.4887 ev at $T_{,R}$ = 300 K, and cr_R = 1 sun. Figure (13) shows the variations of the maximum voltages for several pv cells under different T and cr using cells (0.4887 ev, 1.81 ev, and 3.815 ev) each as a reference cell for each case. Figure (14) shows the comparison between the maximum voltages of conventional method, and approach method for several pv cells both at T =300 K, cr = 1 sun (i) $cell_R$ = 0.4887 ev, (ii) $cell_R$ = 0.5838 ev, (iii) $cell_R$ = 0. 9288 ev, and (iv) $cell_R$ = 3.815 ev. Figure (15) shows the comparison between the maximum power of the conventional method and the approach method for several pv cells, both at T = 300 K, cr = 1 sun for the following reference cells: (i) $cell_R$ = 0.4887 ev, (ii) $cell_R$ = 0.5838 ev, (iii) $cell_R$ = 0. 9288 ev, and (iv) $cell_R$ = 3.815 ev. Table (10) illustrates the calculated values of $V_{OC,u}$, $I_{SC,u}$, $\int N_{ph,u}(E)dE$ with only $cell_{Ui}$ parameter known is the band gap $E_{g,u}$, using eq.(59).

Table (1): Air mass (AM1.5) sunlight radiation, sunlight incident power (P_{in}) versus wavelength [2].

λ, (μm)	W/m^2. μm	λ, (μm)	W/m^2. μm	λ, (μm)	W/m^2. μm	λ, (μm)	W/m^2. μm	λ, (μm)	W/m^2. μm
.295	0	.595	1262.6	.870	843.02	1.276	344.11	2.388	31.93
.305	1.32	.605	1261.8	.875	835.10	1.288	345.69	2.415	28.10
.315	20.96	.615	1255.4	.8875	817.12	1.314	284.24	2.453	24.96
.325	113.48	.625	1240.2	.900	807.83	1.335	175.28	2.494	15.82
.335	182.23	.635	1243.8	.9075	793.87	1.384	2.42	2.537	2.590
.345	234.43	.645	1233.9	.915	778.97	1.432	30.06		
.355	286.01	.655	1188.3	.925	217.12	1.457	67.14		
.365	355.88	.665	1228.4	.930	163.72	1.472	59.89		
.375	386.8	.675	1210.1	.940	249.12	1.542	240.85		
.385	381.78	.685	1200.7	.950	231.30	1.572	266.14		
.395	492.18	.695	1181.2	.955	255.61	1.599	220.46		
.405	751.72	.6983	973.53	.965	279.69	1.608	211.76		
.415	822.45	.700	1173.3	.975	529.64	1.626	211.26		
.425	842.26	.710	1152.7	.985	496.64	1.644	201.85		
.435	890.55	.720	1133.8	1.018	585.03	1.650	199.68		
.445	1077.1	.7277	974.30	1.082	486.20	1.676	180.50		
.455	1162.4	.730	1110.9	1.094	448.74	1.732	161.59		
.465	1180.6	.740	1086.4	1.098	486.72	1.782	136.65		
.475	1212.7	.750	1070.4	1.101	500.57	1.862	2.01		
.485	1180.4	.7621	733.08	1.128	100.86	1.955	39.43		
.495	1253.8	.770	1036.0	1.131	116.87	2.008	72.58		
.505	1242.2	.780	1018.4	1.137	108.68	2.014	80.01		
.515	1211.0	.790	1003.5	1.144	155.44	2.057	72.57		
.525	1244.8	.800	988.11	1.147	139.19	2.124	70.29		
.535	1299.5	.8059	860.28	1.178	374.29	2.156	64.76		
.545	1275.5	.825	932.74	1.189	383.37	2.201	68.29		
.555	1276.1	.830	923.87	1.193	424.85	2.266	62.52		
.565	1277.7	.835	914.96	1.222	382.57	2.320	57.03		
.575	1292.5	.8465	407.11	1.236	383.81	2.338	53.57		
.585	1248.5	.860	857.56	1.264	323.88	2.356	50.01		

Table (2): Calculated electrical parameter of pv cells their band gap energy ranged within (0.4887 ev to 4.275 ev), under AM1.5, T = 300 K, cr = 1 sun, assuming pv cell area (A) = 1cm^2.

PV Cells (ev)	$\int N_{ph}$ dE × 10^{15} cm^{-2}s^{-1}	I_{SC} (mA)	V_{OC} (v)	I_m (mA)	V_m (v)	P_m (mW)	I_0 (mA)	η × 100%	FF	VF
0.48870	363.127	58.173	0.02431	32.6917	0.013468	0.4403	37.2754	0.4403	0.1897	0.0497
0.53448	355.527	56.955	0.05947	37.1160	0.036648	1.3602	6.34508	1.3602	0.3613	0.1112
0.58380	341.394	54.691	0.10545	41.6785	0.071242	2.9692	0.94186	2.9692	0.4956	0.1806
0.63420	329.558	52.795	0.15456	42.9593	0.111404	4.7737	0.13409	4.7737	0.5849	0.2437
0.69580	322.612	51.682	0.21555	44.6547	0.164005	7.3218	0.01237	7.3218	0.6572	0.3097
0.76260	299.582	48.000	0.28040	42.9920	0.221997	9.5443	9.3×10^{-4}	9.5443	0.7090	0.3677
0.82420	276.607	44.312	0.33997	40.5215	0.276400	11.200	8.6×10^{-5}	11.200	0.7434	0.4124
0.92880	271.488	43.492	0.44408	40.6573	0.373325	15.185	1.5×10^{-6}	15.185	0.7862	0.4781
1.01470	248.095	39.744	0.52765	37.5946	0.452231	17.001	5.4×10^{-8}	17.001	0.8107	0.5200
1.12620	226.962	36.359	0.63685	34.7443	0.556336	19.329	7.3×10^{-10}	19.329	0.8347	0.5654
1.25880	194.826	31.210	0.76550	30.0668	0.680008	20.445	4.3×10^{-12}	20.445	0.8557	0.6081
1.37770	178.118	28.530	0.88158	27.6289	0.792755	21.902	4.3×10^{-14}	21.902	0.8708	0.6398
1.50300	151.650	24.294	1.00323	23.6231	0.910420	21.507	3.1×10^{-16}	21.507	0.8824	0.6674
1.65330	123.549	19.792	1.14823	19.3177	1.051793	20.318	1.0×10^{-18}	20.318	0.8940	0.6945
1.74600	107.469	17.216	1.23732	16.8344	1.138879	19.172	2.8×10^{-20}	19.172	0.9000	0.7086
1.81000	97.3042	15.588	1.29875	15.2589	1.199008	18.295	2.4×10^{-21}	18.295	0.9037	0.7175
1.86460	89.0561	14.266	1.35106	13.0776	1.250258	17.475	2.9×10^{-22}	17.475	0.9066	0.7245
1.98400	73.1292	11.715	1.46537	11.4971	1.362387	15.663	2.8×10^{-24}	15.663	0.9124	0.7385
2.19470	50.2980	8.0577	1.66639	7.92632	1.559970	12.364	8.2×10^{-28}	12.364	0.9208	0.7592
2.40700	33.0421	5.2933	1.86783	5.21663	1.758358	9.1727	2.2×10^{-31}	9.1727	0.9277	0.776
2.66000	18.0151	2.8860	2.10515	2.84903	1.992489	5.6766	1.2×10^{-35}	5.6766	0.9343	0.7914
2.91760	8.70000	1.3937	2.34393	1.37775	2.228410	3.0702	5.9×10^{-40}	3.0702	0.9398	0.8033
3.22000	3.19907	0.5125	2.62046	0.50725	2.501982	1.2691	4.9×10^{-45}	1.2691	0.9450	0.8138
3.49300	1.18871	0.9104	2.86786	0.18865	2.746993	0.5182	1.2×10^{-49}	0.5182	0.9489	0.8210
3.81500	0.12681	0.02031	3.13200	0.02014	3.008800	0.0606	5.0×10^{-55}	0.0606	0.9524	0.821
4.27500	0	0	0	0	0	0	0	0	0	0

Table (3): Comparison between electrical parameters: (i) approach, cell$_{Ui}$ = [0.4887 ev up to 3.815 ev], cell$_{Ri}$ = [0.4887 ev, 0.5838 ev, and 0.9288 ev], cr$_{Ri}$ = cr$_{ui}$ = 1 sun and T$_{,u}$ = T$_{,R}$ = 300 K (ii) conventional, T=300 K, cr = 1 sun.

CELL$_R$ (eV)	CELL$_U$ (eV)	$V_{m,u}$, (v)	V_m , (v)	$I_{m,u}$ (mA)	I_m , (mA)	$P_{m,u}$ (mW)	P_m (mW)
0.4887	0.4887	0.0134685	0.0134685	32.69172	32.69172	0.44030	0.4403
	0.5838	0.0697335	0.0712420	40.58552	41.67855	2.83017	2.9692
	0.9288	0.3754015	0.3733255	40.68988	40.67531	15.2750	15.185
	1.2588	0.6833470	0.6800082	30.07220	30.06681	20.5497	20.445
	1.5030	0.9166543	0.9104275	23.62757	23.62313	21.6583	21.507
	1.8100	1.2032799	1.1990085	15.26010	15.25896	18.3621	18.295
	2.1947	1.5645860	1.5599700	7.926710	7.926329	12.4020	12.364
	2.6600	1.9973780	1.9924891	2.849120	2.849030	5.69077	5.6766
	3.2200	2.5070937	2.5019826	0.506773	0.507258	1.27052	1.2691
	3.4930	2.7521861	2.7469930	0.188657	0.188654	0.51922	0.5182
	3.8150	3.0140668	3.0088006	0.020142	0.020142	0.06071	0.0606
0.5838	0.4887	0.0149769	0.0134685	35.01015	32.69172	0.52434	0.4403
	0.5838	0.0712420	0.0712420	41.67855	41.67855	2.96926	2.9692
	0.9288	0.3770871	0.3733255	40.70161	40.67531	15.3480	15.185
	1.2588	0.6848560	0.6800082	30.07461	30.06681	20.5967	20.445
	1.5030	0.9181628	0.9104275	23.62863	23.62313	21.6949	21.507
	1.8100	1.2047883	1.1990085	15.26050	15.25896	18.3856	18.295
	2.6600	1.9987077	1.9924891	2.849144	2.849030	5.69460	5.6766
	3.2200	2.5028224	2.5019826	0.506765	0.507258	1.26834	1.2691
	3.4930	2.7536948	2.7469930	0.188658	0.188654	0.51950	0.5182
	3.8150	3.0155756	3.0088006	0.020142	0.020142	0.06074	0.0606
0.9288	0.4887	0.0113924	0.0134685	29.19378	37.11609	0.332587	0.4403
	0.5838	0.0676574	0.071242	40.25145	41.67855	2.723311	2.9692
	0.9288	0.3733255	0.3733255	40.67531	40.67531	15.18513	15.185
	1.2588	0.6812715	0.6800082	30.06886	30.06681	20.48505	20.445
	1.5030	0.9145782	0.9104275	23.62609	23.62313	21.60791	21.507
	1.8100	1.2012038	1.1990085	15.25955	15.25896	18.32983	18.295
	2.1947	1.5625099	1.5599700	7.926539	7.926395	12.38529	12.364
	2.6600	1.9953023	1.9924891	2.849082	2.849030	5.684780	5.6766
	3.2200	2.5050194	2.5019826	0.507264	0.507258	1.270707	1.2691
	3.4930	2.7501103	2.7469930	0.188656	0.188654	0.518825	0.5182
	3.8150	3.0119910	3.0088006	0.020142	0.020142	0.060668	0.0606

Table (4): Comparison between electrical parameters: (i) approach, $cell_{Ui}$ = [0.6342 ev up to 3.815 ev], $cell_{Ri}$ = 0.4887 ev, $cr_u = cr_R$ = 1 sun, and $T_{,u}$ = 400 K, $T_{,R}$ = 300 K, (ii) conventional, T = 400 K, cr = 1 sun.

$CELL_R$ (eV)	$CELL_U$ (eV)	$V_{m,u}$, (v)	V_m , (v)	$I_{m,u}$ (mA)	I_m, (mA)	$P_{m,u}$, (mW)	P_m (mW)
0.4887	0.6342	0.0131122	0.01144	31.55653	28.5345	0.413777	0.32643
	0.6958	0.0347612	0.03675	31.13652	31.9988	1.082344	1.17595
	0.9288	0.2144199	0.21445	37.47725	37.4779	8.035870	8.03715
	1.2588	0.5089647	0.50632	29.22966	29.2200	14.79491	14.8768
	1.5030	0.7336397	0.73002	23.20338	23.1982	17.02292	16.9351
	1.8100	1.0153607	1.01100	15.07690	15.0738	15.30758	15.2396
	2.1947	1.3679386	1.36305	7.859577	7.85888	10.75141	10.7120
	2.6600	1.7892424	1.78400	2.831431	2.83127	5.066118	5.05099
	3.2200	2.2817590	2.27630	0.504870	0.50485	1.151992	1.14919
	3.8150	2.7592394	2.75370	0.020064	0.02006	0.055363	0.05525

Table (5): Comparison between electrical parameters: (i) approach, $cell_{Ui}$ = [0.4887 ev, 0.5838 ev, 1.81 ev, and 3.22 ev], $cell_{Ri}$ = [0.4887 ev, 0.5838 ev , and 3.22 ev], cr_u = 100 suns, cr_R = 1 sun, and $T_{,ui} = T_{,Ri}$ = 300 K. (ii) conventional, T = 300 K, cr = 100 suns.

$CELL_R$, (ev)	$CELL_U$, (ev)	$V_{m,u}$, (v)	V_m ,(v)	$I_{m,u}$ (mA)	I_m (mA)	$P_{m,u}$ (mW)	P_m (mW)
0.4887	0.4887	0.090465	0.09160	4553.26	4565.832	411.913	418.2302
	0.5838	0.171720	0.17153	4754.26	4753.572	816.405	815.38034
	1.8100	1.320120	1.31575	1528.85	1528.759	2018.27	2011.4652
	3.2200	2.600000	2.61990	50.7501	50.74917	131.950	132.95774
0.5838	0.4887	0.091974	0.09160	4569.92	4565.832	420.314	418.23020
	0.5838	0.173228	0.17153	4759.68	4753.572	824.514	815.38034
	1.8100	1.321631	1.31573	1528.86	1528.758	2020.60	2011.4340
	3.2200	2.626533	2.61987	507.504	507.4916	1332.97	1329.5626
3.22	0.4887	0.085354	0.09160	4493.45	4565.83	383.536	418.2302
	0.5838	0.166609	0.17152	4734.44	4752.78	788.803	815.1963
	1.8100	1.315009	1.31572	1528.74	1528.75	2010.31	2011.418
	3.2200	2.619910	2.61987	50.7491	50.7491	132.958	132.9562

Table (6): Comparison between electrical parameters regarding (i) approach (ii) conventional way, for several randomly selected pv cells, temperature, and irradiance concentration ratio.

$CELL_R$ (ev)	$CELL_U$ (ev)	$V_{m,u}$, (v)	V_m , (v)	$I_{m,u}$ (mA)	I_m (mA)	$P_{m,u}$ (mW)	P_m (mW)
0.4887 ev T=300 K cr= 100 suns	0.4887ev T = 400 K cr=1suns	0.0183117	0.0165	3475.8229	3243.230	63.64824	53.51331
	0.5838 ev T = 300 K cr=200 suns	0.1889838	0.18744	9622.73797	9613.209	1818.542	1801.899
	1.81 ev T = 400 K cr=300 suns	1.2081066	1.2018	4546.620	4545.964	5492.809	5463.34
	3.22 ev T = 500 K cr=1 sun	2.0404550	2.0535	0.50190051	0.5019664	1.024105	1.030788
1.81 ev T=400 K cr=300 suns	0.5838ev T = 300 K cr=200 suns	0.1841802	0.18744	9592.62918	9613.2555	1766.772	1802.004
	1.81 ev T = 300 K cr=1 sun	1.1996103	1.1990085	15.2591248	15.258963	18.30500	18.29562
	2.66 ev T = 400 K cr= 300 suns	1.9777630	1.9772	850.963258	850.95910	1683.003	1682.516
	3.22 ev T = 500 K cr=500 suns	2.3174319	2.3161	251.572112	251.56947	583.0012	582.6600
3.815ev T=300 K cr = 1 sun	0.5838ev T = 300 K cr= 200 suns	0.1825832	0.18744	3.55909235	3.570568	0.649830	0.669267
	1.81 ev T = 300 K cr=1 sun	1.1980133	1.199	15.2586957	15.258961	18.28012	18.29550
	3.22 ev T = 500 K cr = 500 suns	2.3147418	2.3161	251.56677	251.56947	582.3121	582.6605
	2.66 ev T = 400 K cr = 300 suns	1.9758889	1.9772	850.9494	850.959	1681.381	1682.516

Table (7): Comparison between electrical parameters (i) approach, for five cells used as a reference cells at $T_{,ui} = T_{,Ri} = 300$ K and $cr_{Ui} = cr_{Ri} = 1$ sun, (ii) conventional.

$CELL_{Ri}$, ev	$CELL_U$, ev	V_{mu} , v	V_m , v	I_{mu} , mA	I_m , mA	P_{mu} , mW	P_m , mW
[0.9288 , 1.503 , 1.81 , 2.1947 , 3.815]	0.4887	0.01856	0.01346	39.8965	32.6917	0.74082	0.4403
[0.4887 , 1.503 , 1.81 , 2.1947 , 3.815]	0.9288	0.38257	0.37332	40.7391	40.6753	15.5858	15.185
[0.4887 , 0.9288 , 1.81 , 2.1947 , 3.815]	1.503	0.92323	0.91042	23.6321	23.6231	21.8179	21.507
[0.4887 , 0.9288 , 1.503 , 2.1947 , 3.815]	1.81	1.21265	1.19900	15.2625	15.2589	18.5081	18.295
[0.4887 , 0.9288 , 1.503 , 1.81 , 3.815]	2.1947	1.57430	1.55997	7.927510	7.92632	12.4803	12.364
[0.4887 , 0.9288 , 1.503 , 1.81 , 2.1947]	3.815	3.02443	3.00880	0.02014	0.02014	0.06092	0.0606

Table (8): Variations of electrical parameter constants, K_U and K_R, of several pv cells band gap energy at T = 300 K and cr = 1 sun.

A system of pv cells, (ev)	K_U	K_R
0.4887	1.319738831	0.757725677
0.9288	1584991.487	6.30918×10^{-7}
1.5030	1.7855×10^{15}	5.6004×10^{-16}
1.8100	1.2771×10^{20}	7.8300×10^{-21}
2.1947	1.4970×10^{26}	6.6796×10^{-27}
3.8150	3.3325×10^{50}	3.0007×10^{-51}

Table (9): Calculated temperature concerning a pair of different wide band gap pv cells such that their maximum voltage equal.

[$CELL_U$, $CELL_R$] (ev)	$v_{m,u}$ (v)	$v_{m,R}$, (v)	T_R , (K)	T_u(K), Approx. equation	T_u(K), checked exact equation
[2.1947, 1.81]	1.1990085	1.1990085	300	488.88969	484.969
[0.7626, 0.5838]	0.0712420	0.0712420	300	404.65157	407.01
[1.8646, 1.1262]	0.5563366	0.5563366	300	688.72400	683.5
[3.220, 2.660]	1.9924891	1.9924891	300	578.64713	575.12
[0.53448, 0.4887]	0.0134685	0.0134685	300	328.88960	330.0615

Table (10): Calculations of $V_{OC,u}$, $I_{SC,u}$, $\int N_{ph,u}(E)dE$ with only known parameter is the band gap $E_{g,u}$, at $T_{,u} = T_{,R}$, $cr_u = cr_R$, using eq.(59).

$CELL_U$, (ev) $CELL_R$, (ev)	$V_{OC,u}$, (v)	$I_{SC,u}$, (mA)	$\int N_{ph,u}$ $\times 10^{15}$, ($cm^{-2}s^{-1}$)
1.7780 1.7460	1.2688	16.907	105.53
2.5335 2.6600	1.9799	3.0304	18.916
3.6540 3.8150	2.9721	0.0212	0.1323
0.7934 0.8242	0.3101	46.032	287.34
1.5781 1.5030	1.0771	23.138	144.43
0.9717 1.0147	0.4858	41.501	259.05

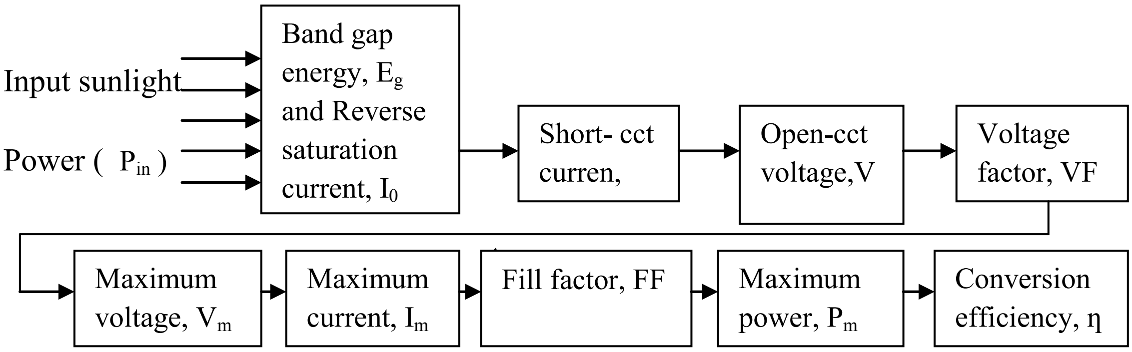

Figure (1): Calculations of electrical parameters of pv cell according to their priority, starting from the input sunlight power (P_{in}) and ending to the conversion efficiency (η)

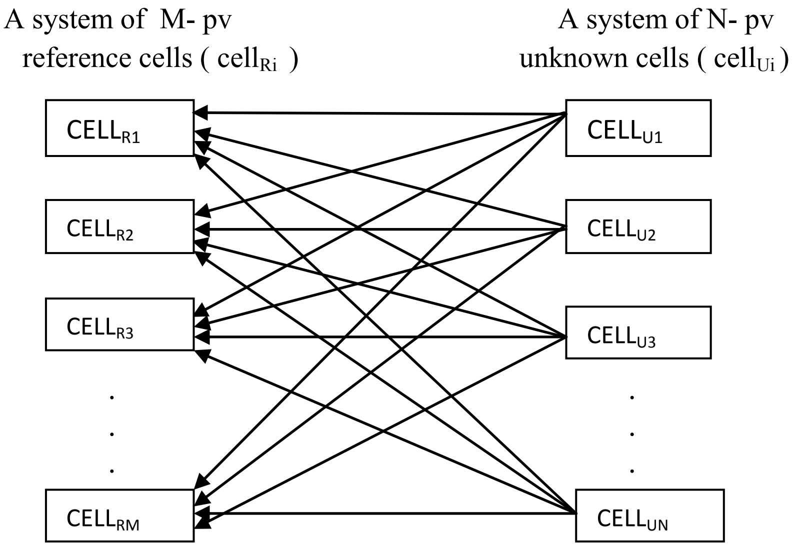

Figure (2): The approach general pv cells net- structure of both groups (N-$cell_{Ui}$ and M $cell_{Ri}$)

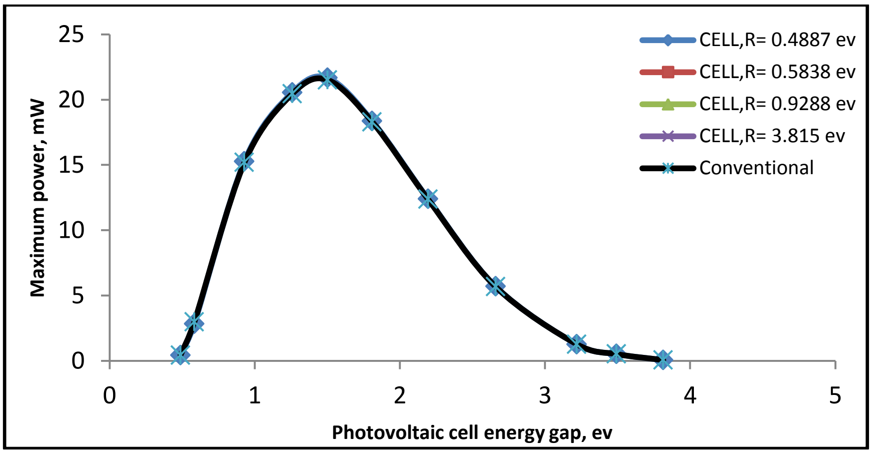

Figure (3): Comparison between maximum power variation for several pv cells (i) approach, $T_{,ui} = T_{,Ri} = 300$ K, $cr_u = cr_R = 1$ sun, $cr_u = 1$ suns, (ii) conventional, T = 300 K, cr = 1 sun.

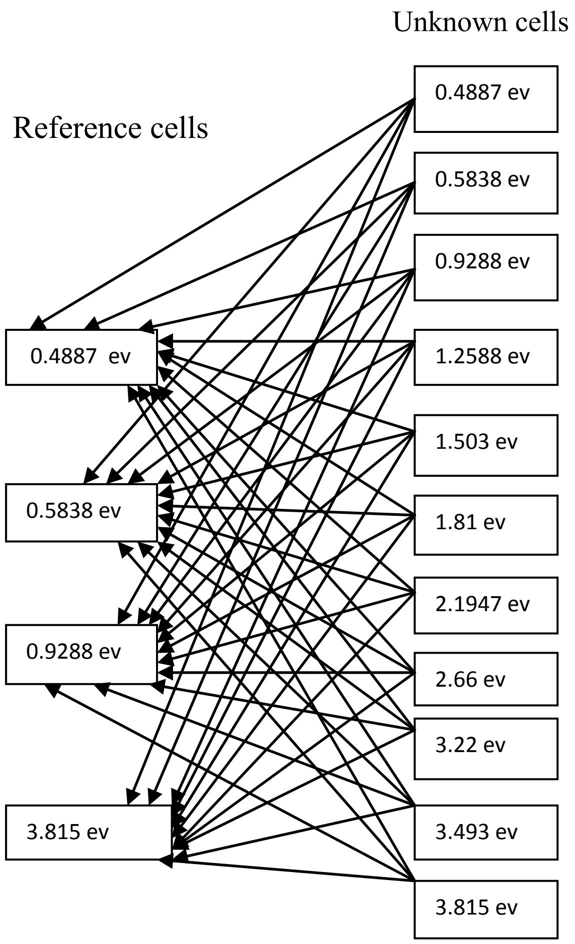

Figure (4): Cell$_{Ui}$ and Cell$_{Ri}$ net- structure, $T_{,ui} = T_{,Ri} = 300$ K, $cr_u = cr_R = 1$ sun.

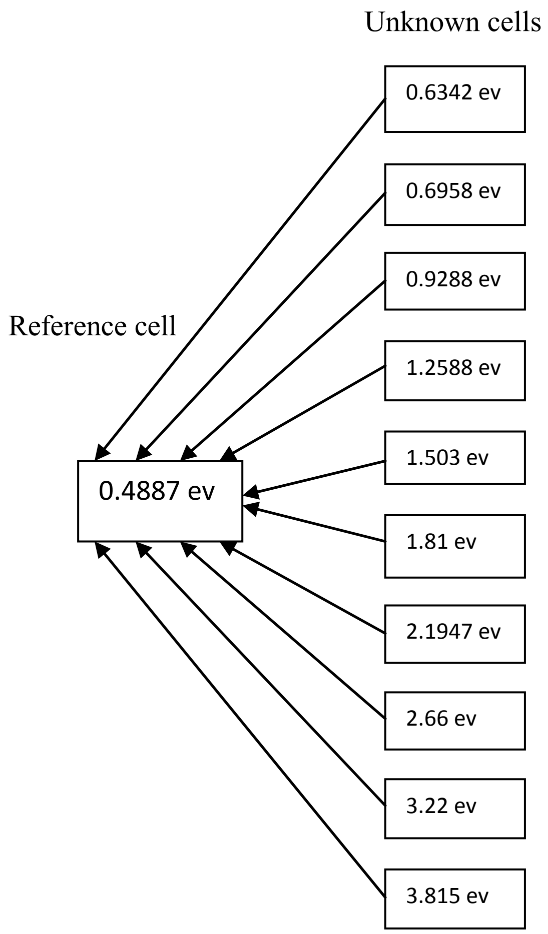

Figure (5): Cell$_{Ui}$ and Cell$_{Ri}$ net-structur, $T_{,ui} = 400$ K, $T_{,Ri} = 300$ K, $cr_u = cr_R = 1$ sun

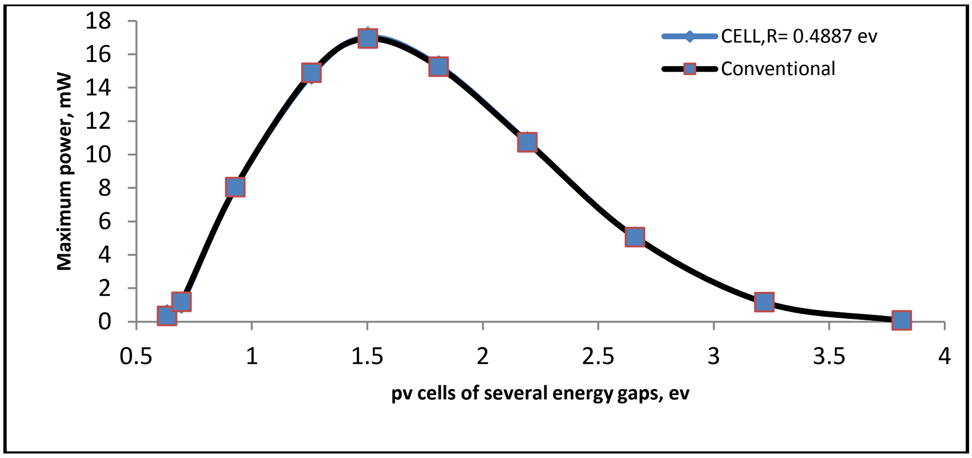

Figure (6): Comparison between maximum power variation for several pv cells (i) approach, cell$_{Ri}$ = 0.4887 ev, $T_{,u} = 400$ K, $T_{,R} = 300$ K, $cr_u = cr_R = 1$ sun, (ii) conventional, T=400 K, cr = 1 sun.

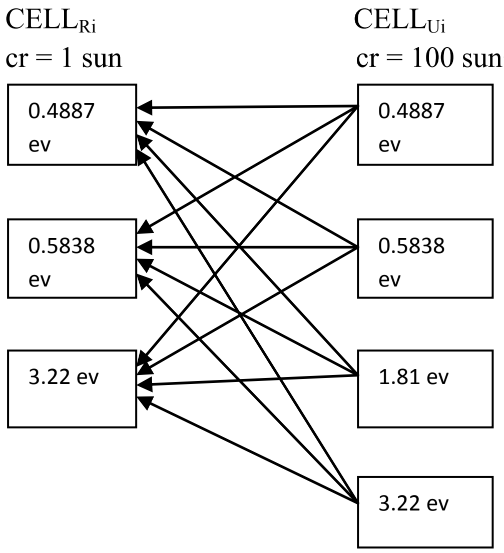

Figure (7): Cell$_{Ui}$ and Cell$_{Ri}$ net- structure, cr$_u$ = 100 suns, cr$_R$ = 1 sun, T,$_{ui}$ = T,$_{Ri}$ = 300 K.

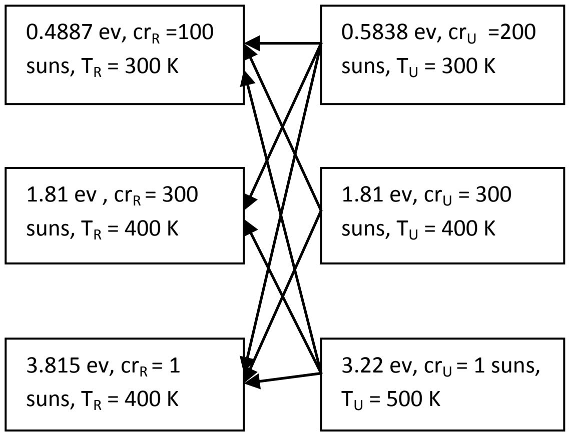

Figure (8): Cell$_{Ui}$ and Cell$_{Ri}$ net-structure for different cr and T.

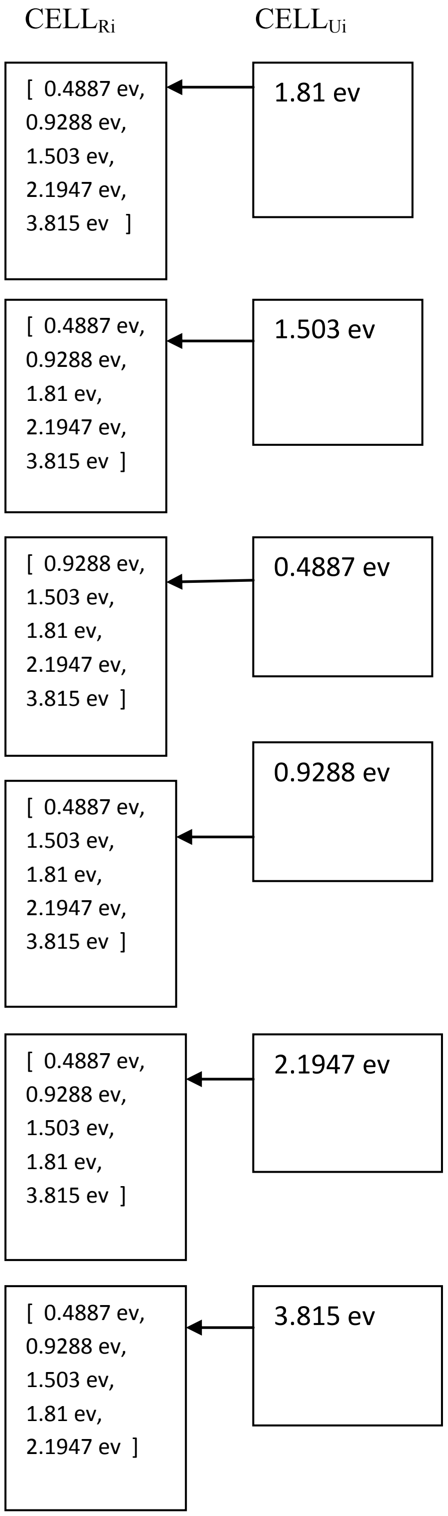

Figure (9): Cell$_{Ui}$ and Cell$_{Ri}$ net-structure for several (five) pv cell$_{Ri}$, T=300 K, cr=1 sun.

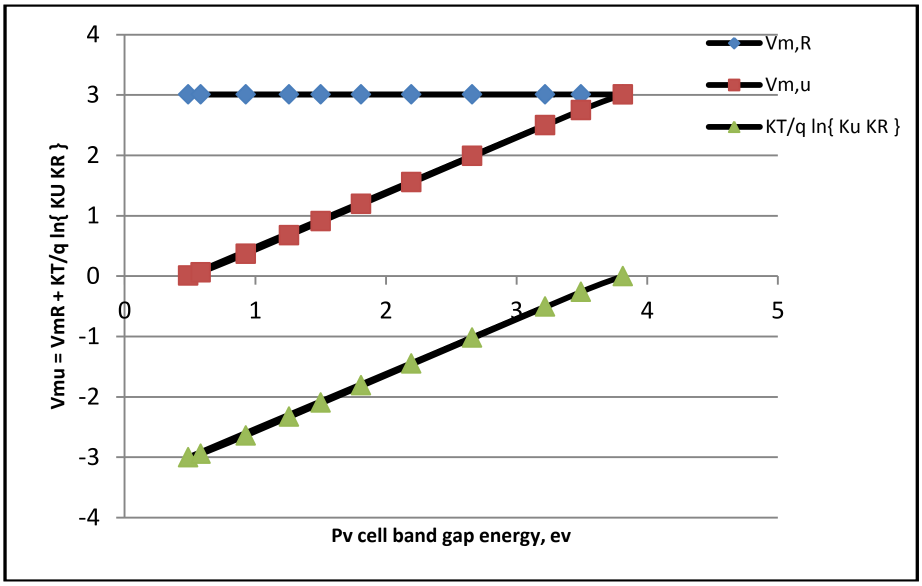

Figure (10): Variations of $V_{m,u}$ with kT/q ln{ K_U K_R } for several pv cells when $cell_R$ = 3.815 ev, $V_{m,R}$ = 3.0088 v, at $T_{,U}$ = $T_{,R}$ = 300 K, cr_U = cr_R = 1 sun.

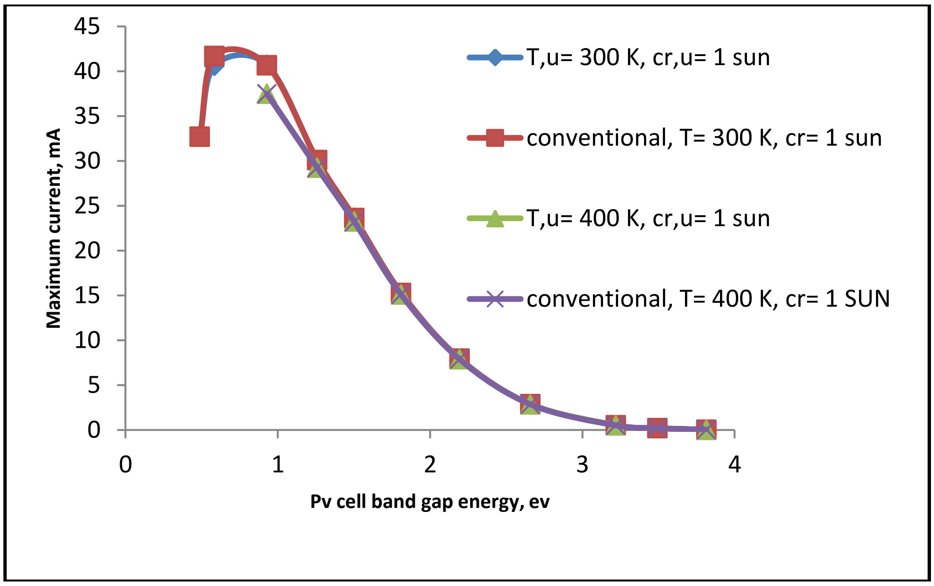

Figure (11): Comparison between the approach and conventional maximum current calculations for several $cell_{Ui}$ at T_{ui} = 300 K, 400 K and cr_u = cr_R = 1 sun, where for all cases the reference cell used is, $cell_R$ = 0.4887 ev at $T_{,R}$ = 300 K, and cr_R = 1 sun.

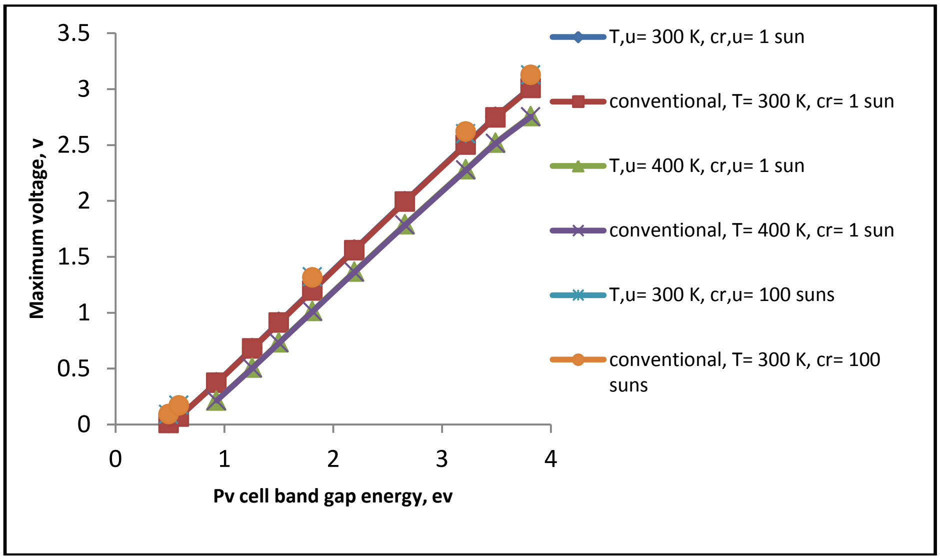

Figure (12): Comparison between the approach and conventional maximum voltage calculations for several cell$_{Ui}$ at T_{ui} = 300 K, 400 K and cr_u = 1 sun, 100 suns, where for all cases the reference cell used is, cell$_R$ = 0.4887 ev at $T_{,R}$ = 300 K, and cr_R = 1 sun.

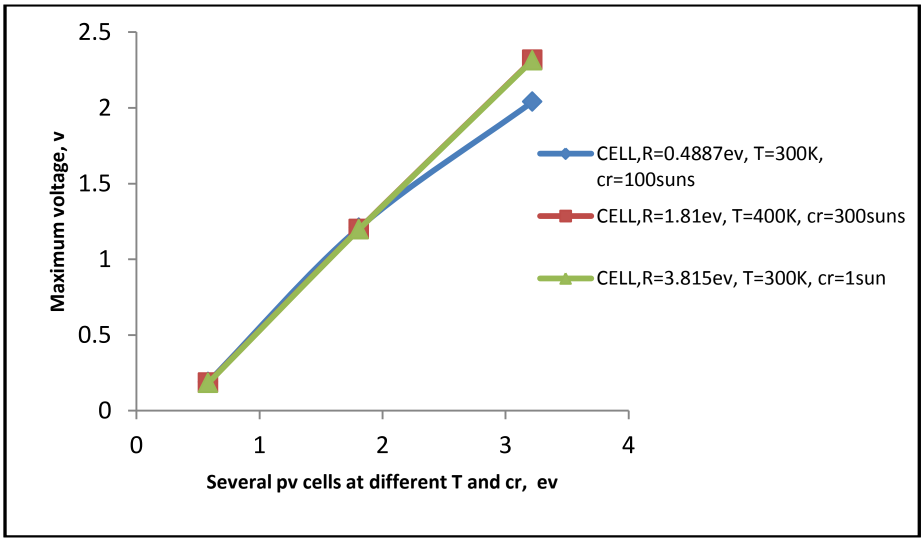

Figure (13): The variations of maximum voltages for several pv cells under different T and cr using cells (0.4887 ev, 1.81 ev, and 3.815 ev) each as a reference cell for each case.

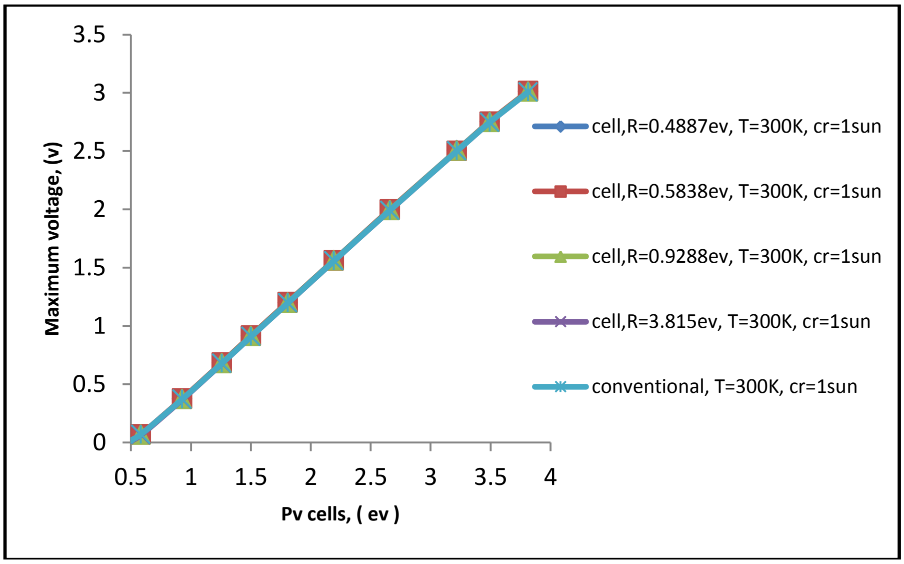

Figure (14): Comparison between maximum voltages of conventional method, and approach method for several pv cells both at T =300 K, cr = 1 sun (i) cell$_R$ = 0.4887 ev, (ii) cell$_R$ = 0.5838 ev, (iii) cell$_R$ = 0. 9288 ev, and (iv) cell$_R$ = 3.815 ev.

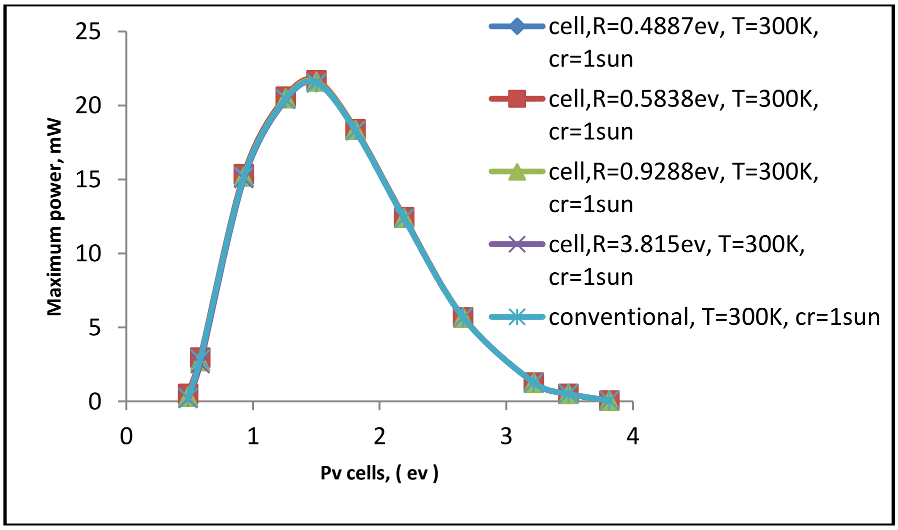

Figure (15): Comparison between maximum power of conventional method and approach method for several pv cells both at T = 300 K, cr = 1 sun (i) cell$_R$ = 0.4887 ev, (ii) cell$_R$ = 0.5838 ev, (iii) cell$_R$ = 0. 9288 ev, and (iv) cell$_R$ = 3.815 ev.

CONCLUSIONS

1- From Table (2) that concerned with the conventional calculations of electrical parameters, at fixed temperature and sunlight irradiance, it is concluded that: the wider are the band gap (E_g) of the utilized pv cells the smaller are their electrical parameters I_0 and I_{SC}, and the larger are their electrical parameters; V_{OC} , FF , V.F , V_m , and I_m because of their larger related ratios $(qV_m /kT) /\{(1 + (qV_m /kT) \}$ and $\{ (I_{SC} / I_0) + 1\}$. Both the maximum power (P_m) and the conversion efficiency (η) increase starting from the narrowest band gap pv cell until the largest maximum power point (I_mV_m) referred to the highest efficient pv cell is reached beyond which P_m and η drop. Regarding this approach analysis and formulations, electrical parameters obtained show a satisfied matched results as compared to the way these electrical parameters are conventionally calculated given in Table (2).

Very narrower pv cells, those, in fact, are theoretically only exist such as the pv cell of referred band gap 0.4887 ev, show a deviation only at high temperatures. This is because the temperature dependent electrical parameter " I_0 " increases with temperature increase making the two ratios, $(qV_m/kT)/\{(1+(qV_m/kT)\}$ and $\{(I_{SC}/I_0)+1\}$, meant by calculation of both V_{OC}, V_m and I_m, being a smaller ratios. Wider band gap pv cells have $(qV_m/kT) >> 1$ and, as a result, both their electrical output parameters are less affected by temperature increase.

2- A simple program, regardless of any of the interpolation techniques, can easily be designed for the computation of all electrical parameters under any irradiance and temperature variation conditions by only inputting the electrical parameter constants K_{ui} and K_{Ri}.
3- Regarding eq.(65) as a very important equation, determining the required increment in temperature regarding certain wide band gap energy pv cell so that its voltage falls down to equal certain maximum voltage referred to certain slightly smaller band gap energy pv solar cell. This in fact may comes to be an important issue in future when different types and different area pv cells have to be connected either in series or parallel or mixed connection (serial-parallel connection). Many pairs of suitable photovoltaic cells may look for in order to support this issue.
4- By inverse way, calculating the open circuit voltage first before calculating the light-generated current is possible regarding this approach by only substituting E_{gu} for $V_{OC,u}$ as given by the approximate equation (eq. 59) and, as a result, the photon flux is easily then obtained by substituting into eq.(3). This is achieved by knowing no other parameter than the band gap of the considered pv cell referred to the known electrical parameter $V_{OC,R}$ and $E_{g,R}$ of pv $cell_R$ as given by eqs.(58 and 59). A new band gap pv cells not covered by Table (2) can be added, as given in Table (10).
5- As wider is $E_{g,u}$ as larger is its K_u. $\{[K_u][K_R]\} \neq 1$ at different T and different cr when same pv cell plays, at the same time, both as $cell_U$ as well as $cell_R$. Under identical thermal and optical conditions, utilizing the same pv cell to acts as $cell_U$ and $cell_R$ yields into: $[K_u][K_R] = 1$, and therefore; $kT/q \ln \{[K_u][K_u]\} = 0$. On the other, hand for different thermal and optical conditions, this case can be stated as: $[K_u][K_R] \neq 1$, and therefore, $kT/q \ln \{[K_u][K_R]\} \neq 0$. $K_u \neq K_R$ means, either (i) the pv cell pair used ($cell_U$, $cell_R$) is non- identical type pv cell pair regardless of any irradiance or thermal conditions, or (ii) the pv cell pair used ($cell_U$, $cell_R$) is an identical type pv cell pair, but each of its pv cells are operating under different irradiance and thermal condition from the other.
6- This work idea can be generalized to any solar spectrum radiation other than the utilized one (AM1.5).

REFERENCES

1- A. El-Shaer M.T.Y. Tadros, Khalifa M. A, August (2014), Effect of light Intensity and temperature on crystalline silicon solar cell module parameters, International journal of energy technology and advanced engineering , Vol. 4, Issue 8, pp. 311-318.
2- Chenming Hu and Richard M. White, (1983), Solar Cells: From Basic to advanced systems, Mc Graw-Hill Book Company.
3- Glunz S. W, (2006), New concepts for high-efficiency silicon solar cells, Solar energy materials & solar cells, 90, pp. 3276-3284.
4- Gokcen N. A, Loferski J. J, (1979), Efficiency of tandem solar cell systems as a function of temperature and solar energy concentration ratio, Solar energy material, pp. 271-286.
5- Green M. A, (1982), Solar Cells: Operating principles, Technology, and System applications, Prentice-Hall, Englewood Cliffs, NJ, p. 881.
6- Green M. A, Stuart R. Wenham, Muriel, et al, (2007), Applied Photovoltaics, Earth Scan, Third edition, pp. 47.
7- Ingersoll J. G, (1986), Simplified calculation of solar cell temperatures in terrestrial photovoltaic array, J. Sol. Energy Eng, Vol. 108, Issue (2), pp. 95-101.
8- Keerthi K. Nair, et al, (2016), Analysis of temperature dependent parameters on solar cell efficiency using MATLAB, IJEDR, Vol. 4, Issue. 3, pp. 536-541.

9- Kon Chuen Kong, Mustafa Bin Mamat, et al., (2012), New approach of mathematical modeling of photovoltaic solar panel, Applied mathematical sciences, Vol. 6, No. 8, pp. 381-401.
10- Martin Wolf, P .E, (1981), Solar energy handbook, CH.24, Pv solar energy conversion systems, Mc Graw-Hill company, pp. 1-24.
11- Mohamed Abdelhady Kamal El-Adawi, Ibtissam Abdelrahman AL-Nuaim, August (2014), New approach to modeling a solar in relation to its efficiency laplace transform technique, Optics and photonics journal, Vol. 4, No. 8, pp. 219-227.
12- Mustapha Belarbi, Amine Boudghene Stambouli, (2016), A new algorithm of parameter estimation of a photovoltaic solar panel, Turkish journal of electrical engineering & computer sciences, 24, pp. 276-284.
13- Petkov M, Markova D, Platikanov S. T, (2011), Contemporary Materials (Renewable energy sources), pp. 171-177.
14- Priyanka Singh, Ravindra N. M, (2012), Temperature dependence of solar cell performance-an analysis, Solar energy materials & Solar cells, 101, pp. 36-45.
15- Richard J. Matson, Keith A. Emery, Richard E. Bird, (1984), Terrestrial solar spectra, solar simulation and solar short-circuit current calibration: A Review, Solar Cells, 11, pp. 105-145.
16- Swapnil Dubey, Jatin Narotam Sarvaiya, Bharath Seshadri, (2013) Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the World-A Review, Energy Procedia, Vol. 33, pp. 311-312.
17- Sze S. M, (1981), physics of semiconductor devices, Second Edition, John Wiley & Sons.

صياغة نظرية جديدة لعوامل الخرج الكهربائية ذات العلاقة بقدرة الخلايا الفوتوفولطائية العظمى

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الملخص

يقدم هذا البحث صياغة نظرية تحليلية جديدة لعوامل الخرج الكهربائية تنتهي باشتقاق معادلة مبسطة لقدرة الخرج العظمى في الخلايا الفوتوفولطائية. يركز هذا البحث بصورة اساسية على العوامل الكهربائية الهامة التي لا يمكن صياغتها صراحة بدلالة المتغيرات الكهربائية الأخرى كالفولتية العظمى والتيار الأعظم وبالتالي القدرة العظمى للخلية الفوتوفولطائية. يستخدم هذا البحث ثابت شمسي ذو كتلة هواء (1.5). بداية: وفقا للقدرة الساقطة-الأطوال الموجية المتوفرة من خلال طيف كتلة الهواء هذا تم ، تقليديا ، حساب جميع العوامل الكهربائية لطيف واسع من الخلايا الفوتوفولطائية يتراوح بين 0.4887 - 3.815 إلكترون فولت لغرض المقارنة بينها وبين القيم المناط بها أسلوب هذا البحث. ثانيا: بعيدا عن النمذجة التقليدية للخلايا الفوتوفولطائية الذي يعتمد استقلالية كل خلية بعينها في نمذجة المتغيرات الكهربائية ينهج هذا البحث اسلوبا مغايرا حيث يتم نمذجة الخلايا الفوتوفولطائية للمتغير الكهربائي المجهول، اعتمادياً غير استقلالياً، بدلالة العديد من الخلايا الفوتوفولطائية المعلومة المتغير ذاته. خلاصة هذا البحث تمخض عن اشتقاق العديد من العلاقات المتحققة حتى نحو يرقى إلى100 %، دون الخوض في تعقيدات الطرق والتقنيات التقليدية.

الكلمات المفتاحية: الخلايا الفوتوفولطائية، عوامل الخلايا الفوتوفولطائية الكهربائية.