A novel method of current matching the ideal series-connected subcells tandem solar cell system maintaining optimal the conversion efficiency

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Abstract. A novel method is explored that maintains optimal the overall conversion efficiency of series-connected subcells tandem solar cell system (same as the theoretical overall conversion efficiency (η_{opt}) of the stacks of independently-operated optimized subcells tandem solar cell system). Series-connected optimized-subcells tandem solar cell systems suffering of un-matching (unequal) their subcells currents and as a result their conversion efficiencies drop down the optimal (η_{opt}) ones because the output current of the series-tandem solar cell system is limited to the smallest of the current produced by any of the individual subcells. If this is the case, the currents through each of the subcells are constrained to have the same value. This novel method, we so called by " The Averaging Method ", solves this problem of un-matching the current through the series-connected subcells by; averaging the sum (dividing the sum by the number of subcells) of all the maximum currents of individual independently-operated subcells, next; applying the resulting average maximum current (as a matching maximum current) to search for what several candidate subcells (other than the optimized ones) such that this matching maximum current is satisfied between each of these candidate subcells. It is proved that the sum of, maximum currents, power, and overall conversion efficiency, of the independently-operated subcells versus those referred to this approach of series-connected candidate subcells, tandem solar cell systems, are equal. Applying this approach method requires no extra than a single; controller, load, as compared to the independently-operated subcells tandem solar system where necessarily is the provision of a special; controller, load, for every subcell utilized; this is simply because now the subcells, both, are current-matched, and in addition, the resulting matching current being maintained equal regardless of solar radiation variations. Calculations are carried under applying solar radiation spectrum of air mass zero (AM0) at several solar intensities and temperatures, for a tandem solar cell systems their subcells ranged, from two up to twelve subcells.

Keywords: matching the currents in ideal series-connected subcells tandem solar cell systems, calculations of the ideal conversion efficiency of tandem/multi-junction solar cell systems, independently-operated versus series-operated subcells tandem solar cell systems.

1 INTRODUCTION

limited theoretical conversion efficiency of conventional single-junction solar cell systems, 23.22 %, under AM0 solar irradiance and temperature of 300 K (N. A. Gokcen et al., 1997), leads into several approaches explored for enhancing this limited conversion efficiency towards a higher values (S. M. Bedair, 1984). The highest efficiency solar cell system explored uses multiple materials with band gaps that span the solar spectrum. This system, of some single-junction solar cells stacked upon each other so that each layer going from the top to the bottom has a smaller band gap than the previous cells, is called multi-junction or tandem solar cell system (S. M. Bedair, 1984), (Rune Strandberg, 2015). Tandem solar cell system allows to convert more of the solar energy to electricity than conventional single-junctionce cells (A. Marti et al., 1996). Concentrator operation is well suited for tandem and multi-junction photovoltaic cells because increasing the concentration ratio improves the performance of the photovoltaic cells even more (N. A. Gokcen, 1979).

Tandem/multi-junction solar cells experience a fundamental limitation relating to the availability of materials with optimal band gaps that simultaneously allow high efficiency. Alloys of groups III-V of the periodic table are good candidates for fabricating such multi-junction cells (M. Yamaguchi, 2001). Chose of the optimized-efficiency subcells is an essential criteria of designing any tandem/multi-junction solar cell system

Optimized-subcell of the tandem/multi-junction solar cell systems may operate either as independently, or series-connected subcells tandem/multi-junction solar cell system. For series-connected multi-junction solar cell system, the band gaps should be chosen so the photocurrents generated in each subcell are matched (Sarah Kurtz et al., 2010), (M. F. Lamorte et al., 1997). This is because, one of the most important design criteria in multi-junction cell is achieving the current-matching between the subcells. Current-matching enables to extract the best performance from a multi-junction cell. The solar cell with a higher band gap provides a higher open circuit voltage (V_{OC}) and lower short circuit current (I_{SC}). For achieving the current-matching condition, ideally the maximum current (I_m) between each subcell should be matched (H. J. Queisser, 2009), (M. A. Green et al., 2013). The series-connected multi-junction solar cells makes matching of currents a desirable characteristics because the output current of the multi-junction solar cell system is limited to the smallest of the current produced by any of the individual subcells. If this is the case, the current through each of the subcells are constrained to have the same value.

The solar cell current is proportional to the number of incident photons (N_{ph}) exceeding the semiconductor band gap (E_G), and the absorption constant (α) of the material. A layer must be made thinner if the photons that exceed the band gap are abundance. At the same time, a layer with a low absorption constant must be made thicker, since on average a photon must pass through more of the material before being absorbed. After materials are selected with desired band gaps and lattice constant, the thickness of each layer must be determined based on the material absorption constant and the number of incident photons with a given energy, so that each layer will generate the same photocurrent (Sarah Kurtz et al., 2010), (P. R. King et al., 2009), (Argyrios C. Varonides, 2011). This series-connected sub cells current is expressed as given by (Aho et al., 2014).

A detailed balance analysis of area de-coupled double tandem photovoltaic modules that can increase the efficiency of two-terminal tandem devices is described (Rune Strandberg, 2015). This model, for two-terminal tandem module can achieve the same theoretical efficiency as stacks of independently operated cells. Here, the cells can be horizontally series-connected and the layers can then be current or voltage-matched with each other in a tandem module. This technique (Rune Strandberg, 2015), is impractical for larger number of area de-coupled subcells, and in addition to that, the matching current fails to continuously being maintained matched when solar radiation varies, this is because of the already fixed the designed area of the decoupled subcells.

To maintain optimal is the conversion efficiency of the series-connected subcells tandem solar cell system, same as the theoretical efficiency the independently-operated stack subcells introduce, a novel method " The Averaging method " is explored and presented by this work. This is simply achieved by averaging the sum of all maximum subcell currents referred to the optimal case (the independently-operated subcell tandem solar cell system), and next, applying the resulting maximum current to search, from the solar spectrum, for a new candidate subcells (each) matches this matching maximum current and as a result, the resulting overall conversion efficiency being maintained optimal regardless of the solar radiation variations. This is simply, because now the subcells all are current-matched and, equal maximum currents between the subcells are achieved.

2 THEORETICAL CONSIDERATION

The calculations are conducted for the AM0 solar spectrum given in Refs.(N. A. Gokcen et al., 1979), (Nasa, 1979). Table (1) shows the integral AM0 photon flux Nph(E) for energies between hν = ∞ and hν = E.

$$N_{ph}(E) = \int_{h\nu=E}^{\infty} n_{ph}(h\nu)\, d(h\nu)$$

(1)

Where nph(hν) is the photon flux at hν. Table (1) also includes the short circuit current which would flow in a cell having an absorption cut-off at hν = E if the collection efficiency were unity, i.e, if every photon having an energy hν > E contributed one minority carrier to the short circuit current Isc(E). Thus:

$$I_{sc}(E) = qN_{ph}(E)$$

(2)

Where " q " is an electron charge.

If a cell based on a photovoltaically active semiconductor having an energy gap (EG) has interposed between itself and the solar source a filter which cut off all photons with energy greater than E, where E > EG, then the limiting short circuit current which this cell can produce is obtained from the relation (N. A. Gokcen et al., 1979):

$$I_{sc}(E, E_G) = I_{sc}(E_G) - I_{sc}(E)$$

(3)

The I-V characteristic equation of solar cell is given by:

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

(4)

where " I0 " is the reverse saturation current given by (N. A. Gokcen et al., 1979):

$$I_0 = 6.03 \times 10^9\left(e^{-qE_G/kT}\right)$$

(5)

The voltage, at maximum power point, (Vm) is given by;

$$e^{\frac{qV_m}{kT}}\left(1 + \frac{qV_m}{kT}\right) = \frac{I_{sc}(E, E_G)}{I_0} + 1$$

(6)

and, the current at maximum power point, (Im) is calculated from:

$$I_m = \frac{\left(\frac{qV_m}{kT}\right)}{\left(\frac{qV_m}{kT}\right)+1}\left[\, I_{sc}(E, E_G) + I_0 \,\right]$$

(7)

The expressions of maximum, voltage and current, given by Eqs.(6 and 7) are based on an equivalent circuit for the illuminated solar cell in which the internal shunt resistance (Rsh) is infinite and the internal series resistance (Rs) is zero.

The maximum power (Pm ,) and the conversion efficiency (η), are, respectively, given by Eqs.(8, 9) below;

$$P_m = (V_m)(I_m)$$

(8)

$$\eta(\%) = \frac{P_m}{(P_{in})(CR)} = \frac{(V_m)(I_m)}{(135.3)(CR)} \times 100\ \%$$

(9)

where " CR " is the concentration ratio, and the AM0 input power (Pin) solar spectrum intensity, it is 135.3 mW/cm2.

2.1 The independently-operated subcells tandem solar cell system

This is, where every subcell operates independently (individually) of the other, tandem solar cell system, subcells. For n-independently operated subcells tandem solar cell system shown in Fig. (1), where every of the optimized subcells is referred-to by the subscript " i ", the calculations of the conversion efficiency of every subcell are conducted referred to Eqs.(1 up to 9); and the overall conversion efficiency of this n-independently operated subcells tandem solar cell system can then be expressed by;

$$\sum_{i=1}^{n}\eta_i = \eta_1 + \eta_2 + \eta_3 + \ \dots + \eta_{n-1} + \eta_n = \sum_{i=1}^{n}\frac{(V_{mi})(I_{mi})}{(P_{in})(CR)} = \sum_{i=1}^{n}\frac{P_{mi}}{(135.3)(CR)} \qquad (10)$$

2.2 The series-connected subcells tandem solar cell system

Series-connecting the n-subcells of the tandem solar cell system results into an output maximum voltage equals to the algebraic sum of all the individual, utilized subcells, maximum voltages, i.e;

$$\sum_{i=1}^{n} V_{mi} = V_{m1} + V_{m2} + V_{m3} + V_{m4} + \dots\dots + V_{m(n-1)} + V_{mn} \qquad (11)$$

while the output maximum current of this series-connected subcells, tandem solar cell system, is limited to the smallest, (Im,small), of the maximum currents produced by any of the individual subcells; thus, the overall power delivered from these n-series connected subcells utilized, can be expressed by:

$$\sum_{i=1}^{n} P_{mi} = (I_{m,small})\left(\sum_{i=1}^{n} V_{mi}\right)$$

(12)

and therefore, the overall conversion is given by:

$$\sum_{i=1}^{n}\eta_i = \frac{\sum_{i=1}^{n} P_{mi}}{(CR)(P_{in})} = \left\{\frac{[(I_{m,small})(\sum_{i=1}^{n} V_{mi})]}{(CR)(P_{in})}\right\}$$

(13)

3 THE APPROACH METHOD (THE AVERAGING METHOD)

For achieving equal (matched) maximum current between all the n-series connected subcells, and at the same time, maintaining optimal is the overall conversion efficiency, the following explored approach method, we named by " The Averaging method ", can be applied. Fig. (2) shows , this approach, series-connection configuration tandem solar cell system where only; a single load (Rm,A) operating at the maximum power point condition, single controller represented by the single zener (Z) diode regulator, are utilized.

3.1 Methodology

Let the maximum currents (Imi) generated by the optimized n-independently operated subcells, tandem solar cell system shown in Fig. (1); being, Im1, Im2, Im3, Im4, ………….. , Im(n-1), Im,n.

By summing all these maximum currents; and next, dividing the result of this sum obtained, by the number of subcells utilized (n-subcells, in this case), the result obtained is nothing but the average subcells maximum current what we called here by " The matching maximum current " and denoted it by " Im,A ", where the subscript "A" stands for the case where this approach method (The Averaging method) is applied. This matching maximum current can be expressed as:

$$I_{m,A} = \frac{(I_{m1} + I_{m2} + I_{m3} + I_{m4} + \cdots\cdots + I_{m(n-1)} + I_{mn})}{n} = \frac{\sum_{i=1}^{n} (I_{mi})}{n} \quad (14)$$

Next; searching from the solar spectrum applied (in this case, AM0 is applied); for the candidate subcells (other than those optimized subcells referred to the independently-operated tandem solar cell system), ranged from subcell 1,A to subcell n,A, those are satisfying, (each), the generation of this obtained matching maximum current (Im,A), given in Eq.(14).

If the new generated maximum currents (Im1,A, Im2,A, Im3,A, ……… , Im(n-1),A, Imn,A, i.e, (Imi,A) referred to the candidate subcells (subcell 1,A, subcell 2,A, subcell 3,A,……., subcell (n-1),A, subcell n,A), respectively, are such that;

$$I_{m,A} = I_{m1,A} = I_{m2,A} = I_{m3,A} = \cdots \ldots \ldots \ldots . = I_{m(n-1),A} = I_{mn,A} \quad (15)$$

then, the following equality relations should be satisfied;

The sum of all the individual subcells; maximum currents, maximum power, and conversion efficiency referred to " the n-independently operated optimized subcells tandem solar cell system", is exactly equals to the sum of all the individual subcells; maximum currents, maximum power, and conversion efficiency referred to " the n-series connected candidate subcells tandem solar cell system (when averaging method is applied). These are as underlined below:

First;

$$I_{m1,A} + I_{m2,A} + I_{m3,A} + \cdots \ldots + I_{m(n-1),A} + I_{mn,A} = I_{m1} + I_{m2} + I_{m3} + \cdots + I_{m,n-1} + I_{m,n} \quad (16\text{ a})$$

i.e;

$$\sum_{i=1}^{n} I_{mi,A} = \sum_{i=1}^{n} I_{mi} \quad (16\text{ b})$$

and as a result;

$$\frac{\sum_{i=1}^{n} I_{mi,A}}{n} = \frac{\sum_{i=1}^{n} I_{mi}}{n}$$
(16 c)

Second;

$$I_{m,A}\left(V_{m1,A} + V_{m2,A} + V_{m3,A} + \ldots.. + V_{m(n-1),A} + V_{mn,A} \right) = (I_{m1} V_{m1}) + (I_{m2} V_{m2}) + (I_{m3} V_{m3}) + \cdots \ldots. + (I_{m(n-1)} V_{m(n-1)}) + (I_{mn} V_{mn})$$
(17 a)

i.e;

$$[(I_{m,A})(\sum_{i=1}^{n} V_{mi,A})] = \sum_{i=1}^{n} [(I_{mi})(V_{mi})]$$
(17 b)

and, thus;

$$\sum_{i=1}^{n} P_{mi,A} = \sum_{i}^{n} P_{mi}$$
(17 c)

Third:

Referring to Eqs.(10, 13, 17a, 17b, and 17c); thus, an equal overall conversion efficiencies; referred to applying this approach method to n-series connected candidate subcells versus the independently-operated (optimized) subcells, tandem solar cell systems, are satisfied, such that:

$$\sum_{i=1}^{n} \eta_{i,A} = \sum_{i=1}^{n} \eta_i$$
(18)

Fourth;

For further exact matching the subcells maximum currents, fine tuning the I-V curves of, some or both, the utilized series-connected candidate subcells, can be applied referring to the following equation:

$$I_{i,A} = I_{0i,A}\left(e^{qV_{i,A}/kT} - 1\right) - I_{sci,A}$$
(19)

where (Vi,A) is the voltage obtained as a result of fine-tuning the candidate subcells for achieving the matched maximum current (Ii), expressed by:

$$V_{i,A} = (kT/q)\ \ln\left[(I_{sci,A} + I_{i,A} + I_{0i,A})/I_{0i,A}\right]$$
(20)

4 RESULTS AND DISCUSSIONS

Un-optimized subcells tandem solar cell systems leads into a drop of their conversion efficiencies down the optimal values, i.e, optimizing the subcells leads into an optimal conversion efficiency tandem solar cell systems. Table (2) illustrates a several combination sets of three-independently operated subcell tandem solar cell systems, under T = 300 K and CR = 1 sun. Among these combinations, the optimal conversion efficiency (η_{opt} = 37.42 %) is no doubt referred to the set (the optimized) of subcells, (2.3 ev, 1.6 ev, 1 ev). Optimal conversion efficiencies of several n-independently operated subcells tandem solar cell system (n = 2 up to 12 subcells), under CR = 1 sun and T = 300 K, are shown in Table (3). Regarding Table (3) where the subcells are independently-operated utilizing the optimized efficient subcells, it is obvious that the individual subcells (ni) utilized, have different individual maximum current values (Imi). Results and calculations of, the individual and, the overall; maximum, voltage, power, and optimal efficiency referring to each subcells number are also illustrated in Table (3). This, overall optimal conversion efficiencies, system of several n-independently operated optimized subcells tandem solar cell system under several solar intensities and temperatures are also shown in Figs. (3 and 4), respectively. In general; at fixed, solar intensity and fixed temperature, the overall conversion efficiency increases with increasing the number of subcells (n). Fig. (3) shows the overall conversion efficiency increases with increasing the solar intensity (CR), while on the other hand, increasing the subcell's temperature decreases the overall conversion efficiency, this is shown in Fig. (4).

While the independently-operated optimized subcells tandem solar cell systems producing the highest (the optimal) overall conversion efficiency, this in fact, at the expense of providing every subcell with a special controller which is impractical to provide, sometimes, especially when larger number of subcells are considered. On the other hand, series-connecting these optimized subcells limits the system current to the smallest subcells current. This absolutely the case where the un-matched currents drop the system overall conversion efficiency to lower values down the optimal ones. Table (4) illustrates, in details, the results obtained regarding this case of series-connecting the several n-optimized subcells, given in Table (3), under CR = 1 sun and T = 300 K. Comparing these Tables (3 and 4); Table (4) shows a drop in conversion efficiencies from the optimal values. For n = 2, 3, 4, 6, 12, sub cells, the overall conversion efficiencies drop from, 32.48, 37.41, 40.47, 43.71, 49.95%, down to, 28.63, 29.63, 29.21, 29.64, 18.94 %. Observe how the conversion efficiency referred to the largest number of subcells (n = 12 sub cells) drops from its optimal value (49.95 %) down to a lower value, 18.94%. All this drop is because of the un-matching current the optimized subcells generate when these optimized subcells have been examined to operate under series-connection configuration.

The conversion efficiency variations of several series-connected subcells (optimized subcells) tandem solar cell system, as compared to the case where these optimized subcells are independently-operated, both, under several solar intensities and temperatures, are shown in Figs. (5 and 6), respectively.

As a solution to this limiting current (the smallest subcells current between the series-connected subcells tandem solar cell system), this approach method (The Averaging method) is applied. The candidate subcells utilized by this approach method, together with their calculated short circuit currents under AM0 solar spectrum, are shown in Table (5).

Table (6) shows several n-series connected candidate subcells tandem solar cell system when applying the averaging method (no fine tuning is applied) under solar intensity and temperature, 1 suns, 300 K, respectively. Both the subcells matching maximum currents ($I_{mi,A}$) are observed very nearly equals to each other, and Eq.(15), $I_{mi,A} = I_{m,A}$, is satisfied. This matching maximum current varies with varying the number of subcells (n), i.e, $I_{m,A}$ decreases as the number of subcells increases; in addition, it is obvious from Table (6) that all the maximum currents ($I_{mi,A}$) through each candidate subcell in this series-connected subcell tandem solar cell system, both are equal. This matching maximum current, for two-subcells (according to Eq. 14) is: (19.2482 + 27.6351)/2 = (46.8834)/2 = 23.4417 mA, and the candidate subcells satisfying this matching maximum current are (1.85 ev, 1.2 ev) as compared to the optimal subcells (2 ev, 1.2 ev) utilized in Table (3). See how equal are the overall conversion efficiencies (referred to this work), to the optimal ones shown in table (3). Comparing Tables (3 and 6) shows an equal overall conversion efficiencies. The variation of the number of subcells (n) versus their referred matching current ($I_{m,A}$) under several solar intensities and temperatures are shown in Fig. (7) and Fig. (8), respectively. These Figures (7 and 8) represent a ready-made curves, introduced by this work, from which the matching current of any number of subcells utilized, may be determined. The composite I-V curves of three-optimized subcells tandem solar cell system, under CR = 1 sun and T = 300 K, when considered; first, individually (as a single-junction solar cell system); and second, as independently-operated tandem solar cell system, are shown in Fig. (9) and Fig. (10), respectively. From the first show, these Figures (9 and 10) show un-matched (un-equal) are the optimized subcells maximum currents, denoted by (Im (E, EG). The maximum currents (Imi) referred to the optimized subcells (2.3 ev, 1.6 ev, 1 ev) of Fig. (10) are 12.92 mA, 17.92 mA, 25.80 mA, respectively. This is also illustrated in Table (4).

While, on the other hand, when applying this approach method (the averaging method) to three candidate subcells under CR = 1 sun and T = 300 K, the I-V curves of these three subcells when considered, first; as a single-junction solar cell system, second; as a series-connected subcells solar cell tandem solar cell system (with, and without fine tuning), are shown in Figs. (11 and 12), respectively. From the first show, Fig. (11) shows a subcells matched maximum currents of both candidate subcells (with no fine-tuning applied), these are 18.6428 mA 18.6206 mA, 18.88396 mA, referred to the candidate subcells (2.025 ev, 1.425 ev, 1.0125 ev), respectively, see also Table (6). While, on the other hand, when applying fine-tuning (referring to Eqs.(19 and 20)) to the candidate subcells (1.425 ev and 1.0125 ev) such that their currents tuned to equal the matching maximum current of the candidate subcell (2.025 ev), it is observed that the three subcells currents are exactly-matched as shown in Fig. (12), and also illustrated with the referred results of calculations in Table (6). Generally, concerning tandem systems, the most top subcell is the highest efficient one as compared to the next top subcells and this is the reason why the most-top candidate subcell mostly is the candidate subcell tuned-to by the other system candidate subcells regarding this work.

Comparing, the conversion efficiency lost, of the independently-operated versus the approach series-connected, tandem solar cells systems, under several solar intensities is shown in Fig. (13). It is observed roughly that a (zero %) the conversion efficiency lost is referred to the averaging method while, on the other hand, roughly (a considerable loss %) in conversion efficiency is shown referred to the individually-operated tandem solar cell system when its optimized subcells are connected in series.

Fig. (14) shows the candidate subcells (EGi,A) versus the optimized subcells (EGi), for several number of subcells; under CR = 1 sun, T = 300 K.

Fig. (15) shows the algebraic sum of the individual candidate subcells band gaps (∑EGiA) versus the algebraic sum of the individual optimized subcells band gaps (∑EGi); under CR = 1 sun, T = 300 K. On the other hand, Fig. (16) shows (∑EGiA) versus (∑EGi), for n = 2, 3, 4, 6, and 12, under several solar intensities. It is observed that the relationship, (∑EGiA) versus (∑EGi), is linear regardless of solar intensity concentration (CR) variations.

The individual; maximum voltages (Vmi,A), (Vmi) versus their referred band gap (EGi,A), (EGi); both under CR = 1 sun and T = 300 K, are shown in Fig. (17). Also a linear relationship is observed relating the individual subcell maximum voltage with individual subcell energy gap.

The variations of the referred approach individual conversion efficiency (ηi,A) versus the individual subcells, (ni,A), band gap (EGi,A) of several n-series connected candidate subcells tandem solar cell system under CR = 1 sun and T = 300 K is shown in Fig. (18). A linear relationship is also observed.

The variation of the matching maximum current ($I_{mi,A}$) versus their referred individual subcells ($n_{i,A}$), band gap ($E_{Gi,A}$), of three candidate subcells series-connected tandem solar cell system under several solar intensities and fixed temperature (T = 300 K), prior to application of fine tuning, is shown in Fig. (19). It should be noted that, the same candidate subcells are utilized by all the several applied values of solar intensities, and as a result, the same (unchanged) matching maximum current between the subcells is satisfied.

Fig. (20) shows the variations of the maximum currents (I_{mi}, $I_{mi,A}$) versus their referred maximum voltages (V_{mi} , $V_{mi,A}$), for several n-subcells tandem solar systems; CR = 1 sun, T = 300 K. The maximum current ($I_{mi,A}$) is seen to be constant with varying the maximum voltage ($V_{mi,A}$), on the other hand the maximum current (I_{mi}) gets alternating its individual maximum values with varying its related individual maximum voltage (V_{mi}).

Fig. (21) shows the variations of the individual subcells maximum currents (I_{mi}, $I_{mi,A}$) versus their individual subcells maximum voltages (V_{mi}, $V_{mi,A}$), respectively, for the three-subcells (n = 3) tandem solar cell system (n = 3), under solar intensity variations. As Fig. (21) shows, the individual maximum subcell currents ($I_{mi,A}$) referred to this approach is constant regardless of the solar intensity concentrations while it is not the case for the individual maximum currents (I_{mi}) referred to the independently-operated subcells tandem system. The same is observed regarding temperature variations as shown in Fig. (22).

Fig. (23) shows the variations of the individual maximum currents ($I_{mi,A}$), referred to this approach tandem solar cell systems (n = 2, 3, 6), versus their individual maximum voltages ($V_{mi,A}$); when these (same) candidate subcells (are examined to operate under shifting their intensity radiation from the referred, (CR = 1 sun), to the examined, (CR = 100 suns). Also, here a constant individual maximum currents is observed and also the same overall conversion efficiency is satisfied. This talk is also true when temperature is varied from the referred (T = 300 K) to the examined (T = 400 K), as shown in Fig. (24).

Fig. (25) shows the I-V curves referred to the approach three series-connected candidate subcells, (1.95 ev, 1.3375 ev, 0.9125 ev), tandem solar cell system; under various solar intensities. Still a constant matched subcells maximum currents are satisfied

Fig. (26) shows the variations of; the individual conversion efficiencies, (η_i) and ($\eta_{i,A}$), versus their referred maximum voltage variations, V_{mi} and $V_{mi,A}$, respectively, for n = 2, 3, 4, and 6; CR = 1 sun, T = 300 K. $V_{mi,A}$ versus $\eta_{i,A}$, (referring to this work) satisfies a linear relationship, while V_{mi} versus η_i (referring to the independently-operated subcells tandem solar system), doesn't. The reason simply is, a matched currents achieved regarding this work approach method.

Fig. (27) shows the variations of; the individual conversion efficiencies, (η_i), ($\eta_{i,A}$), versus their referred individual maximum current, I_{mi}, $I_{mi,A}$, respectively; for n = 2, 3, 4, and 6; CR = 1 sun, T = 300 K. $\eta_{i,A}$ versus $I_{mi,A}$ concerns applying the averaging method with no fine tuning.

Fig. (28) shows the variations of the maximum currents ($I_{mi,A}$) referred to the three individual candidate subcells, (1.95 ev, 1.3375 ev, 0.9125 ev), versus their individual maximum voltages ($V_{mi,A}$); when these (same) candidate subcells are examined to operate under varying their intensity radiation from the referred (CR = 100 suns) to the examined (CR = 90, 80, 70, 60, 50, 40, 30, 20, 10 suns), T = 300 K.

Fig. (29): shows the overall conversion efficiencies, $\sum\eta_{i,A}$ versus $\sum\eta_i$, for n = 2, 3, 4, 6, 12; under several solar intensities, T = 300 K. a linear relationship is still satisfied.

The variation of both; the individual and the overall, subcells matching current, voltage, power, and conversion efficiency, applying average method and with no applying fine tuning;

versus the solar intensity variations (from 100 suns down to 1 sun, keeping T = 300 K) concerning three-series connected candidate subcells tandem solar cell system (1.95 ev, 1.3375 ev, and 0.9125 ev) already designed to operate under CR = 100 suns and T = 300 K, is illustrated in Table (7). Table (7) ensures support the talk, varying solar intensities does not affect the matching currents, and it is maintained fixed through the subcells.

Table (8, a) shows the conversion efficiency comparison regarding six series-connected tandem solar system utilizing Averaging method (before I-V curve fine tuning is applied), and the case when fine tuning is applied versus the optimal case is shown in Table (8, b). Here, the I-V curves of the subcells utilized are fine-tuned such that a matched equal current of 1230.1 mA is satisfied through the tandem subcells solar cell system.

Fig. (30) shows the conversion efficiency concerning applying the averaging method (both; prior, and next-to the fine tuning technique). For several n-series connected subcell tandem solar cell system under several solar intensities and fixed temperature (T = 300 K), it is obvious that; the case next to fine-tuning the subcell's I-V curves shows an improved overall conversion efficiencies.

Finally; the comparison concerning, the independently-operated (optimal subcells) versus this approach method of series-connected candidate subcells (next-to fine tuning is applied), tandem solar cell systems; both operating, under several solar intensities, several temperatures, is shown in Figs. (31 and 32), respectively. As a final result; applying this approach, (The averaging method), to their referred matched candidate series-connected subcells, satisfies the same overall optimal conversion efficiencies referred to the conventional independently-operated optimized subcells tandem solar cell system.

Table (1): Limiting short circuit current as a function of energy gap (E_G) for AM0 radiation (N. A. Gokcen et al., 1979), (Nasa, 1979).

$E = h\nu$, (ev)	λ, (μm)	$10^{14} \times N_{ph}(E)$	$I_{ph}(E)$, mA/cm^2	Solar energy, (mW/cm^2)
7.0	0.1772	0.0	0.0	0.0
5.0	0.2480	2.9	0.046	0.25
4.0	0.3100	31.8	0.510	2.24
3.9	0.3179	41.1	0.569	2.84
3.8	0.3263	53.4	0.856	3.59
3.7	0.3351	68.9	1.104	4.51
3.6	0.3444	85.9	1.377	5.51
3.5	0.3542	104.7	1.678	6.57
3.4	0.3647	125.2	2.006	7.71
3.3	0.3757	149.3	2.392	8.99
3.2	0.3875	174.8	2.800	10.3
3.1	0.3999	203.9	3.267	11.79
3.0	0.4133	249.2	3.993	14.00
2.9	0.4275	301.7	4.833	16.46
2.8	0.4428	358.5	5.743	19.09
2.7	0.4592	433.5	6.945	21.37
2.6	0.4769	518.6	8.309	25.99
2.5	0.4959	611.7	9.800	29.78
2.4	0.5166	711.8	11.404	33.71
2.3	0.5391	818.9	13.12	37.84
2.2	0.5636	935.5	14.987	42.08
2.1	0.5904	1068.3	17.116	46.66
2.0	0.6199	1223.8	19.606	51.53

1.9	0.6526	1382.7	22.152	56.61
1.8	0.6888	1568.6	25.134	61.87
1.7	0.7293	1757.3	28.154	67.32
1.6	0.7757	1966.9	31.512	72.94
1.5	0.8273	2198.8	35.227	78.65
1.4	0.8862	2445.0	39.171	84.43
1.3	0.9539	2715.9	43.512	90.34
1.2	1.0353	3020.5	48.391	96.35
1.1	1.1289	3335.6	53.439	102.23
1.0	1.2418	3674.9	58.875	107.89
0.9	1.3789	4011.4	64.367	113.34
0.8	1.5514	4413.5	70.709	118.60
0.7	1.7724	4817.7	77.184	123.42
0.6	2.0675	5175.4	82.915	127.14
0.5	2.4803	5513.2	88.327	130.17
0.4	3.0996	5854.2	93.790	132.64
0.3	4.1333	6122.0	98.080	134.14
0.2	6.2249	6325.6	101.343	134.95
0.1	12.417	6426.9	102.966	135.25
0.0	0.0000	6476.6	103.762	135.30

Table (2): Variation of the conversion efficiency for several combination sets of three-independently operated subcell tandem solar cell system with varying the upper, lower, band gap subcells keeping fixed (1.6 ev) the mid-subcell band gap, T = 300 K, CR = 1 sun.

Subcells (n_i) Subcell (1) Subcell (2) Subcell (3) (ev)	Subcell (I_{mi}) I_{m1} I_{m2} I_{m3} (mA)	Subcell (V_{mi}) V_{m1} V_{m2} V_{m3} (v)	Subcell (P_{mi}) P_{m1} P_{m2}, P_{m3}, $\sum P_{mi} = \sum(I_{mi})(V_{mi})$ (mW)	Subcell (η_i) η_1 η_2 η_3 $\sum \eta_i$ (%)
2.3 1.6 1.0	12.920 17.927 25.808	1.6760 0.9980 0.4291	21.6557 17.8917 11.0755 50.6229	16.00570 13.22372 8.185932 37.41535
2.3 1.6 1.1	12.920 17.927 21.260	1.6760 0.9980 0.5193	21.6557 17.8917 11.0405 50.5879	16.00570 13.22372 8.160066 37.38948
2.3 1.6 1.2	- - 16.190	- - 0.6081	- - 9.84551 49.3929	- - 7.276802 36.50622
2.3 1.6 1.3	- - 11.570	- - 0.6959	- - 8.05165 47.5990	- - 5.950965 35.18038
2.3 1.6 1.4	- - 7.4137	- - 0.7814	- - 5.79344 45.3408	- - 4.281925 33.51134

2.3 1.6 1.5	- - 3.6065	- - 0.8599	- - 3.10128 42.6486	- - 2.292151 31.52157
2.2 1.6 1.0	14.745 16.106 25.809	1.5809 0.9945 0.4295	23.3128 16.0185 11.0851 50.4163	17.23050 11.83925 8.192901 37.26265
2.1 1.6 1.0	16.823 13.557 -	1.4859 0.4179 -	24.9991 5.66556 - 41.7497	18.47683 4.187412 - 30.85714
2 1.6 1.0	19.248 11.205 -	1.3911 0.4133 -	19.2482 4.63104 - 42.4936	19.79129 3.422800 - 31.40699
1.9 1.6 1.0	21.718 9.1196 -	1.2961 0.9809 -	28.1501 8.94543 - 48.1805	20.805702 6.6115578 - 35.610161
1.8 1.6 1.0	24.604 6.2217 -	1.2013 1.0293 -	29.5576 6.40401 - 47.0466	21.84601 4.733195 - 34.77209
1.7 1.6 1.0	27.511 3.27443 -	1.1063 1.0131 -	30.4368 3.31732 - 44.8391	22.49581 2.451832 - 33.140533

Table (3): Optimal conversion efficiencies of several n-independently operated subcell tandem solar cell system, under T = 300 K and CR = 1 sun.

No. of subcells (n)	Subcells (n_i) (ev)	I_{mi} (mA)	V_{mi} (v)	$P_{mi} = I_{mi} \times V_{mi}$ $\sum P_{mi}$ (mW)	η_i $\sum \eta_i$ (%)
2	2.0 1.2	19.2482 27.6351	1.39117 0.62138	26.7776 17.1719 ------------- 43.9495	19.7912 12.6917 ------------ 32.4829
3	2.3 1.6 1.0	12.9206 17.9275 25.8081	1.67605 0.99800 0.42915	21.6557 17.8917 11.0755 -------------- 50.6229	16.0057 13.2237 8.18593 ------------- 37.4153
4	2.5 1.8 1.3 0.9	9.66600 15.0071 17.7295 19.3330	1.86577 1.18881 0.70665 0.32861	18.0346 17.8410 12.5275 6.3530 --------------- 54.7560	13.3293 13.1862 9.25906 4.69555 -------------- 40.4701
6	2.7	6.85868	2.05442	14.0906	10.4143

	2.3 1.9 1.5 1.1 0.8	6.07878 8.85225 12.7065 17.3401 15.5380	1.63355 1.27335 0.89155 0.51422 0.23195	9.93000 11.2720 11.3285 8.91628 3.60404 ------------- 59.1413	7.33924 8.33113 8.37286 6.59001 2.66374 ------------- 43.7112
12	3.0 2.8 2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2 1.0 0.8	3.94930 1.72889 2.53208 3.04962 3.49903 8.04997 5.40777 6.21261 7.41371 8.83486 9.85604 10.6045	2.45354 2.11802 1.93031 1.73760 1.07744 1.36905 1.16300 0.97121 0.78145 0.59312 0.40580 0.22301	9.22873 3.66182 4.88742 5.29902 3.76985 11.0208 6.28924 6.03368 5.79344 5.23995 3.99958 2.36480 --------------- 67.58830	6.82094 2.70643 3.61228 3.91655 2.78629 8.14546 4.64837 4.45948 4.28192 3.87284 2.95608 1.74782 ------------- 49.9544

Table (4): Conversion efficiencies resulted from n-series connected (optimized) subcells tandem solar cell system, under CR = 1 sun, T = 300 K.

No. of subcells (n)	Subcells (n_i) (ev)	I_{mi} (mA)	V_{mi} , (v) $\sum V_{mi}$, (v)	$P_{m,series}$ = $I_{m,small} \times \sum V_m$ (mW)	η_{series} (%)
2	2.0 1.2	19.2482 27.6351	1.39117 0.62138 $\sum V_{mi}$ = 2.01255	19.2482 × [2.01255] = 38.7381	28.6312
3	2.3 1.6 1.0	12.9206 17.9275 25.8081	1.67605 0.99800 0.42915 $\sum V_{mi}$ = 3.1032	12.92068 × [3.1032] = 40.0954	29.6344
4	2.5 1.8 1.3 0.9	9.666 15.007 17.729 19.333	1.8657 1.1888 0.7066 0.3286 $\sum V_{mi}$ = 4.08977	9.666 × [4.08977] = 39.5319	29.2179
6	2.7 2.3 1.9 1.5 1.1 0.8	6.85868 6.07878 8.85225 12.7065 17.3401 15.5380	2.05442 1.63355 1.27335 0.89155 0.5142 0.23195 $\sum V_{mi}$ = 6.59902	6.07878 × [6.59902] = 40.1139	29.6481
12	3.0 2.8 2.6 2.4 2.2 2 1.8	3.94930 1.72889 2.53208 3.04962 3.49903 8.04997 5.40777	2.45354 2.11800 1.93030 1.73760 1.07740 1.36905 1.16300	1.7288 × [14.8234] = 25.6281	18.9417

	1.6	6.21261	0.97120		
	1.4	7.41371	0.78145		
	1.2	8.83486	0.59310		
	1	9.85604	0.40580		
	0.8	10.6045	0.22300		
			$\sum V_{mi}$ = 14.8234		

Table (5): The candidate subcells ($E_{Gi,A}$) utilized by the approach method (The averaging method), with their referred short circuit currents (I_{sci}), under AM0, CR = 1 sun, and T = 300 K.

$E_{Gi,A}$ (ev)	I_{sc} (mA)	$E_{Gi,A}$ (ev)	I_{sc} (mA)	$E_{Gi,A}$ (ev)	I_{sc} (mA)
3	3.993	1.875	22.8975	1.1	53.439
2.975	4.203	1.8625	23.2702	1.0875	54.458
2.9625	4.308	1.85	23.643	1.075	55.477
2.95	4.413	1.8375	24.0157	1.05	56.157
2.925	4.623	1.825	24.3885	1.0375	56.836
2.9	4.833	1.8125	24.7612	1.03125	57.176
2.875	5.0605	1.80625	24.9476	1.025	57.516
2.85	5.288	1.8	25.134	1.0125	58.195
2.825	5.5155	1.79375	25.3227	1.0	58.875
2.8	5.743	1.7875	25.5115	0.9875	59.561
2.7875	5.89325	1.775	25.889	0.975	60.248
2.775	6.0435	1.75	26.644	0.9625	60.934
2.7625	6.19375	1.725	27.399	0.95	61.621
2.75	6.344	1.7125	27.7765	0.925	62.994
2.725	6.6445	1.7	28.154	0.91875	63.337
2.7	6.945	1.6875	28.5737	0.9125	63.680
2.675	7.286	1.675	28.9935	0.9	64.367
2.65	7.627	1.6625	29.4132	0.875	65.952
2.6375	7.7975	1.65	29.833	0.85	67.538
2.625	7.968	1.6375	30.2527	0.825	69.125
2.6	8.309	1.625	30.6725	0.8125	69.917
2.575	8.68175	1.6125	31.0922	0.8	70.709
2.55	9.0545	1.6	31.512	0.75	73.946
2.525	9.42725	1.59375	31.7446	0.725	75.565
2.5	9.8	1.5875	31.9763	0.7	77.184
2.475	10.201	1.575	32.4407		
2.45	10.602	1.55	33.3695		
2.425	11.003	1.525	34.2982		
2.4	11.404	1.5	35.227		
2.3875	11.6155	1.4875	35.72		
2.375	11.833	1.475	36.213		
2.3625	12.0475	1.4625	36.706		
2.35	12.262	1.45	37.199		
2.3375	12.476	1.4375	37.692		
2.325	12.695	1.425	38.185		
2.3	13.12	1.4125	38.675		
2.275	13.5867	1.4	39.171		
2.25	14.0537	1.375	40.25625		
2.225	14.5202	1.35	41.3415		

2.2	14.987	1.3375	41.88412		
2.1875	15.2531	1.325	42.42675		
2.175	15.5192	1.3125	42.96937		
2.15	16.0515	1.3	43.512		
2.125	16.5837	1.2875	44.12187		
2.1	17.116	1.28125	44.4268		
2.0875	17.4272	1.275	44.73175		
2.075	17.7385	1.25	45.9515		
2.0625	18.0497	1.2375	46.56137		
2.05	18.361	1.225	47.17125		
2.025	18.9835	1.2125	47.78112		
2	19.606	1.2	48.391		
1.975	20.2425	1.1875	49.022		
1.95	20.879	1.175	49.653		
1.9375	21.1972	1.1625	50.284		
1.925	21.5155	1.15	50.915		
1.9	22.152	1.125	52.177		

Table (6): Conversion efficiencies referring applying the averaging method to n-independently operated candidate subcells tandem solar system, with no fine tuning applied; CR = 1 sun, T =300 K.

No. of subcells (n)	$I_{m,A} = \sum I_{mi,A}/n$ (mA)	Candidate Subcells ($n_{i,A}$) (ev)	$I_{mi,A}$ (mA)	$V_{mi,A}$ (v)	$P_{mi,A}$ (mA)	$\eta_{i,A}$, (%) $\sum \eta_{i,A}$, (%)
2	23.4417	1.85 1.2	23.1634 23.7531	1.24875 0.61764	28.9253 14.6709	21.37864 10.84324 -------------- 32.2218
3	18.8854	2.025 1.425 1.0125	18.6428 18.6206 18.8839	1.41490 0.82880 0.43341	26.3777 15.4327 8.18430	19.49574 11.40633 6.049001 --------------- 36.9517
4	15.4341	2.175 1.6 1.21875 0.9	15.2657 15.5875 15.3297 15.6409	1.55725 0.99450 0.62472 0.32350	23.7726 15.5017 9.57680 5.05984	17.57033 11.45733 7.078196 3.739722 --------------- 39.8500
6	11.2296	2.425 1.9 1.55 1.275 1.05 0.85	10.8467 10.9280 10.9162 10.9202 10.8111 10.3789	1.79461 1.27911 0.93680 0.67030 0.45520 0.26780	19.4655 13.9769 10.2263 7.33301 4.92121 2.77948	14.38694 10.33031 7.558253 5.420001 3.637289 2.054313 --------------- 43.3870
12	5.92820	2.775 2.375 2.0625 1.83125	5.97085 5.91559 5.89510 6.02220	2.12495 1.73010 1.42250 1.19630	12.6877 10.2345 8.38578 7.20438	9.377501 7.564355 6.197918 5.324740

		1.6375 1.475 1.325 1.19375 1.08125 0.9625 0.85 0.75	5.90001 5.78606 5.99352 6.01067 5.93489 5.56340 5.88129 5.53806	1.00650 0.84790 0.70365 0.57755 0.47000 0.35680 0.21055 0.16450	5.93743 4.90600 4.21734 3.47146 2.78940 1.98504 1.23830 0.91101	4.388347 3.626020 3.117001 2.565753 2.061641 1.467145 0.915230 0.673327 -------------------- 47.2789

Table (7): The variation of conversion efficiency under varying solar radiation applied to a three-independently-operated candidate subcells, with no fine-tuning, T = 300 K.

Solar intensity variations (Suns)	Candidatesubcells ($n_{i,A}$) (ev)	$I_{mi,A}$ (mA)	$V_{m,Ai}$ (v)	$P_{mi,A}$ (mW)	$\eta_{i,A}$ $\sum\eta_{i,A}$ (%)
100	1.95 1.3375 0.9125	2051.583 2039.316 2062.075	1.4606 0.8616 0.4535	2996.54 1757.07 935.151	22.1474 12.9865 6.91168 ------------ 42.0455
90	1.95 1.3375 0.9125	1846.368 1835.220 1851.885	1.4580 0.8589 0.4509	2692.00 1576.36 835.015	22.1072 12.9454 6.85731 ------------- 41.9100
80	1.95 1.3375 0.9125	1641.155 1631.142 1645.542	1.4549 0.8560 0.4480	2387.71 1396.25 737.203	22.0594 12.8996 6.81082 ------------ 41.7699
70	1.95 1.3375 0.9125	1435.952 1427.085 1439.284	1.4515 0.8526 0.4448	2084.35 1216.80 640.193	22.0077 12.8476 6.75951 ------------- 41.6149
60	1.95 1.3375 0.9125	1230.780 1223.051 1233.089	1.4476 0.8487 0.4410	1781.73 1038.10 543.792	21.9480 12.7876 6.69860 -------------- 41.4342
50	1.95 1.3375 0.9125	1025.574 1019.030 1027.001	1.4430 0.8437 0.4366	1479.90 859.806 448.388	21.8758 12.7096 6.62807

					------------- 41.2131
40	1.95 1.3375 0.9125	820.4025 815.0753 821.0045	1.4373 0.8386 0.4310	1179.18 683.522 353.852	21.7884 12.6297 6.53830 -------------- 40.9564
30	1.95 1.3375 0.9125	615.2464 611.1479 615.1786	1.4300 0.8313 0.4240	879.820 508.102 260.835	21.6758 12.5179 6.42610 ------------- 40.6198
20	1.95 1.3375 0.9125	410.1088 407.2810 409.5505	1.4197 0.8213 0.4140	582.231 334.499 169.553	21.5163 12.3614 6.26585 -------------- 40.1435
10	1.95 1.3375 0.9125	205.0096 203.5054 204.2611	1.4021 0.8038 0.3970	287.443 163.581 81.0916	21.2449 12.0903 5.99347 --------------- 39.3286

Table (8, a): Conversion efficiency comparison referring to Six series-connected sub cells under CR = 100 suns; T = 300 K, Averaging method, before I-V fine tuning is applied.

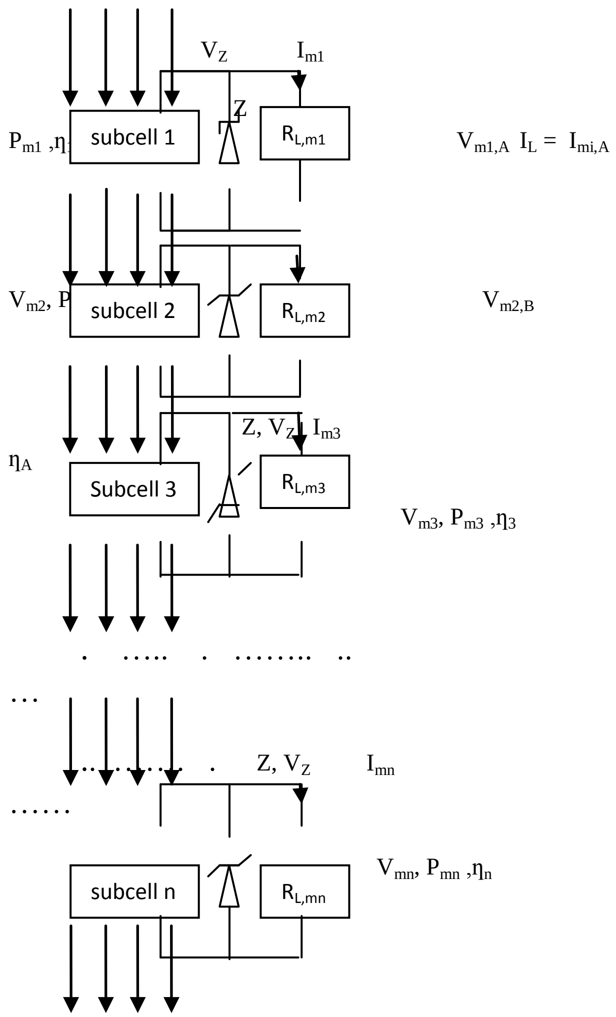
Before I-V curve fine-tuning the candidate subcells				
candidate Subcells (ev)	$I_{mi,A}$ (mA)	$V_{mi,A}$ (v)	$P_{mi,A}$ (mW)	$\eta_{i,A}$ $\sum\eta_{i,A}$ (%)
2.325 1.80 1.4375 1.1625 0.9250 0.70	1230.1 1241.0 1222.3 1213.0 1202.2 1283.3	1.8166 1.3006 0.9459 0.6792 0.4521 0.2446	2234.6 1614.1 1156.3 823.88 543.59 313.90	16.516 11.930 8.5463 6.0893 4.0177 2.3200 49.420

Table (8, b): Conversion efficiency comparison referring to Six series-connected subcells under CR = 100 suns, T = 300 K; (i) Averaging method, after I-V fine tuning is applied, (ii) independently-operated optimized subcells.

After I-V curve fine-tuning the series-connected candidate subcells				Independently-operated subcells (optimal)
$I_{I,A}$ (mA)	$V_{i,A}$ $\sum V_{i,A}$ (v)	$\sum P_{i,A}$ (mW)	$\sum\eta_{i,A}$ (%)	$\sum\eta_{opt}$ (%)

1230.1	1.8167	6673.9	49.33	50.10
1230.1	1.3101			
1230.1	0.9391			
1230.1	0.6673			
1230.1	0.4386			
1230.1	0.2532			
	5.4253			

Incident solar radiation (CR, T) Incident solar radiation (CR, T)



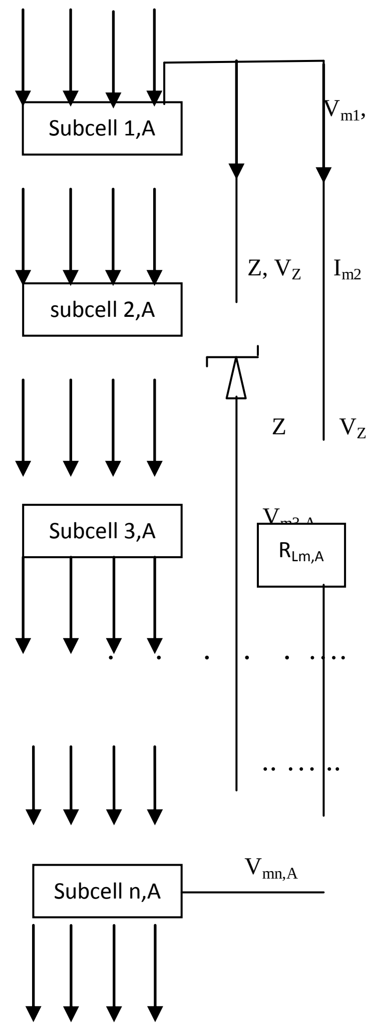


Fig. (1): n-independently operated Fig. (2): n-series tandem

subcells tandem solar cell system.
solar cell system.

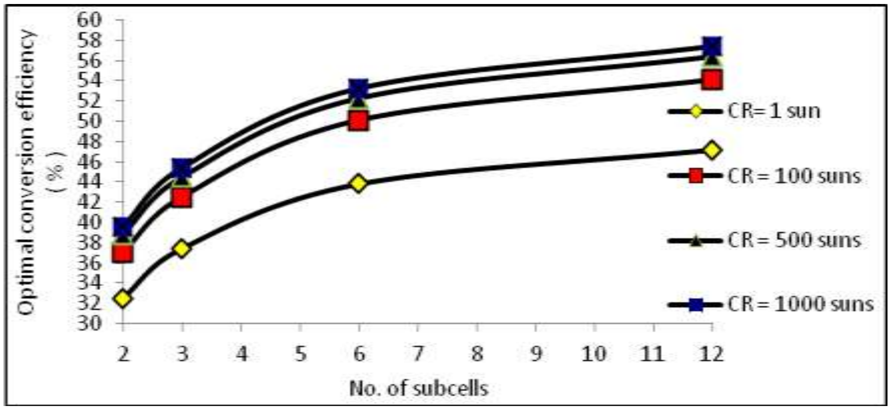


Fig. (3): The variation of the optimal conversion efficiencies with varying the number of the optimized subcells, under T = 300 K and solar intensities; 1, 100, 500, and 1000 suns.

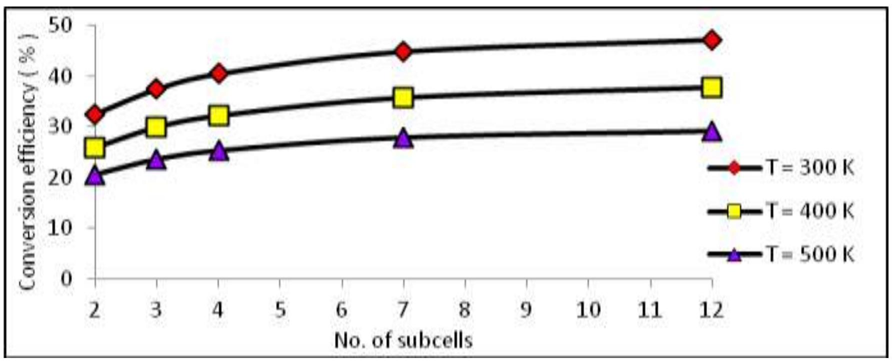


Fig. (4): Variation of the optimal conversion with varying the number of optimized subcells under CR = 1 sun, and temperatures, 300, 400, and 500 K.

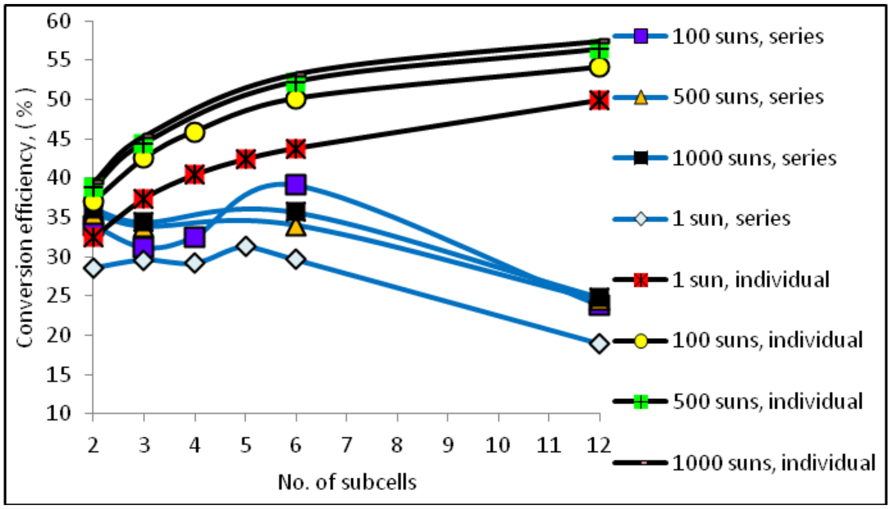


Fig. (5): Comparison of the conversion efficiency variations of the optimized subcells when; (i) independently-operated, (ii) series-connected; under several light intensities; T = 300 K.

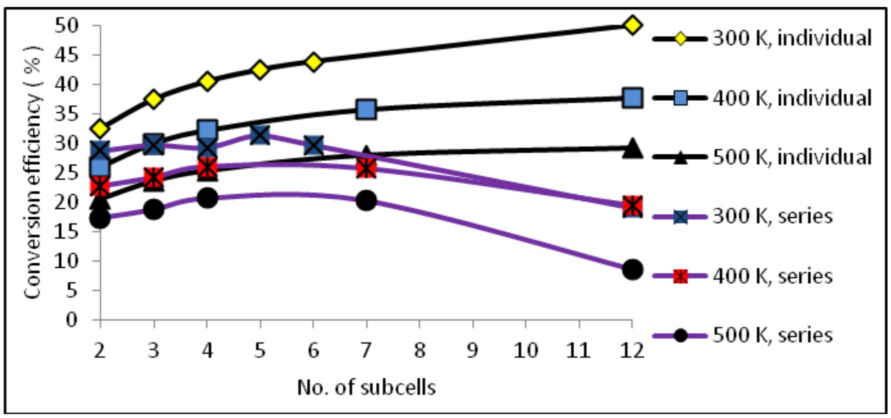


Fig. (6): Comparison of the conversion efficiency variations of the optimized subcells when; (i) independently-operated, (ii) series-connected; under several temperatures; CR = 1 sun.

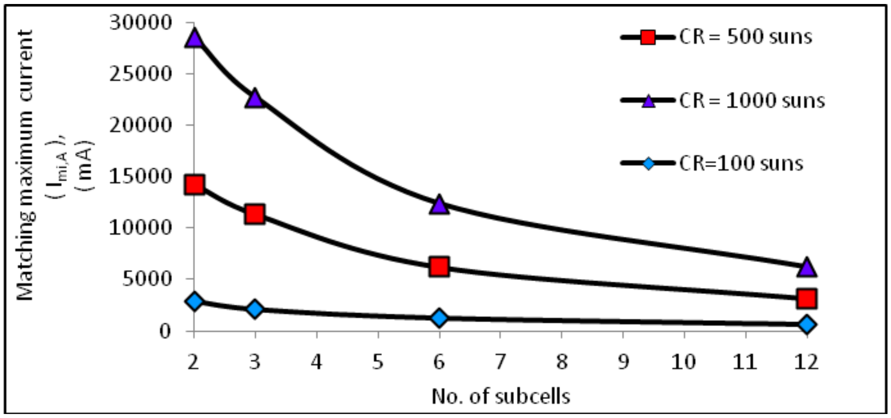


Fig. (7): Variation of the subcells matching maximum currents ($I_{m,A}$) versus their referred number of candidate subcells (n); under several light intensities, T = 300 K.

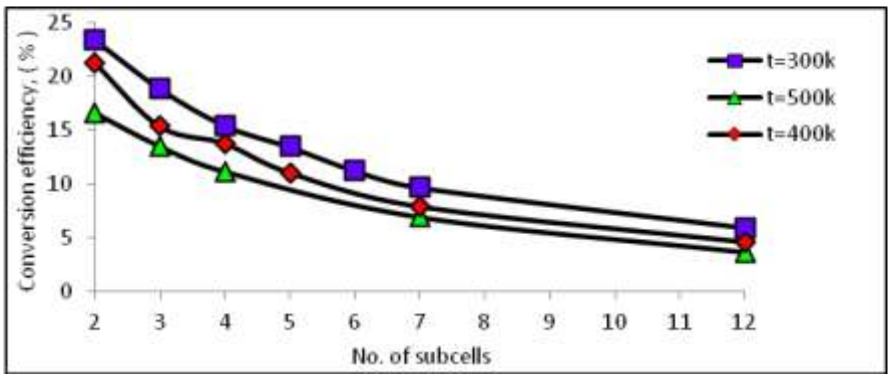


Fig. (8): Variation of the subcells matching maximum currents ($I_{m,A}$) versus their referred number of candidate subcells (n); under several temperatures, CR = 1 sun.

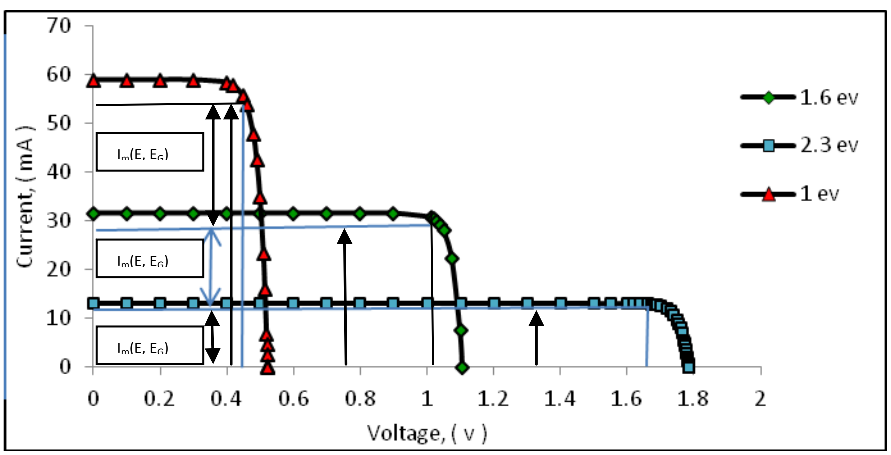


Fig. (9): The I-V curves of three optimized subcells when, each, operated as a single-junction solar cell system; under CR = 1 sun and T = 300 K.

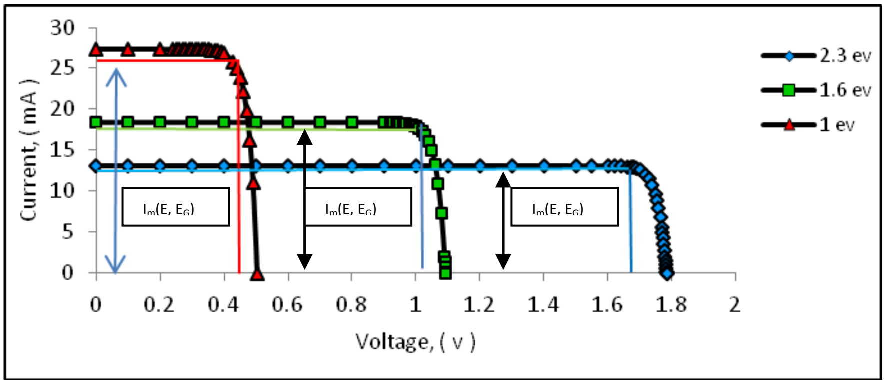


Fig. (10): The I-V curves of three optimized subcells; when, each, operated as an independently tandem solar cell system; CR = 1 sun, T = 300 K.

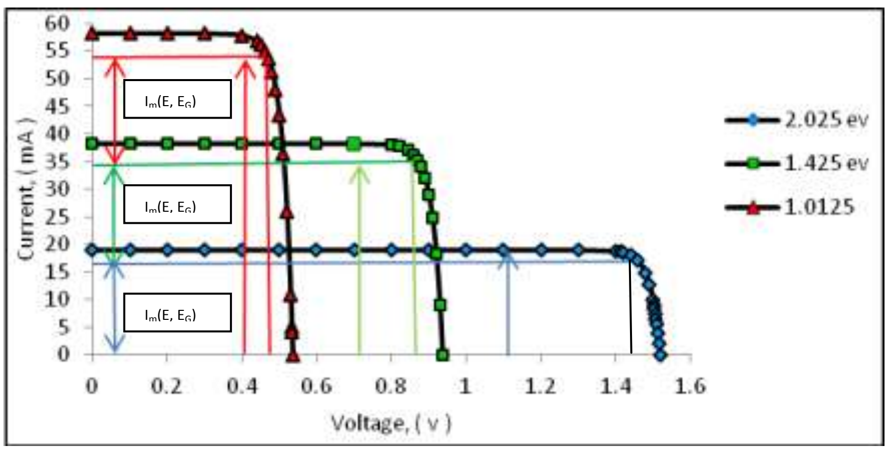


Fig. (11): The I-V curves of three candidate subcells, referred to this work approach " the averaging method" when, each, operated as a single-junction solar cell system; T = 300 K and CR = 1 sun.

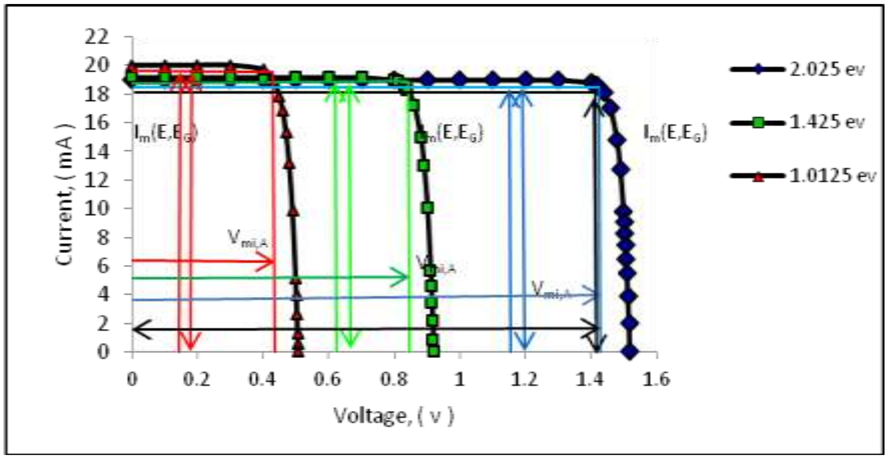


Fig. (12): The I-V curves of three candidate subcells, referred to this work approach " the averaging method " when operated as a series-connected subcells tandem solar cell system, for the cases; prior, and next to applying fine-tuning the I-V curves; under CR = 1 sun and T = 300 K.

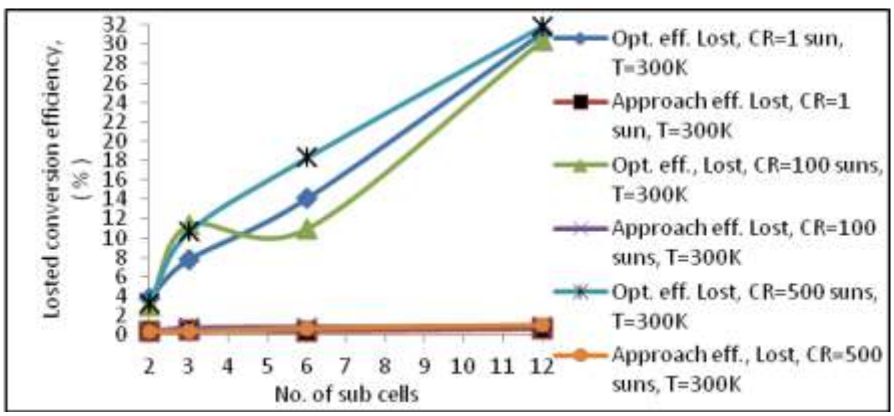


Fig. (13): Comparison between the conversion efficiency lost referred to n-series connected, (i) optimized subcells, (ii) candidate subcells; tandem solar cell system, under several light intensities; T = 300 K.

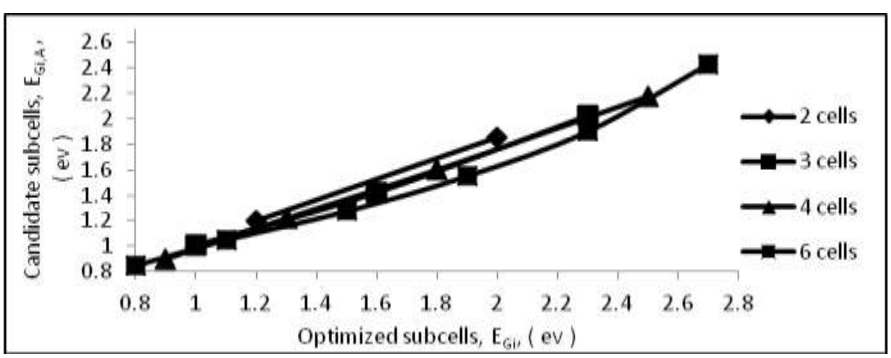


Fig. (14): The candidate subcells ($E_{Gi,A}$) versus the optimized subcells (E_{Gi}); for several number of subcells; under CR = 1 sun, T = 300 K.

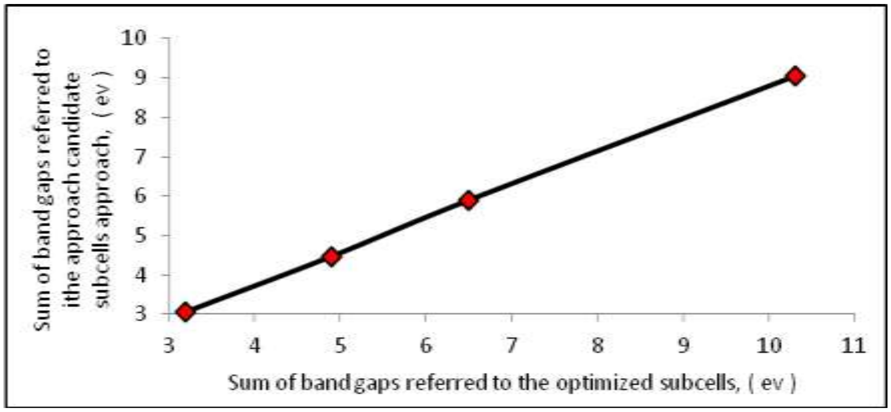


Figure (15): The sum of the individual candidate subcells band gaps ($\sum E_{GiA}$) versus the sum of the individual optimized subcells; CR = 1 sun, T = 300 K.

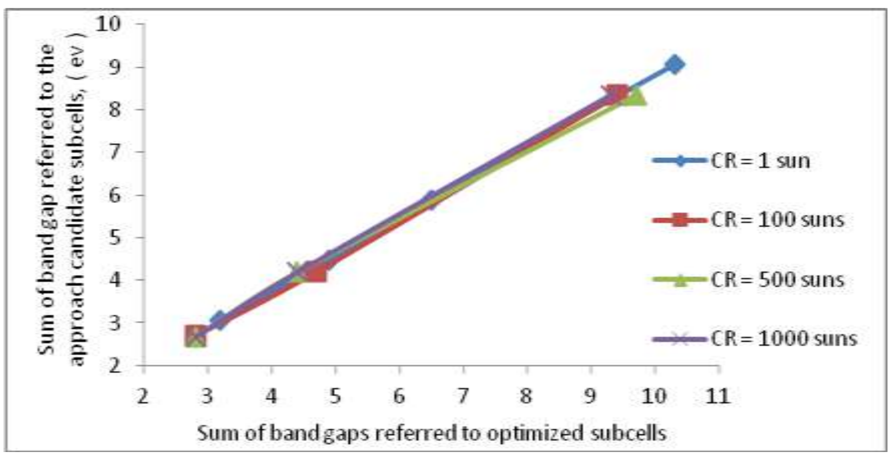


Fig. (16): ($\sum E_{GiA}$) versus ($\sum E_{Gi}$), for n = 2, 3, 4, 6, and 12 subcells under several solar intensities; T = 300 K

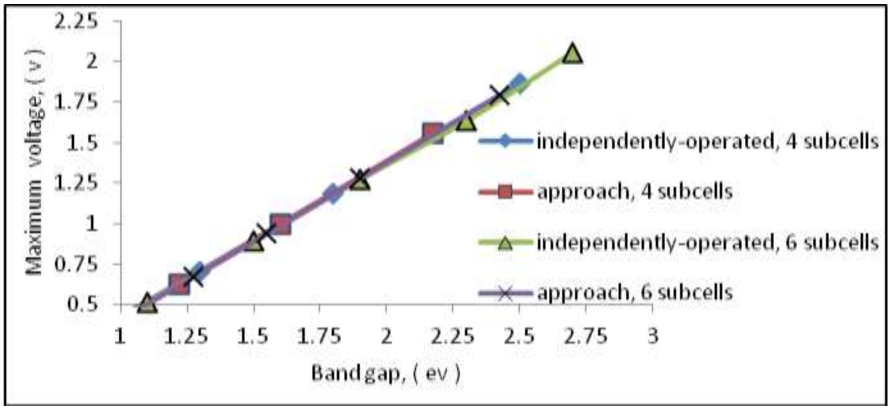


Fig. (17): The individual maximum voltages ($V_{mi,A}$), (V_{mi}) versus their referred band gaps ($E_{Gi,A}$), (E_{Gi}); under CR = 1 sun and T = 300 K.

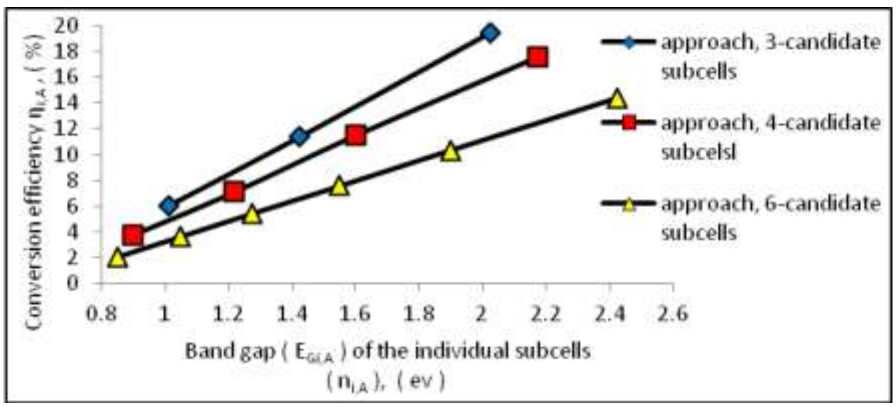


Fig. (18): Variations of the individual conversion efficiency ($\eta_{i,A}$) versus the referred individual band gap ($E_{Gi,A}$), of several (n) series-connected candidate subcells, tandem solar cell system; under CR = 1 sun, T = 300 K.

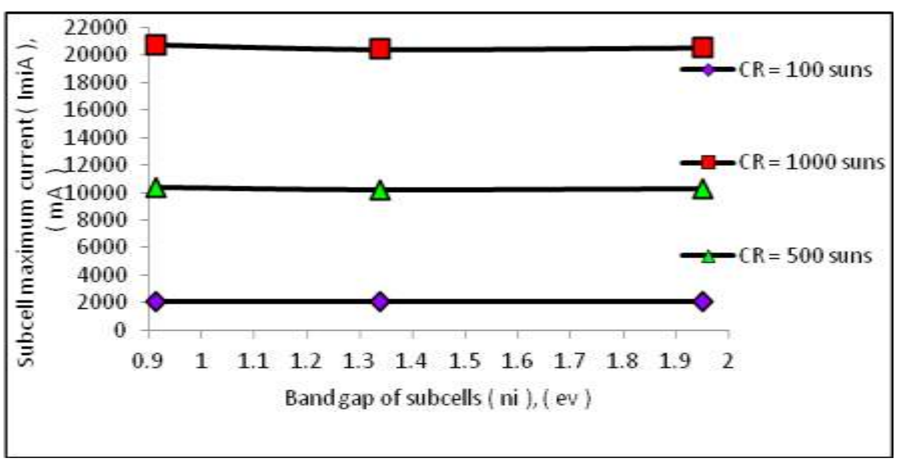


Fig. (19): Variation of the matching current ($I_{mi,A}$) versus its referred individual subcell band gap (E_{Gi}) concerning three series-connected candidate subcells (1.95 ev, 1.3375 ev, 0.9125 ev) tandem solar cell system, prior to applying fine-tuning; under several light intensities, T = 300 K.

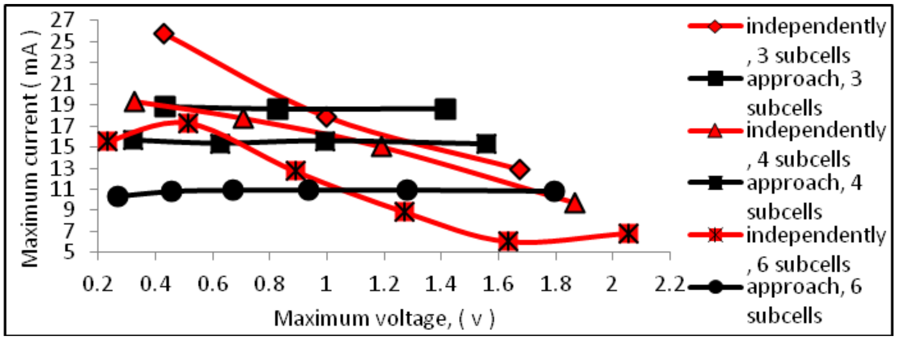


Fig. (20): The variations of the maximum currents (I_{mi}, $I_{mi,A}$) versus their referred maximum voltages (V_{mi} , $V_{mi,A}$), for several n-subcells tandem solar systems; CR = 1 sun, T = 300 K.

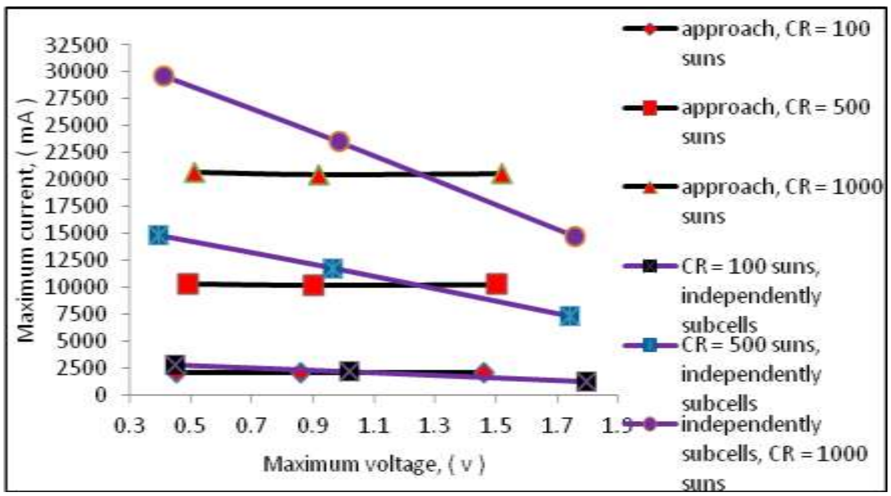


Fig. (21): The variations of the individual subcells, (n = 3), maximum currents (I_{mi}, $I_{mi,A}$) versus their individual maximum voltages (V_{mi}, $V_{mi,A}$), respectively; under solar intensity variations.

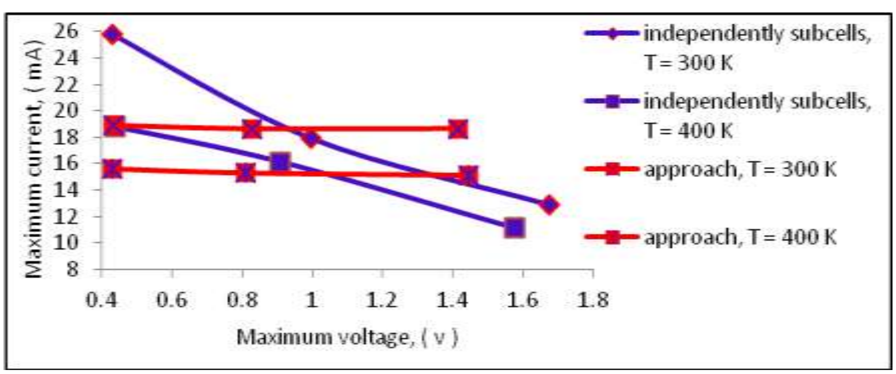


Fig. (22): The variations of the individual subcells, (n = 3), maximum currents (I_{mi}, $I_{mi,A}$) versus the individual maximum voltages (V_{mi}, $V_{mi,A}$), respectively; under temperature variations.

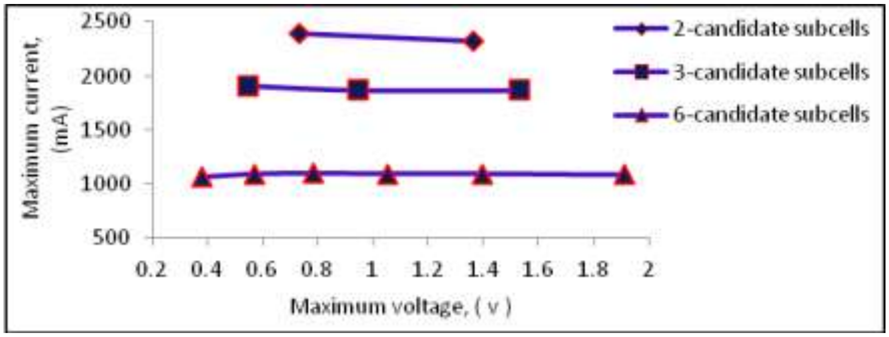


Fig. (23): The variations of the individual subcells, (n = 2, 3, 6), maximum currents ($I_{mi,A}$) versus their individual maximum voltages ($V_{mi,A}$); when these candidate subcells are examined under shifting their intensity radiation from the referred (CR = 1 sun) to the examined (CR = 100 suns).

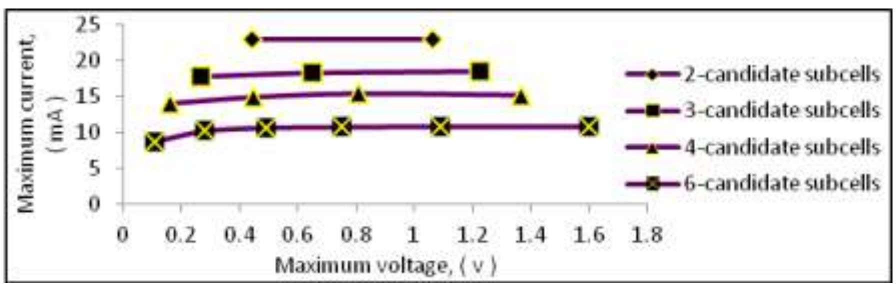


Fig. (24): The variations of the individual subcells, (n = 2, 3, 4, 6), maximum currents ($I_{mi,A}$) versus their individual maximum voltages ($V_{mi,A}$); when these candidate subcells are examined under shifting their temperature from the referred (T = 300 K) to the examined (T = 400 K).

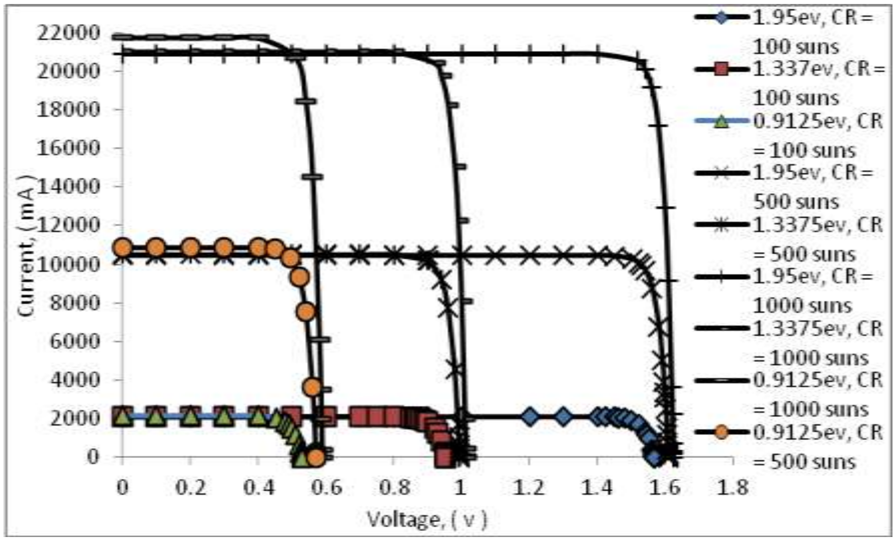


Fig. (25): The I-V curves referred to the approach three series- connected candidate subcells, (1.95 ev, 1.3375 ev, 0.9125 ev), tandem solar cell system; under various solar intensities.

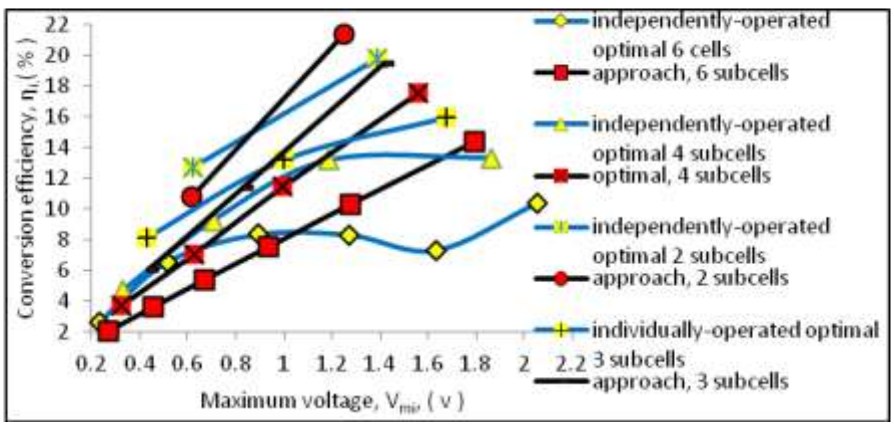


Fig. (26): Variations of; the individual conversion efficiencies, (η_i), ($\eta_{i,A}$), versus their referred individual maximum voltages, V_{mi}, $V_{mi,A}$, respectively; for n = 2, 3, 4, and 6; CR = 1 sun, T = 300 K.

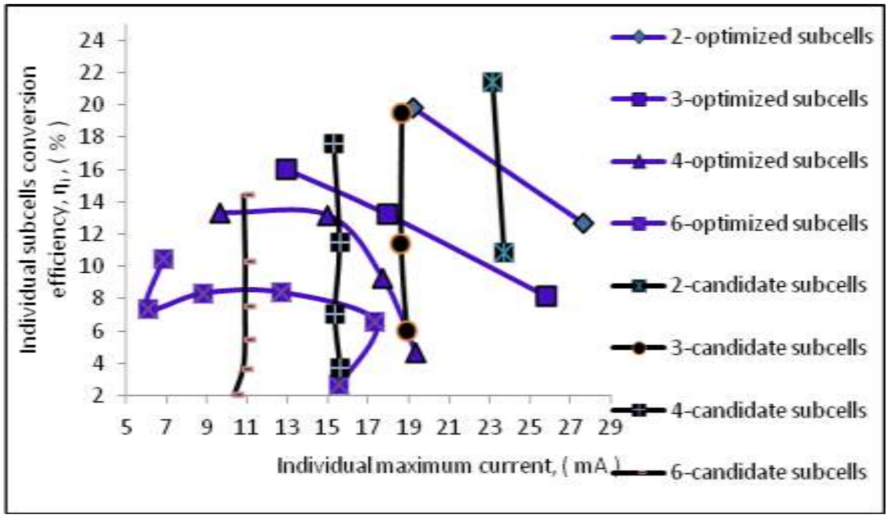


Fig. (27): Variations of; the individual conversion efficiencies, (η_i), ($\eta_{i,A}$), versus their referred individual maximum current, I_{mi}, $I_{mi,A}$, respectively; for n = 2, 3, 4, and 6; CR = 1 sun, T = 300 K. $\eta_{i,A}$ versus $I_{mi,A}$ concerns applying the averaging method with no fine tuning.

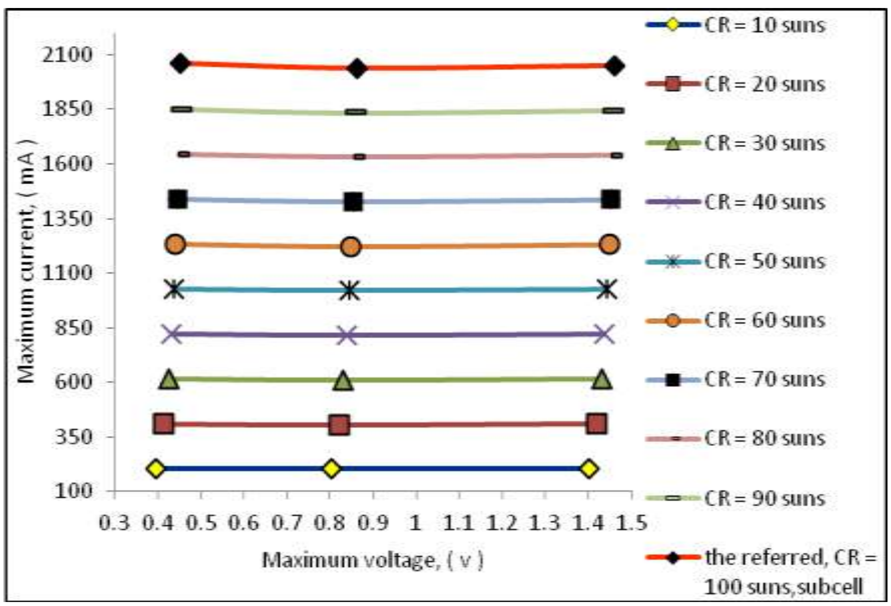


Fig. (28): The variations of the maximum currents ($I_{mi,A}$) referred to the individual three candidate subcells, (1.95 ev, 1.3375 ev, 0.9125 ev), versus their individual maximum voltages ($V_{mi,A}$); when these (same) candidate subcells are examined to operate under varying their intensity radiation from the referred (CR = 100 suns) to the examined (CR = 90, 80, 70, 60, 50, 40, 30, 20, 10 suns); T =300 K.

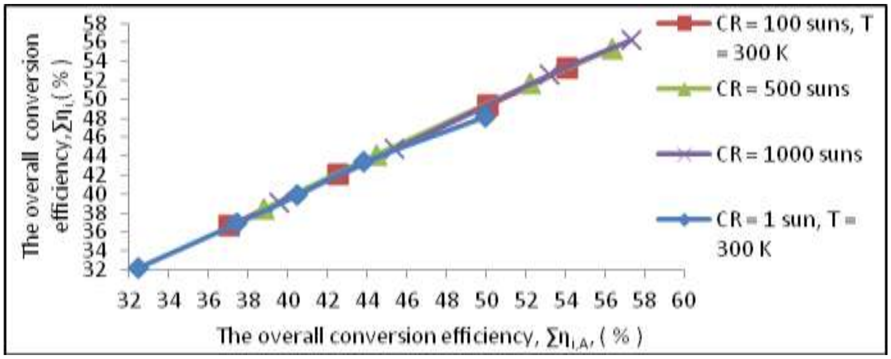


Fig. (29): The overall conversion efficiencies, $\sum\eta_{i,A}$ versus $\sum\eta_i$, for n = 2, 3, 4, 6, 12; under several solar intensities, T = 300 K.

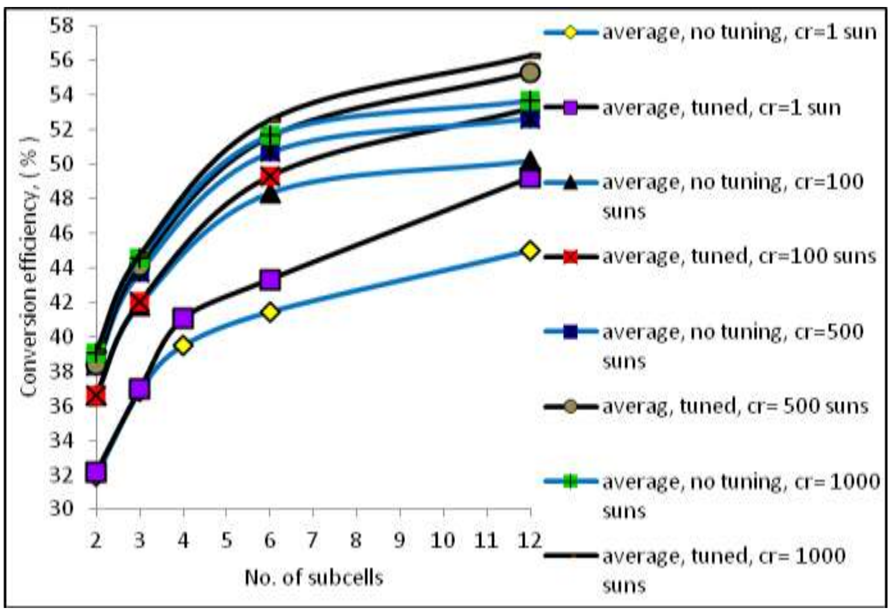


Fig. (30): The conversion efficiency referring to the approach method; under several intensities, T = 300 K, for the cases; (i) no fine tuning applied, (ii) fine tuning applied.

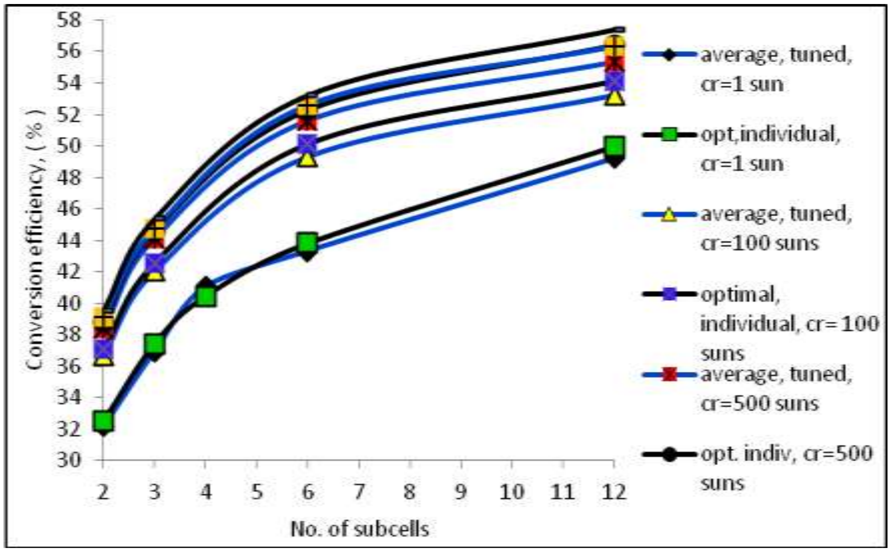


Fig. (31): Conversion efficiency comparison concerning the tandem solar cell systems; (i) the approach, n-series connected candidate subcells, where fine tuning is applied, (ii) the n-independently operated optimized subcells; under several solar intensities, T = 300 K.

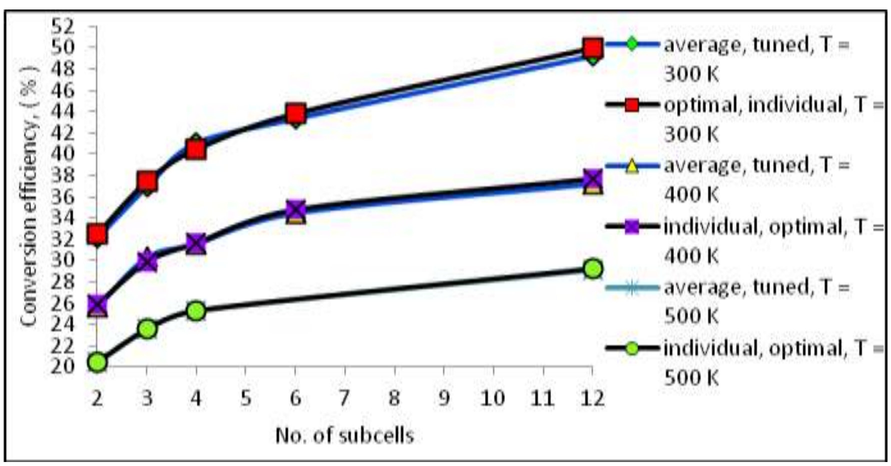


Fig. (32): Conversion efficiency comparison concerning the tandem solar cell systems, (i) the approach, n-series connected candidate subcells, where fine tuning is applied, (ii) the optimized n-independently operated subcells; under several temperatures, CR = 1 sun.

5 CONCLUSIONS

Optimized Individual subcells referred to independently-operated subcell tandem solar cell systems, in addition to their optimal overall conversion efficiencies, they can never at the same time producing a matched maximum subcell's currents. This is because of the wide difference between the maximum currents values these individual optimized-subcells generate; up to the degree where invalid being fine-tuning the I-V curves of these optimized subcells in order to satisfy matched maximum subcell's currents. This in fact the reason why each of the system subcells must operates independently from the other system subcells, but this is at the expense of providing each subcell with a special controller and a special load which is impractical, sometimes, to achieve especially when larger number of subcells should utilized. Achieving, an optimal overall conversion efficiency, tandem solar cell system with single load and single controller is the big challenge question we thought solved involving this work technique referred by " The Averaging Method ".

This approach method (The Averaging method), when applied to a suitable n-candidate series-connected subcells tandem solar cell system, results simultaneously into; a matched subcells maximum currents (equal subcells current), in addition, maintaining the overall conversion efficiency optimal (same as the stack of independently-operated subcells tandem solar cell systems. This matched maximum subcell's current is maintained fixed regardless of solar radiation variations.

Generally, concerning tandem solar cell systems, the most-top subcell is the highest efficient one, while the next-top subcells, their conversion efficiencies alternate in their values. This approach refers to the subcells (candidate subcells) their conversion efficiencies decreasing in descending values starting from that of the most-top subcell down to the most-bottom subcell, without alternation, (for comparison, see Tables (3 and 6).

Results obtained, regardless of whether or not the fine tuning is applied to candidate subcells I-V curves , show a very comparable values, and as a final conclusion; the conversion efficiency regarding this approach reaches the conventionally independently-operated subcells tandem solar cell system (where optimal, but at the expense of multiple controllers and loads, is the conversion efficiency), as discussed above.

As far as the series-connected subcells tandem solar cell system satisfies the matched subcells maximum current, this indicates a possible fill factor evaluation of these systems.

Regarding this work, for certain n-series connected candidate subcells tandem solar cell system; a linear relationship is observed referring to the individual subcells maximum voltages ($_{Vmi,A}$) versus their related conversion efficiencies ($\eta_{i,A}$), as shown in Fig. (17). This linear relationship ($v_{mi,A}$ versus $\eta_{i,A}$), is because equal (matched) made are the subcell's maximum currents. This is not the case when independently-operated optimal subcells tandem solar cells systems are considered, see also Fig. (17). In fact, this linear relationship can never be achieved without subcells transformation from the, optimal (independently-operated) subcell's domain, to the candidate subcell's domain (referred to this work). In addition, a linear proportionality is also observed concerning the algebraic sum of the individual subcell's band gaps of the approach ($\sum$, E_{Gi}), versus the independently-operated ($\sum E_{Gi,A}$), tandem solar cell systems.

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