Optimum Design Of Grid Connected Photovoltaic System Using Concentrators

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Abstract: Due to the increasing demand of electrical energy in Egypt and also in many neighboring countries around the world, the main problem facing electrical energy production using classical methods such steam power stations is the depletion of fossil fuels. The gap between the electrical energy demand and the continuous increase on the fossil fuel cost make the problem of electricity generation more sophisticated. With the continuous decrease of the photovoltaic (PV) technologies cost, it doesn't make sense neglecting the importance of electricity production using solar photovoltaic (PV) especially, that the annual average daily energy received is about 6 $kwh/m^2/\text{day}$ in Cairo, Egypt (30°N).In this work, a detailed simulation model including photovoltaic (PV) module characteristics, and climatic conditions of Cairo Egypt is developed. The model compares fixed PV systems electrical energy output with photovoltaic (PV) system using concentrators and double axis tracker systems. The comparison includes, the energy generated, area required as well as the cost per kwh generated. The optimality criterion is the cost per kwh generated. The system that gives the minimum cost per kwh is the optimum system. To verify the developed model, the simulation results of fixed PV modules and CPV using tracking system obtained by the model are compared with practical measurements of 40KW peak station erected in Cairo Egypt (30°N).Very good agreement between measured values and results obtained from detailed simulation model. For fixed PV system, the detailed economic analysis showed that it gives minimum cost perkwh generated Comparisons among these systems are presented. For Cairo results showed that a cost of about (6 to 9) US cents/kwh is attainable.

Index Terms: (PV) system, Concentrated Photovoltaic (CPV),Fresnel lens concentrator,Multi-Junction solar cell, and ON Gridsystem.

1 Introduction

PHOTOVOLTAIC (PV), is the technology which converts sunlight into electricity, is one ofthe fastest growing sectors of the renewable energy industry. It is already wellestablished in many countries and looks set to become one of the key technologies ofthe 21st century. The market is being driven by concerns about carbon emissions,energy security and the rising price of fossil fuels.Photovoltaic (PV) systems can be grouped into stand-alone systems and gridconnectedsystems. In stand-alone systems the solar energy yield is matched to theenergy demand. Since the solar energy yield often does not coincide in time with theenergy demand from the connected loads, additional storage systems (batteries) aregenerally used. If the PV system is supported by an additional power source forexample, a wind or diesel generator - this is known as a photovoltaic hybrid system.In grid-connected systems the public electricity grid functions as an energy store.In Egypt, most PV systems are connected to the grid, Because of the premiumfeed-in tariff for solar PV plants connected to the public electricity grid in Egypt; all of the energy they generate is fedinto the public electricity grid.

1.1 Concentrated Photovoltaic (CPV)

Solar cells are usually expensive. A potential way of reducing their cost is castingonto them a higher light intensity than is available naturally,forthese solarconcentrators are used.Concentrators are optical elements that collect the Sun's energy in a certain areaand redirect it onto the solar cells. Obviously the collecting optical element has to becheaper per unit area than the solar cell, a necessary although not sufficient conditionto render the concentrated light system less expensive than anon-concentrated one.

Fig. 1.Concentrated Photovoltaic module*

CPV employ mono-crystalline cells (usually multiple stacked) made from III-V semi-conductors.In the PV modules, Fresnel lenses are generally used for optical concentration by a factor of around 500(Figure1).Concentrator modules have to track the sun since only direct radiation can be concentrated then we will use trackers in this system.So calledIII-V semiconductors (multi-Layer semiconductor) with high efficiencyare used instead of conventional crystalline silicon [1],[9].

1.1.1 Multi-Junction solar cells

It consists of elements of group III and group V in the periodic table; enable the production of highly efficient solar cells such as indium gallium arsenide (InGaAs), indium gallium phosphide (InGaP) or germanium. In these multiple solar cell made from different materials and optimized for different parts of the solar spectrum (figure 2) are stacked one above the other (known as multi-junction cells) but since these cells are extremely expensive, low cost lenses are used to collect sunlight from larger receiving area and concentrate it on highly efficient, small cells that are often only a few square millimeters in size [2], [3], [5].

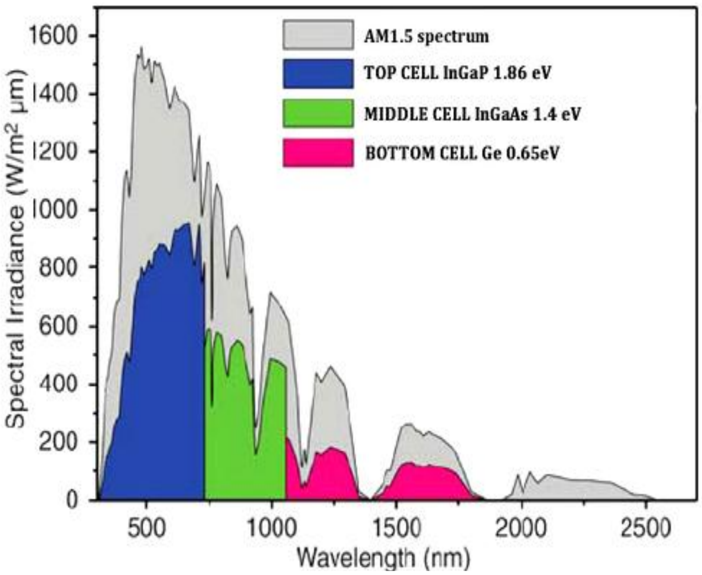

Fig. 2. *Solar Spectrum*

1.1.2 Fresnel Lens concentrator

It's a Positive Focal Length Fresnel lens Used as a Collector (Figure 3), Assuming that the lens has a negligible thickness, the beams are normally incident and all beam at prisms centers accumulated at absorber center [9], then the concentration factor C is defined as [11]:

$$C = \eta_{op} \frac{B}{a} (1.1)$$

Where $(\eta_{op})$the optical efficiency of the system, (B) is is the half width of the lens and (a) is the half width of the absorber (multi-junction solar cell).

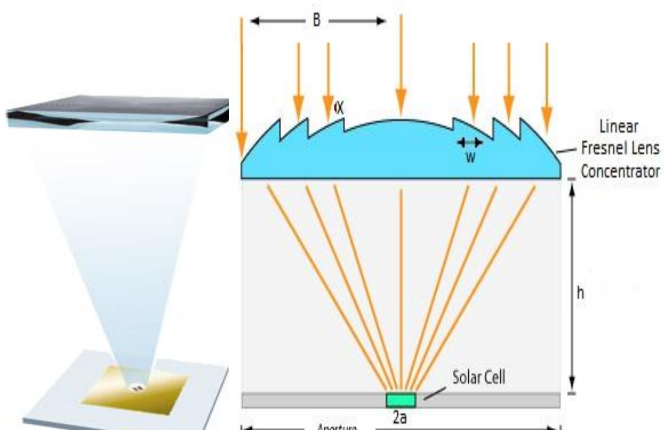

Fig. 3*.Principle of concentration using Linear Fresnel lens.*

For quasi static systems (no tracking system used) the incident beams make an angle θ with the axis of the concentrator varies from $(-\theta_m)$ before noon to zero at noon to $(+\theta_m)$ after noon, we get the concentration factor C is given by [11]:

$$C = \eta_{op}\{1 + \frac{h}{a} tan[\sin^{-1}[n \sin(\alpha_m - \theta_m)] - \alpha_m]\}(1.2)$$

Where (h) is the distance from plane of absorber to the lens plane, (n) is the value of refractive index that depends on the material of the lens n=1.5 for plastic sheets and (α_m) is the maximum prism angle of the outer prisms.

1.2 Tracking system

Trackers is a mechanical steel structure consisting of a mast, a drive with azimuth and elevation motors, ribs, stringers, and brackets to secure the CPV modules. Itperforms two main functions that: supports the CPV modules and moves to follow the sun all the time. The vast majority of the energy gains when using a tracking system are achievedduring summer. First, the absolute energy yield is higher than in winter; theproportion of cloudy days is also much higher in winter.There are various types of tracker systems - that track the sun, single-axis and dual-axis tracking. With dual-axis tracking thesystem always maintains the optimum alignment to the sun [14].

1.2.1 Dual axis (Angles) definition

Here the system can either track the sun's daily path or its annual path.

A system that tracks the annual path is relatively easy to implement. To do this, the tilt angle (β) (figure 4) of the array needs to be adjusted daily so that,

$$\beta = \phi - \delta (1.3)$$

Where (ϕ) the latitude angle of the place of the PV plant and (δ) the solar declination angleare defined in next sections. A system that tracks the sun's daily path. To do this, theazimuth angle (γ) adjusted to be zero.Exact knowledge of the sun's path is important for calculating irradiance values andthe yields of solar energy systems. The sun's altitude can be described at any locationby the solar altitude and the solar azimuth. When talking about solar energy systems, due south is generally given as γ = 0°,Angles to the east are indicated with a negative sign (east: γ = -90°), andto the west;angles are given without a sign (or with a positive sign) (west: γ = 90°) (figure 4) [1], [6], [7].

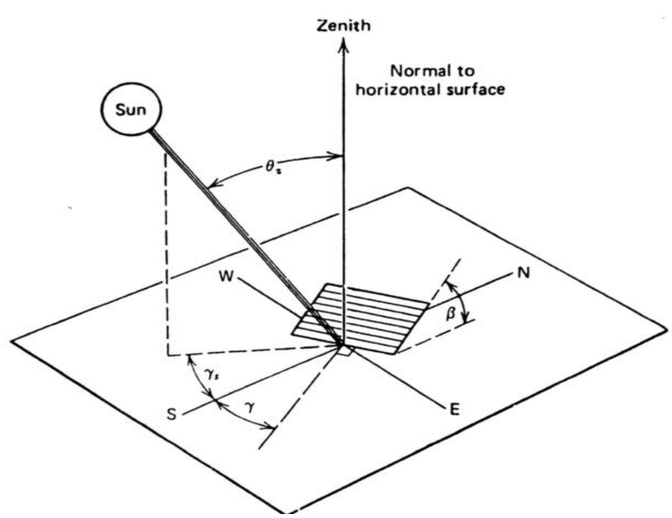

Fig. 4*.Solar angles in the solar sector*

1.2.2 Latitude angle (ϕ)

The earth is divided in to 90 latitudes north and 90 latitudes south, each latitude is a circle drawn on the globe (earth's sphere). As the latitude increases the latitude circles which are parallel circles becomes smaller. The latitudes ϕ=23.45°N (Cancer tropic) and 23.45°S (tropic of Capricorn) (Figure 5) are of special importance since the apparent sun's movement lies between these latitudes as [7], [10].

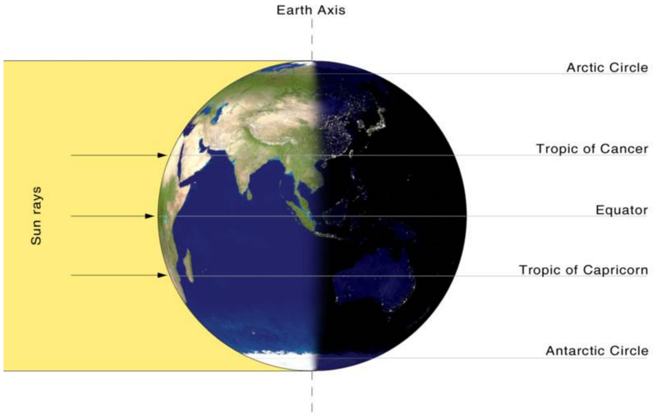

Fig.5*.Latitude angles*

1.2.3 Solar declination angle (δ)

The angle between sunrise line and the axis of rotation of the earth is called the solar declination angle(δ), it varies between(-23.45°) at winter solstice (21 December) and (+23.45°) at summer solstice (21 June) and become (0°) at spring and autumn equinox (21 March, 21 September) (Figure 6). The empirical formulato calculate the solar declination angle (in degrees) is [6], [7], and [11]:

$$\delta = 23.45 \sin\left[\frac{360}{365} \times (284 + n_d)\right] (1.4)$$

Where(n_d)is the day'sindex per year; ($1 \leq n_d \leq 365$).

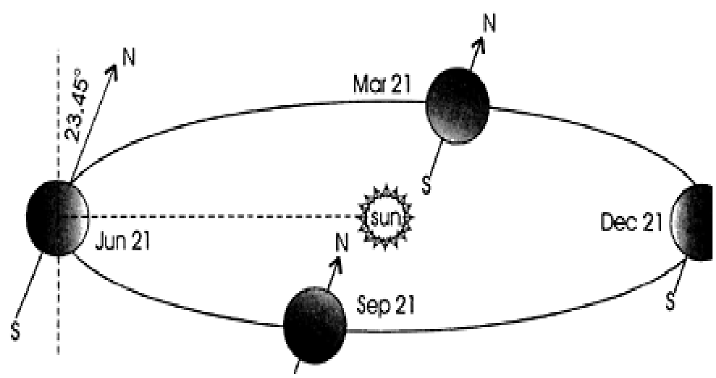

Fig. 6*.The orbit of the earth and the declination at different times of the year.*

1.3 Solar radiation

The sun is a sphere of intensely hot gaseous matter with diameter of $1.39 \times 10^9 m$ and is on the average, $1.5 \times 10^{11}\, m$ from the earth. It has an effective blackbody temperature of 5762°K.The sun is, in effect, continuous fusion reactor with its constituent gases as the "containing vessel" retained by gravitational forces. Several fusion reactions have been suggested to supply the energy radiated by the sun. Measurement were made for extra-terrestrial radiation with variety of instruments in nine separate experimental programs, they resulted in a value of the solar constant G_{sc} of 1353 W/m^2, with estimated error of ± 1.5 percent, is given by [12], [14]

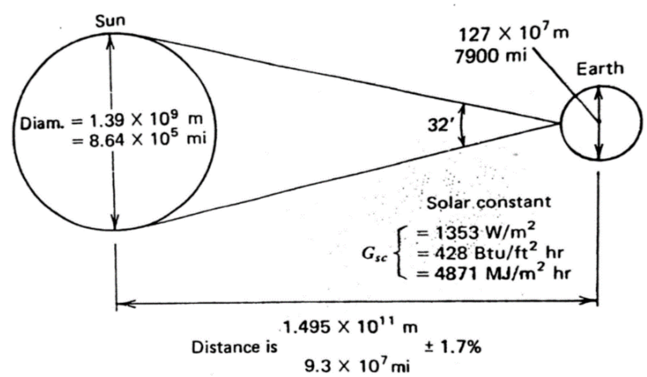

Fig. 7*.Sun-earth relationship*

1.3.1 Radiation on Horizontal Surface

The rate, at which radiant energy is incident on asurface per unit area of surface, is known as global radiation (W/m^2), the symbol G is used, with appropriate subscripts, for beam or diffuse radiation as [6].

$$G = G_{sc}\left(1 + 0.033 \cos\frac{360\, n_d}{365}\right) (1.5)$$

Where G_{sc} is the extra-terrestrial radiation on the plane normal to the radiation on the n_d ofthe year.

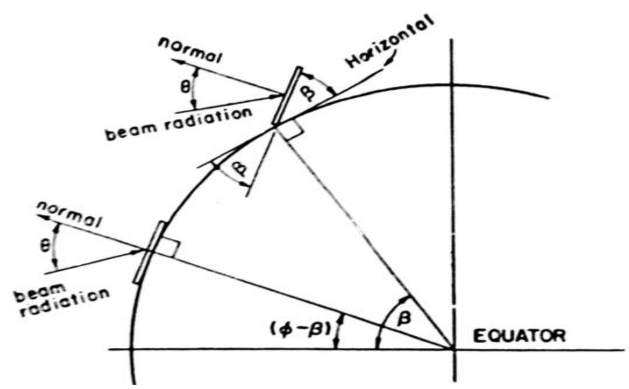

Fig. 8. *Radiation on tilted surface and on a horizontal one*

1.3.2 Radiation on Tilted Surface

The rate at which radiant energy is incident on a surface per unit area on tilted surface (figure 8),is known as instantaneous global radiation on tilted surface (W/m^2), the symbolG_T is used, it is defined mathematically as [15],

$$G_T = \frac{\pi}{24}\, H_T\, \frac{\cos w - \cos w_s'}{\sin w_s' - w_s' \cos w_s'} (1.5)$$

Where w is the hour angle, equal$\frac{\pi}{12} \times (t - 12)$,where t is the solar time, ($t = 12$) at noon, and w_s' is hour Angle on tilted surface, and$H_T$is the monthly average daily radiation on tilted surface ($Kwh/\,m^2$/day), its defined mathematically as [15],

$$H_T = H_B[1.13K_T R_b + 0.5(1 + \cos\beta)(1 - 1.13K_T) + 0.5\rho(1 - \cos\beta)] (1.6)$$

Where K_T is the clearness index defined as the relation between solar radiation measured on horizontal surface ($Kwh/\ m^2$/day) (H_B) and monthly average extra-terrestrial solar insolation (Kwh/m^2/day) on horizontal surface, and ρ is reflectivity of the ground (ρ = 0.2 for normal ground and 0.7 for snowy ground), R_b is the ratio between direct solar radiation on tilted surface to that on a horizontal one (figure 8), its defined mathematically as [6], [12]

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\ \sin w_s' + w_s'\ \sin(\phi-\beta)\sin\delta}{\cos\phi\ \cos\delta \sin w_s + w_s \sin\phi \sin\delta} \quad (1.7)$$

2 DESIGN OFPV POWER PLANT

One megawatt peak PV power plant will be designed by two different technologies:

1. (1MWp) using fixed arrays using mono-crystalline silicon PV power plant.
2. (1MWp) using multi-junction solar cell operating under concentration (CPV) power plant using trackers.

MATLAB simulation programdevelopedin order to simulate the dynamic behavior of the two PV plant systemsin the form of mathematical model (equations), the simulation takes considerations the Mateo data(natural and environmental factors) of Cairo/Egypt,and then compares results with measured values (figure8)obtained from 40 KWp actual fixed (β=25°) mono-crystalline silicon PV plant erected in Nasr City /Cairo/Egypt (30°N) owned by(North Cairofor Electricity Distribution Company).The flow chart of the simulation MATLAB program is indicated in (figure 10).

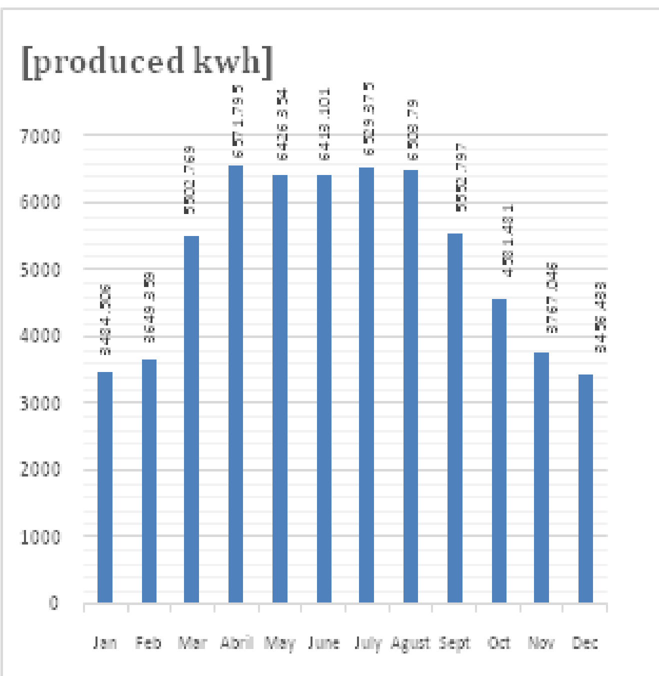

Fig.9.*Measured Produced energy from 40KWp PV plant at Cairo, Egypt duringperiod 1st March 2014 – 28th Feb. 2015.*

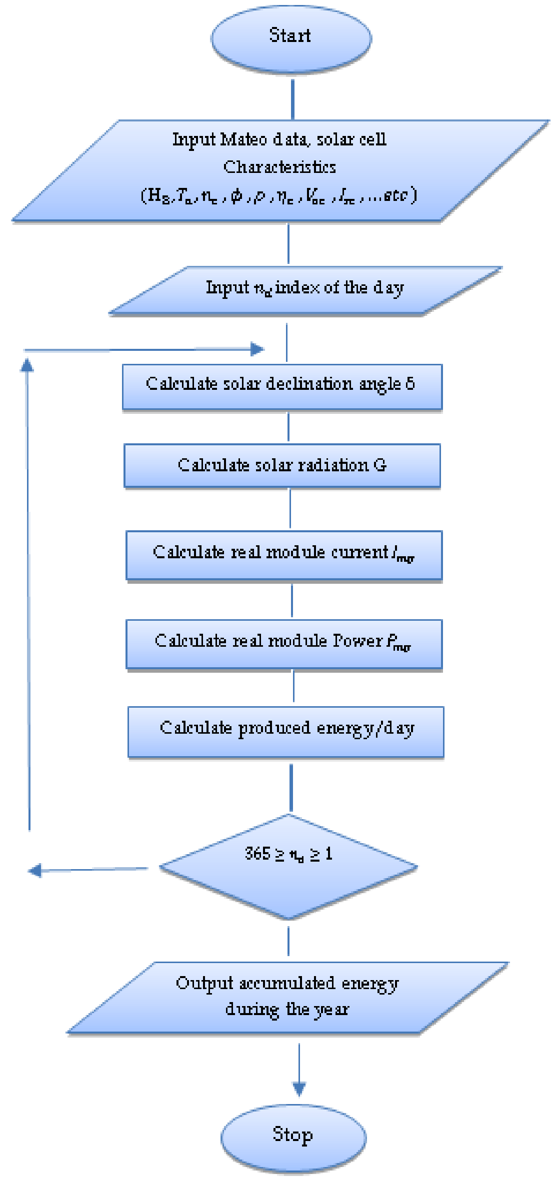

Fig.10. *Flow chart of developed MATLAB simulation program*

2.1 Design of 1MWp using Fixed PV System

The design procedure for MATLAB simulation program takes some inputs in consideration, PV modules fixed attilt angle ($\beta = 20°, 25°, 30°$) , the Mateo data such ($H_B, T_a, n_c, \phi, \rho$) defined in section 1, and n_c the estimated number of successive cloudy days in Cairo, Egypt($n_c = 3$ days), and the characteristics for solar cell module as[6], [14] ($P_p, \eta_c, V_{oc}, I_{sc}, V_{mp}, I_{mp}$),where$P_p$is the peak power of solar cell module (P_p=200Wp),η_c is the efficiency of solar cell module($\eta_c \cong 15\%$), V_{oc} is the open circuit voltage of the module (V_{oc}=30V), I_{sc} is the short circuit current of the module (I_{sc}=8.27A), V_{mp} is the maximum power voltage (V_{mp}=25V), and I_{mp} is the maximum power current (I_{mp}=8A) [6], [14].

For a complete year, the program (figure 10) will calculate the following:

1. Solar declination angle as a function of day

$$\delta = 23.45 \sin\left[\frac{360}{365} \times (284 + n_d)\right]$$

2. Solar radiation on tilted surface

$$G_T = \frac{\pi}{24} H_T \frac{\cos w - \cos w_s'}{\sin w_s' - w_s' \cos w_s'}$$

3. The module current due radiation

$$I_{mp} = (I_{sc} \cdot G_T) - \left(I_o \cdot e^{\frac{V_{mp}}{V_{TC}}}\right) (2.1)$$

Where, T_c isthe solar cell temperature,

$$V_{TC} = 2.33\left(\frac{T_c - 273}{300}\right), \quad I_o = 5.9 \times 10^{-6}\left(\frac{T_c + 273}{300}\right)^3$$

4. The module power

$$P_{mp} = I_{mp} \times V_{mp} \ (2.2)$$

5. The accumulated energy during the day

$$E_{mp} = \int P_{mp} \cdot dt (2.3)$$

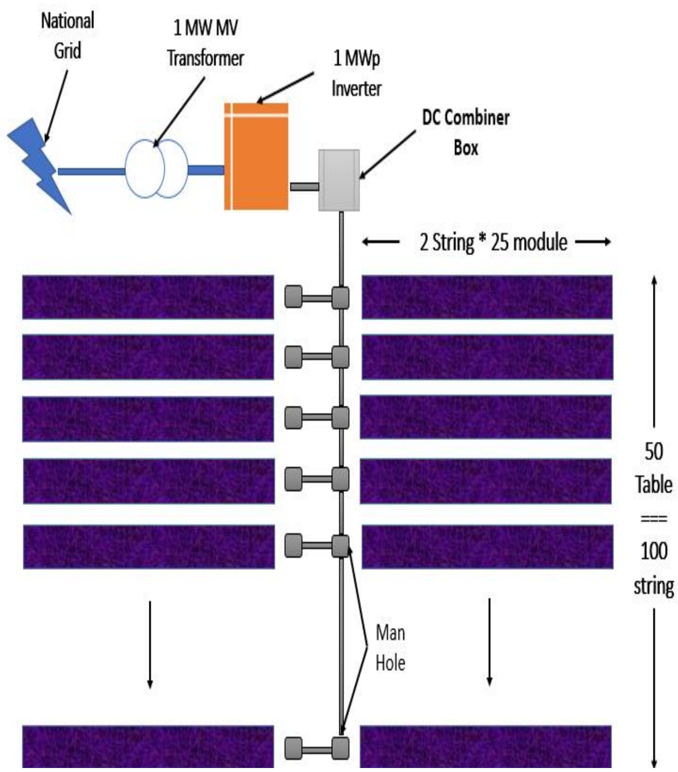

Fig. 11. *Plane of 1MWp fixed PV power plant*

After calculating the accumulated energy from the crystalline solar cell, it transferred to the national grid (figure 11) through 3-phase (1MWp) centralized Inverter and medium voltage transformer that step up voltage from 380V to medium voltage (11 or 22 or 66 KV) with real efficiency about 90%(AC energy≅90% from the DC energy due the efficiency of the inverter ($\eta_{inv} = 90\%$) and the power factor ($\cos\varphi = 0.99$).

2.2 Design of 1MWp using CPV Tracker System

Choosing certain type of CPV modules and tracker system manufactured by Soitec company in USA called (Soitec CX-S530-II CPV system). The design procedure for MATLAB simulation program takes new inputs in consideration for CPV system. The constructions of the (CX-M500) CPV modules have (CX-T030-II) 2-axis tracker system; first axis is the tilt angle where all the time ($\beta = \phi - \delta$), and the second axis is the azimuth angle $\gamma_s = zero$to track the east-west movement of the sun. Also as the fixed system takes the Mateo data for Cairo, Egypt ($H_B, T_a, n_c, \phi, \rho$) in to consideration section (1).The CPV system takes same data in to consideration and concentration ratio C , the Fresnel lens concentrators ($C = 500$).$P_p$is the peak power of multi-Layer solar cell module (P_p=2550Wp ± 10%), η_c is the efficiency of solar cell module ($\eta_c \cong 32.8\%$), V_{oc} is the open circuit voltage of the module (V_{oc}=740V), I_{sc} is the short circuit current of the module (I_{sc}=4.4A), V_{mp} is the maximum power voltage (V_{mp}=645V), and I_{mp} is the maximum power current (I_{mp}=4A) [1].

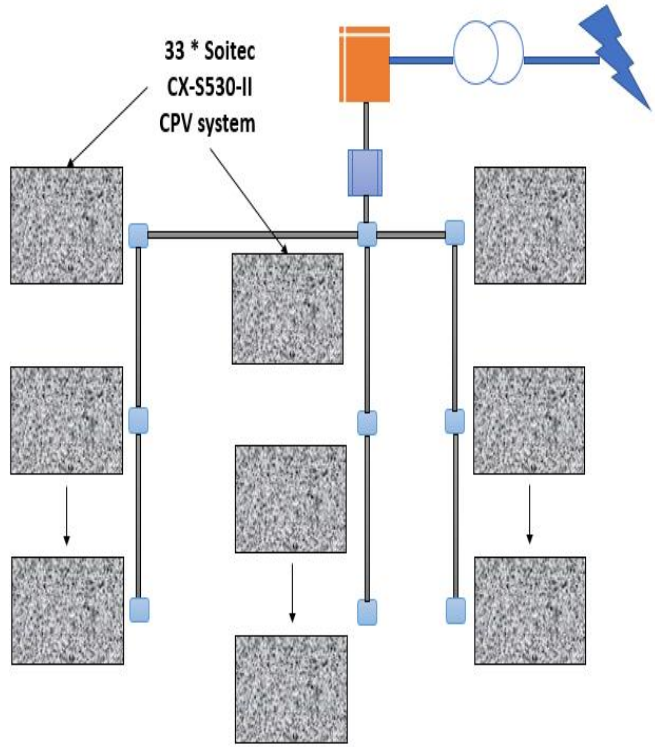

Fig. 12*. Plane of 1MWp using CPV modules and tracker system*

As the fixed system the developed MATLAB simulation program enter the (n_d) loop (figure 9) to calculate the following:

1. Instantaneous tilt angle as a function of latitude angle (ϕ), and solar declination angle (δ)

$$\beta = \phi - \delta$$

2. Instantaneous solar irradiance under concentration

$$G_{eff} = \frac{GT(1-KT)}{\cos\theta_T} + (KT * GT)(2.4)$$

Where:

$\theta_T = \cos^{-1}(\cos\delta\cos(\phi-\beta)\cos w + \sin\delta\sin(\phi-\beta))$,and then it calculate the array current and power, and the accumulated energy over the year using equations (2.1 through 2.3), then the generated energy transferred over the public grid (Utility) through either centralized or decentralized inverters and step up transformer with efficiency 90%.

3 Results

3.1 Fixed Traditional crystalline system

To obtain the optimum design for fixed system, the tilt angles (β= 20°, 25°, 30°) are chosen to be around the latitude angle (ϕ=30°N), and we found that the monthly daily average energy calculated by 1Megawatt peak PV power planterected in Cairo, Egyptis as showed (see Table 1).

TABLE1 *Monthly daily average energy for fixed system*

Month	Energy calculated (MWh /day)		
	β=20°	β=25°	β=30°
Jan	3.4130	3.6091	3.7824
Feb	4.7467	4.9438	5.1078
Mar	5.4987	5.5856	5.6325
Apr	5.5553	5.5037	5.4139
May	5.8551	5.6956	5.4999
June	5.8258	5.6157	5.3726
July	5.7883	5.6022	5.3803
Aug	5.8631	5.7662	5.6286
Sep	5.4031	5.4425	5.4408
Oct	4.8582	5.0285	5.1613
Nov	3.5136	3.7026	3.8688
Dec	3.0693	3.2658	3.4414

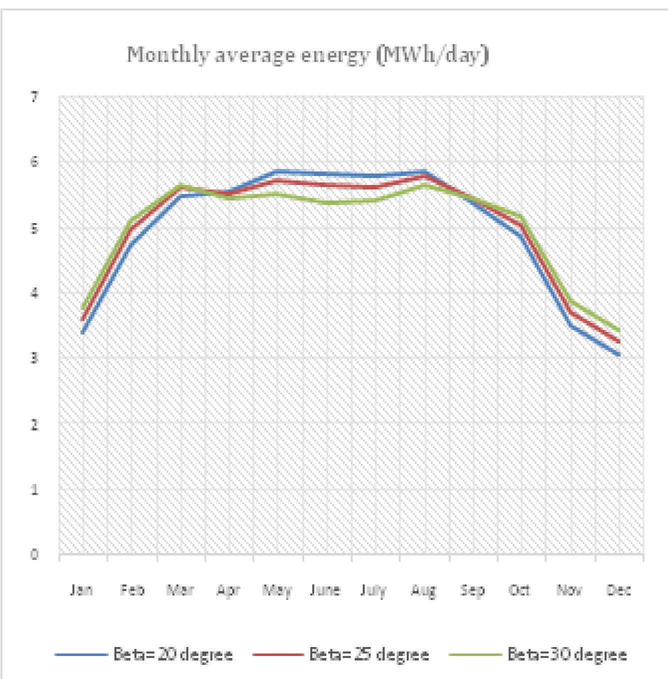

Fig. 13. *1MWp calculated Monthly daily averageenergy*

Then theAnnual yield from this system at (β=20°, 25°, 30°) are represented (see Table 2)

Table 2 *The effect of Annual yield with varying tilt angle*

Annual yield	Tilt angle		
	β=20°	β=25°	β=30°
DC (GWh/year)	1.8065	1.8177	1.8168
AC (GWh / year)	1.62585	1.63593	1.63512

Comparing these results with normalized measured values (figure 14) from 40 KWp actual fixed (β=25°) PV plant installed in Cairo, Egypt (30°N); for more verification of our simulated system results at (β=25°)(see Table 3).

Table 3 *MONTHLY yield for fixed system*

Month	Monthly yield (MWh / month) at (β=25°)	
	Measured	Calculated
Jan	87.11265	100.6939
Feb	91.23398	124.5838
Mar	137.5692	155.8382
Apr	164.2949	148.5999
May	160.6589	158.9072
June	160.3275	151.6239
July	163.2344	156.3014
Aug	162.5948	160.877
Sep	138.8199	146.9475
Oct	114.537	140.2952
Nov	94.17615	99.9702
Dec	86.41083	91.11582
Total Annual yield	1560.97MWh/year	1635.754MWh/year

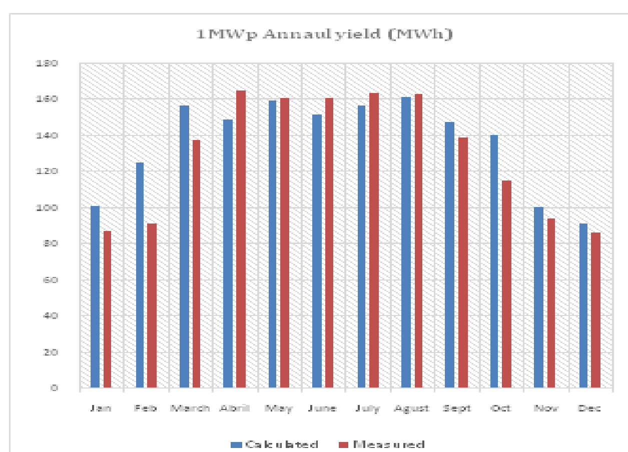

Fig. 14. *1MWp Annual yield (Calculated vs. Measured)*

3.2 Multi-Junction Crystalline that Track Sun

For the multi-junction concentrated photovoltaic (CPV) (Soitec 2550Wp) module; when entering it and it's parameters to our MATLAB developed simulation program tacking in consideration the concentration and tracking systems, we get the values of average monthly daily energy for this module (see Table 4).

Table 4 *Monthly daily average energy of soitec module*

Month	Monthly daily average energy production of 1 Soitec 2550Wp CPV module using trackers (KWh/day)
Jan	11.754
Feb	15.919
Mar	16.935
Apr	18.255
May	20.25
June	22.232
July	22.017
Aug	20.722
Sep	18.661
Oct	17.768
Nov	13.556
Dec	11.6

Finally energy production comparison (figure 14) between two systems the first is (1MWp) fixed crystalline silicon PV power plant and the second is (1MWp) multi-junction solar cell CPV power plant using trackers (see Table 5)

Table 5 *Comparison between two systems*

Month	Energy Production (MWh)	
	First system	Second system
Jan	100.6939	145.7496
Feb	124.5838	197.3956
Mar	155.8382	209.994
Apr	148.5999	226.362
May	158.9072	251.1
June	151.6239	275.6768
July	156.3014	273.0108
Aug	160.877	256.9528
Sep	146.9475	231.3964
Oct	140.2952	220.3232
Nov	99.9702	168.0944
Dec	91.11582	143.84
Total AC Annual yield	1635.754MWh/year	2599.896MWh/year

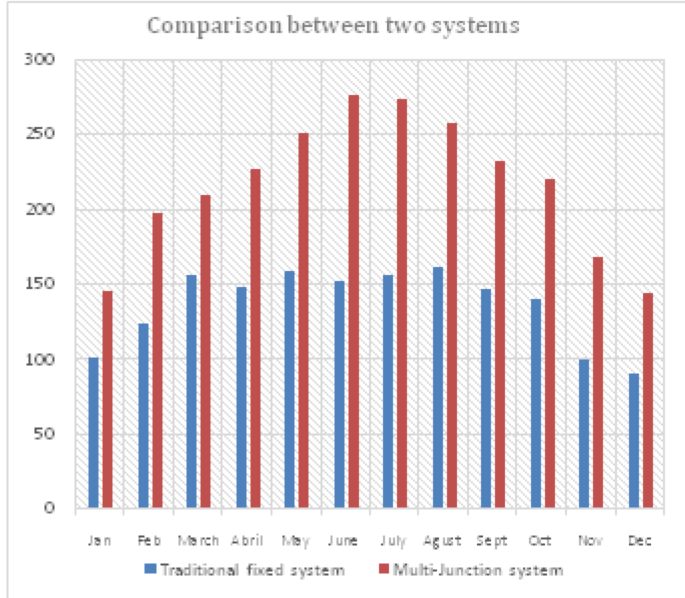

Fig.15. *Traditional fixed system vs. Multi junction one*

4 FINANCIAL FEASIBILITY STUDY

Compare between initial cost of the two systems estimating the prices (Total Initial cost) of each power plant components (see Table 6), the cost ofproduced $(1KWh)$ and interest rate(see Table 7) knowing that, the premiumfeed-in tariff for solar PV planets connected to the public electricity grid (from $500KWp$ to $20MWp$) in Egypt is $C_o = 0.136\ \$/KWh$ for each system, the comparison take in consideration financing the project by three different methods:

1. Taking 70% from the initial cost using bank loan with Interest rate 4% and paying other 30%.
2. Paying all the initial cost.
3. Taking all the initial cost, loan from the bank with Interest rate 14%.

Using the geometric series (figure 16), will calculate the interest rate and the cost per KWh.

Table 6 *Comparison between Initial costs of two 1MWp systems*

Power plant component	Fixed System($)	Soitec System($)
PV modules Price	650,000	2,000,000
Mounting& Trackers Price	190,000	1,000,000
1MWp Inverter Price	300,000	300,000
Land Preparation Price	300,000	100,000
Cables Price	60,000	40,000
Step up transformer Price	26,000	26,000
DAS, Monitoring system Price	10,000	10,000
Earthing, Lightning system Price	5,000	5,000
Installation & Other Accessories Price	25,000	25,000
Total Price (P)	1,566,000	3,506,000

The importance of calculating the interest rate and the price of produced Energy($\$/KWh$) (see Table 7) is to know if the investment is accepted or not. In Egypt, the accepted interest rate that is larger than $(0.11; i = 11\%)$ which is given by any bank when loaning them [13].

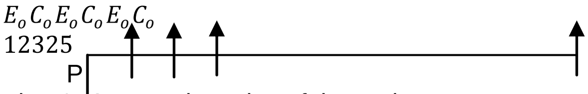

Fig.16. Geometric series of the project

$$P = C_o \left[\frac{1 - \left(\frac{1+g}{1+i}\right)^N}{i-g} \right] \qquad (4.1)$$

Where, C_o is the Feed-In tariff cost, E_o is the energy produced in the first year, i is the Interest rate, N is life time of the project (about 25 to 30 years), and g is the degradation factor ($g = -0.02$)assuming that the PV modules efficiency decreasing yearly about 2% .[8], [13].

Table 7 *Results comparison*

Economical comparison		Fixed System	Soitec System
With Bank Loan ($i = 4\%$)	Investment Interest rate (%)	0.1991	0.11
	Cost of 1KWh ($\$/KWh$)	0.061282	0.086321
Without Bank Loan ($i = 11\%$)	Investment Interest rate (%)	0.11662	0.06951
	Cost of 1KWh ($\$/KWh$)	0.090167	0.127008
With Bank Loan ($i = 14\%$)	Investment Interest rate (%)	0.058	0.036
	Cost of 1KWh ($\$/KWh$)	0.139294	0.196207

5 Conclusion

The research approved that PV power plantsaregreat projects since PV solar cells efficiencies are rising continuously and its cost are decreasing with time. In thisresearch, comparison between two types of 1MWp PV power plants connected to the utility (Fixed System& Soitec System) are made, the comparison include the total Annual energy produced from each system and the cost of every produced KWh along the time life of the systemto reach to the optimum design (solution) for power planet system that produce lowest cost for every KWh. However, it is shown that Soitec system produces maximum energy (KWh/year) (see Table 5) about 60% increase in energy produced and Soitec system take half the land area required at the fixed one because of the increased efficiency, But the fixed system is the Optimum economically (see Table 7) than Soitecone, neglecting the cost of the land that used in the project because of the abundance of desert areas in Egypt, where it produces KWh less expensive than Soitec and it will be profitable, especially when taking 70% from the initial cost of the project (4% Bank loan) as the Ministry of Finance in Egypt encourage such promising projects.

With the premium Feed-In Tariff ($0.136\$/KWh$), sellingthe produced energy to Egyptian government; Ministry of electricity. Feasibility study showed that the profit in this case return on this project is calculated to be (Investment Interest rate=**19.91** %) and also the total cost of producing 1 KWh is about $0.06128\,\$/\,KWh$(**0.49**$EGP/KWh$assuming that $1\,\$ = 8\,EGP$), That is more less than the cost of producing 1 KWh by conventional methods like steam power stations.

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