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Performance Evaluation and Comparative Analysis of Mirror Augmented and 3D CPC Based PV Systems

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Abstract

In this present work, the performance evaluation and comparison between mirror augmented silicon PV solar panel and compound parabolic concentration for a simple poly-crystalline silicon solar cell of area 10 x 10 mm is examined. Readings for the system of compound parabolic concentrator with poly-crystalline silicon solar cell are examined and the power output is observed. In the same way, performance improvement by mirror augmentation is also analyzed for regular silicon solar cell. We compared both the systems in view of productivity increment aspect for different inclination angles from ground horizontal surface ranging from 18° to 28° (as per incidence angle modification methodology). The percentage increment in power output found in case of compound parabolic concentrator is 21% for 18° and 23% for 28°. Hence from the observation we can say that power output is more for an angle of 28° in case of CPC. In mirror argumentation case, we tested different angles to achieve the maximum output by simple ray flooding method. Ray tracing was done with the help of leaser light, which gives real time physical simulation of rays. We achieved best possible result at 25° for the same. Instead of concentrated cell (CPV) which is expensive, Simple poly-crystalline silicon solar cell is used for the experimentation purpose due to its easy availability and low cost.

Keywords: *Compound Parabolic Concentrator, Mirror Augmentation of Solar Panel, Solar Cell Concentration, Non-imaging techniques, Solar Energy, CPC, Solar*

Introduction

The global need for energy is constantly increasing and makes it inevitable to reinforce the use of alternative resources. The sun is one of the richest energy sources in this context and is almost inexhaustible. Energy efficiency and solar technology are important elements to any building or community design. Also, they are important to the nation and to the Earth. The Sun is a massive reservoir of clean energy and the power from the sun's rays that reach the earth is called as solar energy. Solar energy is the most readily available source of energy. Solar energy received in the form of radiation can be converted directly or indirectly into other forms of energy such as heat and electricity which can be utilized by the man. Since the sun is expected to radiate essentially at a constant rate for a billion years it may be regarded as an in-exhaustible source of useful energy. Solar energy has been used since prehistoric times, but in a most primitive manner. Before 1970, some research and development was carried out in a few countries to exploit solar energy more efficiently, but most of this work remained mainly academic. After the dramatic rise in oil prices in the 1970s, several countries began to formulate extensive research and development programme to exploit solar energy.

In the present work, we have made use of two non imaging cost effective solar energy harnessing techniques, i.e, mirror augmented silicon PV solar panel system and compound parabolic concentration for a simple poly-crystalline silicon solar cell system in order to judge effectiveness of the systems for cost reductions.

B. Abdullahi et al. [1] developed a compound parabolic solar collector (CPC) and optimized its performance for domestic use under climatic condition of Kano, Nigeria (Φ =12.05° N). The acceptance angle plays an important role in determining the solar radiation acceptance of the CPC collector. Therefore this paper investigates the effect of the acceptance angle on the CPC design, solar radiation collection and absorption by the heat pipe receiver installed inside the CPC collector. From the radiation data and the analysis used, this study shows that as the acceptance angle increases, the collector height decreases and the concentration ratio increases. H. Tanweer and P. Gandhidasan [2] used a non-imaging concentrator namely Compound Parabolic Concentrator (CPC) with a flat receiver. They carried out modelling of the truncated CPC with a concentration ratio of about 2.3 for concentrating PV strings by solving the governing equations using Engineering Equation Solver (EES) software. Reflection losses occurring at each interface are considered in the model and determined by the angle of incidence of incident radiation and by the refractive indices of the materials at each interface. Absorbed energy is calculated for different cases, with and without cooling, including PV CPC (glazed and unglazed) and simple flat PV. This absorbed energy is further used to solve the energy balance equations on different nodes of the system, to estimate cell temperature; which in turn with the absorbed radiation are used as input to Electrical model.

Electrical model is simulated and performance characteristics curve for the PV CPC systems are obtained. The Performance of the PV string with and without cooling for all the cases is compared in this paper. Results show that electrical power is enhanced up to 49.4% by integrating PV (actively cooled) with unglazed CPC. This indicates that PV CPC is an efficient way to reduce the cost of electricity produced by PV. Yong Kim et al. [3] tried to investigate and improve thermal performance of evacuated CPC (Compound Parabolic Concentrator) solar collector with a cylindrical absorber. Modified types of this solar collector are always combined with the evacuated glass envelop or tracking system. The conventional stationary CPC solar collector has been compared with the single axis tracking CPC solar collector in outlet temperature, net heat flux onto the absorber and thermal efficiency. Numerical model has been analyzed based on the irradiation determined actually and the results have been calculated to predict the thermal efficiency. Based on the comparison of the measured and calculated results, it is concluded that the numerical model can accurately estimate the performance of solar collectors. The result shows the thermal efficiency of the tracking CPC solar collector is more stable and about 14.9% higher than that of the stationary CPC solar collector. Mark A. Schuetz, et al. [4] studied the design, construction, and initial performance measurements of a low-concentration photovoltaic system based on compound parabolic concentrators (CPCs). The system is approximately a 7× concentration system and uses commercially available laser groove buried contact monocrystalline silicon photovoltaic cells. The CPCs are fabricated using a second surface aluminized acrylic mirror with proven weather durability. The asymmetric CPC optical design was driven by a balance between concentration factor, thermal issues, and optical angle of acceptance and was thoroughly evaluated by optical ray tracing. The design was targeted for a single-axis tracking system, with extruded aluminium heat sinks doubling as structural components. They fabricated a 120-cell (10 × 12) prototype array, and over three months of operation, they estimated an approximate peak total system power efficiency of 7.9%, limited mostly by the CPC optical efficiency (55%) and the cell conversion efficiency. Tomas Matuska [5] studied performance of different concepts of solar hybrid liquid collectors for domestic hot water application. He studied the economic aspects based on performance results, energy prices and conventional photovoltaic (PV) and photo thermal (PT) collector prices. B. Fortunato et al. [6] have worked to increase the electric yield of *PV* modules (which can be even doubled with respect to constant tilt configurations), without significantly increasing the system costs, by addition of inclined mirrors at both sides of the *PV* modules, so as to deflect more solar rays towards them, as in Mirror-Augmented Photovoltaic (*MAPV*) systems. The system found to preserve its constructive simplicity with commercial flat *PV* modules even though dual axis tracker must be implemented, since *MAPV* systems harness mainly the direct radiation. The performance analysis of *MAPV* systems starts from the calculation of the global irradiation on the surface of the *PV* module which is a sum of the direct sunlight on it and the irradiation reflected by the mirrors. A mathematical model of a *MAPV* system is presented, which takes into account not only the increase of direct (or beam) radiation, due to the mirrors, but also the reduction of both the diffuse and reflected radiations due to the shadowing effect of the flat mirrors. In particular, under an isotropic sky assumption, a simplified analytical expression, applicable in the case of *MAPV* systems, for the sky-view factor has been developed. The deterioration in the performance of the *PV* system as a result of the increasing cell temperature with radiation augmentation due to mirrors has been also evaluated. Moreover, in order to provide a more realistic view of the process, the energy analysis is accompanied by the exergy analysis. M.M.Isa et al. [7] studied effect of truncation of CPC and consecutive effect on reduction in concentration ratio. Flux distribution is compared with and without truncation of 2D compound parabolic trough concentrator. This paper presents optical simulation of compound parabolic trough concentrator using ray tracing software; TracePro; which show that truncation of CPC height by 45% resulted in reduction in geometrical concentration ratio by 10%.

1. Mirror Augmentation System:

The mirror augmentation of photo-voltaic panels is a cost effective way of increasing the electrical energy produced by such panels. The general idea is to increase the solar energy that reaches the panel by adding a number of mirrors around it. If the mirrors are correctly positioned, a bigger percentage of solar rays will reach the panel, and therefore its effective area, i.e. its solar exposition area, will be increased.

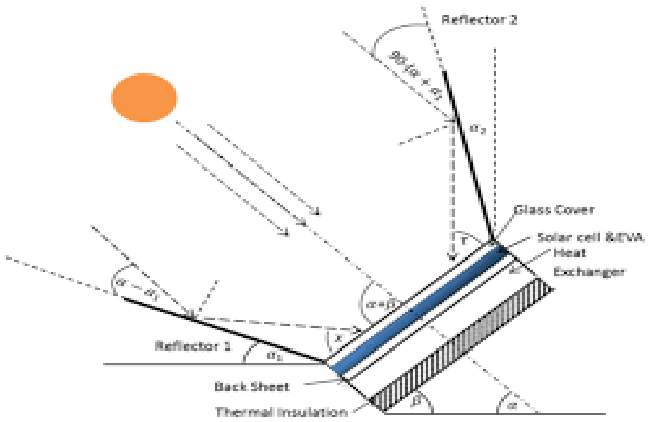

Fig. 1 Configuration of Mirror Augmentation System

Fig. 2 The mirror augmented solar panel with regular solar panel

2. 3-D compound parabolic concentrator:

The design of compound parabolic concentrator is structurally simpler than other types of concentrated collectors. The area of the cell used in a system with CPC is 10 x10 mm, which is considered as the bench marking. The output aperture diameter of the parabola is so adjusted that it will cover the complete cell area so as to concentrate solar radiations impinge upon it. By theoretical calculations, the length of parabola is derived by adjusting the maximum allowable half angle of acceptance in order to harness maximum radiations and is calculated to be L=328.179mm. The length of the parabolic concentrator appears to be excessive for large scale purposes. However, one of the largest hurdles in the use of CPCs for primary optics in PV concentrators is their length and the necessary high material usage. This can in part be offset by reducing the length of the CPCs with the so called truncated CPCs, or T-CPCs, which use far less material without reduction in concentration ratio and optical efficiency. In practice the CPC length is halved, without significant loss of optical efficiency. Thus the truncated length of the parabola is kept half i.e. 160mm. Rectangular method of engineering curves is used for tracing the points of parabola (co-ordinates)and the parabola is drawn by joining the points. The coordinates are derived with the help of parabola calculator software.

Table 1 Values of x, y calculated with the help of the Rectangular method of engineering curve.

Sr No	X-axis	Y axis
1	30	0
2	26.25	37.50
3	22.50	70
4	16.79	97.50
5	15.00	120.00
6	11.25	137.50
7	7.50	150.00
8	3.75	157.50

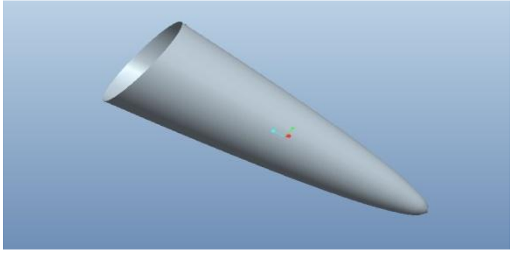

Fig. 3 Model of CPC without truncated

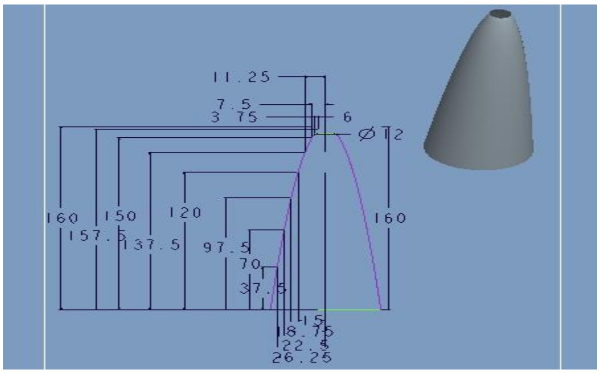

Fig.4 Model of truncated CPC by taking input aperture diameter as 12mm.

Experimental work

This chapter includes the layout of experimentation, the details of instrumentation used with individual specifications. The setup consists of various instruments which were used during the experimental test. The compound parabolic concentrator is mounted on the photovoltaic cell at a fixed angle as the system is non-tracking and the readings are taken during the clear sunny day time. The layout of the experimentation is shown in the figure. It consists of a parabolic concentrator, poly crystalline silicon solar cell, and wooden stand for mounting the cell and temperature sensor, sun meter, watch, multimeter, electric cables and resistance board. The Setup is placed under the sunlight and the readings are taken with and without concentrators after regular time interval. The sunlight passing through CPC is concentrated onto solar cells. The junction of the solar cell is connected to the ammeter and the voltmeter through the resistance and the readings are taken.

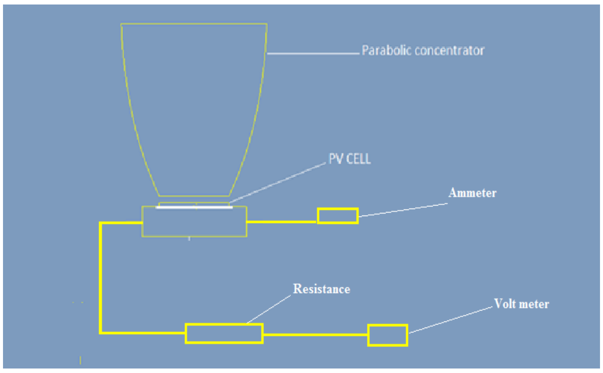

Fig. 5 Layout of Test setup for Compound Parabolic Concentrator

Fig.6 Experimentation setup for Compound Parabolic Concentrator

The main components of the setup are as follows.

The solar photovoltaic cells with concentrators.
The temperature measurement system- thermometers, k type thermocouples.
The current and voltage measurement system (DMM).
The solar radiation measurement system- Sun-meter.
The data acquisition system (sun simulator), data logger.

Measuring instruments and devices:
Following are the some instruments which are used to measure the working of the experimental setup
Data Logger, K type Thermocouple, Ammeter(DMM), Voltmeter (DMM), Sun simulator, Inclinometer, Sun meter, stand for mounting.

Considering efficiency and productivity aspect, experimentation is focused on following three main data collection fields.

1) Result of I-V curve of sun simulator.
2) Result of actual performance of Mirror augmentation system and designed unit parabola with solar cell system under natural atmospheric conditions.
3) Optical performance of designed parabola.

All the data collection points are interconnected during design of concentrated photo voltaic system. Here we have analyzed I-V characteristics of solar cell with and without concentrators. Major objective of our study is to make use of simple poly-crystalline silicon solar cells for concentrated non-imaging system which is helpful to enhance output of solar cells, but at the same time the concentration is limited up to 10X. If it is more, it may result in heating of the cell and de-hydrogenation may take place. Primarily we study the I-V characteristics of regular solar cell without concentration under controlled atmospheric and standard conditions 1000 w/m^2. The concentration ratio of the compound parabolic concentrator is kept 5X and the readings are taken at this concentration ratio. Next (instead of last) data collection point is at the actual experimentation with combining compound parabolic concentrator with cell and placing on stand to analyses the non-tracking performance at different tilt angle.

Result and discussion

Experiments are carried out for solar cell panel, both with mirror augmentation and without mirror augmentation. Also, in case of compound parabolic concentrator, single solar cell is tested with and without Compound Parabolic Concentrator. The following results are obtained with the experimental analysis which is ultimately used for comparison between regular solar cell with compound parabolic concentration system and mirror augmented PV system. The results are shown in the tabulated form and the variation in temperature, time and intensity are represented graphically.

Mirror augmentation system:

10th Feb 2017 , Time -12.40 p.m , Intensity-700 W/m^2
Readings at angle 18 degree with and without mirror augmentation

Table 2 Mirror augmented solar system

Sr. No	Voltage(V)	Current(A)	Power(W)
1	10.3	0.03	0.309
2	10	0.04	0.4
3	9.5	0.26	2.47
4	8.5	0.53	4.505
5	6.5	0.67	4.355
6	2.5	0.68	1.7
7	2	0.68	1.36
8	1	0.68	0.68
9	0.9	0.68	0.612

Table 3 Regular Solar Panel System

Sr. No	Voltage(V)	Current(A)	Power(W)
1	10	0.02	0.2
2	9.6	0.13	1.248
3	9	0.23	2.07
4	8.2	0.32	2.624
5	7	0.36	2.52
6	5.5	0.38	2.09
7	5	0.38	1.9
8	3	0.38	1.14
9	2	0.38	0.76
10	1	0.38	0.38
11	0.9	0.38	0.342

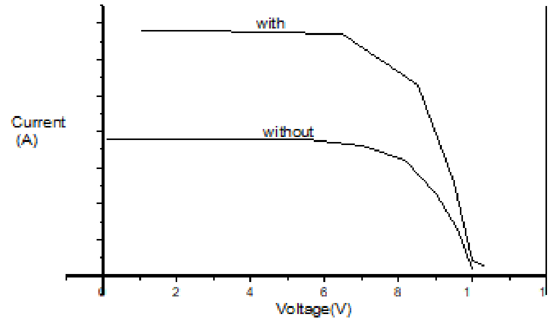

Fig.7 I-V Characteristics for mirror augmentation.

Readings at angle 25 degrees with and without mirror augmentation

Table 4 Mirror augmented solar system

Sr. No	Voltage(V)	Current(A)	Power(w)
1	10	0.02	0.202
2	9.5	0.24	2.28
3	8.6	0.5	4.3
4	7	0.66	4.62
5	3.5	0.69	2.415
6	1.5	0.69	1.035
7	1	0.69	0.69
8	0.9	0.7	0.63

Table 5 Regular Solar Panel System

Sr. No	Voltage(V)	Current(A)	Power(w)
1	10	0.02	0.2
2	9.5	0.12	1.14
3	9	0.23	2.07
4	7.5	0.35	2.625
5	5	0.39	1.95
6	4.5	0.39	1.755
7	3	0.39	1.17
8	2	0.39	0.78
9	1	0.39	0.39
10	0.9	0.39	0.351

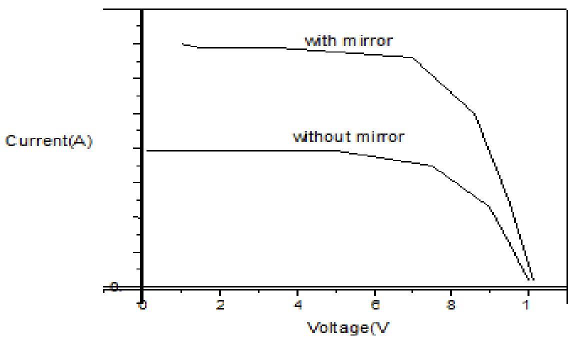

Fig. 8 I-V characteristics for mirror augmentation

Readings at angle 30 degrees with and without mirror augmentation

Table 6 Mirror augmented solar system

Sr. No	Voltage(V)	Current(A)	Power(W)
1	9.9	0.02	0.198
2	9.6	0.16	1.536
3	8.5	0.52	4.42
4	6.6	0.65	4.29
5	3.5	0.65	2.275
6	1.5	0.65	0.975
7	1	0.65	0.65
8	0.09	0.65	0.0585

Table 7 Regular Solar Panel System

Sr. No	Voltage(V)	Current(A)	Power(W)
1	10	0.02	0.2
2	9.5	0.13	1.235
3	9	0.31	2.79
4	7.5	0.36	2.7
5	5	0.38	1.9
6	4.5	0.39	1.755
7	3	0.39	1.17
8	2	0.39	0.78
9	1	0.39	0.39
10	0.9	0.39	0.351

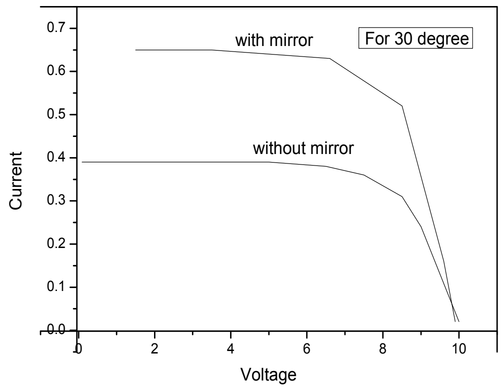

Fig.9 I-V characteristics for mirror augmentation

Result Table for the readings acquired at 18^0 on 20^{th} March, 2017 for 3D Compound Parabolic Concentration system at from 12.00 pm to 04.00 pm

Table 8 Readings at 12 pm without concentrator

Sr. No	Resista-nce(Ω)	Current (I)	Voltage (V)	Radi-ation (Ω)	Power (W)
1	0	25.5	0	890	0
2	1	25.3	0.02	912	0.506
3	1.2	24.6	0.02	898	0.492
4	1.5	24.4	0.03	917	0.732
5	2.2	24.1	0.05	914	1.205
6	3.3	24.9	0.07	927	1.743
7	4.7	24.4	0.1	924	2.44
8	5.6	23.7	0.12	912	2.844
9	6.8	23.2	0.15	911	3.48
10	8.2	22.1	0.17	898	3.757
11	10	22	0.2	922	4.4
12	15	19	0.27	928	5.13
13	20	16.2	0.3	918	4.86
14	30	12	0.35	933	4.2
15	47	8.3	0.37	938	3.071
16	56	7	0.38	934	2.66

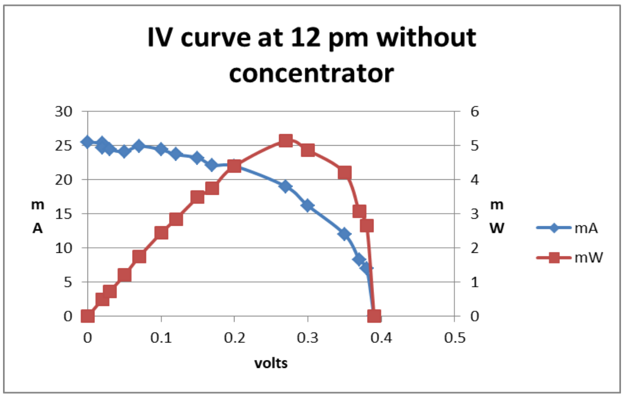

Fig.10 IV curve at 12 pm without concentrator

Table 9 Readings at 12pm with concentrator

Sr. No	Resistance (Ω)	Current (I)	Voltage (V)	Radiation(Ω)	Power (W)
1	0	153.2	0	890	0
2	1	120.2	0.12	912	14.42
3	1.2	115.5	0.13	898	15.01
4	1.5	109	0.15	917	16.35
5	2.2	94.1	0.21	914	19.76
6	3.3	79.8	0.25	927	19.95
7	4.7	66	0.3	924	19.8
8	5.6	59.3	0.32	912	18.976
9	6.8	52.5	0.34	911	17.85
10	8.2	46.1	0.36	898	16.596
11	10	41.1	0.37	922	15.207
12	15	29.4	0.42	928	12.348
13	20	23.1	0.44	918	10.164
14	30	15.9	0.46	933	7.314
15	47	10.6	0.48	938	5.088
16	56	9	0.48	934	4.32

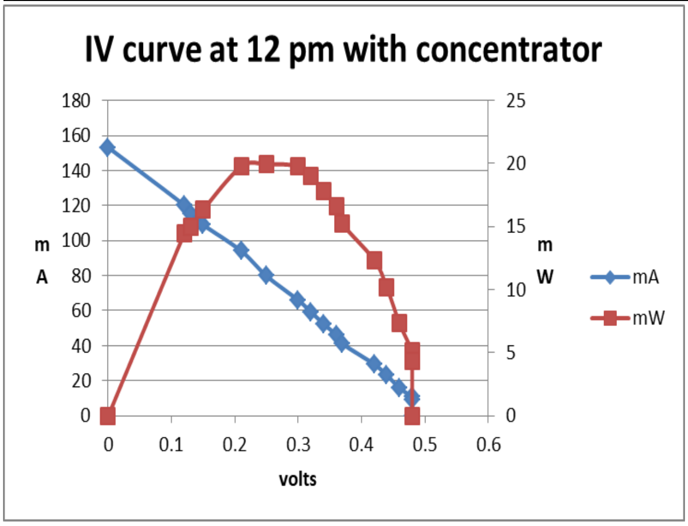

Fig.11 IV curve at 12 pm with concentrator

Table 10 Readings at 1 pm without concentrator

Sr. No	Resistance (Ω)	Current (I)	Voltage (V)	Radiati-on(Ω)	Power (W)
1	0	24.8	0	998	0
2	1	24.8	0.02	997	0.496
3	1.2	24.8	0.03	985	0.744
4	1.5	24.6	0.03	995	0.738
5	2.2	24.4	0.05	990	1.22
6	3.3	24.3	0.08	985	1.944
7	4.7	24	0.1	990	2.4
8	5.6	23.6	0.12	998	2.832
9	6.8	23.2	0.17	994	3.944
10	8.2	22.5	0.2	992	4.5
11	10	20.1	0.26	995	5.226
12	15	15.7	0.29	991	4.553
13	20	12.4	0.3	989	3.72
14	30	11.6	0.32	992	3.712
15	47	8.4	0.36	992	3.024
16	56	7.2	0.36	989	2.592

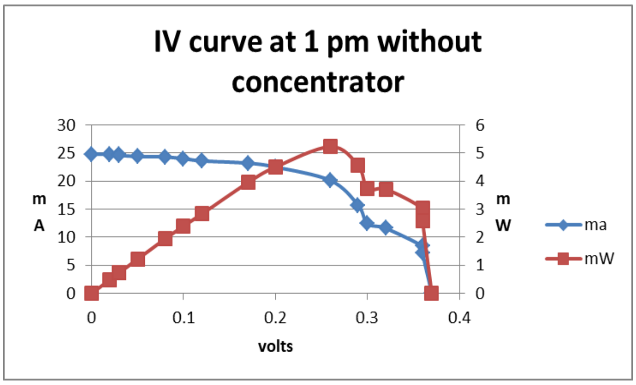

Fig.12 IV curve at 1 pm without concentrator

Table 11 Readings at 1 pm with concentrator

Sr. No	Resista-nce(Ω)	Curre-nt (I)	Voltage (V)	Radiati-on(Ω)	Power (W)
1	0	114.9	0	998	0
2	1	101	0.09	997	9.09
3	1.2	98.1	0.11	985	10.791
4	1.5	97.8	0.13	995	12.714
5	2.2	96.3	0.18	990	17.334
6	3.3	94.2	0.23	985	21.666
7	4.7	78.2	0.23	990	17.986
8	5.6	66.1	0.27	998	17.847
9	6.8	49.2	0.3	994	14.76
10	8.2	42.9	0.32	992	13.728
11	10	38.3	0.34	995	13.022
12	15	27.6	0.36	991	9.936
13	20	21.8	0.39	989	8.502
14	30	15.1	0.41	992	6.191
15	47	10.1	0.44	992	4.444
16	56	8.6	0.49	989	4.214

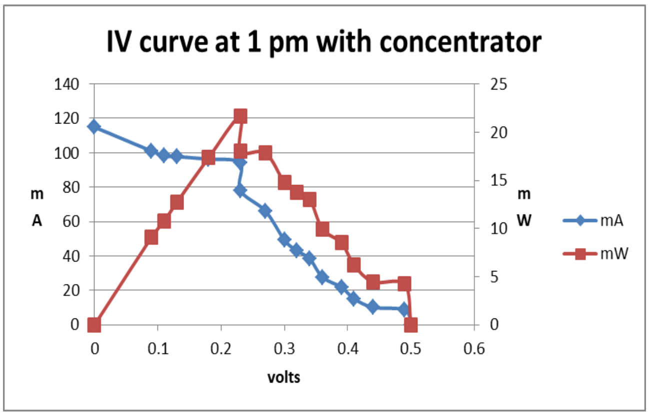

Fig.13 IV curve at 1 pm with concentrator

Final Results obtained for Mirror Argumentation system:

Table 12

Results obtained for Mirror Argumentation system

Sr no	Angle	Power(W) Without mirror	Power(W) With mirror	Intensity (W/m²)
1	18^0	2.62	4.50	700
2	25^0	2.60	4.62	700
3	30^0	2.79	4.42	700

Final Results obtained for Compound Parabolic Concentration system:

Table 13

Results obtained for Compound Parabolic Concentration System

Sr no	Angle	Power (mW) without concentrator	Power (mW) with concentrator	Intensity (W/m²)
1	18^0	5.22	21.66	990
2	28^0	6.35	23.45	992

Table 14

Comparison of the results obtained from Mirror Argumentation system and Compound Parabolic Concentration System for angle 18^0

Type of System	Size of Panel/ Cell (mm²)	Power (W)	Equivalent Power Generated Keeping same Size of Panel and correction factor Applied for Intensity (W)
Mirror Augmentation System	200 x 200	4.50	4.50
CPC based System	10x10	21.66 x 10^{-3}	6.1264

Conclusions

We proposed a performance evaluation and comparative analysis of compound parabolic concentrator and mirror augmented solar panel. Our goal is to make available more solar radiations to impinge the solar cell area resulting in more energy output by the cell. We observed more output delivered with the use of Compound Parabolic Concentrator at the angle of inclination 28^0 but the system seems more costly as compared to mirror augmentation system. Mirror augmentation system is observed to be simpler and cost effective with little low productivity. We could get percentage increment in power output of 13% if mirror augmentation is done at an angle 25^0. We found Compound Parabolic Concentrator system costlier but more effective than Mirror augmented system at ray tracing and actual performance. The comparative results as stated in table no.3 show that the CPC based system is 36% effective than Mirror augmented system. The percentage increment of energy output in case of CPC system is found 21% for 18^0 and 23% for 28^0. The above setup can be arranged in an array of concentrators as per power requirements so as to trap the external light to cover a large solar cell area.

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