

PERFORMANCE EVALUATION AND COMPARATIVE ANALYSIS OF MIRROR AUGMENTED, 2D AND 3D COMPOUND PARABOLIC CONCENTRATOR BASED PV SYSTEMS

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ABSTRACT:

In this present work, the performance evaluation and comparison between mirror augmented silicon PV panel system, 2D CPC based silicon PV panel system and 3D compound parabolic concentration for a simple poly-crystalline silicon solar cell of area 10×10 mm is examined. We compared all the three systems in view of productivity increment aspect for different inclination angles from ground horizontal surface ranging. The percentage increment in power output found in case of 3D compound parabolic concentrator is maximum of all the above mentioned systems i.e, 23% for 28° . As the solar cell temperature increases, its efficiency reduces. Thus, to keep the solar cell temperature within prescribed range and also to make maximum utilization of the heat received by the sun, a thermal heat exchanger unit is installed at the back of solar panel which extracts the heat from solar cells; thereby maintaining the solar cell temperature of 25° . The thermal performance in terms of efficiency achievement for utilization of heat available is evaluated for all above three systems. 3D CPC based system found the best with heat conversion efficiency ranging up to 46%

KEYWORDS: Compound parabolic concentrator, mirror augmentation of solar panel, solar cell concentration, non-imaging techniques, solar energy, CPC, solar efficiency, solar heat exchangers.

I. 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. Currently, the

installed capacity of solar projects in India is about 4.22 GW. India is planning to produce 100 GW of solar power by 2022. Considering the fact that solar cell efficiency degrades by 3% in a first year and less than 1% per year after that, a special attention must be provided to make effective utilization of such a huge solar installed capacity. In the present work, we have compared different non imaging cost effective solar energy harnessing techniques to judge their effectiveness. The mirror augmented system and 2D compound parabolic concentrator system are used for carrying out experimentations on poly crystalline silicon PV panel. Due to design constrains, experimentation is carried out on a single poly-crystalline silicon solar cell in case of 3D compound parabolic concentrator system.

II. TYPES OF CONCENTRATORS:

A. MIRROR AUGMENTATION SYSTEM:

The mirror augmentation of photo-voltaic panels is a cost effective way of increasing the electrical energy output of the panel. 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.

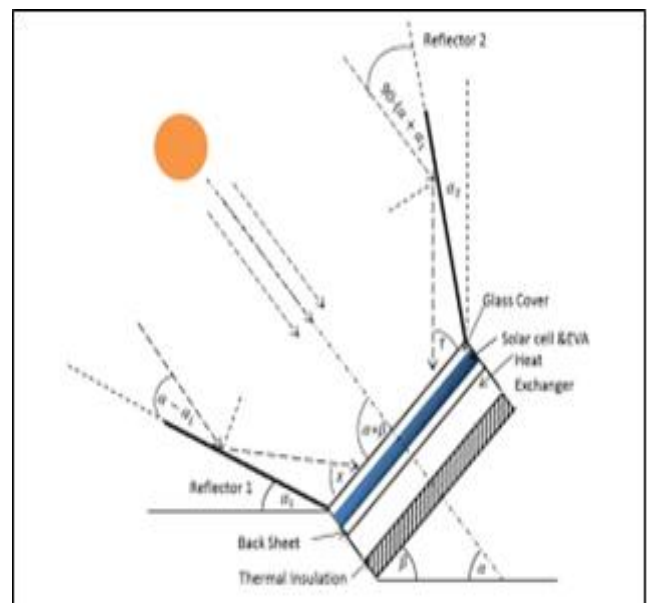


Fig. 1. Configuration of mirror augmentation system



Fig. 2. Mirror augmented solar panel with regular solar panel

TABLE II. DESIGN PARAMETERS OF 2D CPC SYSTEM

Parameter	Value	After Truncation
Concentration ratio	3x	2x
Absorber width	180*180 mm ²	NA
Height of CPC (H)	250 mm	150 mm
Width of entrance aperture	300*300 mm ²	280*280 mm ²
The reflectivity of the reflector (ρ)	91 %	91 %
Average efficiency of thermal	52 %	48 % max theoretical
The acceptance angle	15 +15	15+15
Average number of reflections	3.2	2.8

TABLE III. DESIGN PARAMETERS OF 3D CPC SYSTEM

Parameter	Value	After Truncation
Parameters	Value	After Truncation
Concentration ratio	7x	5x
Absorber width (diameter, d)	12 mm	12 mm
Height of CPC (H)	328 mm	210 mm
Width of entrance aperture (diameter, D)	65 mm	55 mm
Reflectivity of the reflector (ρ)	91 %	91 %
Average efficiency of thermal	80 %	68 % max theoretical
The acceptance angle	15 +15	15+15

TABLE IV. VALUES OF X, Y CALCULATED WITH THE HELP OF THE RECTANGULAR METHOD OF ENGINEERING CURVE FOR 3D CPC

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

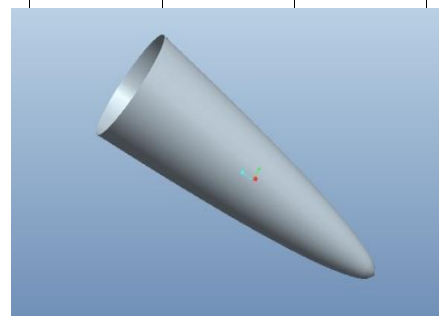


Fig. 3. Model of CPC without truncation

B. 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=328.179 mm. 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.[13]

TABLE I. DESIGN PARAMETERS OF MIRROR AUGMENTATION SYSTEM

Parameter	Value	After Truncation
Concentration ratio	1x	NA
Absorber width	180*180 mm ²	NA
Height of CPC (H)	200mm	NA
Width of entrance aperture	150*150 mm ²	NA
The reflectivity of the reflector (ρ)	88 %	NA
Average efficiency of thermal	32 %	NA
Acceptance angle	15 +15	NA
Average number of reflections	1	NA

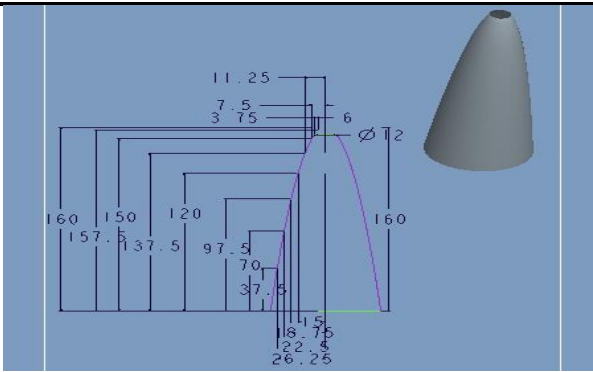


Fig.4 Model of truncated CPC by taking input aperture diameter as 12mm

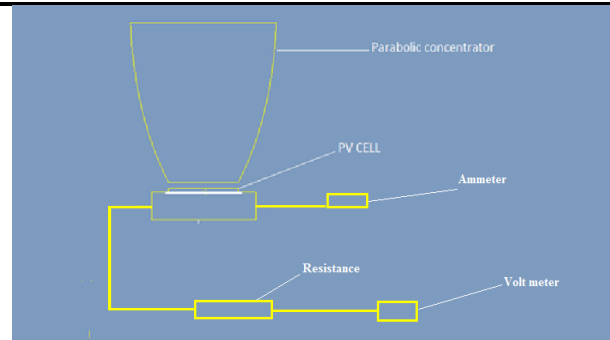


Fig. 7 Layout of Test setup for 3D Compound Parabolic Concentrator

III. EXPERIMENTAL WORK:

This chapter includes the layout of experimentation, the details of instrumentation used with individual specifications.

The 3D 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 8. It consists of a parabolic concentrator, poly crystalline silicon solar cell, wooden stand for mounting the cell, temperature sensor, sun meter, watch, multimeter, electric cables and resistance board. The Setup is placed under the sunlight and the readings are noted with and without concentrators from 10 am to 4 pm, with 30 minutes 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.

In case of mirror augmentation system and 2D CPC based system, same method is followed for noting the readings of PV and thermal unit.



Fig.8 Experimentation setup for 3D CPC based system

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

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 which can reduce its efficiency. However, in the proposed system, besides current generation from photons, the extraction of heat from the photovoltaic modules via a heat transfer fluid is carried out



Fig. 5 PV collector performance evaluation without use of concentrators



Fig.6 PV collector performance evaluation for 2D CPC based system

by incorporation of a thermal unit. Thus the heat extracted results in cooling of the photovoltaic panels which further can be utilized in space heating applications.[6]

IV. RESULT AND DISCUSSION:

Experiments are carried out for solar cell panel, with and without concentrators; for Mirror augmentation system and 2D CPC based system. In case of 3D CPC based system, single solar cell is tested with and without 3D CPC. 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.

A. MIRROR AUGMENTATION SYSTEM:

10th Feb 2017, Time -12.40 p.m., Intensity-700 W/m²
Readings at an angle 18 degrees with and without mirror augmentation

TABLE V. WITH MIRROR AUGMENTATION

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 VI. WITHOUT MIRROR AUGMENTATION

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

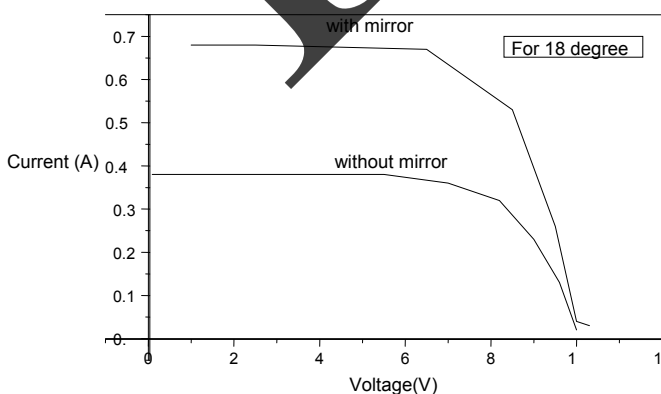


Fig.9 I-V characteristics for mirror augmentation

Readings at angle 25 degrees with and without mirror augmentation

TABLE VII. WITH MIRROR AUGMENTATION

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 VIII. WITHOUT MIRROR AUGMENTATION

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

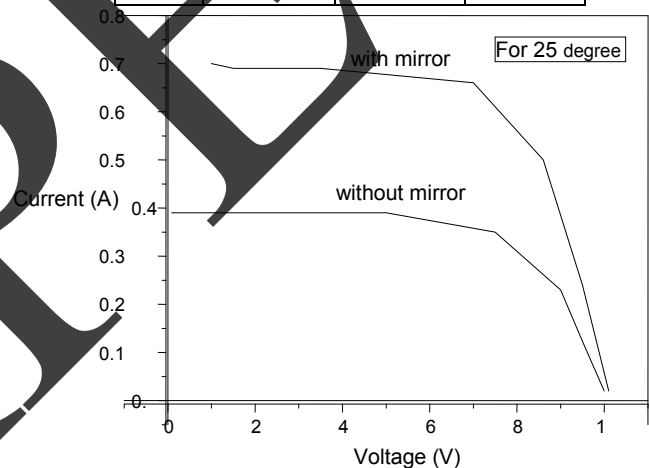


Fig.10 I-V characteristics for mirror augmentation

B. 3D CPC BASED SYSTEM:

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

TABLE IX. READINGS AT 12 PM WITHOUT CONCENTRATOR

Sr. No	Resistance (Ω)	Current (I)	Voltage (V)	Radiation (W/m ²)	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

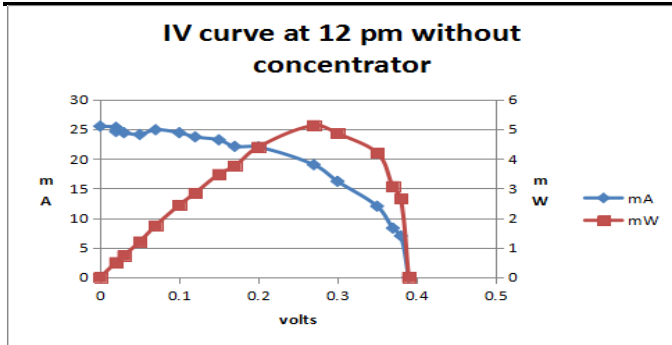


Fig.11 IV curve without concentrator

TABLE X. READINGS AT 12PM WITH CONCENTRATOR

Sr. No	Resistance (Ω)	Current (I)	Voltage (V)	Radiation (W/m^2)	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

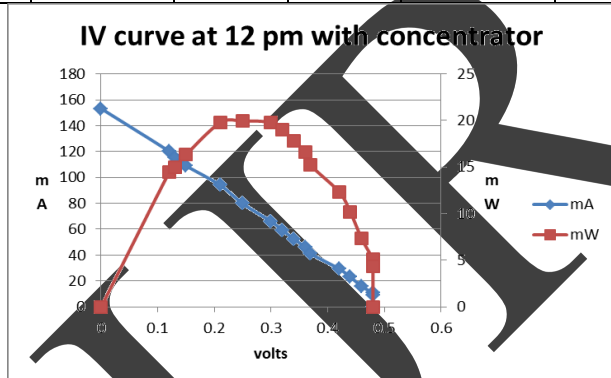


Fig.12 IV curve with concentrator

TABLE XI. RESULTS OBTAINED FOR MIRROR ARGUMENTATION SYSTEM

Sr no	Angle	Power(W) Without mirror	Power(W) With	Radiation (W/m^2)
1	18 $^\circ$	2.62	4.50	700
2	25 $^\circ$	2.60	4.62	700
3	30 $^\circ$	2.79	4.42	700

TABLE XII. RESULTS OBTAINED FOR COMPOUND PARABOLIC CONCENTRATION SYSTEM

Sr no	Angle	Power (mW) without concentrator	Power (mW) with concentrator	Radiation (W/m^2)
1	18 $^\circ$	5.22	21.66	990
2	28 $^\circ$	6.35	23.45	992

TABLE XIII. COMPARISON OF THE RESULTS OBTAINED FROM MIRROR ARGUMENTATION SYSTEM AND COMPOUND PARABOLIC CONCENTRATION SYSTEM FOR ANGLE 18 $^\circ$

Type of System	Size of Panel/ Cell (mm^2)	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

Now, all the above referred three solar energy concentrator techniques are subjected to thermal performance evaluation on the basis of heat energy transferred to heat exchanger. [2] The efficiency is calculated taking into consideration the actual heat received by the heat exchanger and theoretical heat concentration on the heat exchanger and the results obtained are stated as follows:

(a) 3D CPC BASED SYSTEM:

For water kept flowing through the heat exchanger for 5 hours, mass of water accumulated, $m = 0.7$ Kg, $C_p = 4.186$ KJ/Kg $^\circ$ K, Area $A = 0.000121$ m 2

TABLE XIV. THERMAL PERFORMANCE ESTIMATION FOR 3D CPC

Temp in $^\circ$ C	Temp out $^\circ$ C	Radiation, I W/m^2	$m \times C_p \times dt$ (J)	$A \times T \times I$ (J)	Efficiency %
25.9	26.1	890	586.04	1938.42	30.23
25.5	25.8	980	879.06	2134.44	41.18
25.83	26.1	950	791.15	2069.10	38.23
25.41	25.7	961	849.76	2093.06	40.59
26.6	26.9	935	879.06	2036.43	43.16
25.5	25.86	853	1054.87	1857.83	56.77
26.3	26.7	944	1172.08	2056.03	57.01
25.5	26	972	1465.10	2117.02	69.21
25.8	26.1	956	879.06	2082.17	42.22

(b) 2D CPC BASED SYSTEM:

For water kept flowing through the heat exchanger for 5 hours, mass of water accumulated, $m = 2$ Kg, $C_p = 4.186$ KJ/Kg $^\circ$ K, Area $A = 0.0324$ m 2

TABLE XV. THERMAL PERFORMANCE ESTIMATION FOR 2D CPC

Temp in $^\circ$ C	Temp out $^\circ$ C	Radiation, I W/m^2	$m \times C_p \times dt$ (J)	$A \times T \times I$ (J)	Efficiency %
25.50	32.5	980	58604.00	571536	10.25
25.90	29.6	990	30983.80	577368	5.37
26.30	28.65	890	19683.60	519048	3.79
26.40	31.5	810	42727.80	472392	9.04
28.60	33.24	832	38883.20	485222.4	8.01
26.00	30.12	845	34533.84	492804	7.01
24.50	30.88	853	53489.92	497469.6	10.75
26.80	33.2	888	53670.40	517881.6	10.36
26.80	32.66	846	49153.68	493387.2	9.96
29.00	30.2	876	10068.00	510883.2	1.97

(c) SOLAR AUGMENTATION BASED SYSTEM:

For water kept flowing through the heat exchanger for 5 hours, mass of water accumulated, $m=2$ Kg, $C_p= 4.186$ KJ/Kg⁰K, Area $A= 0.0324$ m²

TABLE XVI. THERMAL PERFORMANCE ESTIMATION FOR MIRROR AUGMENTATION SYSTEM

Temp in °C	Temp out °C	Radiation, I W/m ²	$m \times C_p \times dt$ (J)	$A \times T \times I$ (J)	Efficiency %
25.27	29.56	958	35915.88	558705.6	6.43
24.9	28.55	970	30557.80	565704	5.40
23.28	29.3	985	50399.44	574452	8.77
25.68	26.36	845	5692.96	492804	1.16
24.9	28.96	855	33990.32	498636	6.82
25.33	29.32	879	33404.28	512632.8	6.52
25.5	31.2	890	47720.40	519048	9.19
25.7	27.34	876	13730.08	510883.2	2.69
26.3	28.4	754	17581.20	439732.8	4.00
29	32.3	766	27627.60	446731.2	6.18

V. CONCLUSION:

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° 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°. We found Compound Parabolic Concentrator system costlier but more effective at ray tracing and actual performance. The percentage increment of energy output in case of CPC system is found 21% for 180 and 23% for 280. 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. also thermal energy collected in mirror augmentation and 2D CPC is low compared to 3D CPC. From the data collected 3D CPC is more effective for better utility of solar energy and highest possible electric and thermal collection.

We demonstrated the effect of heat exchanger on all above mentioned three thermal concentration systems and in view of harnessing extra energy available in the form of solar cell temperature by subjecting the three systems for thermal performance evaluation. The results obtained for the actual thermal performance of the system is compared with the theoretical performance of the system and the efficiency for all the systems is calculated. We found that the thermal performance efficiency in case of 3D CPC system as solar cell is placed on copper heat exchanger;

heat transfer rate is high as compared with 2D CPC based system and mirror augmentation system. It is also observed in case of 3D CPC that the theoretical useful heat conversion between solar cell and the water is around 46%.

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