Analysis of a novel solar concentrator for building integrated photovoltaic application

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***Abstract*— This research work focuses on developing a novel solar concentrator – a rectangular-based rotationally asymmetrical compound parabolic concentrator (RRACPC) design. This design is unique in its rectangular exit aperture, entrance aperture, and half-acceptance angles. Several concentrators of the same design are created with varied geometry, and their geometrical properties are investigated. From the designs, a particular concentrator is selected for further studies. The selected concentrator has a height of 3 cm, a refractive index of 1.49, and an exit aperture of 1.0 x 1.1 cm. The concentrator has a geometrical concentration gain of 3.6616 and a half-acceptance angle of 45.0368° and 42.5242° in the x- and y-axes, respectively. The annual electrical output is predicted and calculated theoretically and was compared with a conventional photovoltaic (PV) panel. It is observed that the RRACPC-PV reduces the overall cost of the panel by 33% compared to a conventional PV panel.**

Keywords—concentrator, photovoltaic, solar energy, geometrical concentration gain

I. INTRODUCTION

Rising global temperatures are a major cause of climate change. The increased use of fossil fuels raises carbon emissions, and other greenhouse gas emissions that contribute to the rise in global temperature. It is evident that fossil fuels and climate change are inextricably related. To address this issue, fossil fuels must be substituted with more sustainable energy sources. The Paris Agreement was the first step towards controlling the percentage of these emissions and reducing the risk of global warming [1]. Although nuclear power is a better solution, environmentalists oppose nuclear power because of the risk of hazardous waste. Given these realities and the current state of technology, renewable energy is the only viable solution for meeting global energy demand for a sustainable economy.

In 2021, global energy demand rose by 4.6%, surpassing pre-Covid-19 levels (2019-20). During this pandemic time, renewable energy use climbed 3% as the demand for all other oil-based fuels decreased. The aviation industry and other transportation sectors accounted for 60% of worldwide energy (oil) demand, and these industries shrank during this pandemic time, which resulted in a decrease in oil demand. Moreover, there was a 330 TWh rise in electricity generation from solar PV and wind during this period [2]. Long-term contracts, preferential grid connections, and the continuous installation of new plants are all supporting strong development in renewable electricity generation. The combination of falling electricity demand and more renewable production has escalated the stress on coal, gas, and nuclear power. Apart from this, there are several other policies that strongly support the growth of renewable energy sources to tackle carbon emissions.

On average, world domestic electricity consumption in 2019 was 23,104 TWh [3]. Overall electricity demand was rising in 2021 and was expected to increase by 3%, which is around 700 TWh. Fig. 1 shows the global electricity demand change by regions in the 2020 -2021 fiscal year. Most of this growth came from India and China, constituting 390 TWh [4].

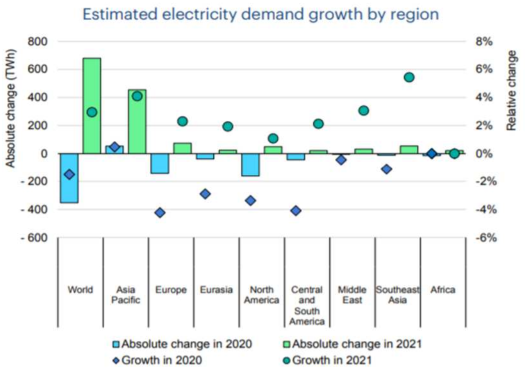

Fig. 1. Global electricity demand rise 2020-2021 by IEA [2].

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Solar energy is the most easily accessible source of renewable energy compared to other renewable energy sources. However, when compared to other sources of energy, solar energy accounts for a very small fraction of current energy production. The sun provides the Earth with 120 PJ of energy per second [5]. Therefore, the energy absorbed by Earth in 1 hr is more than enough to power all human activities for an entire year [5]. However, it is still difficult to install a cost-effective solar photovoltaic (PV) system due to a variety of problems such as the cost of PV material, shading, cost of mechanical tracking devices and weather conditions. The cost of PV material constitutes 50 – 60% of the total cost of a PV panel [6]. Since the weather cannot be controlled, a reliable way is to increase the efficiency of PV material or decrease the amount of PV material in panels without compromising energy output. Concentrator photovoltaics (CPVs) minimise the quantity of PV material needed by replacing it with optical devices (solar concentrators) that collect and concentrate light onto a smaller area of PV [7] .

II. SOLAR CONCENTRATORS

Solar concentrators are a promising device that can reduce PV material usage while producing the same electrical output values. This reduction in PV usage will also aid in reducing the installation costs. Solar energy is captured and focused into a smaller aperture from a larger aperture of entrance in a solar concentrator, wherein a solar cell is connected. A combined solar PV cell and concentrator becomes a concentrating photovoltaic (CPV) device [7], [8]. A CPV device thus reduces the effective area of PV required for producing the same electrical output. Concentrators are made from low-cost materials which include glass, acrylic plastics and mirrors that are less expensive than corresponding PV material costs [9], [10]. Concentrators made of glass and acrylics can be integrated into windows or roof glasses, allowing light to pass into the building and providing illumination.

The CPV can be made based on the reflective or refractive principle with which the solar rays are focused onto the PV material. In this way, the flux generated over a larger area is concentrated on a very small area to produce the same or higher energy output as a normal PV surface.

Many researchers have studied the compound parabolic concentrator (CPC) designs [11], [12], [13], [14], [15]. This paper focuses on developing a novel solar concentrator – a rectangular-based rotationally asymmetrical compound parabolic concentrator (RRACPC) design. However, based on the authors' knowledge, currently there is no 3D CPV design employing a rectangular exit aperture.

The Matlab code used in this novel design is similar to that of Abu-Bakar [16]; the code was modified during the operation of the program so that the exit aperture became rectangular instead of square. The code requires certain input parameters such as the height of the concentrator, the refractive index of the concentrator, and the length and width of the surface where PV material is attached (exit aperture of the concentrator). The program executes the code with the input parameters and the result is generated. The program generates output in the form of a 3D model of the novel concentrator, and it calculates the value of geometrical concentration and two half-acceptance angles. Since the design is asymmetrical and has a rectangular exit, it has two half-acceptance angles on the x- and y-axis.

Fig. 2 shows a 3D view of the RRACPC, which has a height of 3 cm, a refractive index of 1.5, and an exit aperture of 1 cm by 1.5 cm. From the output of the Matlab code, this concentrator has a geometrical concentration gain of 3.2765 and the half-acceptance angles are 55.3913° and 42.9578°. The novel concentrator has a flat entrance and exit aperture, which helps make the assembly process easier during the attachment of PV material to the concentrator.

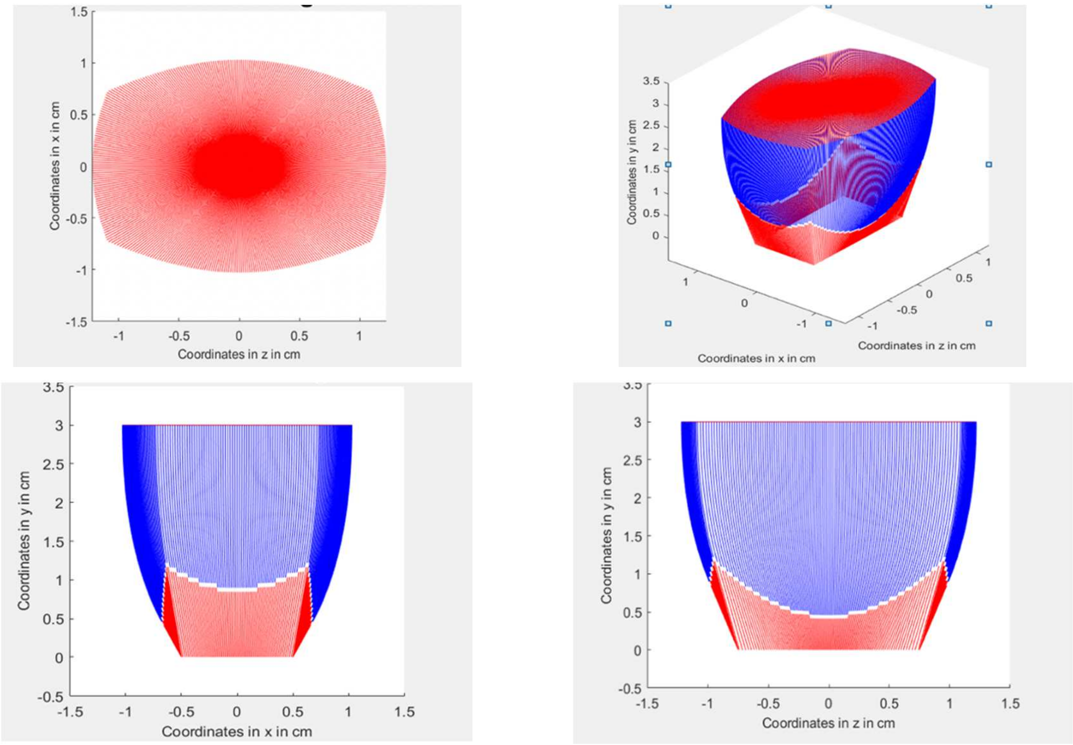

Fig. 2. RRACPC design.

TABLE I. SOME PROPERTIES OF RRACPC

INPUT				OUTPUT		
Height (cm)	Index of refraction	Width solar cell (cm)	Length of solar cell (cm)	Geometrical Concentration Gain Cg	Acceptance Angle 1 (thetaAlpha)	Acceptance Angle 2 (thetaBeta)
2	1.3	1	1.1	1.7024	44.7505	42.4958
3	1.3	1	1.1	2.9536	35.9351	34.1331
4	1.3	1	1.1	4.2834	30.7684	29.2275
5	1.3	1	1.1	5.6642	27.2827	25.9183
6	1.3	1	1.1	7.0814	24.7337	23.4993
2	1.35	1	1.1	1.8827	48.1621	45.6324
3	1.35	1	1.1	3.1927	38.373	36.3996
4	1.35	1	1.1	4.5751	32.7341	31.0626
5	1.35	1	1.1	6.0047	28.9593	27.4875
6	1.35	1	1.1	7.4681	26.2116	24.8847
2	1.4	1	1.1	2.0371	51.6385	48.7904
3	1.4	1	1.1	3.3899	40.7636	38.6096
4	1.4	1	1.1	4.8095	34.6327	32.8286
5	1.4	1	1.1	6.2726	30.5649	28.9858
6	1.4	1	1.1	7.7671	27.6196	26.2011
2	1.45	1	1.1	2.1693	55.254	52.024
3	1.45	1	1.1	3.5525	43.1361	40.789
4	1.45	1	1.1	4.9973	36.4862	34.5455
5	1.45	1	1.1	6.4823	32.119	30.4313
6	1.45	1	1.1	7.9964	28.9744	27.4645
2	1.5	1	1.1	2.2824	59.0998	55.3914
3	1.5	1	1.1	3.6863	45.5137	42.9578
4	1.5	1	1.1	5.147	38.3106	36.2281
5	1.5	1	1.1	6.6449	33.6345	31.8365
6	1.5	1	1.1	8.1697	30.2881	28.6865

III. RESULTS AND DISCUSSIONS

A. *Geometrical Concentration Gain Analysis*

The geometrical concentration is the ratio of the area of the entrance aperture to the exit aperture in 3D concentrators [17]. This section discusses the effect of concentrator height, refractive index, and the area of the exit aperture on geometrical concentration gain and half-acceptance angles of concentrator designs. These are the geometrical parameters of the concentrator; they may be used to anticipate the electrical output of the RRACPC-PV module and to compute the packaging density of the concentrator in a given area, PV material savings, and finally the financial analysis of the system. A total of 125 concentrator designs were developed by varying concentrator height, refractive index, and the area of the exit aperture of the concentrator.

Table 1 shows a set of input parameters and output results from Matlab. In this set, the dimension of the exit aperture of the concentrator is fixed at 1.0 cm x 1.1 cm and other parameters such as the refractive index and height of the concentrator are varied. Since the standard thickness of a PV panel is between 5 cm to 6 cm, the novel concentrator must have a maximum height of 6 cm [18], the novel concentrator must have maximum height of 6cm. The refractive index of the concentrator was varied from 1.3 to 1.5 with an increment of 0.05 in this study to analyse the change of geometrical concentration gain with refractive index.

Fig. 3 shows the variations of geometrical concentration gain when the total height and the refractive indices change, while Fig. 4 shows the variations of half-acceptance angle when the total height and the refractive indices change.

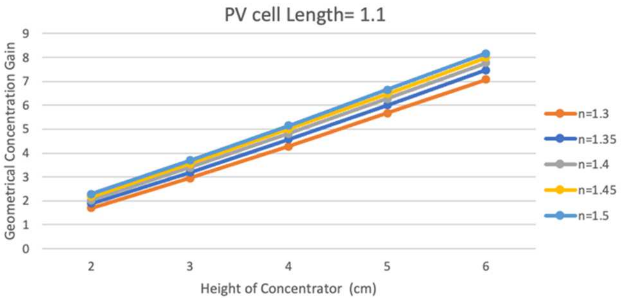

Fig. 3. Geometrical concentration gain of the RRACPC derived from varying total heights and refractive indices.

From the Fig. 3 it is clear that the value of geometrical concentration gain increases as the height of the concentrator increases. For example, from Table 1 the geometrical concentration of concentrator with a height of 3 cm, an exit aperture of 1.0 cm x 1.1 cm and a refractive index of 1.3 is 1.7024. By holding all other factors fixed, the geometrical concentration rises to 7.0814 as the concentrator's height increases.

In Fig. 4, the half acceptance angle decreases as the height of concentrator increases. The refractive index is proportional to both geometrical concentration gain and the half acceptance angle. The values of geometrical concentration gain rise from 1.7024 to 2.284 as the refractive index increases from 1.3 to 1.5, as seen in the table. Similarly, the half acceptance angle 1 is ±44.75° and half acceptance angle 2 is ±42.49° for a refractive index of 1.3, and it is increased to 59° and 55.39° for half-acceptance angle 1 and 2 respectively when the refractive index is 1.5.

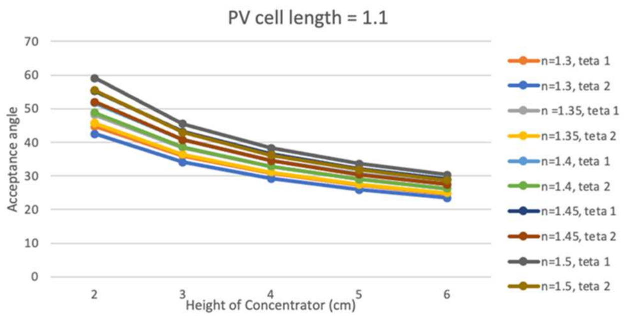

Fig. 4. The half-acceptance angle of the RRACPC derived from varying total heights and refractive indices.

The geometrical concentration gain is in a range of 1.5586 to 8.1697 and the minimum value of half acceptance angle 1 and 2 is in a range of 24.73° and 23.49° respectively and the maximum value of half acceptance angle 1 and 2 is 68.79° and 52.02°.

The overall analysis of this experiment shows that a shorter RRACPC has a lower geometrical concentration gain and a broader half-acceptance angle, whereas a taller RRACPC has a higher geometrical concentration gain and a smaller half-acceptance angle.

B. Electrical Output Prediction

The height of the concentrator is 3 cm since the overall thickness of PV panels is 5 cm to 6 cm [18], and this concentrator can be easily integrated inside the panels. Moreover, concentrators of 3 cm show better results in terms of geometrical concentration gain and acceptance angles. As the height of the concentrator increases or decreases, either the geometrical concentration gain or acceptance angles have to be compromised. When the height of the concentrator is decreased, the volume of the concentrator material is decreased and the overall production cost is decreased. Additionally, an increase in geometrical concentration gain leads to the formation of hotspots in PV material and leads to the formation of higher and lower intensity regions. Then, an internal current flows from a location of higher intensity to a zone of lower intensity, resulting in a voltage drop and affecting the entire PV system [19].

The refractive index of the concentrator is that of PMMA, since other materials undergo discoloration as the concentrator is exposed to sunlight for a long time, and experience material shrinkage. For example, the material acrylic 6091 with a refractive index of 1.51 underwent discoloration after 2-year usage [20]. This will lead to more optical losses and reduce the performance of the concentrator.

From these designs, one concentrator design was chosen to integrate into a 1 m^2 PV panel. For comparing the electrical output of the concentrator, a conventional PV panel of standard size was considered, and the electrical output of this panel was calculated by using a software called PVsyst for 1 year. The electrical output of the same panel was calculated by integrating an array of the selected concentrator in the panel. In this case, PV material is only where the exit aperture of the concentrator is attached to the panel. In the third case, those concentrators were removed from the panel and the electrical output was calculated. Thus, two comparisons were done to understand the performance of the concentrator.

The PV panel is assumed to be installed at an angle of 15° inclined to the south side in a flat surface where there is no shading. The geographical coordinate of the selected place is 9.9252°N, 78.1198°E (Madurai, Tamil Nadu, India) [21]. This site is considered for calculating the energy output, since in India only the Tamil Nadu government follows an FIT (feed-in tariff) scheme for installing PV panels for domestic purposes [22].

From the 5 concentrator designs, one design was selected and it was done by calculating the entrance aperture area of each concentrator design. Though the geometrical concentration gain and acceptance angles are comparable as shown in Table 1, the concentrator with an exit aperture of 1.1 cm^2 was selected so that a greater number of concentrators can be included in the PV material.

As mentioned previously, this section discusses three cases while calculating the electrical output of a photovoltaic panel. Initially, the electrical output of a photovoltaic panel having a 1 m^2 PV material producing 155 kWp was computed for one year at the selected site. The electrical output of the panel was calculated using PVsyst considering the hourly temperature as well as global horizontal irradiation and horizontal diffuse irradiation. The angle of inclination was chosen optimally to collect the maximum amount of irradiation. It was found that at a 15° tilt, the maximum irradiance is collected throughout the whole year. It is evident that the ratio of loss with respect to the optimum is zero at 15° tilt. The transposition factor is 1.02, which is the incident irradiation on the plane, compared to the horizontal irradiation. On the collector plane, 1896 kWh/m^2 is incident at this angle. Ideal conditions without shading were considered during the electrical output calculation. The electrical conversion efficiency of the selected panel is 15.4%.

The electrical output of the selected panel is 223.6 kWh/year when it is mounted on a flat surface with an inclination of 15°. This electrical output was obtained using PVsyst where the panel was tested under standard test conditions in which the temperature of the panel is maintained at 25°C. In actual testing conditions, the temperature of the panel increases, and its electrical conversion efficiency decreases, resulting in a decrease in electrical output.

The electrical output of the panel was calculated when the concentrators were arranged in a 1 m^2 panel and PV material was only at the exit aperture. The selected concentrator had a geometrical concentration gain of 3.6616. The electrical output of this panel can be theoretically predicted by multiplying the geometrical concentration gain by the previous case. Thus, the electrical output in this case is 182.23 kWh.

Due to the fact that this work is restricted to the geometrical properties of a novel concentrator design, the optical concentration gain analysis is excluded. As a result, the value of C_{opt} cannot be estimated or assumed. Though the electrical output obtained is 182.23 kWh, there will be several losses such as optical losses, shrinkage of material, polishing losses etc. These losses will decrease the optical efficiency of the concentrator and cause a decrease in the electrical output from the panel.

C. Cost Analysis

This section compares the average rate of a normal photovoltaic panel to that of a RRACPC photovoltaic panel. For a PV panel of 155 Wp having 1m^2 PV material, the average market price is Rs 4,500 [23]. Assuming 20% is the margin of the supplier company, the manufacturing cost of the PV panel is Rs 3,600 (excluding taxes).

The following data shows the cost breakdown of photovoltaic panel production as a percentage of total cost:

PV material cost – 62%

Cost of Glass, Encapsulation, Frame, Wiring - 26%

Assembling cost/ manufacturing – 12%

Thus, cost of 1m^2 PV material is Rs 2,232 (assuming the whole panel is having PV material).

To produce same amount of electricity using proposed concentrator design, 2,488 RRACPCs are required to be installed in a panel and 0.2736 m^2 of PV material is required.

Cost of 1 concentrator (PMMA) is Rs 0.607.

Thus, cost of 2,488 RRACPC's is Rs 1,510.20. Instead of manufacturing single concentrators, as previously discussed, an array of concentrators is attached using a thin layer of plastic to save assembly costs.

PV material used is 0.2736 m^2, which costs Rs 610.67.

Cost of Glass, Encapsulation, Frame and tabbing decreases by 10% for the proposed panel as the glass is only present on the back part of the panel to which PV cells are attached, which costs Rs 842.

Assembling cost decreased by 31%, which costs Rs 298.

Overall cost of the proposed RRACPC-PV panel is Rs 2,418.87.

Thus, the RRACPC–PV panel costs 33% less than a conventional PV panel.

IV. CONCLUSIONS

The purpose of this research is to develop a novel solar concentrator that can be integrated into building structures for photovoltaic applications. The proposed concentrator is a unique design in CPC called the RRACPC. The design provides a better half-acceptance angle and geometrical concentration gain than other CPCs so that maximum sunlight can be captured into the PV cells throughout the year. During the research, 125 designs were generated using Matlab, and an analysis is done to understand the relation of geometrical concentration gain, half-acceptance angles, height and refractive index of concentrator. This design is unique from other RACPC since it has two half-acceptance angles in x and y directions, which has not been not explored by any other researchers.

Geometrical concentration gain analysis shows that the designs give a geometrical concentration gain from 1.5586 to 8.1697, while the half acceptance angles range from 24.73° and 23.49° in x and y axes respectively to 68.79° and 52.02°. This overall analysis demonstrates that a shorter RRACPC has a lower geometrical concentration gain and a wider half-acceptance angle, whereas a taller RRACPC has a higher geometrical concentration gain and a smaller half-acceptance angle.

The electrical output of a CPV system based on a concentrator design developed in this study is predicted. A concentrator with a refractive index of 1.49 and a concentrator height of 3 cm was selected for the study. The selected concentrator has a height of 3 cm, an entrance aperture of 4.02776 cm^2, an exit aperture of 1.1 m^2, a geometrical concentration gain of 3.6616, and half-acceptance angles of 45.0368° and 42.5242° in the x and y axes respectively. To understand the performance of the concentrator, a comparison with a conventional panel of PV material area 1 m^2 is done. Using AutoCAD, the number of concentrators that can be accommodated in 1 m^2 is calculated, and these concentrators are arranged as an array in 1 m^2, and their electrical output is predicted. The results show that the conventional panel produced 223.6 kWh/year, while the RRACPC-PV produced 182.23 kWh/year. As the concentrators are integrated into the PV panel, the overall PV material is reduced in the second case, causing a reduction in electrical output.

A cost analysis is done to explain how the RRACPC-PV reduces the overall cost of the system. The analysis compares a conventional PV system with an RRACPC-PV system, both of which produce the same electrical output. When producing the same electrical output, the RRACPC–PV system uses less PV material, decreasing the PV material by 27.36%. The RRACPC panel costs Rs 2,418.87, while the conventional panel costs Rs 3,600.

The research work shows that the novel solar concentrator can be integrated into building structures, reducing the overall cost of the PV panel.

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