Design of Nature-Inspired Solar Concentrator for Rural India

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ABSTRACT

Energy consumption is on the rise with technological advancement across the globe and access to conveniences to the majority population. In India that is not the case as the majority of its population lives in rural areas where there is no electrical connectivity, demoting their standard of living. The major reason for this lack of connectivity are, they are located too far from the source of generation, and the revenue as a whole does not make the project viable. Hence the only way to provide them with better living conditions is through the installation of efficient and low cost nature inspired solution that are capable of powering light sources and storing energy. A lot of research has been conducted on increasing the efficiency of solar energy through nature inspired techniques. Solar energy-harvesting has seen a steady progress since its inception, yet price and efficiency barrier prevents photovoltaic cells from becoming more accessible. Acrylic, polycarbonate, or glass lenses and reflectors are current strategies used to increase the amount of sunlight focused onto PV cells. Concentrators and reflectors require additional costs and usually do not track with the sun to intercept direct sunlight. Our project idea is to design and build the hardware required for a Concentrator Photovoltaics (CPV) array. The goal of this project is to study the economic feasibility of using water lenses rather than conventional optics which are usually cost-prohibitive for these kinds of applications. Thereby creating an opportunity to remain self-sufficient, in terms of generating power needed for lighting. Driving it with the concepts of sustainability and green energy would help to fulfill the Atmanirbhar Bharat vision.

Keywords: solar concentrator, water lens, nature inspired design, green energy

I INTRODUCTION

The statement by India to achieve net zero emissions by 2070 and fulfill half of its electricity needs with renewable energy sources by 2030 is a watershed moment in the global fight against climate change. India is pioneering a new economic growth strategy that might sidestep the carbon-intensive paths taken by many countries in the past — and serve as a model for other emerging economies. The magnitude of change in India is astounding. Over the last two decades, its economic development has been among the highest in the world, pulling millions of people out of poverty. This growth could become more tremendous if people living in remote rural parts of the country could utilize electricity. Coal and oil have long been the bedrocks of India's economic expansion and modernization, providing sophisticated energy services to an increasing number of Indians. But since it is not economically viable to set up electric lines to these remote villages, they tend to remain without electrification. In the last decade, India has included adding 50 million new electrical connections each year. Because of its sheer size and enormous economic potential, India's energy consumption is expected to expand faster than that of any other country in the next decades. We predict that most of the rises in energy demand this decade would have to be supplied with low-carbon energy sources on a path to net zero emissions by 2070. In order to meet the rising energy demands, research needs to be conducted for improving the efficiency of solar cells utilizing nature inspired designs.

II LITERATURE REVIEW

Photovoltaic cells have been through tremendous improvement over the last few decades, driving down its manufacturing cost. Various approaches have been explored to further maximise its use case.

A solar tree, (Khan et al [1]) that addresses the issue of space constraints by installing PV modules on a pole with branches. To harvest 2MW of energy from the sun, we require 10 acre of land, acquiring this much land is a huge problem. Hence adopting the solar tree structure can produce the same amount of energy in just 1% of the entire area proposed for the project. In the solar tree, the PV modules are arranged in a spiralling phyllotaxy, which is inspired from the Fibonacci series observed in nature. Here it suggests a span of 144 degrees between the first branch and the second, 288 degrees spanning 2 branches, 720 degrees spanning 5 branches and so on. Thereby capturing solar radiation to generate maximum power.

Sunflower based heliotropism, (Sharma et al [2]) is used to track the sun to absorb more energy; here the panel is held up by a specialised joint, increasing the efficiency by 25%. This joint is a combination of Liquid Crystalline Elastomers and Carbon Nano Tube, which shrinks when heated and expands when cooled, by using a mirror that reflects light to the joint thereby controlling the direction it is facing, functioning as a Maximum Power Tracker (MPT). This technique is inspired from the pulvinus, a joint like thickening at the base of the leaf that promotes growth independent movement, which is referred to as phototropism, hormone auxin is responsible for this phenomenon.

Solar concentrators (Ann Arbor [3]) inspired by diurnal and nocturnal flowers to increase the optical efficiency. Since the parabolic concentrator captures more radiation during the noon and hyperbolic during the rest of the day, we needed a concentrator that could transition and is inspired by the biomimetic structure of flowers. It is designed to transition from a parabolic structure to hyperbolic through smart origami, which is achieved by 4D printing, the additive manufacturing with stimuli responsive material. After analysing various shapes of concentrators against parameters like concentration ratio and optical efficiency, the one that effectively captures most of the radiation from sunrise to sunset is the Compound Hyperbolic Concentrator with entry curvature and trapping zone.

Adopting agrivoltaic system (Elanz et al [4]), this research paper suggests that the efficiency of solar PV cells depend on factors like air temperature, wind speed, vapour pressure. Maximum power potential is observed in croplands, grasslands and wetlands, where there is increased insolation, light wind, moderate temperature, reduced humidity. Agrivoltaic system leverages the superposition of energy and food production for mutual benefits. In this system crops are grown in intermittent shade casts, researchers have successfully grown maize, lettuce, tomatoes, aloe vera and pasture grass.

Biomimetic PV cells inspired by surface morphology (Soudi et al [5]), moth eye structure is used as anti-reflectance coating and quasi honeycomb structure is used for scattering light more efficiently. Surface morphology of natural organisms inspires innovations such as surface coating to maximise light absorption and anatomical features to focus light or reduce reflection. A common theme is to use tapered shapes like cones to gradually change refractive indices.

Research so far suggests that the efficiency of solar cells can be improved by adopting nature inspired designs. Yet these solutions are not viable, in terms of cost, infrastructure and technical capacity required for its application in rural India. An efficient nature inspired solution can be designed by adopting a viable alternative for maximizing the amount of light captured for absorbance by solar cells. Thereby solving the problem of basic lighting in rural India that has not been electrified.

III OBJECTIVES & METHODOLOGY

(a) **Objective- The** objective of this paper is to eliminate the problem of efficiency pertaining to PV cells through nature inspired solutions and thereby lighting up rural India with clean energy.

   (i) To design an apparatus that should provide an improvement in power output when compared to bare solar cells
   (ii) Design is to be simple and bare, such that it is easy to setup
   (iii) Low cost, utilising locally available and recycled materials
   (iv) Minimal intervention for operation
   (v) Viable lighting solution

(b) **Methodology** - Primary research needs to be conducted to develop a viable design solution that can be constructed and utilized in remote rural areas. To understand the feasibility of the solution, Quantitative data need to be collected for analyzing the concept viability. The first step would be to conceptualize a theoretical model based on the principles of light. The primary objective here is to maximize the amount of captured light falling on the aperture of the concentrator. Then the secondary objective here is to increase the absorbance by focusing the captured light onto a smaller area. Mathematical analysis was performed to find the values that satisfy the design criteria, like: aperture area, aperture angle, and concentration ratio. An experimental set up was made to quantify the observed results, creating a data driven approach to solving the problem.

Secondary research was conducted to understand the qualitative aspects of the proposed solution. The feasibility of the solution with regards to the type of materials used for construction, cost of procuring them, skills required for processing, serviceability and maintenance. This aspect of research helps to identify the type of materials and resources that can be availed for implementing the solution effectively.

IV CONCEPTUALIZATION

Our project idea is to design and build the hardware required for a solar concentrator; this requires us to study the existing concentrators. A multitude of optical devices are used to focus light onto a smaller area, increasing the output power delivered by the solar panel.

(a) **Fresnel lens CPV:** This concentrator system uses Fresnel lenses, shown in fig.1, to focus light onto the PV cell, the lens are usually made of glass or acrylic. These kinds of solar panels also require 2-axis tracking since the incident rays must come in at 0 degrees incidence for the light to be focused properly.

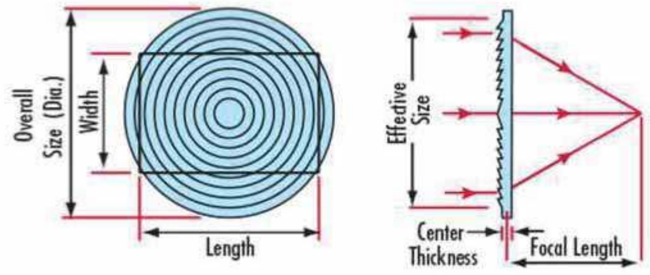
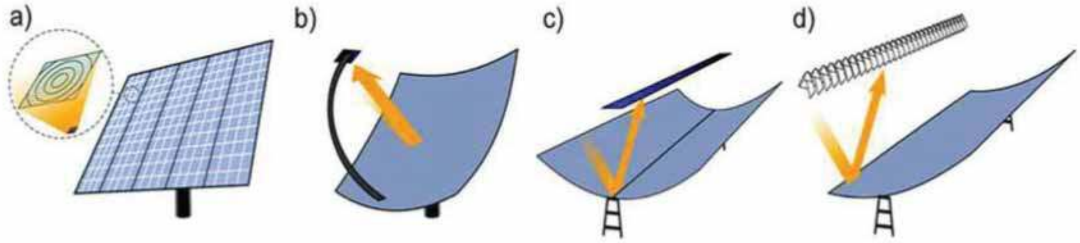


Fig.1 profile of a Fresnel lens. Source: Edmund optics
Source: Experimental demonstration of high concentration photovoltaics, Thomas A Cooper



	a)	b)	c)	d)
C_g:	>500x	>500x	<200x	>500x
POE geom.:	3D	3D	2D	2D
POE tracking:	two-axis	two-axis	one-axis	one-axis
η_{system}:	30 - 35%	30%	15%	>20%

Fig. 2 Typical CPV optical configurations and their main characteristics: (a) point-focus lens/mirror parquet with one cell per optic; (b) point-focus dish with dense array; and (c) line-focus parabolic trough with linear array. The proposed line-to-point (LTP) focus configuration (d) combines the advantage of configuration (c), namely one-axis tracking and 2D primary construction, but can match the high concentration capabilities of the two-axis tracking 3D configurations (a) and (b).

(b) **Parabolic mirror CPV:** This concentrator system uses reflective surfaces to focus the light onto the PV cells, as shown in fig.2. Like most other CPV methods, it requires 2-axis tracking to minimise the angle of the incident rays.

The goal is to study the economic feasibility of using water lenses rather than conventional optics which are usually cost-prohibitive for these kinds of applications.

(c) **Litre of light:** It is an open source design for a low-cost light tube that refracts solar light to provide daytime interior lighting for dwellings with thin roofs. Daylighting is cheaper than using indoor electric lights during the day.

Optical properties like refraction shown in fig.3, and total internal reflection helps the litre of light to provide 360 degree lighting like that of a 60 watt bulb in a 40 square meter room. This solution has helped to light up homes in crowded living spaces where daylight does not penetrate.

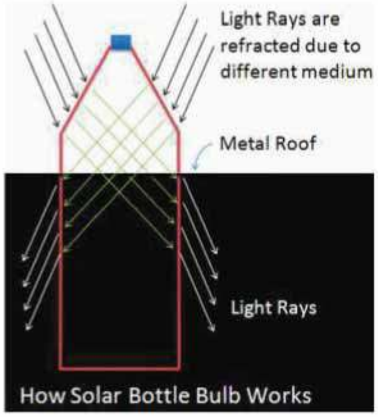


Fig.3 Ray diagram of how light behaves when interacting with bottle of water.
Source: Critical View on Daylighting Through Solar Bottle Bulb, Chen Wang

(d) Focusing device: Taking inspiration from the form of a nano focusing device, as shown in fig.4, which has a tunnel like channel where light travels through internal reflection. This tunnel like channel then narrows down to tapered cuboidal structure, focusing light into tinier spaces such that its intensity increases.

Fig.4 CalTech's nano focusing plasmonic wave-guide
Source: Nano focusing device shrinks light beams, Brian Dodson

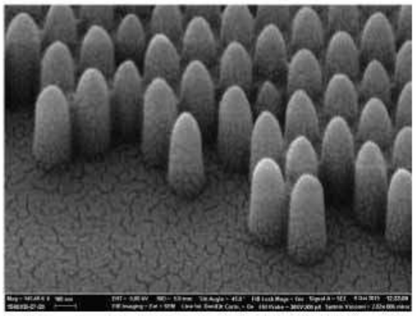


Fig.5 Microscopic view of moth eye structure
Source: Moth-eye smart windows cut cleaning costs and heating bills, Anthony Capkun

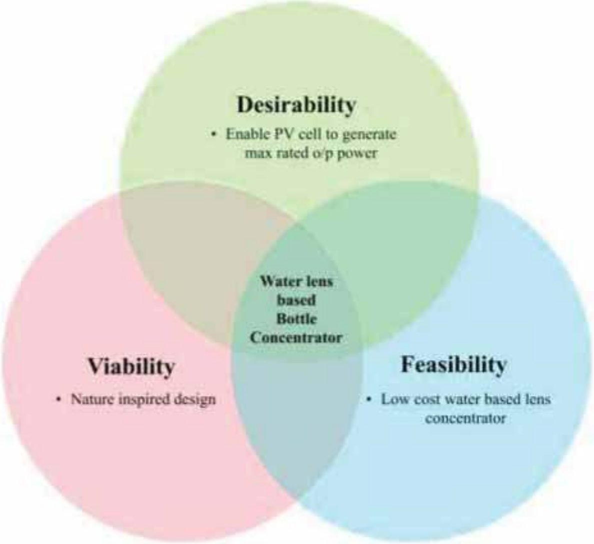


Fig.6 Three lenses of innovation - Venn diagram

(e) **Moth eye structure:** Taking inspiration from the surface morphology of the moth eye structure, as shown in fig.6, to maximise the absorption of light. The light that falls on this structure refracts through, and reflects among them and internally before getting absorbed into the moth's eye.

The concepts discussed above could be brought together to design a solution that fulfill the need of improving the efficiency of a solar cell. The next step was to implement a design thinking approach that can coherently align the various concepts to envision an ideal solution. The three lenses of innovation: desirability, feasibility and viability have been used here to better visualise the solution as shown in fig.6.

V IDEATION

In this phase, we incorporate the concepts discussed in the previous phase to design the prototype. Utilising the bottle from litre of light concept to maximise the amount of light captured, then multiplying the number of bottles to further increase its capacity to capture light. Arranging the bottles in hexagon shape to maximise the surface area occupied by the bottle, and to resemble the moth eye structure. This structure ensures that the amount of light absorbed by all the bottles as a single unit is maximised. Now that the amount of light captured is maximised, the next step is to focus all of this light into a smaller region. To achieve this, tapered structure of the light focusing device is taken into consideration.

We now have a solar concentrator where the capacity to absorb light is improved by using the conical shaped bottles filled with water. This water filled bottles act as a water lens, which refracts and internally reflects light into the tapered concentrator. Hexagon arrangement of bottles was preferred over the grid arrangement to replicate the morphology of the moth's eye. The reflecting surface is inclined at an angle of 60 degrees, the inside reflects the light rays onto the panel, thereby the ability to focus the absorbed light is also improved. The area of the PV cell is measured at 7x7cm, to achieve a concentration ratio of 16, the aperture area is to be 28x28cm, as can be seen in fig.7.

Tapered concentrator with filleted edges enhances the capacity of focusing light onto the panel. The two types of arrangement that were tested include the hexagon arrangement with 7 bottles and grid structure with 9 bottles. This was done to understand how mimicking the morphology of moth eye structure can improve the capacity to absorb light.

The three defining factors for improving the efficiency were evaluated in terms of the type of bottles used for capturing and focusing light. The alignment pattern, the angle of bottle, depth of insertion into the tapered concentrator, surface area that is exposed to light, volume of water, and gap between each bottle.

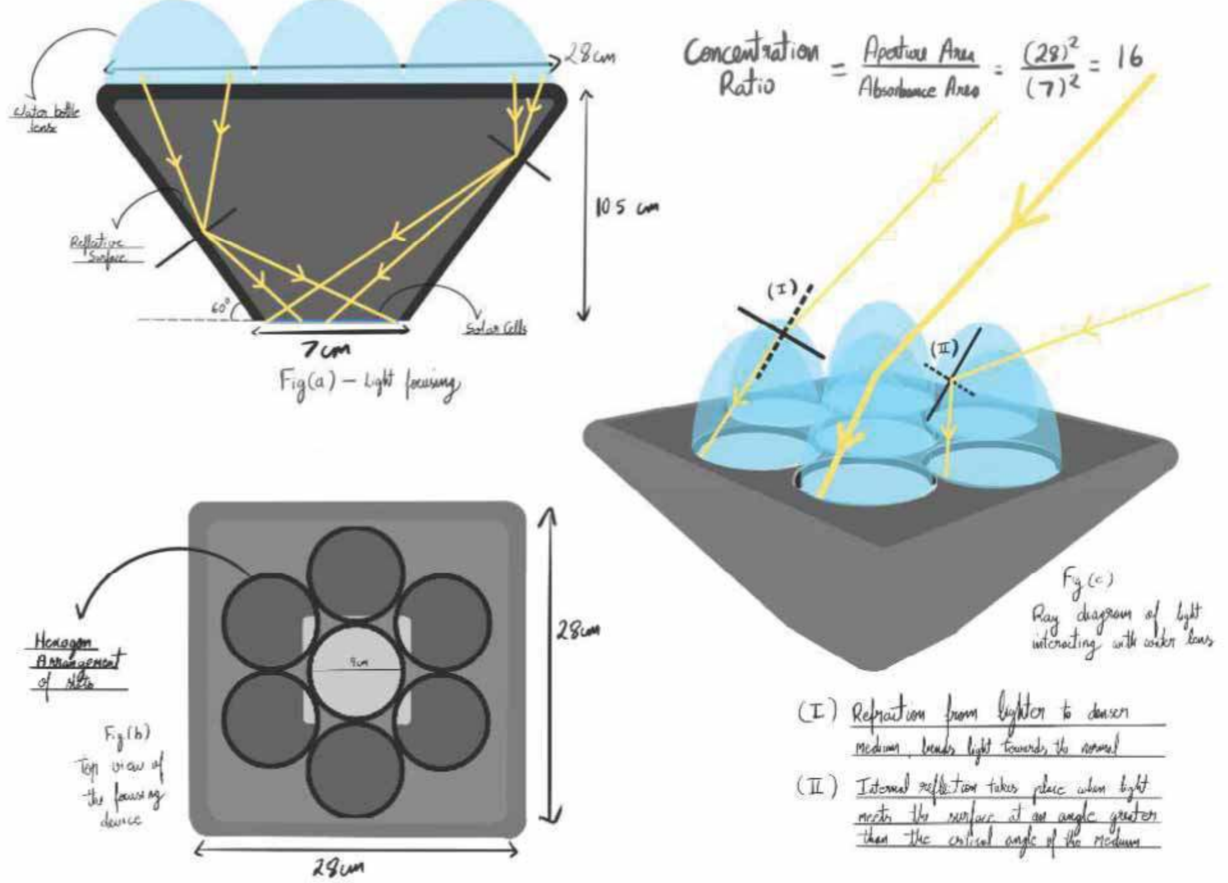


Fig.7 Ideation sketch of prototype

VI PROTOTYPE

In this stage, the final concept after evaluation from the ideation stage is rendered using CAD software to simulate for the real life proportions. The different views, including side view, top view, and three fourth views were rendered to better understand proportions of the model. Different views of the render were utilised for taking reference to construct the physical prototype.

Construction of the physical prototype was done using cardboard pieces that were bent at an angle of 90 degrees. Four such pieces were used to put together the edges of the concentrator; the pieces were cut at an angle such that the structure makes an angle of 60 degrees. Once the structural frame was created, it was further reinforced with pieces of cardboard providing it with a balanced and even finish. The inside of the concentrator was lined with a reflective packaging wrapper. The slot for placing the bottles were cut out from cardboard using a circular saw drill of the appropriate size. Two such slot boards one with a hexagon arrangement and grid arrangement were created. Once the frame was created, 250ml bottles filled with water were placed to make the functional concentrator.

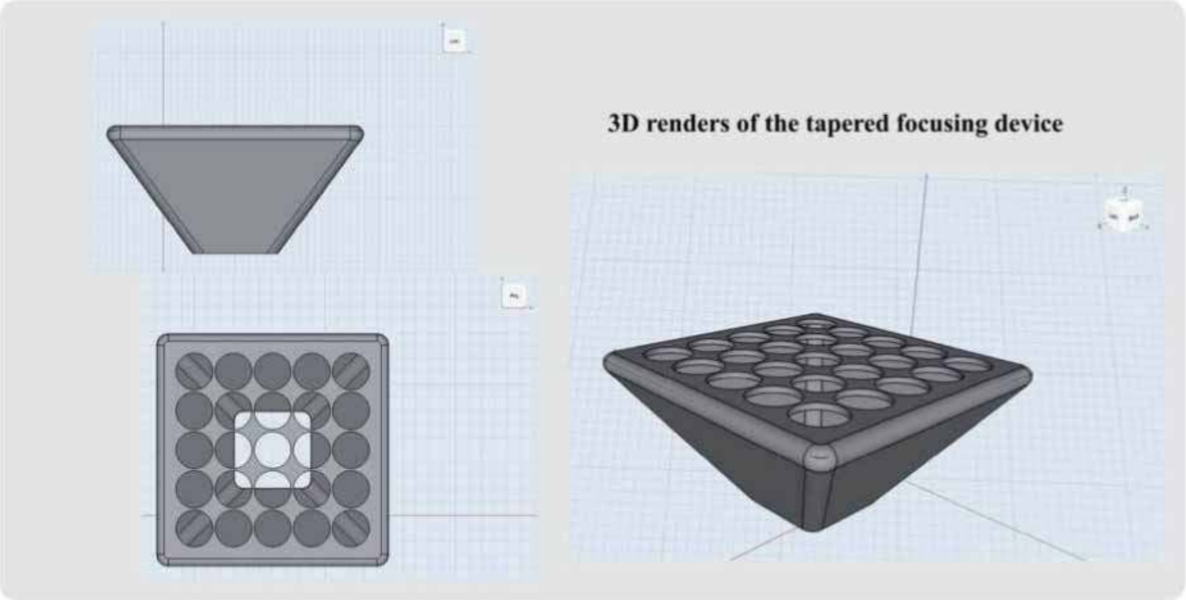
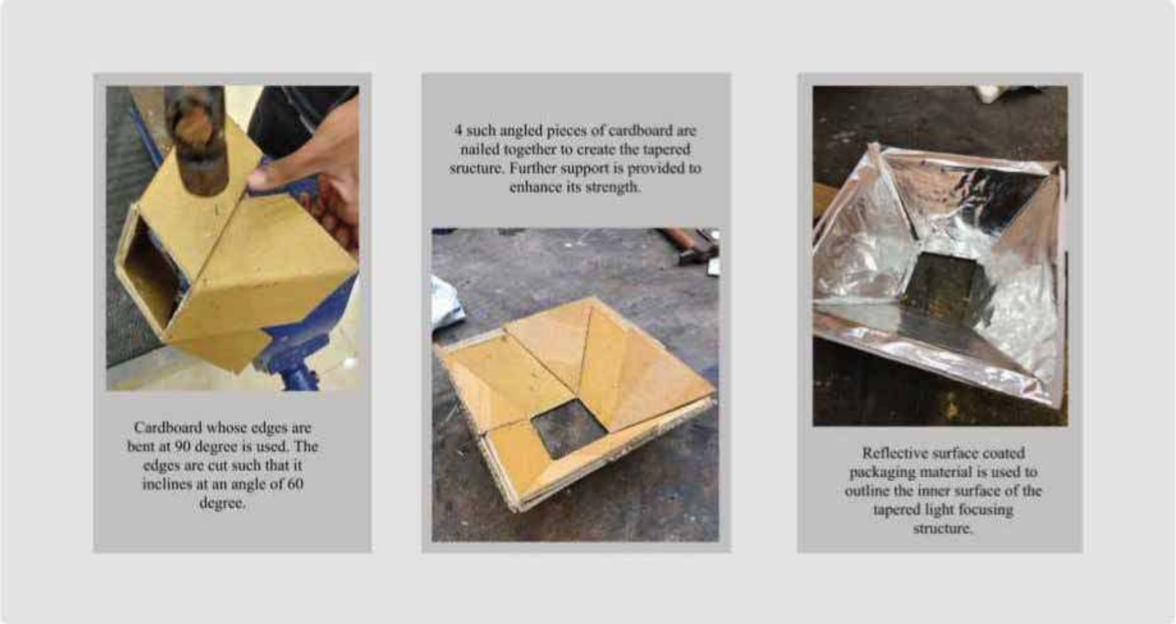

3D renders of the tapered focusing device

Fig.8 CAD renders of the concentrator from multiple perspective


Cardboard whose edges are bent at 90 degree is used. The edges are cut such that it inclines at an angle of 60 degree.

4 such angled pieces of cardboard are nailed together to create the tapered sructure. Further support is provided to enhance its strength.

Reflective surface coated packaging material is used to outline the inner surface of the tapered light focusing structure.

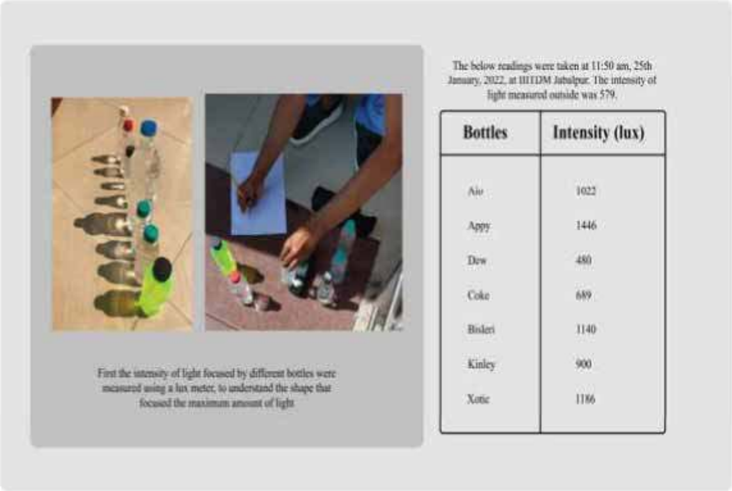
Fig.9 Construction of the physical prototype

VII TESTING

In this phase we strive to arrive at promising results as speculated from the ideation stage. Experiments are setup to understand the working result of the physical prototype. Initial step taken was to understand the intensity of light focused by each type of bottle with varying shapes. Once the bottle with the maximum capacity to capture light was identified, then the next step was to test it by arranging it in the shape of hexagon. This hexagon structure replicates the morphological structure of the moth eye, enabling it to maximise the amount of light captured. The intensity of light was measured using a lux meter.


Final prototype with the water lens bottle to maximise the absorption and a tapered focusing structure to maximise the light intensity

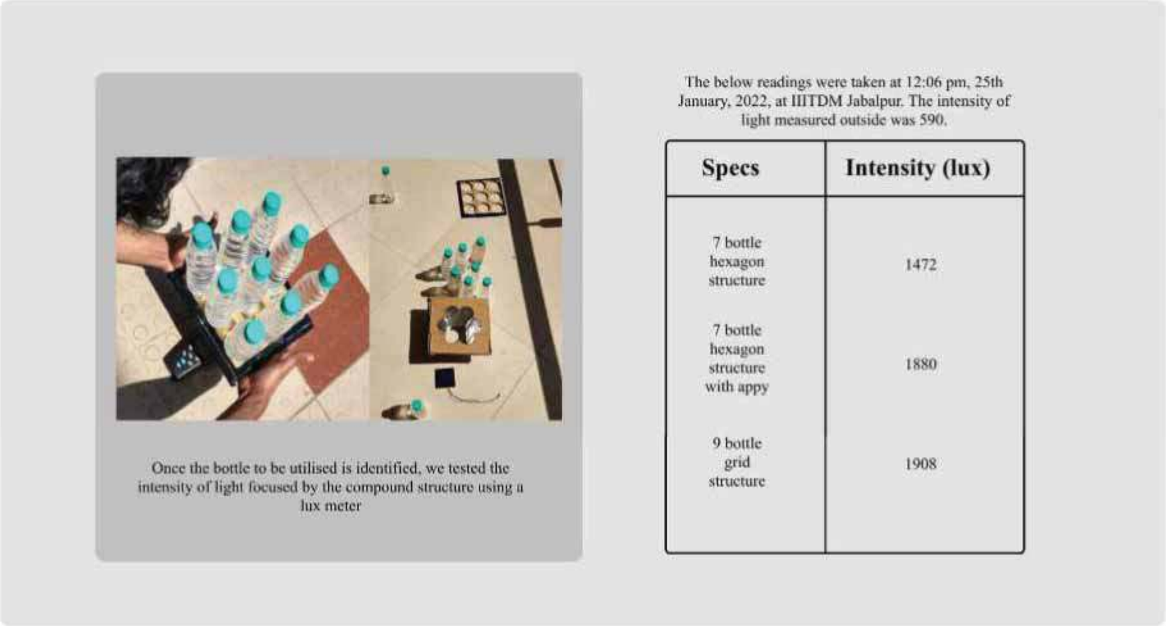
Fig.10 Final prototype


First the intensity of light focused by different bottles were measured using a lux meter, to understand the shape that focused the maximum amount of light

The below readings were taken at 11:50 am, 25th January, 2022, at IIITDM Jabalpur. The intensity of light measured outside was 579.

Bottles	Intensity (lux)
Aio	1022
Appy	1446
Dew	480
Coke	689
Bisleri	1140
Kinley	900
Xotic	1186

Fig.11 Light intensity test results of different bottles arrangement



Once the bottle to be utilised is identified, we tested the intensity of light focused by the compound structure using a lux meter

The below readings were taken at 12:06 pm, 25th January, 2022, at IIITDM Jabalpur. The intensity of light measured outside was 590.

Specs	Intensity (lux)
7 bottle hexagon structure	1472
7 bottle hexagon structure with appy	1880
9 bottle grid structure	1908

Fig.12 Light intensity test results of different bottle arrangement

The results collected could be verified with the theoretical expectation; it was observed that the intensity of light when focused through a bottle of water can increase upto 3 times, while the intensity of light when focused through the concentrator had increased upto 4 times.

VIII CONCLUSION

Among the many existing technologies that have the capacity to increase the efficiency of a solar panel, the water lens based bottle concentrator has proven to exhibit great potential in improving efficiency of a PV cell. This viable concept can be utilised in association with any solar panel to improve the overall efficiency of the output power. Since the construction of the frame is simple and can be replicated using available resources, it can be effectively replicated with ease across different remote rural areas.

The low cost construction of the PV concentrator utilising packaging waste greatly supports the Atma Nirbhar Bharat. India as a country is known for its innovation in terms of achieving results with a fraction of the actual cost incurred. The bottle concentrator based on water lens can be constructed and utilised in remote rural areas with no electrification. This can uplift their living conditions by providing a viable source of energy to depend on, for their lighting needs. The goal of this project is to maximise the capacity of power generated by the PV cell, one of the key motivation here is to enable the rural communities to engage in the construction process of the concentrator utilising locally available materials.

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