Design of a linear Fresnel lens system for solar photovoltaic electrical power source

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ABSTRACT

The object of the paper is to describe how a linear Fresnel lens is designed using I-DEAS® (Integrated design, engineering and analysis software) package. The design is carried out by drawing three curves from the focal point at specific radii. A vertical line is drawn at the extreme right end of the curve. By drawing a tangent and a normal at that point, the refracted angle is found out using Snell's law. The refracted ray is extended to meet the arc at a point where another tangent and a normal are drawn to find the incident angle. By joining this point and the focus, the angle of refraction is determined. Then suitable angles of incidence and refraction are found such that it satisfies Snell's law. The new normal is drawn and the perpendicular to it forms a lens tooth. Equidistant points are plotted on the profile of the lens and by Lagrange's interpolation the groove angles at each point are determined. By drawing the lens tooth at the suitable groove angles, one half of the lens profile is created which is then mirrored and extruded to get the full profile. The significance of this work is that it ensures the precise focusing of the entire incident light along a straight line without any scatter. This reduces the effective photovoltaic cell area needed and hence cuts the cell cost tremendously. The thickness of the lens is 4mm, which enables it to be bent and mounted easily.

Key Words: Fresnel lens, photovoltaic cell, I-DEAS®, Lagrange's interpolation, Snell's law.

1. INTRODUCTION

The energy needs of man have been increasing everyday. The fossil fuels are the primarily utilized resources and it is a well-known fact that they wont last for long. The need for conserving energy and for developing energy alternatives has led to considerable research and development work in this direction, and significant progress has been made. However much remains to be done. One of the promising options is to make more extensive use of the renewable sources of energy derived from the sun. Solar energy can be used both directly and indirectly. It can be used directly in a variety of thermal applications like heating water or air, drying, distillation, and cooking. The heated fluids can be used for applications like power generation or refrigeration. A second way in which solar energy can be used directly is through the photovoltaic effect in which it is converted to electrical energy. This paper deals with designing a Fresnel lens system that converges the entire sunlight incident on it to a line focus. The Fresnel lens is a thin sheet, flat on one side and with fine longitudinal grooves on the other. This lens is usually made of extruded acrylic plastic sheets. The Fresnel lens system was preferred to the others because of its inherent advantages. But the most predominant advantages of the Fresnel lens is that it concentrates, even diffused sun radiations incident over it and converges it as a high intense beam on a line. The picture below shows how a Fresnel lens can be used to focus the sunrays on the photovoltaic cell. The design of the Fresnel lens is done using I-DEAS® (version 7) package.

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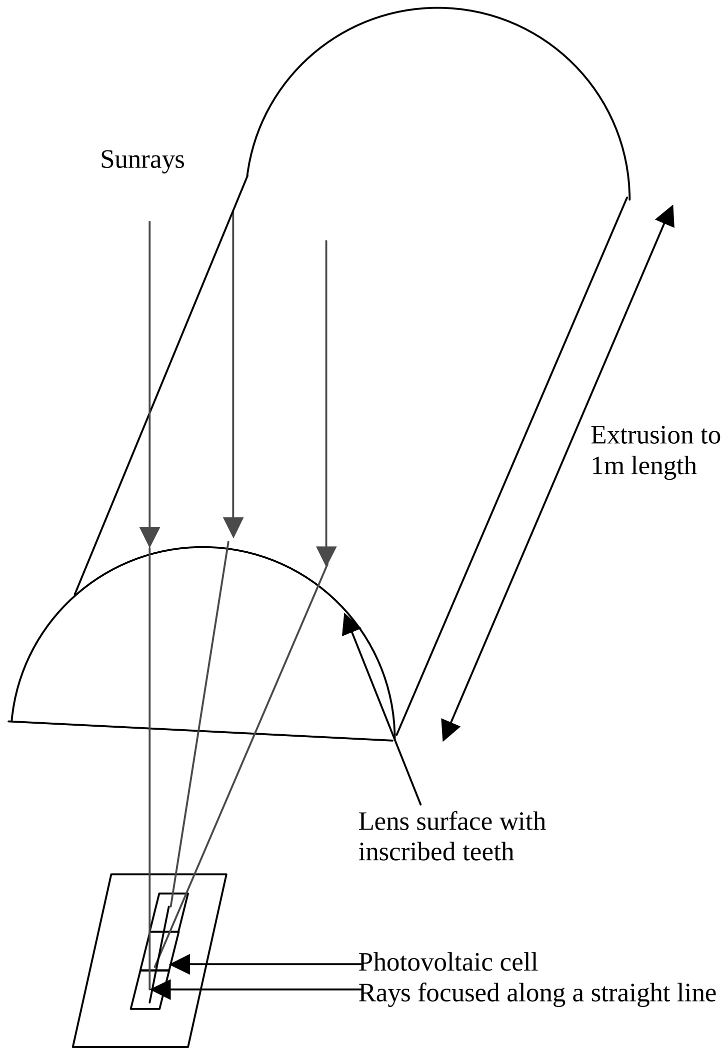

Figure 1. Basic working principle of the designed Fresnel lens system

2. DESIGN OF LINEAR FRESNEL LENS

A Fresnel lens is a type of convex lens, which is used to focus the incident light. A physicist Fresnel, with some modifications in convex lens introduced the Fresnel lens. Figure 1 shows the shaping of lens by cutting it at appropriate sections. The grooves are created by this cutting operation, which does the function of concentrating the incident light. By performing this cutting operation throughout the curvature of convex lens, the Fresnel lens is obtained.

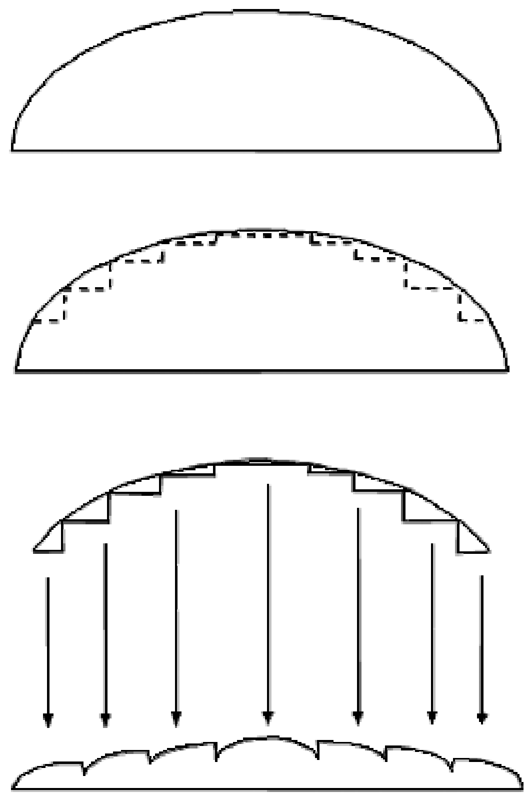

Figure 2. Construction of a Fresnel lens.

2.1 Basic design procedure

The design of Fresnel lens is divided into four segments, which includes,

- Constructing the shape of the Fresnel lens to pre-determined dimensions,
- Constructing grooves on to focus the incident ray,
- Mirroring about the vertical axis and
- Extruding the 2D drawing to a 3D model by giving appropriate width for the lens.

2.2 Considerations in design

The considerations which are to be studied before going into the design aspect are area of focus, loss in grooves structure, focussing efficiency, types of loads and stresses, selection of materials, form and size of parts, convenient and economical features, cost of construction and assembling.

2.3 Specifications of the Fresnel lens

1. Radius of curvature : 762 mm
2. Length of the lens : 1152 mm
3. Thickness of the lens : 4mm [2mm for groove thickness, 2mm for material thickness]
4. Focal length of the lens : 762mm from top surface of lens.

2.4 Construction of prismatic type Fresnel lens

The initial requirements include
1.Setting radius of curvature of the lens,
2.Thickness of the lens,
3.Groove thickness selection,
4.Fixing the focal point of the lens,
5.Fixing the segment length of the lens.

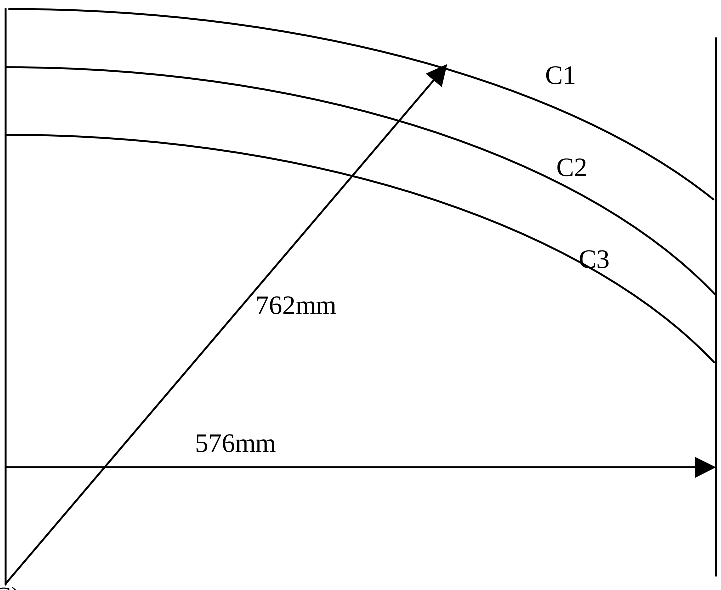

Figure 3. Construction of one half of the Fresnel lens to pre-determined dimensions

With respect to the above said dimensions the initial lens segment is constructed by fixing an arbitrary point C and with this point as center and radius as 762mm, a curve is drawn. This curve is the top surface of the lens and is marked C1.The vertical line from center C is drawn to touch the surface of the curve C1.This line is the center line and suitable constraints for the line and the curve are given. To fix the length of the lens, another vertical line parallel to the centerline at a distance of 576mm is drawn. A parallel constraint is given to these lines. These lines will cut the curve C1.The distance between the two vertical lines gives the segment length of the lens. To end the curve at these intersecting points, collinear constraints are given between the curve and the line. This is to ensure that the curve end points will be on this line. With C as center again, another curve is drawn at a radius of 760mm.This curve is also constrained between the two lines. The curve is marked C2. The distance between the curves C1 and C2 is 2mm and this gives the material thickness of the lens. Another curve is drawn at a radius of 758mm from the same center C. The curve is constrained similar to the curve C1 and C2. This curve is marked C3. The distance between the curves C2 and C3 is 2mm and grooves are constructed between these curves. The distance between the curves C1 and C3 is 4mm and this gives the total thickness of the lens. The center point C also serves as a focal point F as its length from the curve C1 is 762mm, which is apparently the focal length.

The basic formulae used are,

$1/f = (\mu - 1) * [1/R1 + 1/R2]$ where (1)

f= Focal length of the lens,

R1= Outer radius of curvature of the lens.

R2 = Inner radius of curvature of the lens.

μ = Refractive index of the medium (1.49).

Snell's law,

μ=Sin i/Sin r (when light travels from rarer to denser medium) and (2)

μ=Sin r/Sin i (when light travels from denser to rarer medium) where (3)

i= angle of incidence

r= angle of refraction.

A vertical line (incident ray) is made to touch the extreme right end of the outer curve (C1). At the point of intersection, a tangent and a normal are drawn. The angle between the incident ray and the normal is the angle of incidence $i_{1.}$ Using equation (2), the angle of refraction r_1 is found out. Then the refracted ray is extended to meet the second arc C2 at some point, say P. At this point P, again a tangent and a normal are drawn. The refracted ray is now the incident ray for the curve C2. The angle between the second incident ray and the normal gives the angle of incidence $i_{2.}$ The point P is then joined to the focus (C). The angle between the line joining to the focus and the normal gives the angle of refraction r_2. Having known i_2 and r_2 values, by interpolation we find suitable values such that it satisfies equation (3)(since light travels from denser to rarer medium). The line representing i_2 and r_2 with the refracted ray is the new normal. A perpendicular is drawn to the new normal that represents the lens profile or the groove structure of the extreme corner of the lens. On the curve C2 from the corner point where the groove is drawn, points along the curve are established at a distance of 1mm between each point. The groove angles at each of these equally spaced points are found using Lagrange's interpolation (4). Then the lens teeth are drawn using their corresponding groove angles. Frequent checks are made to ensure that the rays converge along the focal line. The lens profile is trimmed so that the grooves are continuous, smooth and its thickness is maintained at 4mm. The profile of lens design gives only half of the total system. To get the full system mirror/reflect technique in I-DEAS® is used. This mirrors the profile drawn in one side to the other side and the full lens design is obtained.

In this way, the grooves are constructed at a distance of 1mm for the full length of the lens. The lens profile provides the exact focus of the sunrays along a straight line. Thus the second segment of constructing the grooves between the curves C2 and C3 is followed such that it will focus the sunrays falling parallel on the curve C3 to a narrow line. The next step which is the final process involved in the design is the extrusion of 2-D drawing into 3-D. The extrusion length is for 1m taking into consideration the weight factor, lens curvature, lens material and it's thickness. This process of extrusion is the final process.

2.5 Methodology for determining the groove angles

The technique adopted to determine the groove angles is Lagrange's Interpolation method. By this method, we determine an increment value δ, which can be found out using the formula,

$$\delta = 1/(n_2 - n_1) * \{\theta_2 - \theta_1\} \quad (4)$$

where n_1 and n_2 represent the groove numbers, θ_2 and θ_1 represent the groove angles.

For example, let us consider the groove number 1 and groove number 20. We calculate the groove angles at these positions. To determine the groove angles of the intermediate positions, equation (4) is used. By this formula, the incremental value is calculated, which has to be added to the previous angle, in order to obtain the next angle. For determining the angle for groove number 2, the incremental value is added to the first groove angle.

$$\delta = 1/(20 - 1)*\{21.1632^o - 20^o\}$$

$$\delta = 0.06122^o.$$

The groove angle for groove number 2 is $20^o + 0.06122^o = 20.06122^o$

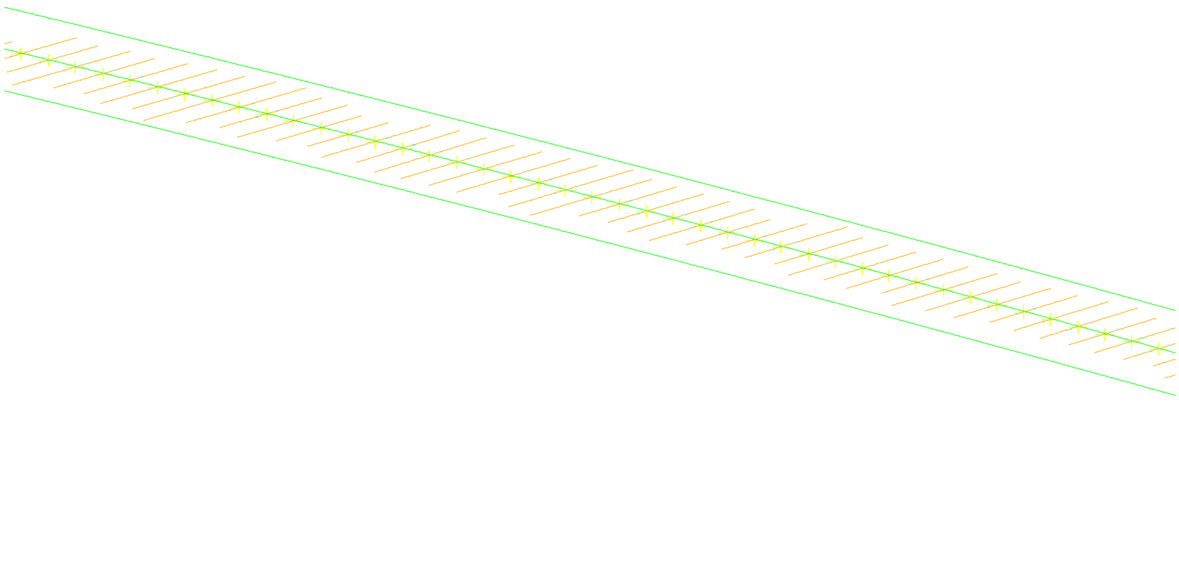

Figure 4. Lines drawn through equidistant points with appropriate groove angle inclinations

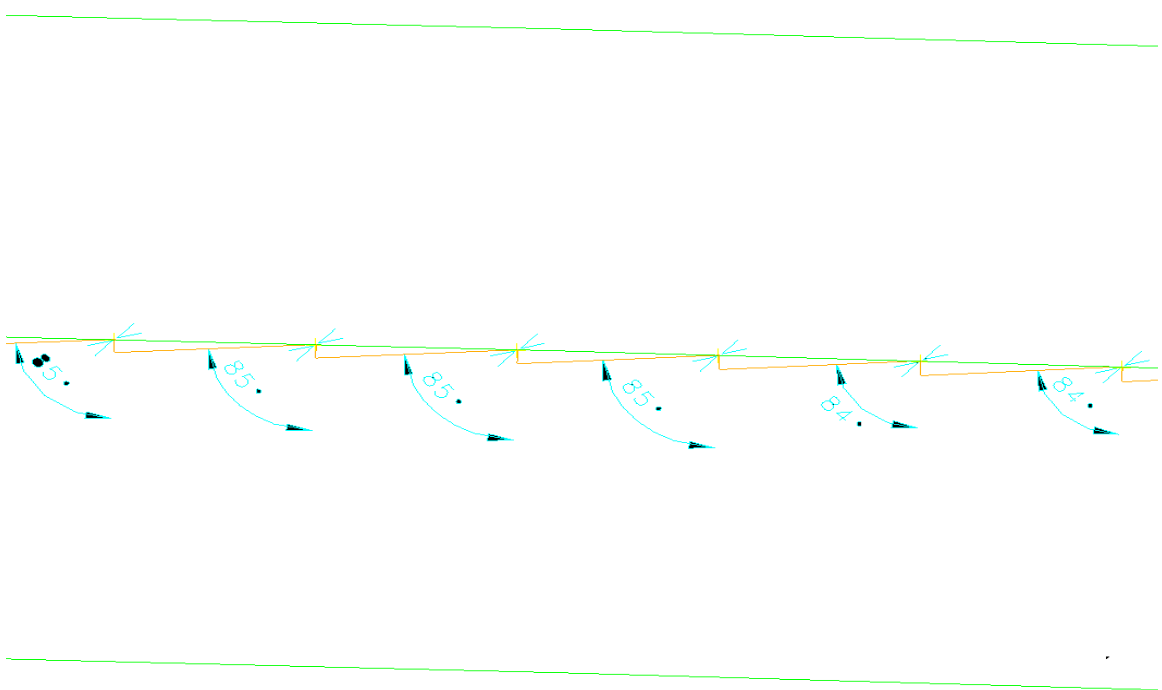

Figure 5. Mid-section of the lens

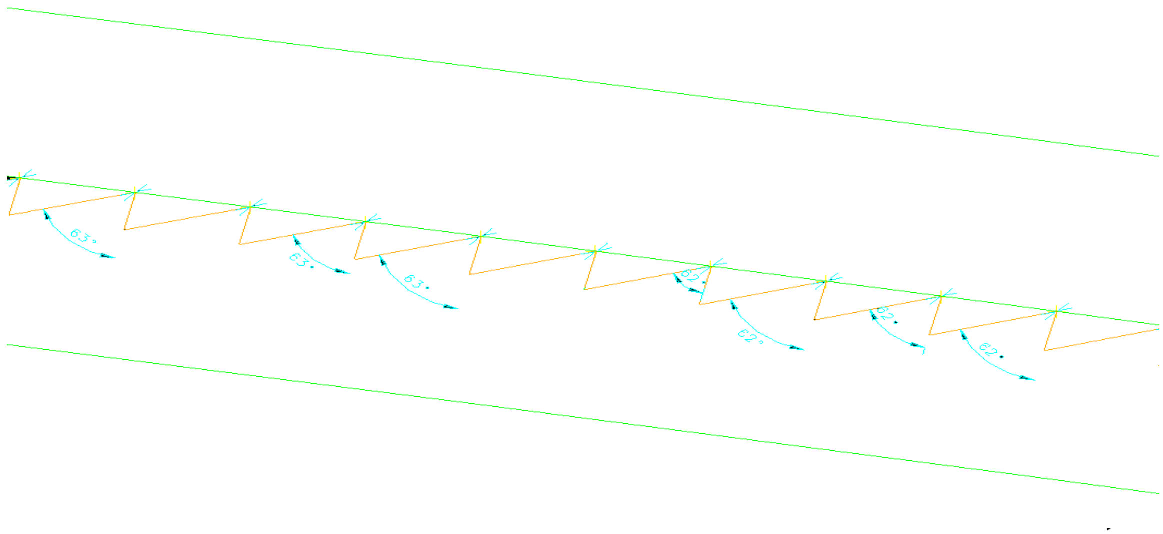

Figure 6. Section at the right end of the lens

3.THEORETICAL VERIFICATION

At some point on the outer curve C1, a vertical line is drawn to represent a sunray. By drawing tangent and a normal at this point, the angle of incidence i_1 is determined. Then using equation (2), the refracted angle r_1 is found out. The refracted ray is then extended to meet the second arc. At this point, another tangent and a normal are drawn to find the angle of incidence i_2. Now using equation (3), the angle of refraction r_2 is found out. This refracted ray is extended and it is found that it converges exactly at the focal point. This procedure can be done at several points to test the accuracy of the lens in focusing the sunrays.

4. DISCUSSION

During the design stage, as the grooves are constructed from the right end of the curve, it is found that the groove length exceeds the minimum thickness of 2mm for the first few grooves. Therefore, the lens is trimmed at the point where the thickness exceeds 2mm. The Fresnel lens can be fabricated using an Acrylic polymer sheet. Initially a scriber has to be fabricated with each of its grooves at the appropriate inclination. Then, this can be scribed on the polymer sheet to get the Fresnel lens.

Today the cost of conventional solar energy generation remains prohibitively high for most applications. High concentration solar systems however hold the potential to tremendously reduce the cost of electricity generated from solar energy. By concentrating sunlight with Fresnel lens, the effective photovoltaic cell area required can be significantly reduced. One of the greatest strengths of this design is that all the normal rays falling on the lens surface are focussed to a narrow line. The photovoltaic cells can be arranged straight along the focal line. This saves an enormous amount of the storage cell area since there is no scatter of rays focussed on it and hence cuts the cost of the cells drastically. Fabricating large plastic lenses will be substantially easier and cheaper than fabricating large semiconductor materials (solar cells).

The Fresnel lens is a very powerful concentrator. The concentration of lens varies from 20 times to 400 times depending on its type. The Fresnel lens is thus capable of producing a high temperature intense sunbeam on a small area. This gives a high heat generation potential and this heat can be tapped for a variety of uses. For example, if the ambient temperature of sunrays at a particular time of a day is about 25^o C, if we consider a magnification factor of 20, then the concentrated solar beam will have a temperature of 20 x 25 = 500^o C.

It is a necessity that the sunrays have to be constantly tracked to focus it exactly along the desired focal line. So a sun-tracking cradle can be used to tilt the Fresnel lens system at a constant speed. This cradle can be integrated with a suitable tracking system. The tracking system consists of a Timer drive system, a motor, a gear reduction unit, worm and pinion gears and limit switches. The timer drive system has a magnetic impulse sensor embedded in it. It gives programmed pulses to a motor unit for about 2 minutes. The magnets are excited at the pre-programmed time as a result of which an Electro-motive force (Emf) is produced which runs the motor. The motor receives the impulse from the timer drive system and provides the required rotational movement to the gear reducer unit. The gear reducer unit reduces the input speed from the motor by 10 times and gives the motion to the worm and pinion gear. The worm receives input from the gear unit and in turn drives the pinion gear. The pinion wheel is coupled to the solar cradle unit and hence makes it rotate from east to west. The worm gives very small rotational movement to the pinion based on its input. There is a limit switch on either side. When the limit switch on the west side is activated, it sends the signal to timer drive, which gives impulse so as to provide a continuous quick rotation of the solar cradle back to its original position. Thus a high intense sunbeam incident on the photovoltaic cells can be used for power generation.

Photovoltaic systems have been widely used to power satellites and space probes. The critical issues met in space power systems are weight and reliability: weight, because of the high cost of boosting equipment into space and reliability, because servicing a system is difficult and expensive. Around the world, there are more than 100,000 off-grid residential PV systems. Metal corrosion causes damage to pipes, tanks, wellheads, bridges, and buildings. PV-generated electricity prevents electrolytic corrosion of such structures. Utilities are using PV in many applications, including large centralized generation, transmission and distribution support, demand-side management, distributed residential and commercial systems, and remote, stand-alone monitoring systems.

5.CONCLUSION

The Fresnel lens holds the most important advantage that for any other lens to produce the same amount of concentration, the thickness has to be nearly 10-20 times greater than that of this design. The minimum thickness of 4mm allows us to bend the lens and mount it easily. The line focussing helps reduce the storage cell costs and hence proves to be an economical and efficient way to generate electricity.

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