Designing an innovative secondary optics for parabolic trough

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Abstract

A secondary optics for CPV parabolic troughs was developed to reduce the photovoltaic cells number. The proposed solution is a cylindrical Fresnel lens that transforms the focal line into a series of focal points. Its insertion inside the Concentrating PhotoVoltaic trough increases the solar concentration keeping unchanged the total collection efficiency of the system. The research includes optical design of the secondary collector and auxiliary analyses to control trough operation and to optimize trough collection efficiency.

Keywords: *secondary optics, optical design, trough, CPV, solar concentration*

1. Introduction

This paper describes a solution studied to reduce the number of photovoltaic cells in a linear parabolic trough (Bakos et al 2000, Kearney 2007, Kruger et al 2008, Prapas,et al 1987, Price et al 2002), which is used for the combined production of heat and electricity (Klapp et al 2007, Weiss and Rommel 2005). This solar trough combines photovoltaic and thermal systems: PV cells directly exploit the sunlight concentrated on them and their cooling system supplies thermal energy. Given that the linear concentrators act only in a direction that is normal to their length, consequently with a linear parabolic reflector the entire focal line must be covered by photovoltaic cells (Kearney 2007).

The secondary optical system examined in this study is interposed between the parabolic mirror and the linear row of photovoltaic cells. The sunlight collected by the parabolic reflector is intercepted by the secondary optics and concentrated, in portions, precisely in the direction where the concentrator may not work (along the longitudinal axis of the trough).

The working principle of the additional optical system appears evident placing a screen in the focal area: the secondary optics transforms the focal line into a series of focal points. Hence the proposed solution allows to reduce the number of PV cells while maintaining unchanged the total collection efficiency of the system because it simultaneously increases the concentration. In practice the production of electricity is not affected by the reduction of cells number, because it is balanced by an enhancement of solar concentration.

2. Positioning of the secondary optics in the solar trough

The starting point was an existing solar trough that combines photovoltaic and thermal systems (Bakos et al 2000, Klapp et al 2007, Kearney 2007 Kruger et al 2008, Prapas,et al 1987, Price et al 2002, Weiss and Rommel 2005). It concentrates the sunlight by means of a linear parabolic reflector over an articulated absorber. The focal image is a rectangle and it is focused on a row of squared photovoltaic cells. The cells are placed on a metallic tube of rectangular section, which acts as cooling system by means of a liquid flowing inside. The absorber is completed by an external protection tube in glass, enclosing cells and cooler. The photocells directly exploit the concentrated sunlight providing electricity, while the cooling system of the cells furnishes heat.

In this concentration geometry the secondary optical system must be located inside the first mirror (parabolic reflector) around and near the absorber, constituted by a glass tube enclosing a row of photovoltaic cells placed over a rectangular tube (cooler).

The parabolic reflector concentrates the solar rays in the direction transversal to the solar trough axis. Then the secondary optics intercepts these rays and it re-concentrates them also in direction of the trough axis. So the concentration is performed transversally by the trough; while it is performed transversally and longitudinally by the secondary lens. Hence the secondary optical system realises a concentration in the direction where the

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trough does not concentrate. In practice this secondary optics transforms the focal line into a series of focal points. This result can be easily visualized placing a screen in the focal area of the solar trough.

3. Design criteria for the secondary optics

The secondary concentrator (Giannuzzi et al 2010 Giannuzzi, et al 2011 , Giannuzzi, et al 2014, Jafrancesco et al 2010) was optically designed for an solar trough realized for the combined production of electricity and heat. It has a primary parabolic mirror that focuses the solar rays over a row of PV cells placed on a linear cooler. The aim is to decrease the number of required cells introducing a secondary optics that concentrates the light along the longitudinal direction of the trough.

The optical design of this secondary optics should be based on the characteristics of the existing solar trough and of the photovoltaic cells. The preliminary phase of the optical design is to simulate the optical system. Successively the solar trough parameters are analysed, to optimize the collection efficiency that maximised the obtainable energy. Finally the optical project of the secondary optics, in terms of geometrical parameters and optical characteristics (Winston et al 2005), is selected on the base of the analyses of the irradiance concentrated on the receiver (photovoltaic cells) (Güven and Bannerot 1986, Kandpal et al. 1985).

Auxiliary studies can assist in monitoring trough performance and in keeping high efficiency. Some examples of these additional analyses are summarised in Sect. 7: effects of collector deformation, axial defocusing, tracking errors and receiver alignment errors.

The proposed secondary optics is a lens, with cylindrical symmetry, which focuses in a point all the rays that arrive in a direction perpendicular to its surface, as shown in Fig. 1.

Considering that the rays coming from the parabolic reflector converge at the same point (the PV cell) is sufficient to design only a radial section of the lens that will be subsequently replicated on a cylindrical surface of radius R.

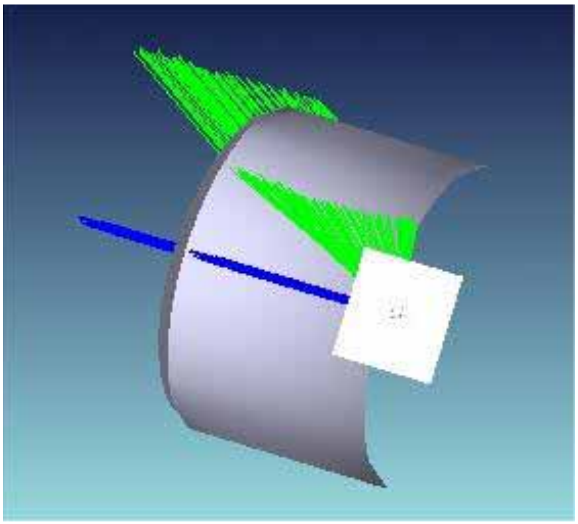


Fig. 1 - The secondary optics is a cylindrical Fresnel lens. It focuses in a point all the rays that arrive in a direction normal to its surface.

The criteria used to optically design the secondary cylindrical lens are summarised below.

1) The radius R of the cylinder depends on geometrical considerations linked to the size of the secondary optics and its position over the array of PV cells. There was a superior limit agreed with the optical manufacturers.

2) The transversal dimension Dt of the lens is determined by the f-number Fn = Dt / f, where f is the focal length of the lens, which must not be greater than R. Dt is chosen to have Fn <1, since it is known that the characteristics of an optical system are less critical for f-number less than 1.

3) Since the intention was to obtain a thin and weightless lens, it was established that his type had to be prismatic (Fresnel).

The result is a cylindrical Fresnel lens, whose profile is illustrated in Fig. 2. The figure shows the section of the lens, which contains 12 prisms that distribute the light on the PV cell. The total lens width L is composed of 12 prisms, each of which has width l, while the maximum height of the tooth is H. All the prisms in the central part have height equal to l, the width of each tooth.

The light intensity distribution on the PV cell obtained with the insertion of this secondary cylindrical Fresnel lens is presented and discussed in Section 5.

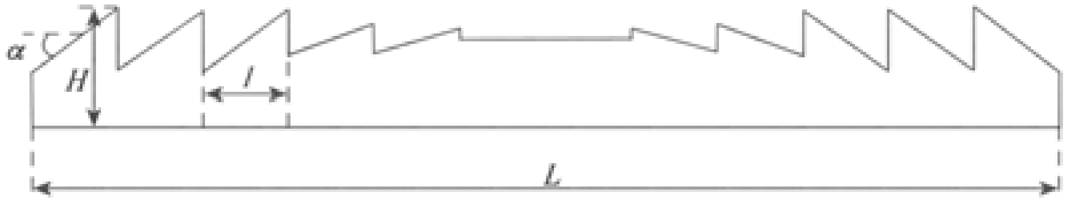


Fig. 2- The secondary optics is a cylindrical Fresnel lens with this profile.

4. Results of the optical design

The secondary optical system (Giannuzzi et al 2010, Giannuzzi, et al 2011, Giannuzzi, et al 2014, Jafrancesco et al 2010) was defined to be a cylindrical prismatic lens, of Fresnel type.

Figure 2 reports in detail the profile of the Fresnel lens with the characteristic angles αi of the individual prisms that define the optical design of the lens. The angle of prism surface inclination are symmetric, as the figure shows. From left to right of Fig. 2, the characteristic angles of the second face of each prism are: α1, α2, α3, α4, -α4, -α3, -α2, -α1, where a negative angle corresponds to a surface with the same inclination but in the opposite direction. The specific angles αi of each prism slope are calculated in the optical design simulation in order to optimise the light intensity distribution on the PV cell, balancing maximum obtainable power and maximum obtainable uniformity.

These data of the prismatic lens profile were used to generate the 3D cylindrical lens according to the criteria expressed in the previous section. This phase was executed using the Rhinoceros software, which allows to generate a three-dimensional file with IGES format. The screen output of the Rhinoceros software, reporting four different views of the secondary optics, is show in Fig. 3: the top-left image is a superior view, the top-right image is a perspective view, the bottom- left image is a frontal view, the bottom-right image is a lateral view from the right side.

As illustrated in Fig. 2, in the central part the upper surface of the prisms is almost flat: the angles α4 and -α4 approach zero.

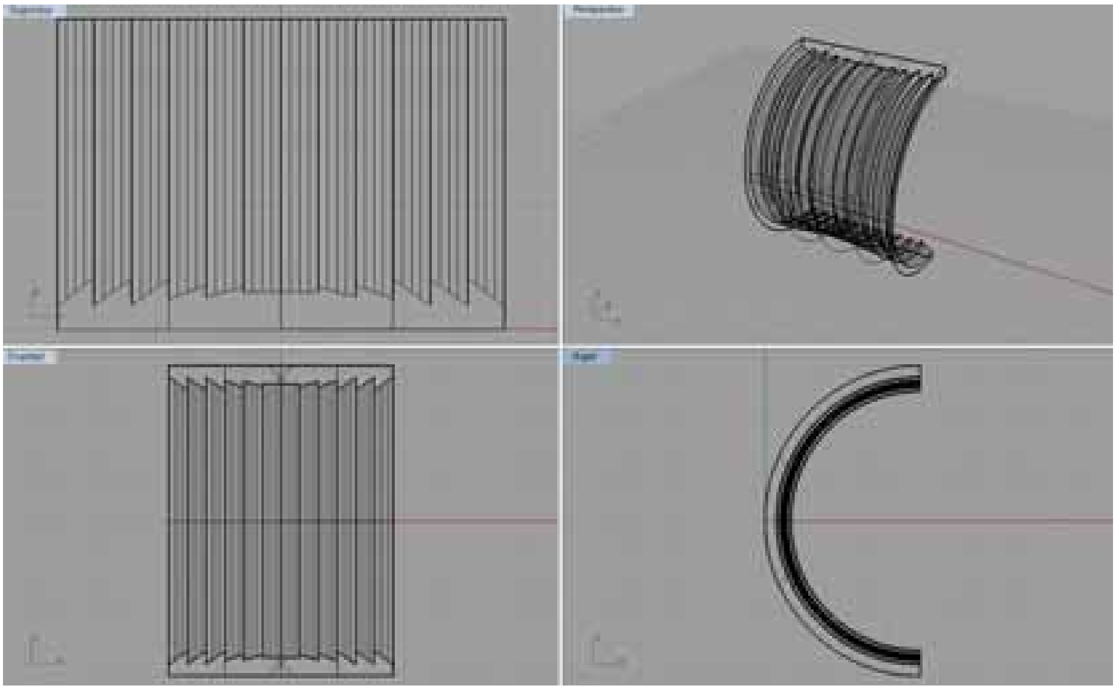


Fig. 3 - Rhinoceros drawings of the cylindrical Fresnel lens.

5. Behaviour of the prismatic lens in the parabolic trough

The prismatic lens is calculated for a photovoltaic cell of squared shape with dimensions 10mm x10mm, located at a distance d from the central flat face of the lens. The final cylindrical Fresnel lens has a diameter D, obtained from optical design simulations performed for a lens width L, with 12 prisms of size l.

The simulations were developed using a the specific ray-tracing software package Zemex-EE (by Radiant Zemax). One of their result, reported in Fig. 4, is the tri-dimensional rendering of the cylindrical Fresnel lens. The lens profile, corresponding to Fig. 2 is evidenced in orange in Fig. 4.

However the most significant result of the simulation is the irradiance light distribution over the photovoltaic cell, plotted in Fig. 5 in false colours. Figure 5 shows the irradiance distribution considering the prismatic lens inserted in the parabolic trough concentrator. The image frame is a square of 10mm x 10mm, which corresponds to the size of each PV cell.

The light focused by the secondary optics is quite uniformly distributed on the cell square. The great result is that the shape of the image is squared and it is illuminated almost with the same irradiance level. Only near the perimeter the irradiance has lower values. The uniformity of light distribution is a fundamental aspect when photovoltaic cells are employed, since they will work correctly only if they are uniformly illuminated. When the light is mostly focused on a portion of the PV cell, the cell converts light into electricity with a lower conversion factor. This loss of illumination uniformity can also affect (unbalancing the series of cells) the performance of the other PV cells.

The total collection efficiency is the product of the collection efficiency of the parabolic concentrator (95%) multiplied by the collection efficiency of the cylindrical Fresnel lens. Considering the entire solar spectrum was estimated a value of 75% for the total collection efficiency

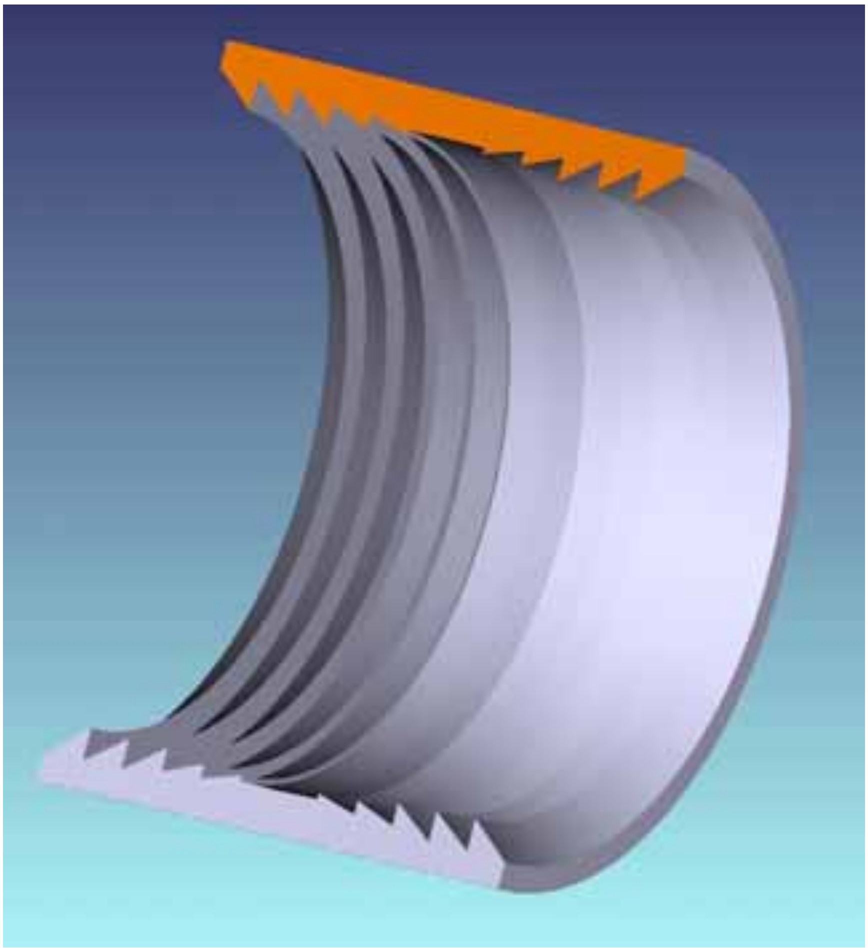
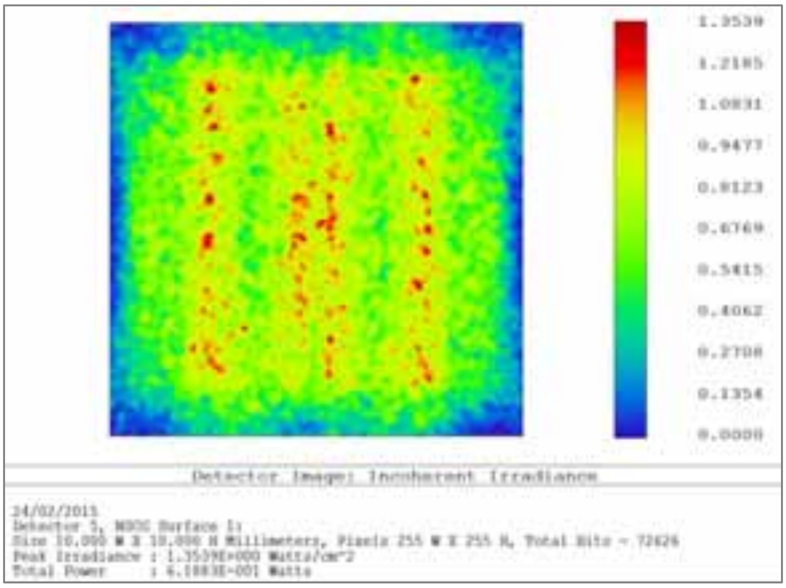


Fig. 4 – 3D rendering of the cylindrical Fresnel lens.



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Detector Image: Incoherent Irradiance

24/02/2015
Detector 5, NSCG Surface 1:
Size 10.000 W X 10.000 H Millimeters, Pixels 255 W X 255 H, Total Hits = 72626
Peak Irradiance : 1.3539E+000 Watts/cm^2
Total Power     : 6.1883E-001 Watts
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Fig. 5 – Image of the cylindrical Fresnel lens on the PV cell.

6. Simulations for the optical design

The optical design work (Güven and Bannerot 1986, Kandpal et al. 1985 , Sansoni et al. 2011, Winston et al

2005) consisted in simulating, analysing and optimising the optical configuration of the solar trough system. The optical simulations reproduced the system, whose main components are parabolic mirror (primary optics), cylindrical Fresnel lens (secondary optics) and photovoltaic cell (receiver). In particular the optical system was simulated in order to verify the optical behaviour in case of axial defocusing, tracking errors, alignment errors and deformations of the collector. For each of these cases were calculated:

- the collection efficiency of the system, that indicates how much of the power incident on the parabolic collector arrives at the receiver;

- the irradiance distribution on the receiver, that can give an idea of the uniformity of illumination of the receiver along a certain direction;

- the integrated power, that assesses the power collected by the receiver as a function of its width.

These analyses were exploited to define the optical parameters of the secondary optics; moreover they give fundamental information to optimise the solar trough performance. The results of the detailed studies are briefly discussed in Sect. 7.

The parabolic collector has a development of 1600 mm, a radius of curvature of 1600 mm and a focal length of 800 mm. The receiver, a PV cell of size 10mm x10 mm, is placed in the focal plane of the parabolic mirror. The Fresnel lens is placed at a distance d from the cell, on the side of the parabolic mirror.

For these simulations was considered only a small section of the parabola, of a width corresponding to that of the lens (L) and placed behind it. The reason is that it is this section that contributes to the collection efficiency; possible contributions from adjacent areas are compensated by the loss of light that impinges near the edges of the section.

The following list summarizes the parameters used in the simulations, subdivided for every principal optical component.

- Parabolic Concentrator: Parabolic Trough Concentrator (PTC) type; section width; curvature radius; total chord length; focal length; surface reflectance.
- Secondary Lens: cylindrical Fresnel lens type; dimensions; material; distance from the receiver; distance from parabolic mirror vertex.
- Screen: dimensions; distance from the receiver.
- Receiver 1 (for collection efficiency): dimensions; distance from parabolic mirror vertex.
- Receiver 2 (for irradiance profiles): dimensions; distance from parabolic mirror vertex.
- Source: plane with rectangular divergence; divergence angle; dimensions; distance from parabolic mirror vertex; power; wavelength (in these simulations the reference wavelength was 550nm).
- Number of rays (in these simulations 5 million rays were sufficient to have reproducible results).

The source projects on the parabolic reflector a homogeneous rectangular beam. The screen placed behind the receiver has the purpose of intercepting the rays emitted by the source in arrival on the receiver and on the secondary lens. In this way the obscuration effect of the tube is considered in the calculation of the collection efficiency of the whole optical system.

Receiver 1 and Receiver 2 are two detector planes of different size that are placed in the same position. They are used interchangeably for the calculation of collection efficiency (Receiver 1) and distribution of illumination irradiance (Receiver 2).

The z-axis is the optical axis, along which the propagation occurs rays; the x-axis is perpendicular to the drawing plane and is parallel to the longitudinal axis of the parabolic collector; the y-axis completes the right-handed triad. This reference system is used with all the objects (parabolic mirror, secondary lens and receiver).

The collection efficiency η of the whole optical system is defined as

$$\eta = \frac{P_{out}}{P_{in}} \qquad \text{(eq. 1)}$$

where Pout is the power that reaches the detector and Pin is the power that impinges on the section of the parabolic reflector.

7. Auxiliary investigations of trough performance

The study is completed with some analyses devoted to aspects essential for the correct functioning of the linear parabolic collector, assessing how to optimize the performance of the system (Diver and Moss 2007, Fontani et al. 2006, Fontani et al. 2011, Kandpal et al. 1985, Sansoni et al. 2011). These investigations examine in detail the consequences of axial defocusing of the receiver, deformations of the parabolic mirror, error in sun tracking, errors in aligning the optical components.

The axial defocusing (Sansoni et al. 2011) is an incorrect positioning of the receiver with respect to the focus of the parabola. It is studied by varying the distance of the receiver from the vertex of the parabola with displacement along the parabola's axis. The results are expressed using the trough collection efficiency η as a function of defocus, using the irradiance distribution on the receiver as a function of the distance from the centre varying the defocus and using the concentric integrals as a function of the cell width for various defocus values.

The collector deformations (Fontani et al. 2006) are the mechanical deformations of the primary parabolic mirror and they can be expressed by a variation of the conic constant K (K = 0 for perfect parabola). The results are expressed using the trough collection efficiency η as a function of K or as a function of the vertical displacement of the edge of the deformed collector.

The sun tracking errors (Fontani et al. 2011) occur when the sun's rays do not arrive perpendicularly to the entrance surface of the parabolic mirror because of an imperfect pointing. The effects of this tracking error are simulated by rotating the source around the x-axis and translating it in the y direction by an amount $A \cdot \tan\Phi$, where A is the source - parabola distance and Φ is the angle of rotation (tilt Φx); this is equivalent to the entire concentrator rotate about the longitudinal axis of the parabola. The results are expressed using the trough collection efficiency η as a function of tilt Φx, using the irradiance distribution on the receiver as a function of the distance from the centre for several tilt Φx values, using the concentric integrals as a function of the width of the cell varying the tilt Φx.

The errors of alignment (Diver, R.B., Moss, T.A, 2007) are the effects on the system performance due to any misalignment of the collector axis with respect to the North - South direction. In Parabolic Trough Collectors (PTC) without secondary lens the effect is a translation of the focal line along the linear receiver; in PTC with secondary lens the system collection efficiency may drop due to the small size of the PV cell. The situation is identical to the tracking errors but the source is rotated around the y-axis and translated along the x-axis. The results are expressed using the trough collection efficiency η as a function of tilt Φy.

The typical reference parameter for the system performance is the collection efficiency η of the whole solar trough (including primary parabolic mirror and secondary cylindrical Fresnel lens). The image focused by the secondary lens should concentrate the maximum power (maximise the trough collection efficiency η), but also uniformly illuminate the photovoltaic cell (maximise the receiver irradiance distribution, in Fig. 5).

8. Conclusion

The purpose was to develop a secondary optics for a solar CPV parabolic trough that increases the solar concentration and reduces the photovoltaic cells number keeping unchanged the total collection efficiency of the system. The solar trough is a Concentrating PhotoVoltaic system whose primary collector is a linear parabolic reflector. The proposed secondary concentrator is a cylindrical prismatic lens of Fresnel type. The primary parabolic mirror of the CPV trough concentrates the sunlight in a focal line, which is successively transformed by the cylindrical Fresnel lens into a series of focal points.

The research started with the optical design of the secondary component, selecting a configuration that optimizes collection efficiency of the whole system and uniformity of the PV cell illumination. The study proceeded with auxiliary analyses to optimize operative conditions and collection efficiency of the whole system. Finally specific simulations evaluated the possible future implementations.

The secondary optics was optically designed for an existing solar trough, already realized. This trough is used for the combined production of heat and electricity, with a parabolic mirror concentrating the sunlight over a line of photocells placed over a linear cooling system. The idea is to reduce the number of photovoltaic cells introducing a secondary optics to concentrate the light along the direction of the trough axis, where the trough does not concentrate.

The optical design of this secondary concentrator must take into account the characteristics of the existing trough and of the photovoltaic cells. The optical parameters of the secondary optics are principally determined by examining the irradiance distribution on the receiver. The study is completed by analyses and simulations of the effects due to collector deformation, axial defocusing, tracking errors and receiver alignment errors. The purpose of these auxiliary analyses is to maintain elevated performance of the solar trough in real working conditions.

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