RESEARCH ARTICLE | NOVEMBER 08 2018

Point-focus multi-receiver Fresnel loop – Exploring ways to increase the optical efficiency of solar tower systems

Clotilde Corsi; Manuel Blanco; Jin-Soo Kim; John Pye

AIP Conf. Proc. 2033, 170001 (2018)
https://doi.org/10.1063/1.5067165

Point-Focus Multi-Receiver Fresnel Loop – Exploring Ways to Increase the Optical Efficiency of Solar Tower Systems

Clotilde Corsi[1,2,a)], Manuel Blanco[3, b)], Jin-Soo Kim[2], John Pye[1]

[1]*Solar Thermal Group, Australian National University (ANU). Research School of Engineering, Building 31, North Road, Canberra ACT 0200, Australia.*
[2]*CSIRO Energy Centre, 10 Murray Dwyer Circuit, Mayfield West, NSW 2304, Australia.*
[3]*The Cyprus Institute. Athalassa Campus. 20 Konstantinou Kavafi Street, 2121 Aglantzia. Nicosia. Cyprus.*

[a)]Corresponding author: clotilde.corsi@csiro.au
[b)]m.blanco@cyi.ac.cy

Abstract. For commercial solar tower systems of relevant size, state of the art of light collection and concentration (LCC) subsystems (heliostat field plus receiver envelope) do not achieve annual optical efficiencies larger than 65%. Achieving optical efficiencies substantially higher than that requires departing from the traditional mono-tower design. Although multi-tower systems were identified long time ago as candidates to achieve high annual optical efficiencies, so far no multi-tower concept has emerged as a clear alternative to the mono-tower system. In this article, we introduce a variant of the multi-tower concept that combines the modularity and high land coverage of linear focusing technologies with the low thermal losses and high operating temperatures of solar tower technology, and overall represents a disruptive departure from the traditional mono-tower design.

INTRODUCTION

To increase the cost-competitiveness of solar tower systems it is essential to reduce the cost and improve the optical efficiency of the light collection and concentration (LCC) subsystem (heliostat field plus receiver envelope). This is the case because this subsystem represents a very large fraction of the total investment cost. While in recent years the LCC subsystem has markedly reduced its cost, it has not improved significantly its overall annual efficiency. State of the art of LCC subsystems do not achieve annual optical efficiencies larger than 65% for solar tower systems of relevant size[1]. Achieving substantially higher optical efficiencies requires departing from the traditional mono-tower design. Although multi-tower systems were identified long time ago as candidates to achieve high annual optical efficiencies[2,3], and are being the subject of attention recently[4] so far no multi-tower concept has emerged as a clear alternative to the mono-tower system. This article presents a variant of the multi-tower concept that combines the modularity and high land coverage of linear focusing technologies with the low thermal losses and high operating temperatures of solar tower technology, and overall represents a disruptive departure from the traditional mono-tower design. The article first describes the technological concept proposed, the methodology followed to generate a concrete example of such a concept, and the results obtained. The emphasis on the example or proof concept is on the heliostat field design, to show that indeed this concept leads to high optical efficiency LLC subsystems.

POINT-FOCUS MULTI-RECEIVER FRESNEL LOOP CONCEPT

The variant of the multi-tower system we are proposing differs from the classical multi-tower concept in the following aspects:

- It is an in-loop multi-receiver concept not a multi-tower concept. A piped loop structure, placed above the ground, integrates and inter-connect several receivers. Thus, few pillars, appropriately located,

SolarPACES 2017
AIP Conf. Proc. 2033, 170001-1–170001-7; https://doi.org/10.1063/1.5067165
Published by AIP Publishing. 978-0-7354-1757-1/$30.00

support the structure holding the piping and the receivers, avoiding the need of building a tower per receiver and the need of pipes going up and down from one tower and receiver to the next.

- The heat transfer fluid travels through the loop structure from one receiver to another. The piping connecting the receivers makes it possible to control the mass flow that circulate through each receiver and to adjust it to accommodate for the variations of the incident solar power on the receivers along the day.
- The concept is completely modular, with a power plant compose of as many loops as needed to provide the required nominal power, storage capacity and annual electrical energy. Because of this modularity, for a given multi-receiver loop design, transmissivity losses are invariant to power plant size, and can be keep at bay.
- The geometry of the loop, the number of receivers, location, heights above the ground, thermal power, the characteristics of the loop supporting structure, and other characteristics can be optimized for the specific plant location and other boundary conditions. Methodologies for some of these optimizations have already being developed[5]

Because of the above, the concept can be summarily described as *"point-focus multi-receiver Fresnel loop"*. This is the case, as one can arrive at the concept using as a starting point a traditional u-loop formed by two linear Fresnel collectors parallel to each other, connected in series. Starting from this linear Fresnel u-loop configuration, one can reach the configuration we are proposing by carrying out the following thought experiment:

- Transform the longitudinal strips of mirrors of the collectors, which concentrate the direct sunlight onto a linear receiver located high above them, into a collection of heliostats that can concentrate the sun at specific points on the longitudinal receivers.
- Install point-focus receivers at those points and insulate the rest of the longitudinal receivers, transforming the insulating parts just in pipes joining the point-focus receivers.
- Allow the heliostats to point to different receivers along the day to maximize their optical performance and relocate and reduce their density as to maximize the join annual overall optical performance.

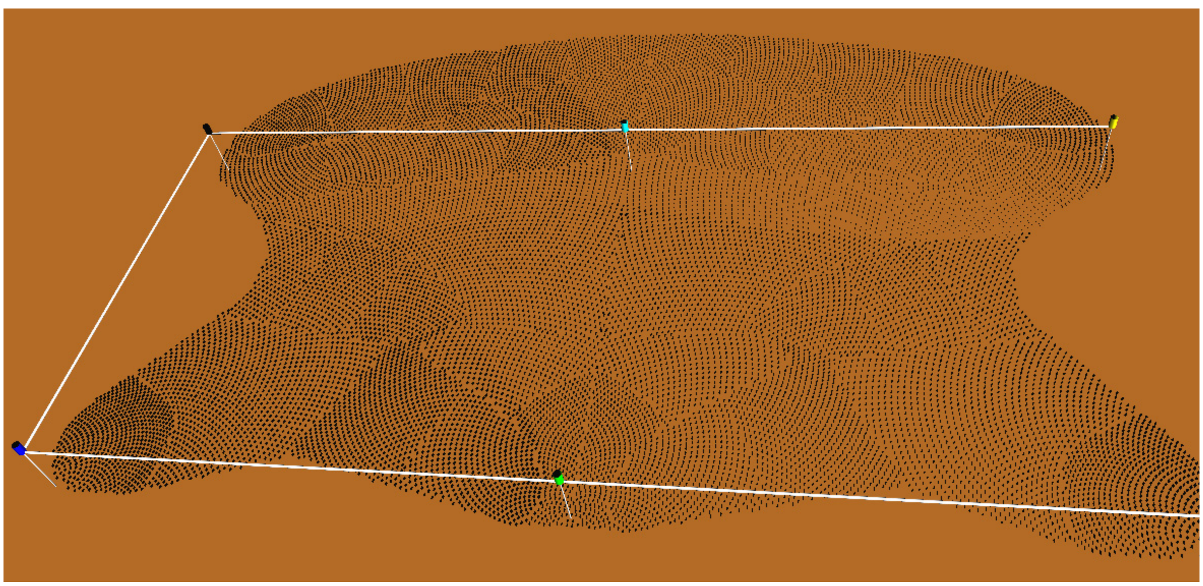

FIGURE 1. 3D-model in Tonatiuh of a 6-receiver Fresnel loop.

FIGURE 1 shows a 3D-model of a 6-receiver Fresnel loop carried out with Tonatiuh[6]. The receivers are located 75 meters above the ground. They are integrated into a u-loop type structure, which provides the infrastructural support, and facilitate their interconnection by pipes. The process followed to size and design this system is explained in the next section of this article, where a comparison between the characteristics of this system and the characteristics a typical commercial mono-tower system is also carried out.

RESEARCH GOALS

Our overall goal is to design an instance of the proposed concept to demonstrate its value and to prove that it is possible to realize this value in practice. The main goal is to provide a concrete example of how to address successfully all the challenges this new concept poses and end up with a multi-receiver loop design that makes technical and economic sense, and is substantially more cost-competitive than traditional alternatives.

However, the challenges are too many to address all of them in this article. First we need to prove that, beyond theoretical speculations, it is possible to develop a concrete instance of a heliostat field for the multi-receiver concept that, while making technical and economic sense, has an optical behavior that substantially outperformance the state of the art. Then, we need to proof that the challenges associated with the drastic variations in input power that some of the point-focus receivers will experience through the day can be properly addressed at a sensible cost from all relevant point of views –technical and financial. Finally, we need to carry out a risk assessment of the different technological aspects and define a roadmap to move this concept from low TRL to very high ones in the shortest possible time.

The specific goal of the research presented in this article is to establish that it is possible to develop a concrete instance of a heliostat field for the multi-receiver concept that makes sense. Subsequent articles will address the rest of the challenges previously discussed.

HELIOSTAT FIELD OPTIMIZATION

Software Tools

Since there are not readily available software tools to assist on the optimization of multi-receiver heliostat fields, we have started to develop one. At this early stage, to develop, as a proof of concept, an instance of the multi-receiver Fresnel loop, we used three main software tools:

- Mathematica, a multipurpose modeling, analysis and visualization program.
- A set of ad-hoc C++ functions, which we are drafting as part of the program we are developing to address this matter in a thorough and fully comprehensive way.
- Tonatiuh, an open source Monte Carlo ray tracer for the simulation and analysis of solar concentrating systems, which is commonly used and whose development was started by one of the authors or this article.

Methodology

Specific Goal for the Design of the Multi-Receiver Heliostat Field

With the assistance of the mentioned software tools, the task of designing a heliostat field with an annual overall optical efficiency substantially higher than the current state of the art for relatively large (50 to 100 MW) commercial solar tower power plants was undertaken. Without considering the optical losses associated to the mirrors' reflectivity, the annual optical efficiency of state-of-the-art of commercial power plants within the 50 to 100 MW range seldom exceeds 65%, if ever[1]. Thus, the aim was:

"*To design a multi-receiver heliostat field with an optical efficiency greater than 75% with all the receivers located just 75 meters above the ground -half the height of the tower of a typical solar tower power plant."*

Boundaries

The approach adopted for the design of the heliostat field was to improve the different factors that affect the annual optical efficiency of the heliostat field in stages. The goal of the first stage was to ensure that in an annual basis the DNI-weighted product of the cosine times the transmissivity factor for all the heliostats in the heliostat field was larger than 90%. Each factor on this product is a function of the heliostat position and the aiming point. Since in our case, the heliostats could aim to different aiming points, the product is a function also of the aiming strategy. If this DNI-weighted product of the cosine times the transmissivity factor is called *"instantaneous ideal optical efficiency"*, η_o, then, the aiming strategy can be defined in a straightforward and relatively simple terms as follows: *"If an heliostat,* *has the option to aim to several receivers / aiming points, at every instant it will aim to the receiver / aiming point with respect to which it has the maximum optical efficiency."*

$$\eta_o(x, y, z, targets, sun_{pos}, \beta) = \max_i(\tau \cos\theta) \qquad (1)$$

Once the aiming strategy is defined, it is possible to use Equation (1) to compute the instantaneous ideal optical efficiency for any point on the horizontal plane where the heliostat field was going to be located. To do this, the following information was needed:

- The plant latitude.
- The bounds of the region of interest in the horizontal plane where we wanted to locate the heliostat field.
- A model of the transmissivity losses as a function of the conditions of the local atmosphere.
- The position of the different aiming points.

The plant latitude was selected to be 37 degree North, equivalent to Seville latitude in Spain. The bounding rectangle of the heliostat field considered was 1000 m wide (West – East direction) by 800 m high (South – North direction). The model of the transmissivity losses used was that of Vittitoe and Biggs[7], implemented in Tonatiuh. Finally, the number and position of the different aiming point was established based upon the following optimization procedure.

Based upon considerations related to symmetry and economy of means, the number of receivers / aiming points was established in six, whose East and West positions are symmetric with respect to a central North-South line. Three parameters define univocally such a pattern:

- The height, h, of the receivers above the ground, assumed to be the same for all receivers;
- The distance, d, between two consecutives receivers in the direction North-South; and
- The distance, w, between two consecutives receivers in the direction East-West.

Of the three parameters, h, d, and w, for the sake of expediency only w and d where optimized. The height, h, of the receivers with respect to ground level was purposely established in 75 m, which is half the height of typical towers of large state-of-the-art solar tower power plants. The optimization criteria used to fix the values of the parameters w and d was to maximize the area within the heliostat field's bounding rectangle with an annual ideal optical efficiency larger than 90%.

The result of this optimization and its comparison with the ideal annual efficiency of a 150 m single-tower is presented in **FIGURE 2** a) and b). In this figure, *the boundaries of the green contours, which are the contours of more than 90% efficiency, define the boundaries of the heliostat field being designed*. Notice that while for the 6-receiver system the area of the land with an annual ideal optical efficiency larger than 90% is 793 928 m^2 for the single-tower system that area is zero.

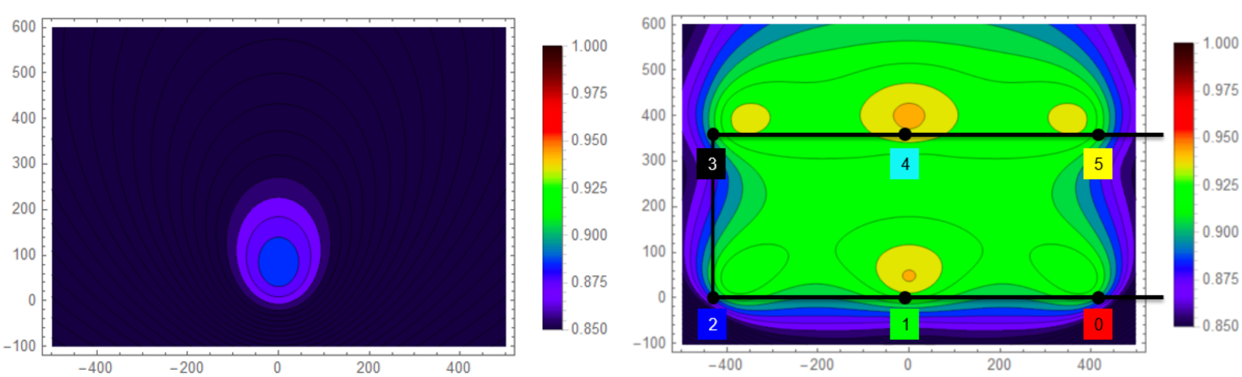

FIGURE 2. Annual ideal optical efficiencies of a 150 m high single-tower (left) and a 75 m high 6-receiver system (right).

Heliostat Dimensions

Once the location of the receivers / aiming point and the boundaries of heliostat field are optimized in such a way that any heliostat located within the established boundaries of the heliostat field will have an ideal annual optical efficiency of 90%, the next challenge consists in designing a "real" heliostat field with an annual optical efficiency greater than 75%. Since the aim is to design a "good" multi-receiver heliostat field not "the best", for the sake of expediency some of the parameters that in other circumstances we would have considered part of the variables to optimize were fixed, such as the heliostat tracking system (azimuth- elevation), and the dimensions of the heliostat reflective area (width 2.44 m, height 1.85 meter). The values adopted, although, may not be the optimum are quite sensible. Small heliostats are needed in a multi-receiver configuration to decrease spillage and compensate for the fact that heliostats will be aiming to different aiming points during the day without being able to modify their focal length.

Shadowing and Blocking Minimization

The fact that, in this concept, the receiver to which a heliostat aims to depends upon the location of the heliostat in the heliostat field and upon the position of the sun in the sky adds complexity to the shadowing and blocking optimization. To reduce this complexity, the heliostat field was subdivided in areas of similar aiming behavior along the year, **FIGURE 3**.

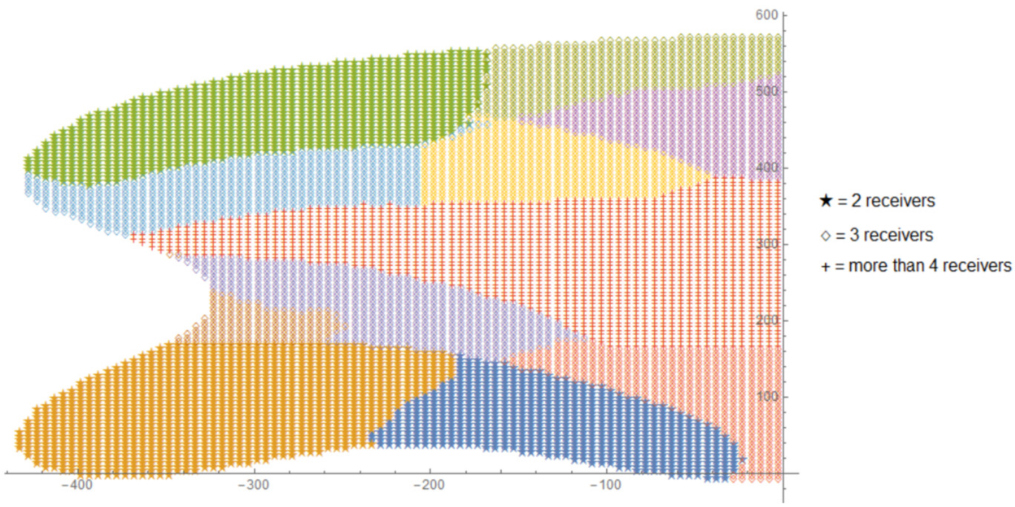

FIGURE 3. Areas of similar aiming behavior within the heliostat field. Since both the heliostat field and the areas are symmetric with respect to the North-South direction only half field is shown.

At all areas of similar aiming behavior, the same layout-generating function was used to deploy the heliostats in the area. For the preliminary design presented in this article a biomimetic pattern[8], whose parameters a and b from Equations (2) and (3) vary within a defined range. The starting point of the biomimetic pattern was randomly located.

$$\theta_k = 2\pi\varphi^{-2}k \tag{2}$$

$$r_k = a \cdot k^b \tag{3}$$

For every area of similar aiming behavior, both the annual optical efficiency of the central heliostat in that area and the density or land coverage ratio of the areas were used in the definition of the objective function to maximize. This function was defined as the product of the land coverage ratio times the optical efficiency to the square. In addition, a constraint of 20% minimum land coverage ratio and 70% annual optical efficiency was applied whenever possible. The annual optical efficiency used at this stage of minimizing shadowing and blocking combines cosine, atmospheric attenuation, shading and blocking factors. The lasts two factors were estimated using parallel projection and polygon clipping.

RESULTS

After the optimization to minimize shadowing and blocking, the heliostat field layout obtained and the 6-receivers were modeled in Tonatiuh and simulated for 45 sun positions along the year using that program. During the simulations the reflectivity of the heliostat's mirrors was assumed to be 100%. Simulations were run in Tonatiuh using Buie's sunshape model with a circumsolar ratio (CSR) of 0.02. For each one of the 45 simulations, the weighted annual efficiency η_{annual}, Equation (4) was computed by bicubic interpolation with Catmull-Rom splines[9] over the 45 efficiency values achieved.

$$\eta_{annual} = \frac{\int_{year} \eta_t \cdot DNI(t)dt}{\int_{year} DNI(t)dt} \quad (4)$$

The DNI-weighting was carried out using the 1977 ASHRAE DNI model of a clear day.

The resulting heliostat field (presented in **FIGURE 1**) has a total reflective area of 89 435.9m^2, representing 19 813 heliostats. Its DNI-weighted annual efficiency is 76.48%, which is more than 10% higher than the best corresponding DNI-weighted efficiency of a state-of-art[1] large commercial solar tower system. Both, the efficiency of the multi-tower concept presented in this article and the efficiency of the state-of-the art mono-tower system used for comparison do not include spillage or reflectivity losses. **FIGURE 4** presents the instantaneous efficiency of the field mapped over azimuth and elevation angles for an entire year. It can be noticed that above 20° elevation, the instantaneous efficiency of the field is always higher than 70%.

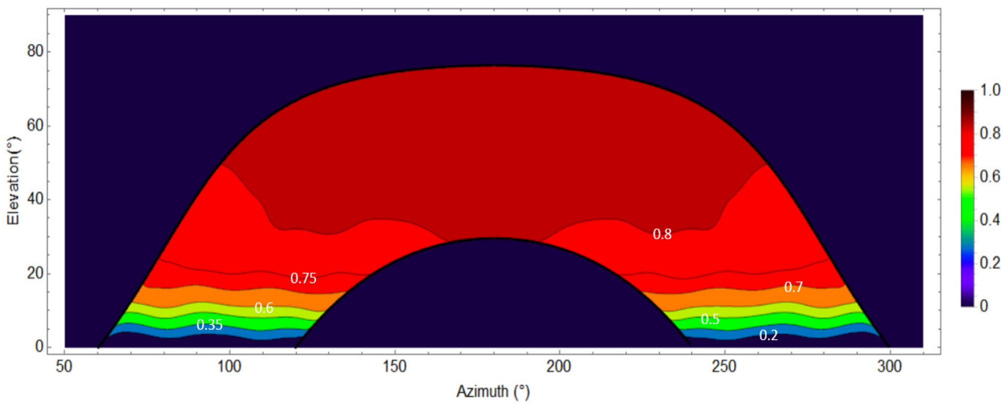

FIGURE 4. Instantaneous optical efficiencies of the designed heliostat field as a function of azimuth and elevation.

CONCLUSIONS

A new concept of linear Fresnel multi-receiver system has been introduced in this article. A specific instance of this concept was designed as a proof of concept using an ad-hoc and relatively simple optimization strategy that has substantial room for improvement. Even with this simple optimization strategy the heliostat field of the proof of concept generated has an annual DNI-weighted optical efficiency of more than 76%, which is substantially higher than the corresponding DNI-weighted optical efficiencies of the heliostat fields of large state-of-the-art commercial mono-tower systems, which typically do not exceed 65%. Thus, from the optical point of view the concept clearly has the potential to substantially outperform the classical mono-tower system. To fully realize this potential, we are currently developing tools and methodologies to improve the optimization of the heliostat field and to explore a large variety multi-receiver system configurations. However, substantially outperforming the optical performance of mono-tower systems is not enough. To fully develop the concept many other aspects have to be addressed and further developed. This will be systematically done in future studies.

ACKNOWLEDGEMENT

This research was performed as part of the Australian Solar Thermal Research Initiative (ASTRI), a project supported by the Australian Government, through the Australian Renewable Energy Agency (ARENA).

The participation of the Cyprus Institute on the research was partly funded by European Union's Horizon 2020 research and innovation program under the CySTEM project with grant agreement number 667942.

REFERENCES

1. J.G. Barberena, A.M. Larrayoz, M. Sánchez, and A. Bernardos, Energy Procedia 93, 31 (2016).
2. P. Schramek and D.R. Mills, Sol. Energy 75, 249 (2003).
3. P. Schramek and D.R. Mills, Energy 29, 701 (2004).
4. P. Piroozmand and M. Boroushaki, Energy 106, 240 (2016).
5. J. Cumpston and J. Pye, Sol. Energy 119, 383 (2015).
6. M. Blanco, J.M. Amieva, and A. Mancilla, Proc. IMECE2005 157 (2005).
7. J. Ballestrín and A. Marzo, Sol. Energy 86, 388 (2012).
8. C.J. Noone, M. Torrilhon, and A. Mitsos, Sol. Energy 86, 792 (2012).
9. V. Grigoriev, M. Blanco, and C. Corsi, in SolarPACES 2015, Cape Town, 13-16 Oct. 2015 (American Institute of Physics, 2015), p. 8.