Etendue-Matched Solar Tower Beam-Down System for High-Temperature Industrial Processes

Diogo Canavarro[1, a)], Gonçalo Delgado[1, b)], Vikas Patil[2, c)], Manuel Blanco[3, d)] and Pedro Horta[1, e)]

[1] *University of Évora, Casa Cordovil, Rua D. Augusto Eduardo Nunes, nº7, 7000-651 Évora, Portugal,*
[2]*Department of Mechanical and Process Engineering, ETH Zurich, Sonneggstrasse 3, 8092 Zurich, Switzerland.*
[3]*European Research Area Chair in Solar Thermal Technologies for the Eastern Mediterranean, Energy Division, The Cyprus Institute, Athalassa Campus, 20 Konstantinou Kavafi Street, Aglantzia, Nicosia 2121, Cyprus*

[a)]*Corresponding author: diogocvr@uevora.pt*
[b)]*gdelgado@uevora.pt*
[c)]*vpatil@ethz.ch*
[d)]*m.blanco@cyi.ac.cy*
[e)]*phorta@uevora.pt*

Abstract. The standard Concentrating Solar Thermal (CST) mono-tower technology, which uses one receiver placed on top of a tower to which all heliostats in the heliostat field aim to, is regarded as one of the best and most promising technologies for various CST-driven applications, namely CST power plants, solar metallurgical processes, thermochemical production of solar fuels and waste materials recycling. However, the technology has some technical challenges concerning optical performance/tolerances, system dimensions, operation and maintenance issues, etc. An alternative to this standard CST mono-tower technology is the so-called beam-down technology, where a special mirror is placed on the top of the tower, instead of a receiver, to redirect the incident radiation from the heliostat field onto a receiver/reactor placed closer to the ground and potentially delivering higher concentrations at the receiver than the standard CST mono-tower technology. This paper presents a new approach to improve the optics of beam-down systems, applies it to the optical design of a specific system, and shows the optical behavior of this design at two locations: Évora (Portugal) and Hurghada (Egypt). The approach uses etendue-matching between all the optical stages to minimize the optical losses between them. To analyze the optical behavior of the system designed, as an example, using the etendue-matching approach, raytracing simulations were carried out and are presented also in the paper.

INTRODUCTION

During the last years, several beam-down solutions for solar tower (BD-ST) system have been proposed, including some commercial projects [1–3]. These systems are well-known for many years but regarded as an inferior option due to their lower optical efficiency and higher complexity in comparison to conventional mono-tower technologies [4]. However, there are several aspects that, together, might represent an opportunity for such configurations:

- They have room for improvement: The presence of several optical stages is an opportunity to use non-imaging optics [5,6] to boost their overall concentration factor (compensating the loss of optical effiency);
- Practical aspects: The receiver can be placed closer to the ground, facilitating operation and maintenance (O&M) and eliminating heat losses due to transport of media from top of the tower, further compensating for the lower optical efficiency;

- Renewed interest by industry: As mentioned before, some commercial projects are already taking place such as the "Yumen Xinneng" power plant in China [3] and the "STEM" project in Italy [7].

Therefore, there is room for improvement as well as potential for market penetration in BD-ST systems. However, to be feasible, such system must achieve high concentration factor and high energy collection to become competitive.

BD-ST solutions proposed in the literature are usually based on a hyperbolic-type secondary mirror and a CPC-type (Compound Parabolic Concentrator) as a tertiary mirror (to manage the optical tolerances) [1,8]. However, none of these works address the possibility of using the concept of etendue-matching. This concept has already been successfully used in a previous work on the design of a parabolic-dish type concentrator [9] and it could be an important tool to achieve both high efficiency collection and a high concentration factor. In the next sections, the process of design will be explained as well as a calculation of the total amount of collected energy for the two locations of Évora, Portugal and Hurghada, Egypt.

ETENDUE-MATCHED SOLAR TOWER RECEIVER DESIGN METHOD

The foundation of the design method is based on the concept of etendue-conservation. In simple terms, as light travels through an optical system (e.g., a solar concentrator) it requires area and angular space (see Fig. 1). These two "rooms" define a geometric quantity known as etendue. For 2D systems, the etendue U_{2D} is given by [6]:

$$2nasin(\theta) \tag{1}$$

U_{2D} is the etendue of the radiation crossing the length a immersed in a medium of refractive index n within an angle $\pm\theta$. For 3D systems the etendue, U_{3D}, is given by:

$$2n^2asin(\theta)^2 \tag{2}$$

Where a is now the area of the entrance of the optical system.

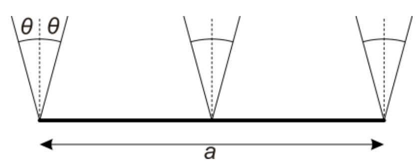


FIGURE 1. Etendue of the radiation crossing the length a within an angle ±θ.

In practice, usually n=1 (and it has been used for all the calculations presented in this work) and θ is chosen according to the fundamental law of concentration [5,6]:

$$C_{3D} = \frac{n^2}{sin(\theta)^2} \tag{3}$$

This amount of etendue must remain constant throughout the whole optical system to achieve maximum concentration.

The process of etendue-coupling means the conservation of the etendue throughout all the optical stages of the concentrator till the light reaches the receiver. This etendue-coupling process can also be used to establish the proper dimensions of the system (aperture entrance, height of the tower, etc.), since there is, for a set of inputs, a physical constraint on the system in order to conserve the etendue.

This process can be adopted to solar tower concentrators and it is particularly important for BD-ST configurations, as there are multiple optical stages and the loss of light (etendue) will severally penalize the overall performance. A general configuration of a BD-ST concentrator can be seen in Fig. 2.

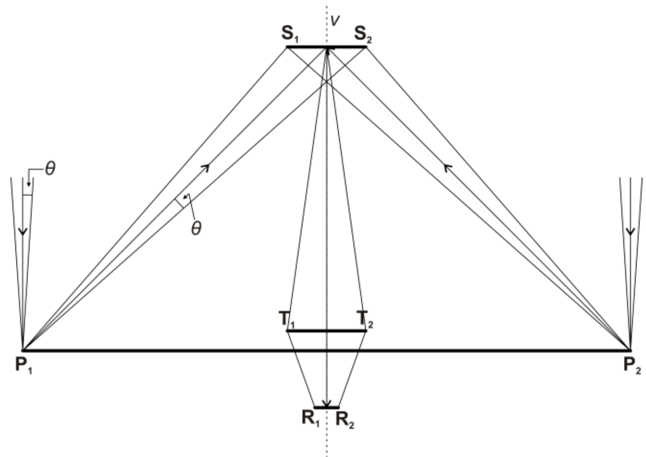


FIGURE 2. Schematic representation of a BD-ST system. The light reflected by the primary field $\mathbf{P}_1\mathbf{P}_2$ is reflected to a secondary mirror $\mathbf{S}_1\mathbf{S}_2$ and then reflected down to entrance of a tertiary optic $\mathbf{T}_1\mathbf{T}_2$ finally reaching the receiver $\mathbf{R}_1\mathbf{R}_2$.

The light hits the primary $\mathbf{P}_1\mathbf{P}_2$ and it is reflected towards the secondary $\mathbf{S}_1\mathbf{S}_2$. Then the light is reflected towards the tertiary $\mathbf{T}_1\mathbf{T}_2$ and finally collected by the receiver $\mathbf{R}_1\mathbf{R}_2$. The inclusion of the tertiary is related to the fact that, without it, the distance between the secondary and the receiver (which can be seen as an optical channel) would be very large, considerably increasing the size of the former, thus increasing the shading losses. Moreover, the size of the receiver "seen" from the secondary would be very small, hence decreasing the acceptance-angle (penalizing the overall concentration). Due to these reasons, it is necessary to introduce an intermediate optical element between the secondary and the receiver and that is why the tertiary stage is included.

The first step is to set the proper dimensions of each stage through which the light passes. This can be done using an etendue-coupling between all the stages using the Hottel's string method [6]. Note that, although the final configuration is a 3D-optic, the design and optimization can be done in 2D since the final solutions can be achieved by rotation symmetry. Suppose then, that the positions of $\mathbf{P}_1\mathbf{P}_2$ are known as well as the half-acceptance angle θ. The etendue reaching $\mathbf{P}_1\mathbf{P}_2$, U_{P1P2}, is then given by:

$$U_{P1P2} = 2[\mathbf{P}_1, \mathbf{P}_2]\sin(\theta) \tag{4}$$

where $[\mathbf{A},\mathbf{B}]$ is the Euclidean distance between two points $\mathbf{A}$ and $\mathbf{B}$. This etendue must remain constant throughout all the optical stages to reach maximum concentration. Let us consider now that $\mathbf{P}_1\mathbf{P}_2$ is a Lambertian source fully illuminating $\mathbf{S}_1\mathbf{S}_2$, i.e. each point between $\mathbf{P}_1$ and $\mathbf{P}_2$ fully illuminates the secondary. Consider also that $\mathbf{S}_1\mathbf{S}_2$ fully illuminates the tertiary $\mathbf{T}_1\mathbf{T}_2$ as well and that there are no other optical elements connecting both. The etendue exchanged between $\mathbf{S}_1\mathbf{S}_2$ and $\mathbf{T}_1\mathbf{T}_2$, $U_{S1S2\text{-}T1T2}$, is given by Hottel's string method:

$$U_{S1S2-T1T2} = [\mathbf{S}_1, \mathbf{T}_2] + [\mathbf{S}_2, \mathbf{T}_1] - [\mathbf{S}_1, \mathbf{T}_1] - [\mathbf{S}_2, \mathbf{T}_2] \tag{5}$$

In order to conserve the etendue $U_{P1P2} = U_{S1S2\text{-}T1T2}$ and since the system is symmetric with respect to the vertical line v, points $\mathbf{S}_2$ and $\mathbf{T}_2$ are the symmetric of $\mathbf{S}_1$ and $\mathbf{T}_1$, respectively. To get the solution one can, for instance, force a certain height for points $\mathbf{S}_1$ and $\mathbf{T}_1$ relatively to $\mathbf{P}_1\mathbf{P}_2$ and find the appropriate width which fits the conservation of the etendue.

A similar process can now be applied to find the dimensions and position of the receiver $\mathbf{R}_1\mathbf{R}_2$. Again, consider that the tertiary $\mathbf{T}_1\mathbf{T}_2$ fully illuminates the receiver and that there are no optical elements connecting both. The etendue exchanged between $\mathbf{T}_1\mathbf{T}_2$ and $\mathbf{R}_1\mathbf{R}_2$, $U_{T1T2\text{-}R1R2}$, is given by:

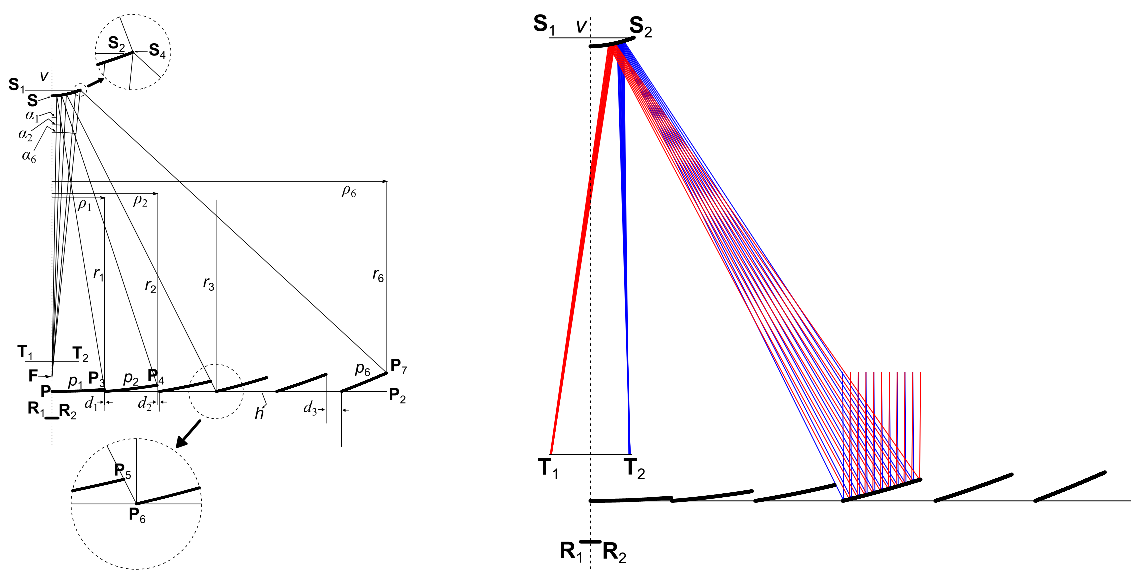
$$U_{T1T2-R1R2} = [\mathbf{T}_2, \mathbf{R}_1] + [\mathbf{T}_1, \mathbf{R}_2] - [\mathbf{T}_2, \mathbf{R}_2] - [\mathbf{T}_1, \mathbf{R}_1] \quad (6)$$

It is, of course, possible to add more optical stages to reduce the distance between them. This has the advantage of reducing the size of each optical component but the drawback of increasing the complexity of the system. Nevertheless, the process is still the same by using the conservation of the etendue.

Design Process using the Aplanatic Method

As mentioned in the previous section, once the dimensions of the system are well defined, it is necessary to properly design the optical components to reach the maximum concentration. In this sub-section, a solution based on the Aplanatic optics method [10] is presented. This method is a limit case where the solar source is a point and, therefore, the edge-rays collapse into a single ray. This approximation is quite reasonable for high concentration factors since in this case the acceptance-angle is small and, therefore, the error of considering the source as point is small. This method is also relatively easy to apply, especially compared to the Simultaneous Multiple Surface (SMS) method [6] , which can be an advantage for its application in real world conditions by the interested users (researchers, companies, etc.). In fact, this method is a limit case of the SMS when the acceptance-angle goes to zero.

The general process of the design of a BD-ST concentrator is shown in Fig. 3a. Having the dimensions of the system, i.e., portions $\mathbf{P}_1\mathbf{P}_2$, $\mathbf{S}_1\mathbf{S}_2$, $\mathbf{T}_1\mathbf{T}_2$, $\mathbf{R}_1\mathbf{R}_2$ defined, one can start the design of the system. Once again notice that the concentrator is designed in 2D and the full 3D version is obtained by rotation symmetry. The design starts by choosing the first point of the primary mirror, **P**, the first point of the secondary mirror, **S**, and a focal point **F**.



(a) (b)

FIGURE 3. The design process of the BD-ST concentrator. (a) Aplanatic approach is used to design the primary and secondary mirrors; (b) The optimization of the focal point of the secondary mirror can be done by launching the edge-rays (red and blue rays) over the heliostat mirrors to check if they end up (approximately) near the edges of the tertiary optics (T1 and T2). This is done for all the heliostats but for better visualization, it is shown for just one heliostat. The edge-rays are not perfectly coupled on the edges due to the aplanatic approximation.

The position of **S** must be between $\mathbf{S}_1\mathbf{S}_2$ and along the vertical axis v. Its final position must be adjusted in order to match the size of $\mathbf{S}_1\mathbf{S}_2$, i.e., the last point of the secondary mirror, $\mathbf{S}_4$, must be point $\mathbf{S}_2$ so as to match the etendue. This, however, does not happen for reasons that are discussed further. Similarly, point **F** must be chosen between $\mathbf{T}_1\mathbf{T}_2$ and along v. Its final placement is a matter of optimization of the optic, although one simple criterion can be to collect the edge rays coming from the heliostat mirror, as shown in Fig. 3b, following the Edge-Ray Principle [5]. In this way, we are increasing the optical tolerances (acceptance-angle) of the concentrator, leading to a better performance.

Suppose now we already know the position of point $\mathbf{P}_3$ of the first mirror p_1 as well as the path of the ray r_1. Between point **P** and $\mathbf{P}_3$ there is a distance ρ_1 which is called magnification and it is what defines an aplanatic optic. ρ_1 is given by:

$$\rho_1 = f\sin\alpha_1 \tag{7}$$

where f is given by:

$$f = \frac{nR}{2\sin\theta} \tag{8}$$

R is the size of the receiver $\mathbf{R}_1\mathbf{R}_2$, n is the refractive index of the medium in which the receiver is immersed (in this case we consider n=1) and α_1 is the angle that ray r_1 makes to v after its reflection off the secondary mirror. Now we can move to another heliostat by intersecting $\mathbf{P}_3$ with the horizontal axis h (for better visualization see the path of ray r_3 hitting point $\mathbf{P}_6$ and crossing $\mathbf{P}_5$) leaving a distance d_1 between p_1 and the second heliostat mirror p_2. Now we move to a point $\mathbf{P}_4$ using a magnification ρ_2:

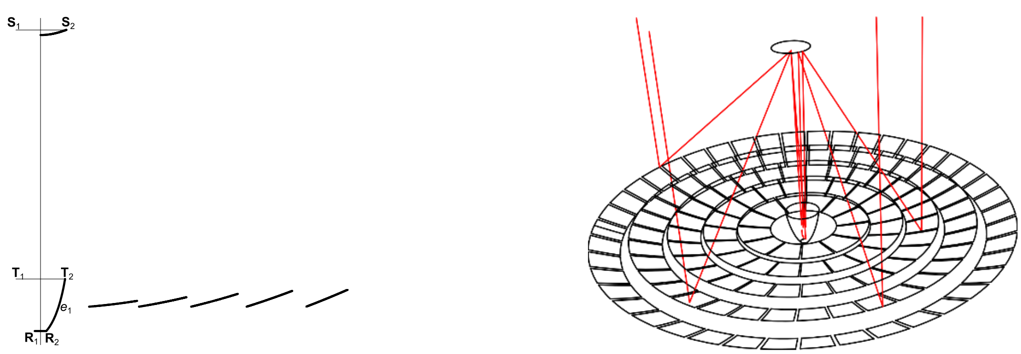
$$\rho_2 = f\sin\alpha_2 + d_1 \tag{9}$$

where α_2 is the angle that ray r_2 (hitting point $\mathbf{P}_4$) makes to v after its reflection of the secondary mirror. Now the process goes on and on until point $\mathbf{P}_7$ (belonging to heliostat mirror p_6) vertically above point $\mathbf{P}_2$, filling the primary field $\mathbf{P}_1\mathbf{P}_2$. ρ_6 is given by:

$$\rho_6 = f\sin\alpha_6 + d_1 + \ldots + d_5 \tag{10}$$

After reflection on $\mathbf{P}_7$, ray r_6 hits the secondary mirror at point $\mathbf{S}_4$ and it is reflected to point **F**. Ideally, point $\mathbf{S}_4$ should be $\mathbf{S}_2$, which would correspond to a match of the etendue (as discussed before). However, this does not happen due to the approximation considered in this method (source considered as a point) as well as by the fact the primary is discontinuous, having the "cosine losses of etendue" in each mirror. Nevertheless, changing the position of point **S** and inducing a small step of calculation of each heliostat is possible to minimize this effect.

A simple solution for the tertiary optic is to use a CEC (Compound Elliptical Concentrator), as shown in Fig. 4a. In this case, the right side of the elliptical mirror, e_1, as foci $\mathbf{S}_1$ and $\mathbf{R}_1$ and passes through $\mathbf{T}_2$. The left side is symmetric with respect to the vertical axis v. It is possible that, in the end, there is an overlap between the first heliostats (the closest to the vertical axis v) and the tertiary optic. In this case, the mirror must be removed. The final solution can be obtained by rotation symmetry, as shown in Fig. 4b.



(a) (b)

FIGURE 4. The final steps of the design process. (a) A CEC can be used as a tertiary optic; (b) The final configuration can be obtained by rotation symmetry.

SYSTEM DATA AND EXPECTED PERFORMANCE

Table 1 shows the main geometric data of the system as well as some reference optical parameters of the system considered in this study. It is important to mention that these dimensions can be changed to satisfy a certain power input on the receiver aperture.

TABLE 1. Etendue-Matched BD-ST concentrator data.

Parameter	Data
Primary field	116 heliostats for a total area of 3800 m^2
Secondary mirror	35 m^2 of area and placed at a height of 34 m.
Tertiary mirror and receiver	73 m^3 cavity volume (tertiary) and a receiver with an aperture of 1.65 m^2
Material properties	Mirror reflectivity of 0.92 and receiver apparent absorptance of 0.9
Optical parameters	C_g = 2088X, η_{opt0} = 0.7

Where C_g is the geometric concentration and η_{opt0} is the optical efficiency at normal incidence (position of the optical design). The latter is calculated by dividing the total power absorbed by the effective total power hitting the primary field. Using the software Tonatiuh [11], the performance of the BD-ST concentrator was analysed. This analysis was based on the calculation of the Incidence Angle Modifier (IAM) profile, enabling the calculation of the total amount of energy collected in a year for a specific location (latitude) and DNI (Direct Normal Irradiance) data. Table 2 shows the IAM profile for different elevation angles (θ_s) and azimuth angle (φ_s). The IAM, $K(\theta_s, \varphi_s)$, is given by:

$$K(\theta s, \varphi_s) = \frac{\eta_{opt}(\theta_s, \varphi_s)}{\eta_{\text{opt0}}} \tag{11}$$

where $\eta_{opt}(\theta_s, \varphi_s)$ is the optical efficiency for a given incidence direction. Each one is calculated using Tonatiuh dividing the total amount of collected power of the receiver by the total effective power hitting the primary field (already considering the cosine losses effect).

TABLE 2. IAM profile of the BD-ST concentrator.

	Azimuth angle (φ_S)							
Elevation angle(θ_s)		0	30	60	75	90	110	130
	90	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	65	1.103	1.087	0.990	1.019	0.973	0.918	0.854
	45	0.919	0.910	0.805	0.768	0.699	0.612	0.532
	25	0.713	0.6804	0.508	0.427	0.337	0.227	0.154
	15	0.531	0.505	0.332	0.2439	0.150	0.061	0
	5	0.157	0.180	0.115	0.080	0.036	0	0

An energy collection analysis was carried out considering the IAM profiles of the system and meteorological data from the location of Évora, Portugal (Latitude: 38°34.0002′ N, Longitude: 7°54′ O) and Hurghada, Egypt (Latitude: 27°15'26.57"N, Longitude: 33°48'46.48"E.) [12]. The choice of two locations is justified to measure the impact of lower latitudes on the performance of the system. From the meteorological data, an annual DNI value of 2214 kWh/m^2/year and 3047 kWh/m^2/year for Évora and Hurghada was obtained, respectively.

The energy collected in a year, E_{year}, can then be given by the following expression (for all the 8760 hours of the year):

$$E_{year} = \sum_{i=1}^{8760} \eta_{opt0}\, K_T(\theta_T) K_L(\theta_L)\, A_{net} I_b \quad (12)$$

Where $K_T(\theta_T)$ is the transversal IAM, $K_L(\theta_L)$ is the longitudinal IAM, A_{net} is the total mirror area and I_b is the DNI value. Here, it is assumed that the variation of the optical efficiency for different incidence angles can be obtained by the product of the two components of the IAM, an approximation successfully used in the past in other systems [13].

TABLE 3. Etendue-Matched BD-ST concentrator data.

Location	Annual DNI (kWh)	Collected energy (kWh)	Annual system yield (%)
Évora	2214	$4\,050 \times 10^3$	48
Hurghada	3047	$6\,029 \times 10^3$	52

As expected, the annual system yield is higher in Hurghada due to the lower latitude value (less cosine losses).

Comparison with a Conventional Solar Tower System

In order to measure the impact on the optical performance in the studied BD-ST system, a comparison with a conventional ST system was carried out. The data of the ST system was taken from the literature [13] and its corresponding IAM profile was then calculated and it is shown in Table 4.

TABLE 4. IAM profile of a ST of 2.4MW$_{th}$. Adapted from [13].

		Azimuth angle (φ_S)						
		0	30	60	75	90	110	130
Elevation (θ_S)	90	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	65	1.122	1.106	1.008	1.037	0.992	0.936	0.872
	45	1.126	1.117	1.012	0.975	0.906	0.819	0.739
	25	1.091	1.058	0.885	0.804	0.714	0.605	0.531
	15	0.970	0.942	0.770	0.682	0.588	0.499	0.428
	5	0.531	0.554	0.489	0.455	0.411	0.326	0.288

The results for Évora and Hurghada are shown in Table 5.

TABLE 5. Estimated performance results of ST and BD-ST systems in Hurghada and Évora.

System	Annual DNI (kWh), Évora | Hurghada		Collected energy (kWh), Évora | Hurghada		Annual system yield (%) Évora | Hurghada	
ST system	2214	3047	$5\,679 \times 10^3$	$7\,956 \times 10^3$	68	69
BD-ST system			$4\,050 \times 10^3$	$6\,029 \times 10^3$	48	52

As can be seen, the BD-ST system has a lower efficiency when compared to the ST system. This is mainly related to the additional optical losses (more reflections of the light). However, one can notice that the overall efficiency of the BD-ST system increases by around 8% going from Évora to Hurghada, whilst it increases only by about 1.5% for the ST system. This might indicate that the BD-ST can benefit more being placed at lower latitudes. Nevertheless, this is a clear drawback of this configuration and one of the reasons why ST systems have prevailed during the last years.

CONCLUSIONS AND FUTURE WORK

The results of the Monte Carlo raytracing analysis of the BD-ST system show that this system has lower optical efficiency when compared to conventional ST systems. The studied configuration, like the present state-of-the-art, was optimized but this optimization process seems not enough to avoid the additional reflections of the light which lowers the overall system efficiency.

An analysis of the annual system efficiency was carried out for two different locations (Évora and Hurghada). The results show a clear advantage for ST systems, although it seems that BD-ST systems can eventually benefit more being placed at lower latitudes when compared to ST systems, a result that might be explained with BD-ST unique design optimization which was done for the normal incidence. Regarding the later, this is a standard in the design of solar concentrators as normal incidence corresponds to the maximum power from the sun and the “middle-point” of its trajectory during the daytime. However, other incidence angles might be explored in the future seeking an optimization for a particular location (latitude impact).

Despite these results, BD-ST can be still seen as a viable option, especially for high-temperature thermal and thermochemical processes that require high concentration ratios. The penalty of having lower efficiency may be compensated by a more compact system and elimination of heat losses along tower height, due to the receiver being placed closer to the ground. Moreover, due to the light path of the BD-ST, it is possible to have the solar flux hitting the receiver aperture at roughly normal incidence, regardless of the incidence angle of the light - something that does not happen in conventional ST systems. Eventually, this might induce a better irradiance distribution over the receiver cavity, a key-aspect in thermochemical processes. In future works, such analysis will be carried out as well as adaptation of the BD-ST to existing cavities in ST systems. Performance vs cost-effectiveness must be explored seeking thermochemical applications such as biomass gasification/pyrolysis for H_2/syngas production along with a cost-reduction strategy to overcome the penalty of efficiency loss. In fact, a first analysis of the potential of several biomass samples from Alentejo region for H_2/syngas was already been explored in “BioHydrogen” activity within INSHIP project [14]. The results of this activity showed a clear need of point-focus technologies for such applications and, therefore, the present configuration is a possible candidate for such task.

ACKNOWLEDGMENTS

We gratefully acknowledge the financial support by the European Union's Horizon 2020 Research and Innovation Program (Project INSHIP – Grant No. 731287).

REFERENCES

1. B. Grange, V. Kumar, A. Gil, P. R. Armstrong, D. S. Codd, A. Slocum, and N. Calvet, "Preliminary Optical, Thermal and Structural Design of a 100 kWth CSPonD Beam-down On-sun Demonstration Plant," Energy Procedia **75**, 2163–2168 (2015).
2. A. Segal and M. Epstein, "The optics of the solar tower reflector," Sol. Energy **69**, 229–241 (2001).
3. "Yumen Xinnengv Power Plant," http://helioscsp.com/tag/yumen-xinneng/.
4. L. Vant-Hull, "Issues with Beam-down Concepts," Energy Procedia **49**, 257–264 (2014).
5. R. Winston, J. C. Miñano, and P. Benítez, *Nonimaging Optics* (Elsevier, 2005).
6. J. Chaves, *Introduction to Nonimaging Optics* (CRC Press, 2016).
7. Magaldi Power s.p.a., "Concentrated solar power system with thermal energy storage | STEM® - Solar Thermo-Electric Magaldi," .
8. M. B. Mokhtar, "The Beam-Down Solar Thermal Concentrator : Experimental Characterization and Modeling," Mit.Edu 1–117 (2011).
9. D. Canavarro, J. Chaves, and M. Collares-Pereira, "Simultaneous multiple surface method for the design of new parabolic dish-type concentrator using a Cassegranian approach," in (2019), p. 050001.
10. J. M. Gordon, "Aplanatic optics for solar concentration," Opt. Express **18**, A41 (2010).
11. M. J. Blanco, J. M. Amieva, and A. Mancillas, "The Tonatiuh Software Development Project: An Open Source Approach to the Simulation of Solar Concentrating Systems," in *Computers and Information in Engineering* (ASMEDC, 2005), pp. 157–164.
12. "Meteonorm Software," https://meteonorm.com.
13. A. Rabl, *Active Solar Collectors and Their Applications* (Oxford University Press, 1985).
14. "INSHIP Project," http://inship.eu.