Optical Assessment using Ray Tracing for a Beam-Down Receiver with Solid Thermal Storage

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Introduction and System Overview

Concentrated solar thermal (CST) power plants have been proposed widely as a suitable energy technology on a transition energy mix, due to their dispatchability (through efficient energy storage) and their potential for integration with existing conventional infrastructure (such as existing fossil fuel generators). However, their penetration has stagnated in the last decade due to its higher levelized cost of energy (LCOE) compared to photovoltaic, wind, and conventional generators. Novel power cycles, like supercritical CO_2, might overcome this bottleneck by increasing overall efficiency, but they require operation temperatures above the existing limit given by conventional heat transfer fluids, which are constrained to temperatures below 600°C [1]. Solid (sensible) storage materials represent a promising option to work on higher temperatures, but the receiver design is challenging [1].
At the same time, Beam Down Receivers (BDRs) represent an alternative design which could enable an efficient solid medium receiver which is located on the ground, avoiding the problem of transporting the solid material to the top of the tower and allowing a dual receiver-storage concept (as was discussed in our 2019 APVI paper [2]). To the best of our knowledge, though, the solar irradiation profile from these types of designs is not available in the literature. To address this, this study tries to give new insights of this concept using a Monte Carlo ray tracing (MCRT) method. Figure 1 shows the main components of the system. The heliostat field (HF) concentrates the radiation toward a focal point, a hyperboloid mirror (HB) intercepts these rays and redirect them to the ground on a second focal point. Due to the magnification involved, a final optic device (typically a CPC) is also required to re-concentrate the radiation in the final receiver. To reduce the CPC's size, an array of concentrators is proposed for this, which are built with a polygon shape instead of a revolution, allowing for easier their manufacture, as was originally proposed by Cooper et al. [3]. In the present work, 7 hexagon CPCs were used. The BDR's main limiting factors are the additional mirror surface required (HB and CPC) and the loss of concentration ratio due to the magnification factor.

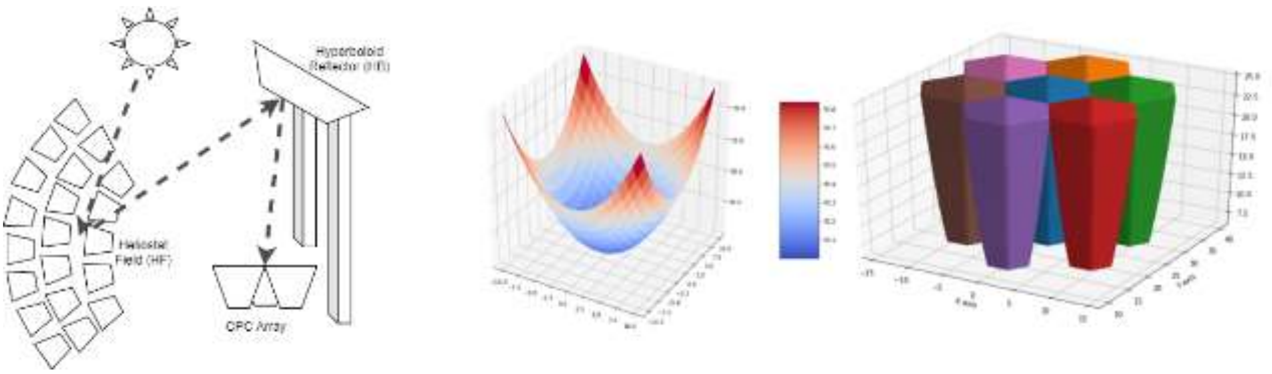

Figure 1. Schematic of the Beam Down Receiver concept. Overall (left) and Hyperboloid shape (centre) and CPC shape (right).

Method and Simulation

The MCRT method allows to study the optic behaviour of complex geometries, such as CST plants. A set of rays are generated from the sun position, including a degree of randomisation to correctly represent the sun irradiance. From this dataset, it is possible to simulate the final distribution in the receiver aperture after interacting with different optic devices. SolarPILOT [4] is a NREL software which can be used to assess and optimise CST plants because it can generate a heliostat field layout and run a MCRT simulation (using the well-known SolTrace engine) for a solar field with a focal point at the top of the tower. In this study, the dataset was exported and used to intercept the hyperboloid mirror and the CPC array. A $25MW_{th}$ solar field is designed for a $z_f = 50(m)$ focal point (the conventional tower height). This thermal power could drive a $10MW_e$ power block if a receiver efficiency of 0.8 and a sCO_2-Brayton cycle efficiency of 0.5 were considered. The design point is solar noon on the equinox for a plant located at Alice Springs (latitude 23.7°S) with DNI=950 (W/m^2). The overall optical efficiency, η_{opt}, was used as an initial optimisation metric since it considers several factors, including heliostats (ρ_{hel}), HB (ρ_{HB}), and CPC (ρ_{CPC}) reflectivities; cosine (η_{cos}), blockage (η_{blk}), shadowing (η_{shd}), HB intercept (η_{HBi}), and CPC intercept (η_{CPCi}) efficiencies:

$$\eta_{opt} = (\eta_{cos} \cdot \eta_{blk} \cdot \eta_{shd} \cdot \rho_{hel})(\eta_{HBi} \cdot \eta_{CPCi} \cdot \rho_{HB} \cdot \rho_{CPC}) = \eta_{conv} \cdot \eta_{BDR}$$

Where η_{conv} is the optical efficiency of the conventional solar tower, while η_{BDR} is the BDR's optical efficiency, which includes the extra devices required in the design. The overall efficiency (η_{CSP}) should consider the receiver, storage, and power block efficiency. If the receiver and storage efficiencies are kept constant—for a conventional steam cycle efficiency of $\eta_{el,conv} = 0.4$ and a sCO2-Brayton cycle efficiency of $\eta_{el,CO_2} = 0.5$—the minimum η_{BDR} to keep the overall efficiency the same is $\eta_{BDR} \geq 0.4/0.5 = 0.8$. If the mirror reflectivity is 0.95, an intercept efficiency of $\eta_{HBi} = \eta_{CPCi} = 0.95$ for both HB and CPC, would meet this requirement ($\eta_{BDR} = 0.95^4 = 0.8145$). Therefore, in each simulation, the size of HB and CPC elements were calculated to ensure an intercept efficiency of 0.95 (where possible).

The simulation calculates the intercepts with HB and CPC of the entire dataset, the different efficiencies, and the optical efficiency for each heliostat in the solar field. With these, the heliostats are sorted by efficiencies and the highest ones are selected until meet the required thermal power. Later the size of HB and CPC are calculated to ensure the required intercept efficiencies. As this process could change the heliostat's optical efficiency, an iterative procedure is needed to ensure that the output thermal power and optical sizes converge.

Results

For a given focal point height (the top of conventional tower), the main design factor is the location of the vertex of hyperboloid mirror (z_v). The lower it is located, the larger the HB mirror should be to intercept the rays from the solar field. However, the magnification factor is smaller (because it is proportional to hyperboloid semiaxis ratio), which means a smaller required CPC array size. Therefore, a trade-off exists between these two phenomena. The maximum CPC height is limited to $H_{CPC} = 20(m)$ to avoid shadowing over the first row of heliostats. Figure 2 shows the CPC and HB surface for different HB height. In this figure, the HB, CPC and BDR (HB+CPC) mirror surfaces are presented. Hyperboloid size decreases exponentially if the HB vertex point increases. The magnification factor is not important below 44m, which is reflected in CPC size. If the HB is located so close to the focal point ($\geq 48m$), the CPC size reaches its maximum possible size and does not reach the required intercept factor. An optimum exists at $z_v = 0.9z_f = 45(m)$ where the minimum mirror surfaces are $S_{HB} = 364m^2$ and $S_{CPC} = 193m^2$. As shown in Figure 3, the heliostat optical efficiency ranges from 25 to 75% (i.e. with an average efficiency of ~56.6%, for $N_{hel} = 479$).

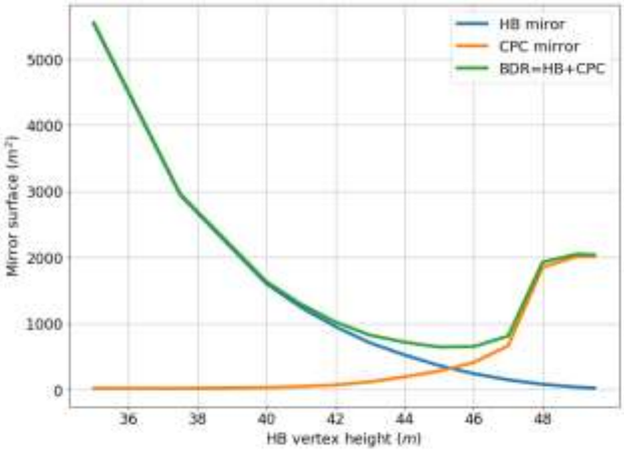

Figure 2. HB and CPC surface for different HB height. Hyperboloid mirror (blue), CPC mirror (orange), and total Beam Down Mirror (green)

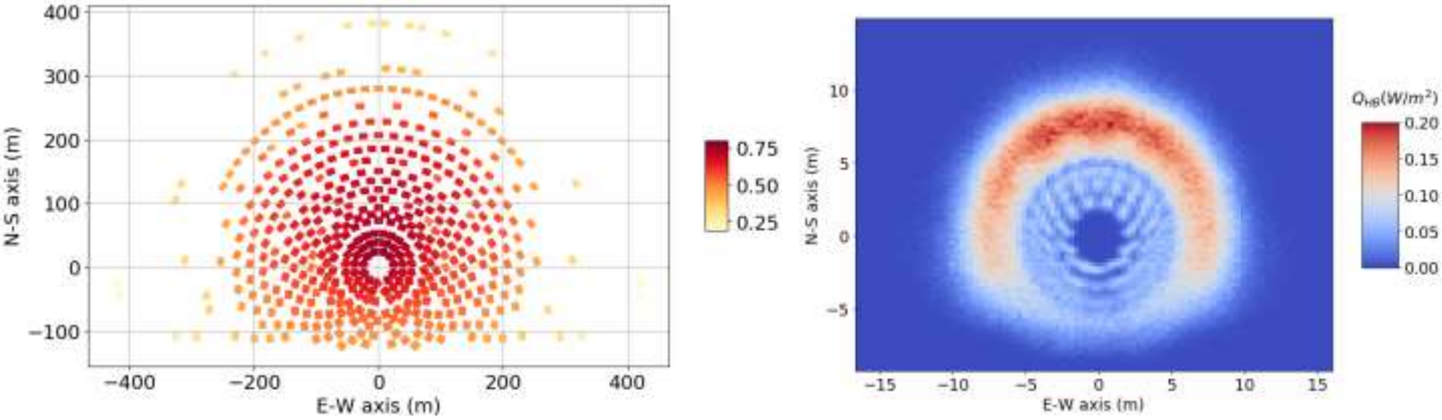

Figure 3. Solar field with optical efficiency for each heliostat (left) and; Radiation distribution map on CPC aperture area (right).

Conclusions

A raytracing simulation was conducted to design a BDR system for modular, high temperature CST plants. The method allows us to test different parameters and obtain the size of required HB and CPC mirrors (which are needed in the final design). A trade-off between the sizes in both components was found. Without doing a full techno-economic optimisation, it can be concluded the best optical design involves HB located at 90% of conventional tower height, with 557m^2 extra mirror surface and a $\eta_{BDR} = 83.5\%$, which means an overall optical efficiency of 56.6%.

References

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