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Design Optimization of a Horizontal Particle Receiver for a Modular Beam Down Receiver CSP

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Abstract. CSP research is focused on increasing the economic competitiveness of this technology as compared to conventional and emerging energy generators. Higher temperature operation conditions represent a pathway toward cost reductions since they enable a relatively smaller solar field area (typically ~40-50% of the plant cost) for the same electrical output. For example, supercritical CO_2 power cycles with solid particles as the HTF could enable >600°C operations and a ~50% power bloc cycle efficiency (considerably higher than steam cycles, <40%). Additionally, small modular systems could increase competitiveness through reduced financial risk, increased system flexibility, and the value of additional services that a modular CSP could offer to the electricity grid (frequency control, peaking supply, etc.). This study investigates the Beam Down Receiver (BDR) configuration as a design that could be well-suited to meet these goals while also overcoming some of issues with particle receivers, such as particle attrition, advective losses, and operation control. In particular, this work introduces a novel horizontal particle receiver (HPR) and analyzes the main design parameters, including tower height, BDR size, radiation flux on the receiver, and receiver nominal power. The analysis shows that tower heights between 35m to 60m are ideal for high temperature receiver capacities of 8-15 MW_{th}, and that this configuration can achieve a minimized LCOH of ~24 USD/MW_{th}. These results suggest that BDRs combined with particle mediums could represent a viable high temperature, high efficiency CSP alternative.

Keywords: Beam Down Receiver, Horizontal Particle Receiver, High-Temperature CSP

1. Introduction and Problem Description

Beam-Down Receivers (BDRs) have been proposed as an alternative design option which can solve some of the problems related to conventional tower receivers [1,2]. In this design, concentrated light is redirected to a receiver located on the ground, so that the tower only supports optical components (a hyperboloid mirror in this case), rather than a receiver and the associated heat transfer flow loop, as shown in Figure 1 (a). Among the main benefits of this concept are that the receiver and storage unit can be placed close to each other, which reduces thermal losses and parasitic power in transportation. Also, the tower and receiver costs can be reduced, along with their maintenance costs, because operating/servicing these components on the ground is easier. Finally, the impact of wind and convective losses are reduced, which is particularly important for high temperature receiver designs, such as particle-based receivers. However, implementing the design is not without challenges. The most obvious of which is the loss of optical efficiency due to additional optical elements. Additionally, a design trade-off exists between increasing size of the hyperboloid mirror and the cost of the tower structure exists, particularly as the nominal power increases. Thus, this study aims compare key component and system designs which can find a good balance between this concept's main trade-offs and constraints.

In a previous work by the authors [3], the optics of BDRs for modular CSP plants were analyzed using the MCRT method. This work identified the main parameters for the hyperboloid mirror geometry and the tertiary optical device (TOD). Several arrays were considered and tested, and it was found that an array of three paraboloid concentrators with a hexagonal aperture and concentration ratio of 2.0 was the best alternative in terms of optical efficiency and radiation flux, as shown in Figure 1 (b). An additional work [4] presented an optimization algorithm to obtain the main design parameters of a BDR system for a high-temperature industrial heat application. These works considered a constant receiver thermal efficiency, then were not able to analyze the coupled optical-thermal performance of the whole thermal energy collection subsystem.

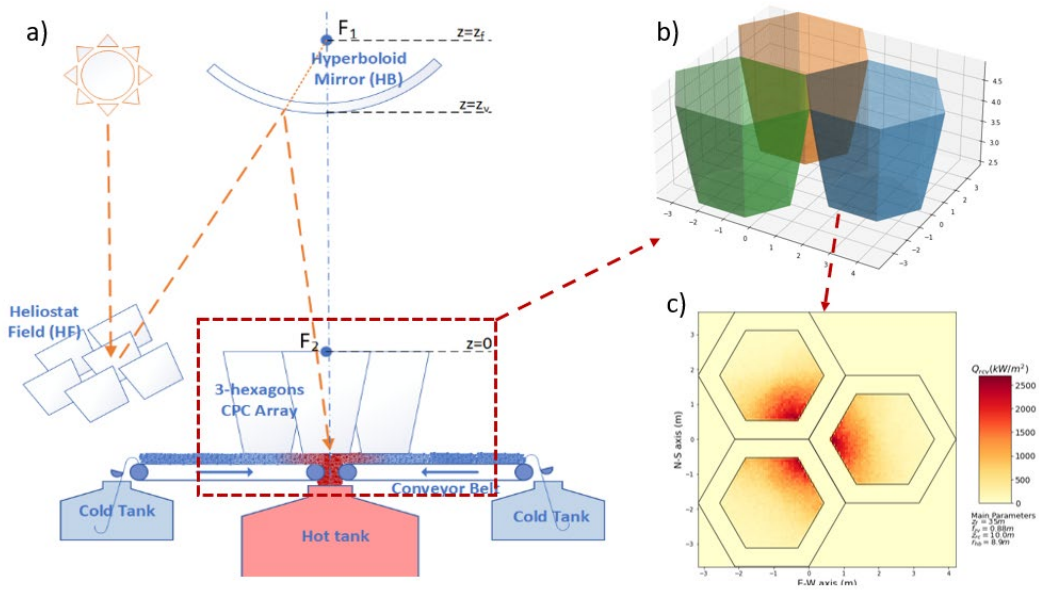


Figure 1. Proposed design for the Beam Down Receiver. a) Overall system with main components. b) Detailed TOD geometry selected from previous work. C) Radiation map on receiver aperture obtained from previous work [3].

Several particle receivers have been proposed in the literature [5], including free-falling, obstructed falling, centrifugal receiver, rotating kiln, and fluidized receivers. Of these configurations, falling particle receivers are the most mature and has been experimentally tested with on-sun facilities by Ho et al. [6]. The present work proposes a novel Horizontal-Flow Particle Receiver (HPR). The main idea is to replicate the falling particle idea but taking advantage of the beam-down optics. A thin layer of particles is transported between the cold tanks to a conveyer belt and on to the hot tank. In this process, the thin layer is directly irradiated by the beam-down radiation. This concept has the potential to overcome the following issues of conventional particle-based receiver designs:

- Particle attrition and loss through the aperture, which is a critical problem among most particle receivers.
- Convective and advective losses due to wind, since a ground mounted receiver would not be affected by wind direction and intensity changes.
- Parasitic pumping power consumption, which can be an issue when particles must be transported to the top of a tower.
- Flow control issues, since a conveyor belt would enable tighter control of the residence time, mass flow rate, and temperature.

The present work uses the methodology described previously [4] to optimize the design parameters of this novel Horizontal Particle Receiver Design (HPR). The problem is split into two parts: i) Development of a receiver's thermal model to be coupled with the optical model already introduced, and ii) Optimization of the solar thermal subsystem to minimize the levelized cost of heat (LCOH).

2. Numerical Model and Optimization Algorithm

A numerical model that considers optics, heat transfer, and costing calculations was built and wrapped to optimize the main dimensions of the beam-down receiver. A flow diagram showing the different steps for the optimization is shown in Figure 2.

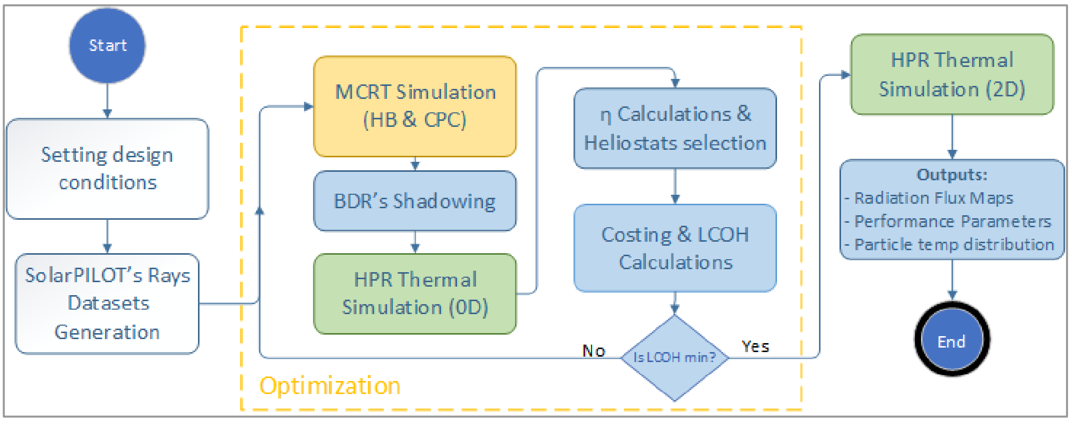


Figure 2. Flow diagram of the optimization algorithm.

The objective function minimizes the LCOH. Initially, fixed conditions were set, and a ray dataset for an oversized solar field was generated using SolarPILOT's motor SolTrace [8]. Each simulation uses 3×10^6 rays, limb-darkened sun for sunshape model, and DELSOL3 clear day attenuation model. The dataset was processed, and MCRT calculations were performed in hyperboloid and the TOD optical devices. The shadowing between the hyperboloid mirror and solar field was also included in this stage, and all the heliostats shadowed more than 10% of the yearly sunny hours were removed. The resulting radiation map from the MCRT was used to calculate the receiver thermal efficiency. Then, the optical efficiencies for each heliostat were obtained, and the most efficient ones were selected until the required thermal energy was reached. The costing calculations were then performed with these results, to obtain the LCOH. These steps are repeated during the optimization process to find the minimum LCOH.

Table 1. Technical parameters used in optimization.

Parameter	Value	Parameter	Value
Plant latitude (Alice Springs, NT, Australia)	-23°	Heliostat size (1 flat mirror)	2.97x2.97 m
Design point	α=58°, z=0°	Mirror reflectivity, ρ_{mirr}	0.95
Design DNI	950 (W/m^{2}d)	Total refl. image error, ϵ_{mirr}	2 mrad
Tower height, z_f	20-75 m	Maximum field radius	600 m
Second focal point, z_{rcv}	10 m	Particles material	CARBOHSP
TOD Concentration ratio	2.0	Inlet particle temp. (T_{ini})	900 K
Receiver avg. radiation	0.25-1.5 MW/m^2	Outlet particle temp. (T_{out})	1200 K

Four independent parameters were identified for optimization: the vertex ratio f_{zv}, the receiver nominal power P_{rcv}, the tower height (or primary focal point, where the heliostat field is aiming) z_f, and the receiver average radiation flux Q_{avg}. The rest of the parameters of interest, such as hyperboloid radius and surface area, receiver aperture area, TOD mirror surface, and the number of heliostats, are dependent on the initial design conditions and those four key parameters. This problem to be solved is complex and non-linear due to the nature of the problem. For example, the number of heliostats is a discrete variable with a significant impact on vertex ratio and land use, impacting the hyperboloid size and capital cost, obtaining erratic or unexpected results at the end. Additionally, the dataset is generated for one specific tower height before the optimization process due to its computational costs and, therefore, cannot be changed internally. Therefore, a full 4-dimension optimization using built-in software does not provide good results and an own-made code is developed for this purpose. First, one-variable optimizations using the Brent method were carried out consecutively to obtain initial guesses for f_{zv} and P_{rcv}. Then, a two-dimension optimization using the Nelder-Mead method was performed to obtain the final values for these two variables. This process was repeated for the expected value ranges of z_f and Q_{avg}, and the final optimal values were identified. All the calculations were programmed in Python and using well-known scientific libraries such as pandas, SciPy, and NumPy.

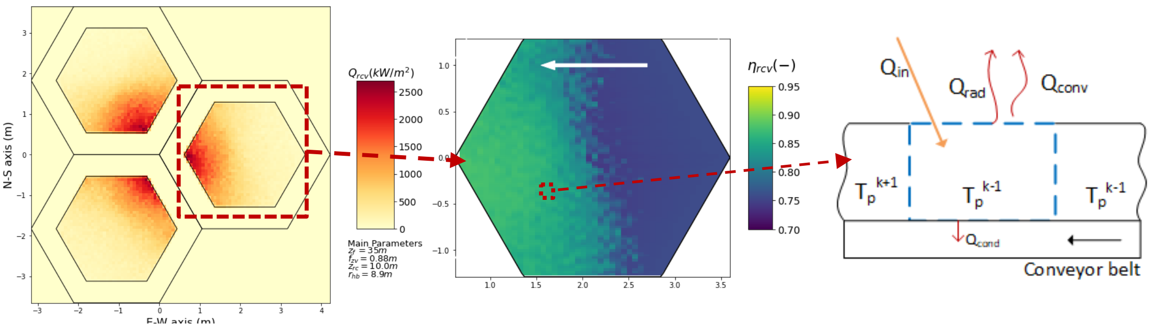
2.1. Numerical Model for the HPR

Two numerical models were made to assess the receiver performance: A 0D model and a 2D model. The 0D model is used during the optimization process to estimate the receiver efficiency with enough accuracy and a low computational cost. Once the optimized parameters are found, the 2D model was used to obtain a more accurate thermal efficiency, estimate the particles' temperature distribution, and determine the required residence time and conveyor belt velocity. The 0D model considers the average radiation flux as the energy inlet and losses by convection, radiation to the environment, and conduction to the conveyor belt:

$$\dot{m}c_p\Delta T = Q_{in} - Q_{conv} - Q_{rad} - Q_{cond} = Q_{avg}A_{rcv} - Q_{losses} \quad (1)$$

$$\eta_{rcv} = \frac{\dot{m}c_p\Delta T}{Q_{in}} = \frac{P_{rcv}}{Q_{avg}A_{rcv}} \quad (2)$$

The losses depend on the ambient and the average particle temperatures. The radiative losses were calculated using the Stefan-Boltzmann law, while the convective losses were calculated using natural convection loss correlations from the literature [7]. All the temperature-dependent air properties are calculated using the Cantera module for Python, while the CARBOHSP properties are obtained from the literature.



a) b) c)

Figure 3. HPR thermal model. a) Radiation flux on receiver aperture. b) specific efficiency on one of the receivers. The white arrow indicated particle flow direction. c) Energy flows and discretization used for 2D model.

The 2D model is based on the simple 0D model. The receiver surface is discretized spatially, each element is assumed to be a lumped system and the particle flow is assumed as a continuum. As the primary energy flux is the irradiance and contiguous particles have similar temperatures, no conduction is considered between particles horizontally. Additionally, it is assumed that all the particles have the same initial temperature T_{ini} and move in the conveyor belt at the same speed. Due to the thermal efficiency depending on the particle temperatures, an iterative process is required to get the average residence time (t_{res}) to ensure the required output temperature T_{out}.

2.2. Costing Calculations

The cost structure considers typical values used in the literature (SAM and/or SolarPILOT [8]), except for BDR-specific devices, specifically for BDR mirror and tower costs.

Table 2. Economic parameters used in optimization.

Parameter	Value	Parameter	Value
Heliostat cost	100 USD/m^2	Site-to-field land ratio	1.3
BDR mirror cost (HB & TOD)	500 USD/m^2	Cost of land	2.47 USD/m^2
Receiver cost	40 USD/W$_{th}$	Site improvement costs	16 USD/m^2
Storage material cost	1.0 USD/kg	O&M cost (% of capital cost)	2 %/yr
Solar multiple	2.0 (-)	Eng. and contingency costs (% of capital cost)	40%
Storage capacity	6 hrs	Discount rate	5%
Capacity factor	20%	Plant lifetime	30 yrs

Conventional tower cost used in CST power plants assume a monolithic concrete tower will be employed. However, a hyperboloid mirror would be significantly lighter and would only require a steel structure composed of four pillars. Costs for this kind of structure would depend on the terrain type, the wind loads, and anti-seismic regulations of the location. Rea et al. [9] proposed the following correlation for a short tower (less than 50m) for CST small plants.

$$C_{tower} = (123.21 + 362.6 m_{HB})\ e^{0.0224 z_f}\ [USD] \quad (3)$$

Where m_{HB} is the mass of the structure on top (the hyperboloid mirror in this case) and z_f is the height. For the BDR structure, four pillars are considered, and the total weight is distributed among these pillars. For example, for a 50m tower with a hyperboloid mirror surface of $1000 m^2$, which has an estimated weight of 540 tons distributed in 4 towers, the cost is around 0.6 MMUSD compared with around 4 MMUSD for a conventional tower. The weight of the hyperboloid mirror was obtained assuming 50mm mirror thickness with a density of aluminum plus the required fins to ensure natural cooling. The number of fins is calculated using cylindrical fins efficiency, avoiding an increase in temperature higher than 100K. On the other hand, active cooling will most likely be required for TOD mirrors. The required cooling is estimated using water with the same allowed temperature increase. The heat exchanger cost is calculated using Hall's correlation [10]. No costs were considered for the storage containers and primary heat exchanger, as they depend on the specific application (power generation and/or industrial heat).

Finally, the Levelized Cost of Heat is calculated as:

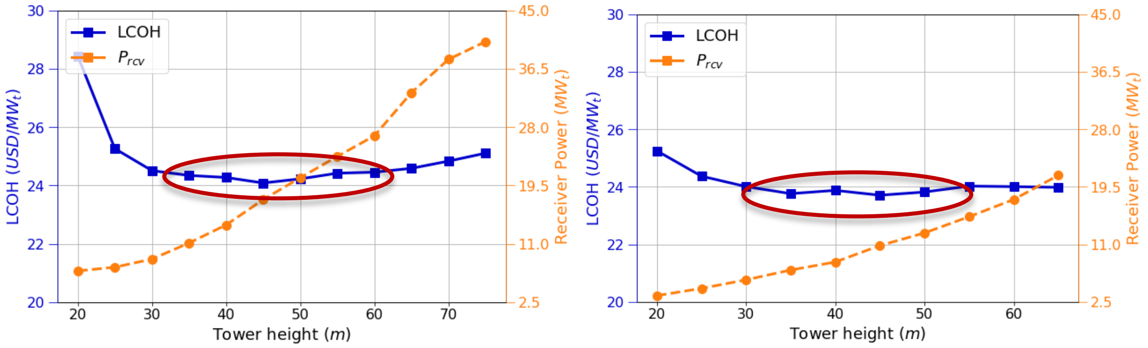
$$LCOH = \frac{C_C(1 + C_{O\&M} TPF)}{TPF\ P_{yr}} \quad (4)$$

$$TPF = \frac{1}{DR}\left(1 - \frac{1}{(1+DR)^N}\right) \quad (5)$$

Where C_C is the capital cost, including land, heliostat, BDR mirrors, tower, receiver, storage, engineering, and contingency costs. P_{yr} is the annual generation, DR is the discount rate, and N is the plant lifespan.

3. Results and Discussion

The results for the solar thermal subsystem optimization are shown in Figure 4. In Figure 4, the minimal LCOH (blue) and the correspondent receiver power (orange) are presented for each tower height. Two different average radiation flux in receive aperture are shown 0.5 MW_{th}/m^2 and 1.0 MW_{th}/m^2. It is observed that a minimum LCOH of ~24 USD/MW_{th} is obtained for a tower height in the range of 35-60m. Initially, there are benefits to increasing tower height. However, it plateaued, and increases at tower heights above 60m because of the increased tower costs and lower BDR optical efficiency for larger towers.



a) Q_{avg}=0.5MW/m^2 b) Q_{avg}=1.0MW/m^2

Figure 4. LCOH curves (blue, solid) and obtained receiver power (orange, dashed) for different tower heights. Red circles indicate identified design zones.

This process is repeated for different average radiation fluxes. The results for a 35m tower height are shown in Figure 5. A higher radiation flux improves receiver thermal efficiency but decreases solar field optical efficiency. Thus, an optimal value is found with around 8.8MW_{th} and 0.64MW_{th}/m^2 of nominal power and average radiation flux in the receiver, respectively.

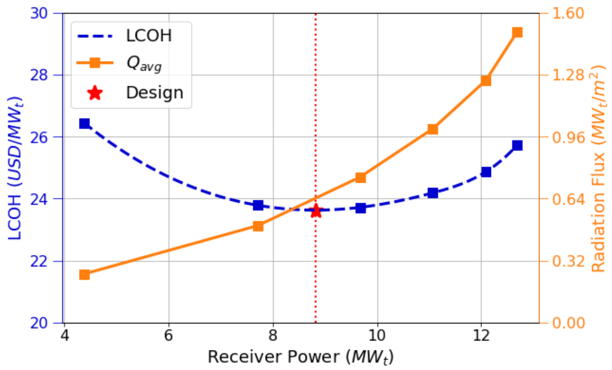


Figure 5. Resulted minimum LCOH (blue, dashed) as a function of optimized receiver power (X-axis) for different radiation fluxes (orange). A red star indicates the selected design.

Detailed results for the selected case are shown in Table 3. Figure 6 shows the specific efficiency on one of the receiver apertures (a), the corresponding temperature map (b), and the final distribution of particle temperatures in the Y axis (c). An overall efficiency of 83.3% is found, which in the range of expected values for particle receivers (50-90%). The particle distribution ranges between 1026 to 1405K, which is explained by the uneven radiation flux on the receiver (as shown in Figure 3.a) and the different residence times due to receiver hexagonal geometry. This undesired result could be improved with a heliostat control strategy to obtain more homogeneous radiation flux and including recirculation of particles on the receiver to allow additional mixing and homogenization between passes.

Finally, Figure 6 (bottom right) presents the capital cost distribution of the main components. It is observed that more than half of the total cost corresponds to the heliostat field. This result is higher than in conventional central tower plants, probably because the tower cost savings outweigh the extra costs of BDR mirrors, resulting in both combined being a smaller fraction (9.3% among both). In addition, the overall optical efficiency is lower than conventional plants, requiring more heliostats for the same output, increasing its slice of the total cost. These facts reflect the trade-offs mentioned in the Introduction regarding BDRs.

Table 3. Detailed results for the selected case.

Parameter	Value	Parameter	Value
Tower height	$35\ m$	TOD height	1.67 m
Receiver Thermal Power	$8.8\ MW_{th}$	Receiver efficiency	83.3%
Receiver Mean Rad. Flux	$0.64\ MW/m^2$	Solar Field efficiency	64.7%
Vertex ratio, f_{zv}	$0.88(-)$	Receiver Max Radiation	$2.64\ MW/m^2$
Receiver Area	$17.32\ m^2$	Effective Conc. Ratio	673 (-)
Number of Heliostats	$2021(-)$	Particle Temp. Range	$1026 - 1405\ K$
HB mirror radius	$8.90\ m$	Mass flow rate	$21.94\ kg/s$
HB Mirror Surface	$256.3\ m^2$	Mean Residence time	$72\ s$
TOD Mirror surface	$57.21\ m^2$	LCOH	$23.7\ USD/MW_{th}$

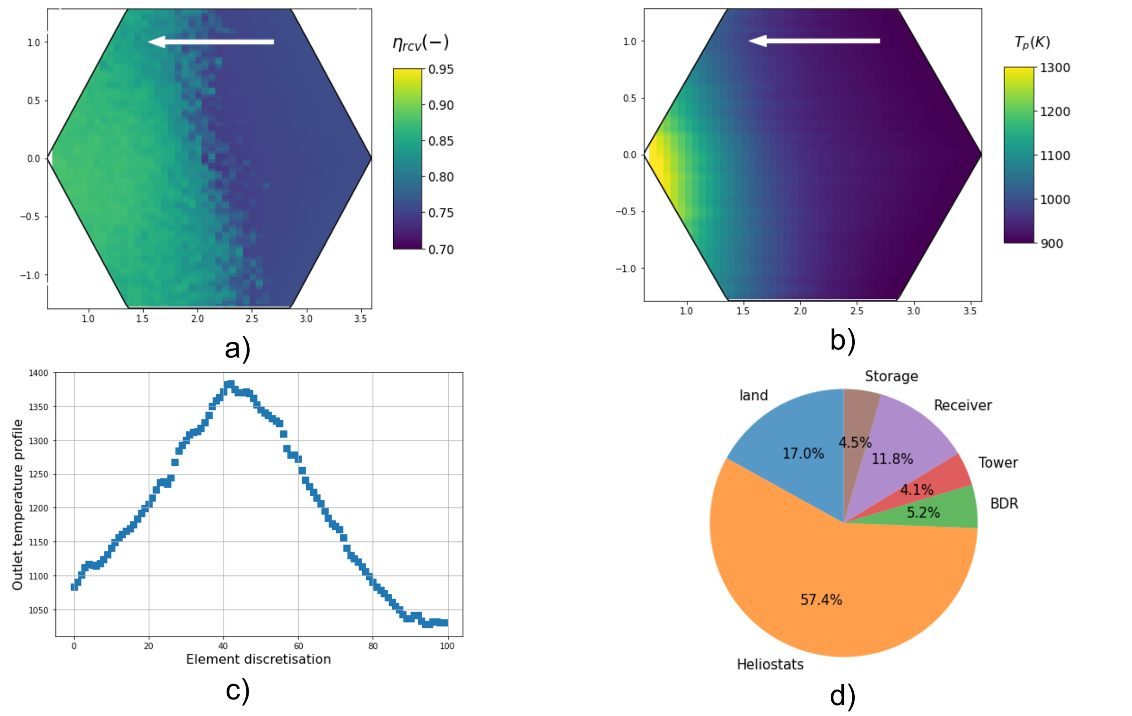


Figure 6. Detailed results for receiver performance and capital cost distribution. a) specific efficiency, b) particles temperature map, c) final particle temperature distribution, d) Capital costs distribution.

4. Conclusions

A novel particle receiver was presented and optimized for use with the Beam-Down optics. A simplified thermal model was developed to be coupled with an already published MCRT model, and a techno-economic optimization is performed. Four main variables were optimized, and preliminary design parameters and constraints are identified. It was found that there is a tower height range of 35-60m where the LCOH is around ~24 USD/MW_{th} for a receiver power between 7-15 $MW_{th.}$ The proposed HPR shows good results in terms of thermal efficiency and is a promising alternative to overcome some of the issues with proposed particle receivers. Additional numerical and experimental research should be done on the dynamics and heat transfer processes of this concept, to include the thermal stratification in the particles layer and detailed estimation of convective/advective losses. A more detailed costing calculations, including the design of conveyor belt, storage containers, and primary heat exchanger, would be beneficial to improve the LCOH estimation. These findings suggest that BDRs coupled with solid particles as heat transfer medium could be a viable alternative for modular CST plants to drive small power generation plants or industrial heat applications.

Author contributions

David Saldivia: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – Original Draft. **Anna Bruce:** Supervision, Writing - review & editing. **Robert A. Taylor:** Conceptualization, Project administration, Supervision, Writing – Review & editing.

Competing interests

The authors declare no competing interests.

Data Availability Statement

The scripts used to generate the datasets and run the simulations can be obtained in https://github.com/DavidSaldivia/BDR_MCRT.

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References

1. A. Segal and M. Epstein, "The optics of the solar tower reflector," Solar Energy, vol. 69, pp. 229–241, Jul. 2001, DOI: https://doi.org/10.1016/S0038-092X(00)00137-7.
2. E. Leonardi, "Detailed analysis of the solar power collected in a beam-down central receiver system," Solar Energy, vol. 86, no. 2, pp. 734–745, Feb. 2012, DOI: https://doi.org/10.1016/j.solener.2011.11.017.
3. D. Saldivia, J. Bilbao, and R. A. Taylor, "Optical analysis and optimization of a beam-down receiver for advanced cycle concentrating solar thermal plants," Applied Thermal Engineering, vol. 197, p. 117405, Oct. 2021, DOI: https://doi.org/10.1016/j.applthermaleng.2021.117405.
4. D. Saldivia et al., "Optical Optimization of Beam Down Receiver Geometry for High Temperature Heat Processes using the MCRT Method" in AIP Conference Proceedings, online, 2021, (*Accepted*).

5. C. K. Ho, "A review of high-temperature particle receivers for concentrating solar power," Applied Thermal Engineering, vol. 109, pp. 958–969, Oct. 2016, DOI: https://doi.org/10.1016/j.applthermaleng.2016.04.103.
6. C. K. Ho et al., "Highlights of the high-temperature falling particle receiver project: 2012 - 2016," Abu Dhabi, United Arab Emirates, 2017, p. 030027. DOI: https://doi.org/10.1063/1.4984370.
7. G. Nellis and S. A. Klein, Heat Transfer, 1. paperback ed. Cambridge: Cambridge Univ. Press, 2012.
8. M. J. Wagner and T. Wendelin, "SolarPILOT: A power tower solar field layout and characterization tool," Solar Energy, vol. 171, pp. 185–196, Sep. 2018, DOI: https://doi.org/10.1016/j.solener.2018.06.063.
9. J. E. Rea et al., "Performance modeling and techno-economic analysis of a modular concentrated solar power tower with latent heat storage," Applied Energy, vol. 217, pp. 143–152, May 2018, DOI: https://doi.org/10.1016/j.apenergy.2018.02.067.
10. A. C. Caputo, P. M. Pelagagge, and P. Salini, "Heat exchanger design based on economic optimization," Applied Thermal Engineering, vol. 28, no. 10, pp. 1151–1159, Jul. 2008, DOI: https://doi.org/10.1016/j.applthermaleng.2007.08.010.