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Techno-Economic Analysis on Optimum Size of a Heliostat for High-Temperature Applications

Ahmed Gamil[1], Alexander Zolan[1,*], Chad Augustine[1], Guangdong Zhu[1], and Kenneth Armijo[2]

[1]National Renewable Energy Laboratory, United States of America

[2]Sandia National Laboratories, United States of America

*Correspondence: Alexander Zolan, alexander.zolan@nrel.gov

Abstract. This study investigates the impact of heliostat size on the levelized cost of heat (LCOH) and explores the trade-off between performance and cost for a baseline 160 MW_{th} concentrating solar thermal (CST) tower system at high temperatures (565°C – 1550°C). The analysis assumes blackbody radiation for thermal losses at the receiver and employs ray tracing to assess optical losses in the heliostat field. A surrogate cost model is used to break down component costs for a specific commercial heliostat design (i.e., SunRing), considering volume production and operations and maintenance (O&M) costs to determine installation costs. The results indicate that heliostat size significantly affects the LCOH at different temperatures, with installation costs being a crucial factor in determining the optimal heliostat size. These installation costs vary by temperature and plant size due to power requirements and volume production considerations. The results motivate ongoing research to further refine the cost model and explore the projects of different sizes.

Keywords: Concentrating Solar Thermal, Solar Tower Systems, Techno-Economic Analysis, Industrial Process Heat

1. Introduction

The heliostat field is a significant cost factor in concentrating solar thermal (CST) plants, comprising up to 30 – 40% of the total installed cost in electricity applications [1]. The reflective area of individual heliostats currently under development and deployed to active CST project range from 1 m^2 to over 150 m^2 [2], with no agreement on the most cost-effective size. Early heliostat studies focused on maximizing size to reduce cost per unit area based on "economies of scale" philosophy [3], including a 2007 analysis by Sandia National Laboratories of heliostats sized between 30 m^2 and 148 m^2 which concluded the optimal range is between 50 m^2 and 150 m^2 [4]. However, more recent studies have shifted to optimizing size for cost effectiveness as the cost of individual heliostat components, such as power electronics and communications devices, have been reduced, which has led to smaller optimal sizes. In 2014, Coventry and Pye noted that as a design rule volume manufacturing favors smaller sizes [5]. Bhargav et al. found 64 m^2 heliostats to be most cost-effective for a specific field size, with potential for further cost reduction with more heliostats around 40 m^2 for large field sizes [6]. Pfahl et al. suggested 16 m^2 for smaller fields and 32 m^2 for larger fields as cost-optimal for an assumed facet size of 8 m^2 [7]. Pidaparthi and Hoffmann favored medium-sized heliostats (43.3 m^2) for their lowest optimum cost [8], while Blackmon advocated for sizes between 25 and 40 m^2 due to lower cost per unit area compared to larger sizes using a capital cost scaling function proportional to the ‘three-halves power law’ [9]. Von Reeken et al. determined that heliostat sizes 40 to 50 m^2 has the lowest energy costs per meter squared among all heliostat variants analyzed which resulted in developing the Stellio heliostat (48.5 m^2) [10].

All the above studies focus on measuring and minimizing installed costs per meter squared. However, this measure does not account for CST tower system costs or performance. Other measures, such as the levelized cost of heat (LCOH) or levelized cost of energy (LCOE), are better suited to accommodate cost and performance trade-offs for CST systems, especially for high-temperature industrial process heat (IPH) applications which require higher concentration ratios to offset the thermal losses at the receiver as compared to current Gen2 technology [11].

This study performs a techno-economic analysis (TEA) to determine the impact of heliostat size on CST power tower system performance and cost. It is motivated by the Heliostat Consortium (HelioCon) framework which aims to lower the solar collection costs and improve the performance of CST tower systems [12]. The analysis considers three different operating temperatures (900°C, 1200°C, and 1550°C) for IPH applications, as they represent a potential market for the CST power tower technology, in addition to one case at 565°C for comparison to the operating temperature of currently deployed tower plants. The TEA mainly focuses on the trade-off between performance and cost in high-temperature IPH applications, in which radiation losses are significant and the resulting high concentration ratios (CR) can cause significant reductions in system optical efficiency [11]. The main contribution of this work is a collection of levelized cost indices that feature the change in LCOH as a function of heliostat size, operating temperature, progress ratio, and plant size due to the changing trade-off between optical and thermal losses at the receiver aperture while accounting for differences in cost functions and optical performance as the heliostat size changes. We use the case study in the results to illustrate the methodology and note priorities for refinement of both the cost and performance models in future work.

2. Methodology

This section describes the approach and assumptions employed in the study. The general framework integrates a performance and cost model to evaluate the LCOH of a paired heliostat design and project. These two models simplify the analysis by focusing on the heliostat field, tower, and receiver dimensions and remaining agnostic to IPH heat off taker requirements. The subsections that follow elaborate on these two integrated models.

2.1 Performance model

The case studies cover multiple operating temperatures (i.e., 565°C for electricity, 900°C for calcination, 1200°C for solar fuels, and 1550°C for clinker production) to assess the impact of heliostat size on system efficiency and economic viability. The methodology accepts as input a design-point receiver power rating for the CST plant like the approach in the work by Zolan et al. [11]; our case studies use 160 MW_{th} instead of 20 MW_{th}. The developed performance model in this study follows the prior work [11], that employs SolarPILOT via the Python API [13] to generate a CST tower plant field layout and performance evaluation [14]. However, we adopt a different heliostat aspect ratio, and we parameterize the heliostat size separately from the receiver. The CR, tower height, and receiver acceptance angle are obtained using the same telescoping grid search performed in [11].

2.1.1 Heliostat field

The plant location is Daggett, California in which a radial stagger field layout is employed, similar to prior work in [11]. The heliostats are assumed to have a single-axis slope equivalent error of 2 mrad and are arranged in order of energy delivery for a four-day profile until the design-point power delivery (i.e., the rated receiver power at noon on the spring equinox) is met. For all heliostats, the height to width aspect ratio is assumed to be 2.62 with 6 facets (in one row), a departure from the square, single-facet heliostat in [11], that aligns with the Sun-Ring heliostat design from SolarDynamics [15], [16].

2.1.2 Receiver

This analysis adopts an idealized, blackbody cavity receiver in which the radiation losses are described by the Stefan-Boltzmann law. The cavity aperture is modeled in SolarPILOT as a square flat plate receiver and its size is specified by the designed concentration ratio at a specific receiver temperature. The blackbody and radiation assumptions follow the work of Li et al. [17], and the ideal windowed cavity receiver is consistent with the work of Steinfeld and Schubnell [18].

2.2 Cost model

Similar to prior work [19], the cost of the CST tower subsystems (i.e., heliostat field, tower, and receiver) are included, while other subsystems, such as the power block and storage systems, are excluded from the total system cost, as this study is focused on the heliostat. However, a unique feature of this methodology is that the heliostat cost model varies with the size of the heliostat instead of a fixed per-meter-squared installed cost.

2.2.1 Tower and receiver costs

The default tower cost function in SolarPILOT is used to estimate the tower cost as a function of tower height, assuming a concrete tower. The cavity receiver cost is assumed to be a fixed multiple of the receiver power rating to be consistent with the assumption in [17] and [19]. SolarPILOT default receiver cost function is not used because at higher CR and temperature the material requirements change significantly, hence the temperature impact on receiver cost is ignored in the analysis.

2.2.2 Heliostat field costs

In contrast to assuming a fixed specific heliostat cost (about 127 $/m^2 [12]), the analysis utilizes the SolarDynamics SunRing heliostat design (27 m^2) for components cost breakdown based on the Design for Manufacturing and Assembly (DFMA) analysis by Kurup et al. [16]. The SunRing is an upgraded version of Abengoa Ring-of-Power (ROP) heliostat [20] and has been documented to an installation of approximately $96/m^2 in [15], [16].

This study adopts Blackmon's model as a surrogate for heliostat cost modeling [3], where the cost of a heliostat is based on 3 categories: (1) constant costs per m^2 (e.g., mirrors, parts of field connections and alignment), (2) size-dependent costs per m^2 based on imposed moments (e.g., support structure, drive, pedestal), and (3) fixed costs per m^2 based on the number of heliostats in the field (e.g., sensors, encoders, switchers) [9]. Other costs, such operations and maintenance (O&M), optical improvement, and production rate (learning curve), were also considered. Blackmon relied on the 'three-halves power law', which is considered conservative because it yields a scaling exponent of 0.5 cost per unit area proportionality; thus, it was modified to 0.65 in their latest publication [3]. The following Blackmon's correlation is used to determine the heliostat N cost per unit area, $C(N)$ with a scaling factor, $s = 0.65$.

$$C(N) = C_1 + C_2\left(\frac{A_N}{A_{ref}}\right)^s + C_3\left(\frac{A_{ref}}{A_N}\right) \tag{1}$$

where A_{ref} is the reference heliostat area (i.e., SunRing of 27 m^2), A_N is heliostat N area (in m^2), C_1, C_2, and C_3 are the cost of Category 1, 2, and 3, respectively.

Blackmon's study did not evaluate the LCOH for a specific CST tower plant, thereby neglecting the overall impact on other subsystems and the trade-off between performance and cost at elevated temperatures. Blackmon argued that to better understand the implications of cost on design choices, a systems-level approach is ultimately required so that it includes optical performance and other costs such as transport, site infrastructure, finance, and O&M.

Table 1 highlights the categorization of component costs based on Blackmon's model, with the inclusion of overhead and O&M costs.

Table 1. *Model categories from Blackmon [3], applied to the SunRing heliostat.*

SunRing components	**DFMA cost ($/m²)**	**Category 1 ($/m²)**	**Category 2 ($/m²)**	**Category 3 ($/m²)**
Mirrors and adhesives	15.88	15.88		-
Mirror support	8.11	-	8.11	-
Linear actuators	16.39	-	16.39	-
Electric cabling and interconnection	6.00	-	3.00	3.00
Controller	6.74	-	3.37	3.37
Rotation assembly	7.08	-	7.08	-
Base assembly	11.12	-	11.12	-
Foundation	6.01		6.01	-
Site infrastructure	0.82	0.41	-	0.41
Fasteners	8.64	-	8.64	-
Transportation and shipping	1.37	1.37	-	-
Site labor	7.79	7.79	-	-
Total installed cost/area	95.95	25.45	63.72	6.78
Overhead / profit (20%)	19.19	5.09	12.74	1.36
Total installed price/area	115.14	30.54	76.46	8.14
O&M (7.15%)	8.23	4.94	1.65	1.65
Total installed price/area with O&M (Life-cycle Cost)	123.37	35.48	78.11	9.78
Fraction category to total cost (%)		26.5	66.4	7.1

Since the costs of transport and site infrastructure are included in the DFMA cost analysis [16], the O&M cost per unit area is assumed to be 7.15% of the total installed cost (including overhead and profit) [3]. O&M cost is allocated as 60%, 20%, and 20% to Category 1, Category 2, and Category 3, respectively [3]. Other financial costs (e.g., contingency, indirect costs, insurance, etc.) are included in the LCOH calculation using SolarPILOT default values.

The heliostats mass production effect, or "progress ratio," utilizes the 40,000-unit price (i.e., 123.37 $/m²) assumed in [16], and is expressed as the cost of N heliostats, $C(N)$, using a progress ratio, pr, with the exponent of the number of doublings, as given in below equation.

$$C(N) = C(1)\, pr^{\log_2(N)} \tag{2}$$

where $C(1)$ is the cost of the first heliostat which is estimated based on the reference cost, i.e., $C(40{,}000) = 123.37\ \$/m^2$, e.g., for a pr of 0.98, the 1st heliostat cost of a 27 m² is $C(1) = C(40{,}000)/(0.98)^{\log_2(40{,}000)} = 168.02\ \$/m^2$.

2.3 Levelized cost of heat (LCOH)

The fixed cost ratio (FCR) method is employed to determine the LCOH, which assumes an analysis period of 30 years and 6% discount rate with construction costs realized at year zero [11]. Then, an LCOH index is created by normalizing the lowest-LCOH baseline case to a value of an index of one and reporting the cases as the multiple of that case's LCOH [19].

3. Preliminary results and discussion

This section presents the results for the baseline case of a 160 MW_{th} design power at four different temperatures: 565°C, 900°C, 1200°C, and 1550°C, with a pr of 0.98. The highlighted results primarily focus on the impact of heliostat size on the LCOH, installation costs, system efficiency (both optical and thermal), total field area, and the total number of heliostats. Additionally, the effects of various plant sizes and progress ratios are evaluated. The section closes with a discussion of future work to enhance the quality of analysis from our methodology.

3.1 Baseline designs

Table 2 summarizes the main design parameters and outputs for each operating temperature in our analysis. The results show that the lowest LCOH is achieved with a heliostat size of 9 m^2 for each case. As temperature increases, the field size increases to offset increased thermal and optical losses, and the progress ratio causes the installation cost to decrease slightly despite the heliostat and project size remaining unchanged. The system efficiencies in this study are lower than those of [19] primarily due to lower heliostat costs, yielding systems with smaller, less expensive towers and, in turn, more heliostats in a less efficient solar field. While the optimal size using the cost model from Blackmon is relatively small as compared to prior analyses, we anticipate that updates to the component cost and performance models are likely to change the optimal size of the heliostats, in addition to other factors, such as the size of the project.

Table 2. *Summary of minimum-cost solar field designs as a function of operating temperature, for a contrived 160 MW_{th} plant.*

	565°C	**900°C**	**1200°C**	**1550°C**
Design CR (suns)	500	900	1400	2100
Receiver aperture (m^2)	338.7	201.8	141.2	108.6
Tower height (m)	150	150	175	210
LCOH index	1.00	1.11	1.30	1.72
Installation cost ($/$m^2$)	106.2	105.6	105.0	103.9
Heliostat size (m^2)	9	9	9	9
Heliostat number	29,606	35,857	43,324	61,113
Field optical efficiency (%)	74.07	65.09	58.00	46.86
Overall system efficiency (%)	70.27	57.83	47.52	33.45

When evaluating other design powers (plant sizes), the minimum LCOH is achieved at heliostat sizes which vary by both temperature and project size. Table 3 presents a parametric analysis conducted for various plant sizes at all examined temperatures to illustrate the impact of the plant size on the LCOH for different heliostat sizes. The LCOH is influenced by the plant size, with higher LCOHs observed at smaller plant sizes. Additionally, smaller heliostat sizes tend to have lower LCOH for each plant size, with near-optimal values typically in the range of 4 m^2 – 11 m^2, owing to relatively low installation costs and reduced optical losses. For instance, the lowest LCOH at 900°C is achieved with heliostat sizes ranging from 7 m^2 to 10 m^2 as plant size increases from 10 MW_{th} to 240 MW_{th}, respectively.

Table 3. *Summary of LCOH index as a function of plant size and operating temperature.*

Plant size (MW_{th})	Heliostat size (m^2)				LCOH index			
	565°C	900°C	1200°C	1550°C	565°C	900°C	1200°C	1550°C
240	11	10	9	8	0.96	1.08	1.28	1.78
160	9	9	9	9	1.00	1.11	1.30	1.72
100	9	9	9	9	1.05	1.17	1.35	1.77
80	11	10	9	7	1.08	1.21	1.39	1.81
20	9	8	7	5	1.48	1.62	1.84	2.33
10	8	7	5	4	1.90	2.07	2.37	3.09

Table 3 shows that optimal heliostat size increases as the project size increases and as the operating temperature decreases, and that the LCOH index increases with higher temperatures and smaller project sizes.

Table 4 highlights the effect of progress ratio (learning rates) on LCOH and installation cost in the range of 80% - 98% from similar studies incorporating these analyses [21], [22]. The results show that the optimal heliostat size decreases with the progress ratio for each operating temperature. This indicates that a lower progress ratio, which accelerates the cost reduction as heliostat production increases, favors smaller heliostat sizes, a result consistent with the work by Coventry and Pye [5].

Table 4. *Summary of LCOH index and installation cost at various progress ratios for 160 MW_{th}.*

		LCOH index			
Progress ratio	**Heliostat size (m^2)**	**565°C**	**900°C**	**1200°C**	**1550°C**
0.98	9	1.00	1.11	1.30	1.72
0.9	7	1.01	1.11	1.29	1.68
0.8	5	1.00	1.09	1.26	1.61
		Installation cost ($/m^2)			
Progress ratio	**Heliostat size (m^2)**	**565°C**	**900°C**	**1200°C**	**1550°C**
0.98	9	106.2	105.6	105.0	103.9
0.9	7	108.8	105.7	102.7	97.5
0.8	5	106.4	100.0	94.2	84.5

3.2 Caveats

The TEA identifies several key areas for improvement in the modeling of heliostat costs and performance which we intend to incorporate in future work. The adopted Blackmon's surrogate heliostat cost model will be updated to account for multiple changes in heliostat technology over the past decade. The fixed scaling factor of 0.65 for Category 2 (i.e., size-dependent) components will be revisited, as it does not account for the potential step changes in costing because of heliostat size, such as changing the azimuth and elevation drive mechanism. O&M will incorporate a more detailed cost function that includes failure rates and repair times in place of a fixed percentage. Finally, we intend to revisit the existing performance model, which may be too optimistic due to the assumption of perfect transfer from the flat-plate aperture to a cavity, and an ideal focal length for each heliostat in the field instead of the 2-3 focal lengths deployed in existing solar fields.

4. Conclusions

The presented techno-economic analysis of heliostat sizes explores the trade-off between performance and cost at different high-temperatures for the baseline case of 160 MW_{th} tower system and other design powers, considering the SunRing heliostat as the reference. The assumptions of blackbody radiation for the receiver and optical slope error of 2 mrad for all examined heliostats simplify the analysis, allowing the focus to be solely on heliostat installation costs by using a surrogate model for heliostat component costs.

The following conclusions are drawn from the preliminary results in this study:

- The LCOH is significantly affected by the heliostat size and progress ratio for a wide variety of IPH operating temperatures for a specific plant size.
- The manufacturing progress ratio cost reduction effect tends to favor smaller heliostats due to higher volume of production as operating temperature and project size increase.

Future work will focus on investigating various focal lengths for different heliostat groups to optimize optical performance in a setting closer to that of currently deployed plants. A sensitivity analysis will examine different O&M cost formulas and alternative surrogate cost models for heliostats. Additionally, the work will perform a comparative analysis for different commercial heliostat designs.

Data availability statement

The data supporting this analysis can be made available upon request.

Author contributions

The author contributions are as follows. Ahmed Gamil: Writing – original draft, methodology, conceptualization, visualization, software, data curation, and software. Alexander Zolan: Writing – review and editing, methodology, investigation, and validation. Chad Augustine: Writing – original draft, conceptualization, and visualization. Ken Armijo: Writing – review and editing, investigation, and methodology. Guangdong Zhu: Methodology, investigation, validation, and funding acquisition.

Competing interests

The authors declare that they have no competing interests.

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