Heliostat Sizing Methodology for Solar Heat for Industrial Processes

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Agenda

1. Motivation
2. Methodology
3. Case Studies
4. Discussion
5. Conclusions
6. Accessing the Work
7. Next Steps

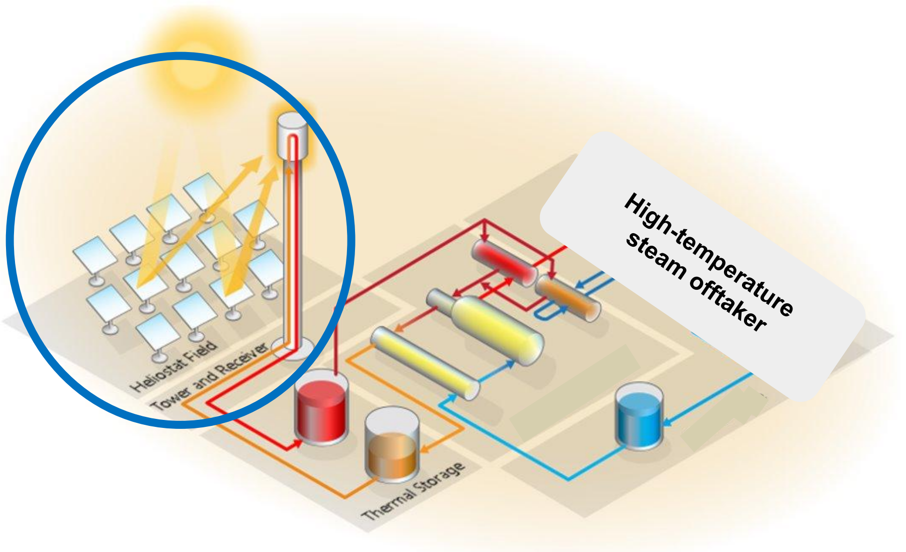
Heliostat Consortium (HelioCon) Objectives

- Form U.S. centers of excellence focused on heliostat technologies to restore U.S. leadership
- Develop strategic core validation and modeling capabilities and infrastructure at DOE’s national labs (NREL and Sandia)
- Promote workforce development by integrating academia, industry, and all stakeholders

Image source: https://heliocon.org/about/about_heliocon.html

Results of HelioCon TEA gap analysis

- Identified TEA gaps:
    - Lack of a validated model for:
        - solar field O&M costs
        - **high-temperature solar heating for industrial processes (SHIP)**
- Path forward:
    - Develop a heliostat field O&M model that accounts for the cost of mirror washing and heliostat repairs and replacements, and their impact on heliostat field performance.
    - **Develop a model that creates and incorporates correlations for tower and receiver costs for SHIP applications**.
    - **Develop an approach to determine the best heliostat size given a collection of design parameters (e.g., project size, operating temperature).**
    - Coordinate work with other HelioCon topics, perform sensitivity analysis in models, and engage industry to improve knowledge gaps.



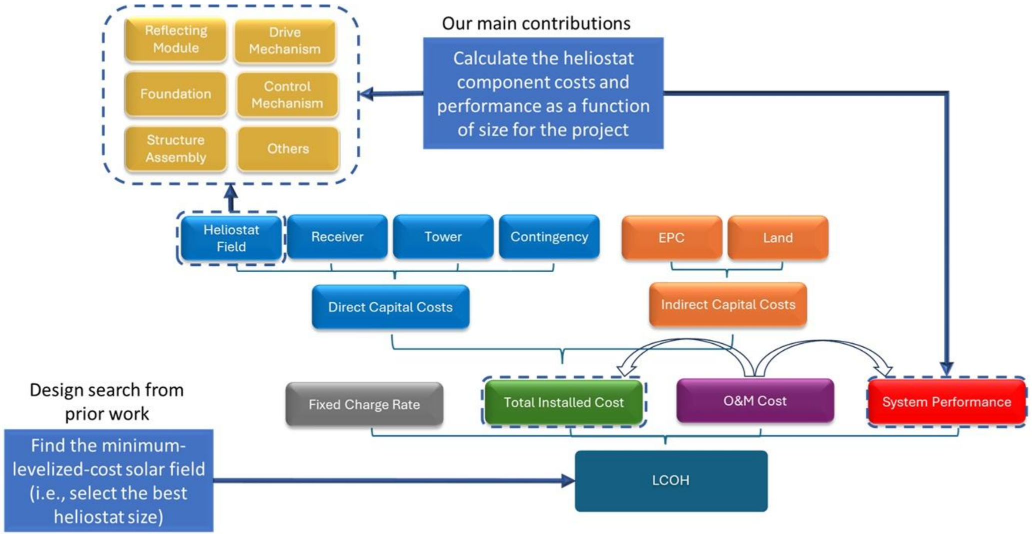
Example schematic of a SHIP system in which red and orange arrows denote hot and cold molten salt flows and blue arrows denote water and steam flows; our analysis is primarily focused on the solar field, tower and receiver encircled above.
Image adapted from Cox et al. (2023)

Key questions we seek to answer

- How does operating temperature impact the tradeoff between optical and thermal losses at the receiver, and how does the heliostat size impact these?
- What is the impact of heliostat size on cost and performance of a solar field for a given project?
- How do we select a heliostat size for a given project that minimizes the levelized cost of heat (LCOH)?

Goal of methodology: Minimizing LCOH for a project's solar collection

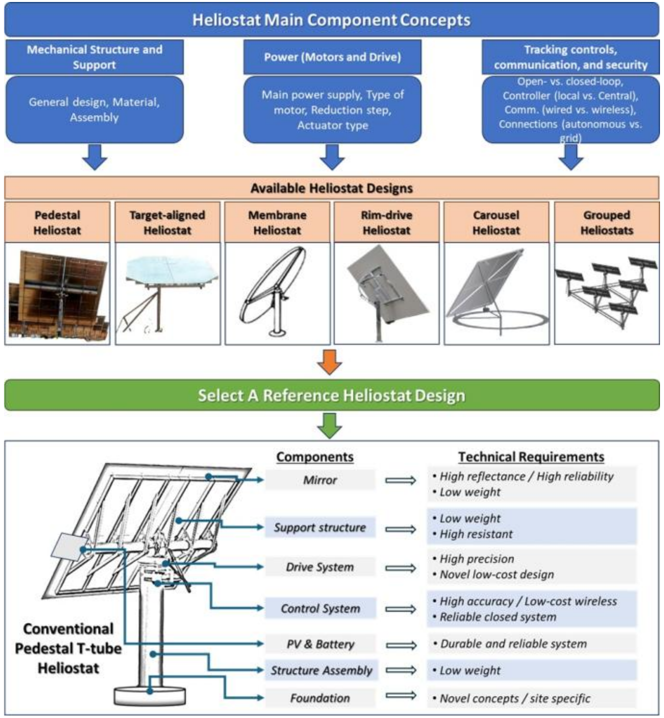
- We subdivide the method into the following submodels:
  - System performance
  - Installed costs
  - O&M
- The design selection assesses the tradeoffs between these three factors as heliostat size changes



Workflow for LCOH calculation

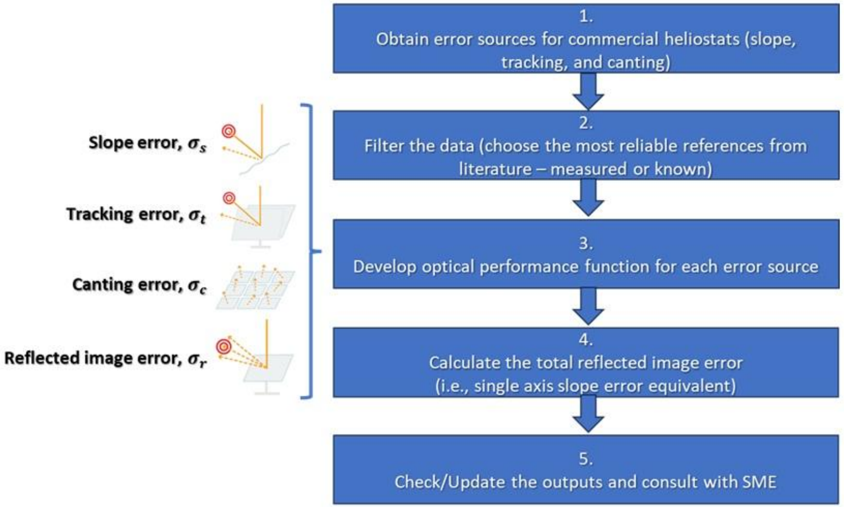
Design requirements

- There are many options for a heliostat design, including several options for each component
- In the case study we present, there are some design measures we include for the sake of simplicity:
  - Pedestal foundation
  - Size-based canting configurations
  - Wireless controls
  - Size-dependent drives



Schematic of available designs, and summary of the downselect process of design requirements for our case study

Optical performance model



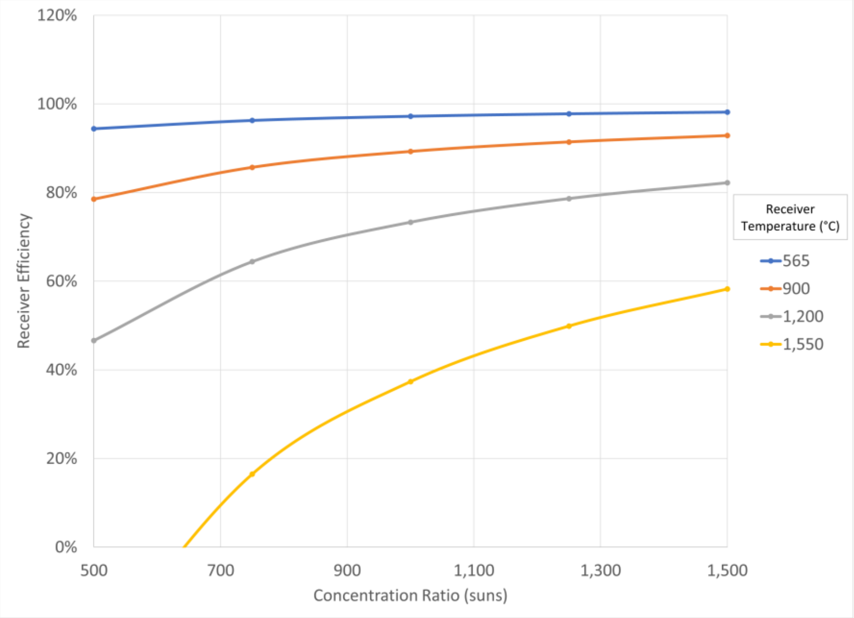
Methodology for determining optical performance

$$\sigma_{SSEE} = \frac{\sqrt{\sum_{j\in J} 8 \cdot \sigma_j^2 + 2 \cdot \sigma_r^2}}{2\sqrt{2}}, \forall j \in J$$

Equation: aggregation of error sources into a single-axis equivalent slope error

Thermal performance model

- A square, flat-plate receiver in SolarPILOT represents the aperture of a cavity receiver
- We assume uniform, blackbody loss at the aperture
  - Consistent with assumptions by Steinfeld and Schubnell (1993) and, more recently, Li et al. (2021)
- Radiation losses increase significantly with temperature
  - Stefan-Boltzmann's law: radiation directly proportional to the 4th power of temperature (losses ~ T^4)

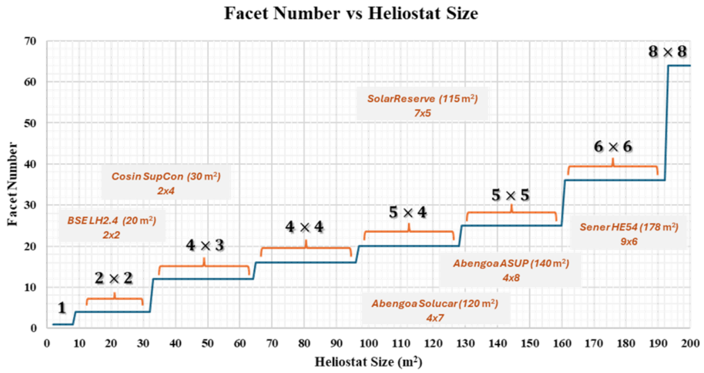


Summary of a blackbody receiver's thermal efficiency as operating temperature and concentration ratio vary

Cost function assumptions and canting configurations

Component	Assumptions
Mirror	· Mirror cost is a fixed cost rate (per m^2). · Heliostat sizes $\leq$ 8 m^2 have one facet. · Heliostat sizes above 8 m^2 are multi-faceted in a size-dependent array.
Support Structure	· Cost rate is size-dependent and depends on the amount of steel required.
Drive	· Azimuth/Elevation tracking mechanism. · Size-dependent cost function sourced from supplier quotes · Drive configurations change with size ranges
Controls	· Power electronics defined as a per-heliostat cost · Fully wireless communication
Power Supply	· Size-dependent cost function for mounted PV and battery
Foundation	· Size-dependent cost function
Others	· Onsite fabrication and assembly platform is a size-dependent, project-specific cost · Site infrastructure, site labor, and transport & shipping employ cost functions that are part fixed (per m^2) and part per heliostat.

Cost function assumptions for individual heliostat components



Canting configurations as a function of heliostat size

Heliostat cost function (adapted from Blackmon 2013)

$$\boxed{C_i} = \boxed{C_i^f} + \boxed{C_i^h \left(\frac{A}{A^0}\right)^{S_i}} + \boxed{C_i^m \left(\frac{N}{N^0}\right)}, \forall i \in I$$

The installed cost rate of component *i* [$/m²] is a function of:

- a fixed cost rate,
- a size-dependent rate (in which the size relative to a baseline is raised to an exponent), and
- a per-heliostat cost

For some components, such as drives, these are piecewise functions that have separate coefficients for difference size ranges

Tower costs are from System Advisor Model; receiver costs are fixed per kW

Selecting cost function coefficients

Bottom-up cost analyses can serve as input to the cost models

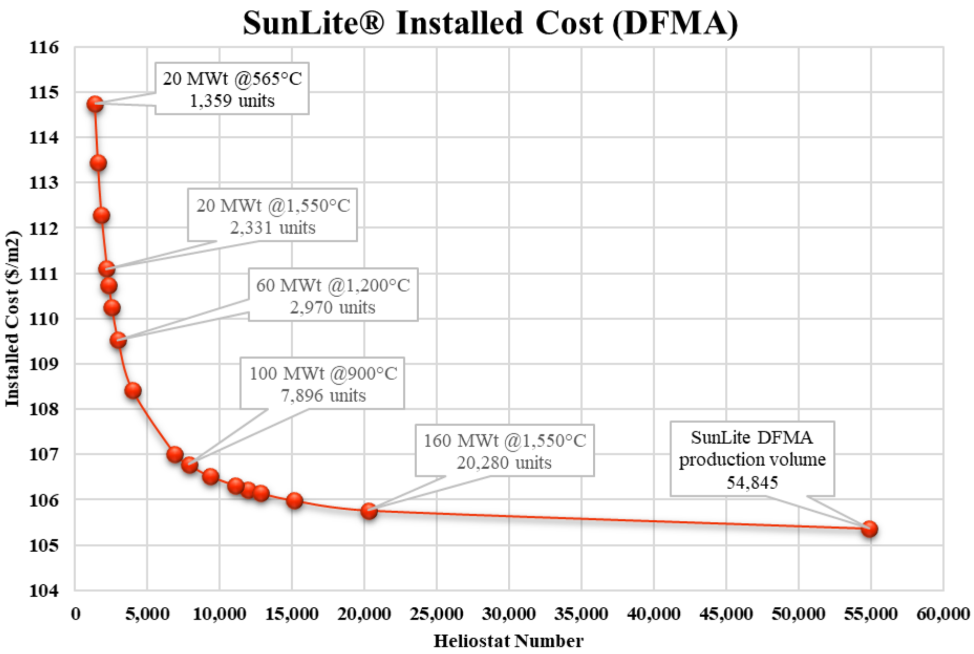
- In the example study, we utilize a bottom-up costing the SunLite design by SolarDynamics as the reference
- Cost exponent assumptions for components sourced from expert elicitation
- Some components, such as drives, include mode changes and so have piecewise functions
    - This case study includes quotes from drive suppliers for each mode

Size range (m^2)	Elevation	Azimuth	Reference heliostat
$A \leq 15$	Linear	Linear	Vast solar (6.4 m^2)
$15 < A < 30$	Linear	Slew	LH-2.3 (19 m^2)
$A \geq 30$	Linear	Slew	Cosin Solar (30 m^2)

Summary of drive mechanisms as a function of heliostat size

Cost adjustment for economies of scale

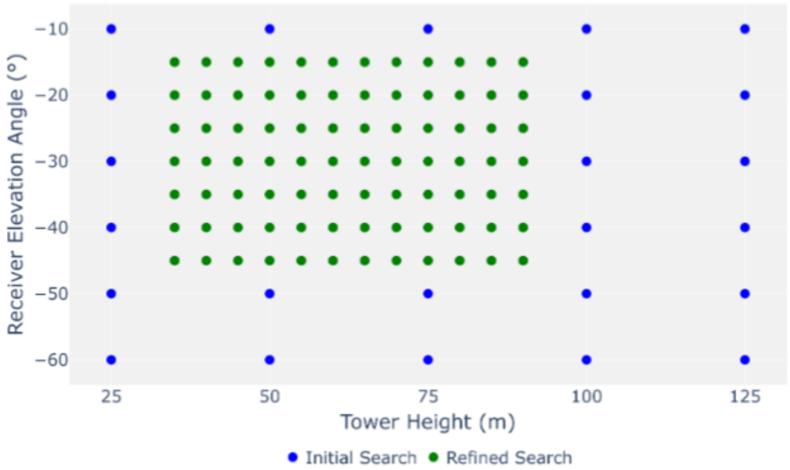
- We assume that the project size leads to cost reductions due to economies of scale
- Note: a stable supply chain of projects can mitigate this effect land revise cost estimates



Design selection method: Telescoping grid search

- We perform a telescoping grid search for the best-found design, in which we vary:
  - Design-point concentration ratio (CR) (translates into receiver surface area)
  - Tower height
  - Receiver elevation angle

  And calculate the min-LCOH project delivering the specified energy to the receiver for each candidate system size.
- Prior work (Zolan et al., 2025) showed empirical results suggesting the LCOH function is convex in these three parameters



Example of the nested grid search to obtain near-optimal tower receiver designs for our methodology

LCOH multiple calculation

- We use a fixed cost ratio (FCR) to balance capital and annually recurring costs of the solar field, tower and receiver, then use the performance model to estimate annual energy production to calculate LCOH:

$$\text{LCOH } (\text{¢}/\text{kWh}_{\text{th}}) = \frac{100(\text{Annual Cost } (\$) + \text{FCR} \cdot \text{Capital Cost } (\$))}{\text{Annual Energy Production } (\text{kWh}_{\text{th}})}$$

- We divide the LCOH for a project by that of a commercial-scale, electricity-producing plant to obtain an LCOH multiple for this analysis

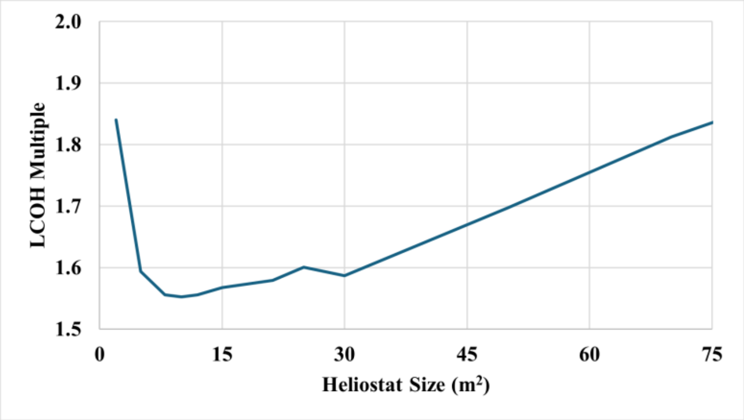
- This is calculated for every solution in the telescoping grid search, for every heliostat size, to obtain an estimate of LCOH and best-found design as a function of size

Baseline case study

- We consider an aluminum treatment process that requires 50 GWth of 565 C heat input to the receiver per year:
  - Offtake temperature of 500 C, 7.5 MWth input
  - Shift process (16 hours per day)
  - 75% solar fraction
  - 12.5% system-level loss, 65C temperature drop

Baseline case study results

- Key insights:
  - 8-15 m^2 is a near-optimal range for the heliostats under the given cost assumptions
  - A wide range of sizes are within 10% of the best-found LCOH, indicating flexibility in the size if other design advantages are found
  - The cost curve is neither monotonic nor convex, due to the nature of the cost function and discontinuities for some components



Summary results for baseline case of 50 GWh-th energy delivered to the receiver at 565 C

Sensitivity analysis suggests a small best-found heliostat size is robust to change in project size and temperature

Results of heliostat sizing study sensitivity analysis, including solar collection design variables as temperature and energy requirements change

Energy target (GWh_{th})	Temp (°C)	Design CR (suns)	Tower height (m)	Heliostat size (m^2)	LCOH multiple ($¢/kWh_{th}$)
50	565	550	45	10	1.55
	900	1000	50	8	1.65
	1200	1700	60	8	1.78
	1550	2600	75	8	2.02
250	565	500	110	12	1.07
	900	900	120	10	1.14
	1200	1400	140	10	1.28
	1550	2100	190	8	1.63
400	565	500	150	10	1.00
	900	900	150	10	1.07
	1200	1400	175	10	1.21
	1550	2100	210	8	1.51

Changing the reference heliostat for component costs yields similar results, except for the Stellio heliostat

Summary of best found heliostat size and LCOH multiple as reference design changes

Reference heliostat	Best found heliostat size (m^2)	LCOH multiple ($¢/kWh_{th}$)
SunLite	10	1.57
SunRing	10	1.53
Stellio	30	1.58

- However, all best-found heliostat sizes under this methodology are significantly lower than that of the design

Discussion

- The methodology requires some refining upfront; our selected prerequisites simplify the case study but are not intended to be recommendations
- The receiver is the most early-stage cost and performance model, due to a lack of experience serving high temperature processes at scale with SHIP
- The results exhibit the potential for smaller heliostats to reduce project costs, which is consistent with recent research and prototype development (Pfahl et al. 2025)

Conclusions

- We present a methodology that can select a heliostat size, as well as tower and receiver characteristics for a given project (i.e., operating temperature and energy requirements) that minimizes LCOH
- The model is intended to be sufficiently general to cover a wide collection of component-specific options
- Results of a case study using a state-of-the-art design as a reference point exhibit the potential for smaller heliostats to reduce project costs
- Opportunities for future work include:
  - Incorporating uncertainty in performance modeling
  - Increasing fidelity of the performance model to include multiple focal lengths
  - Generalizing the scripts from this study for public consumption (GitHub release to follow)

Thank you!

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References

[1] IRENA, Renewable generation costs in 2024, Tech. rep., International Renewable Energy Agency, Abu Dhabi (2024).
URL https://www.irena.org/-/media/Files/IRENA/Agency/Publica

[2] A. Pfahl, J. Coventry, M. Röger, F. Wolfertstetter, J. F. Vásquez-Arango, F. Gross, M. Arjomandi, P. Schwarzbözl, M. Geiger, P. Liedke, Progress in heliostat development, Solar Energy 152 (2017) 3–37. doi:10.1016/j.solener.2017.03.029.

[3] J. B. Blackmon, Chapter 16 - heliostat size optimization for central receiver solar power plants, in: K. Lovegrove, W. Stein (Eds.), Concentrating Solar Power Technology (Second Edition), second edition Edition, Woodhead Publishing Series in Energy, Woodhead Publishing, 2021, pp. 585–631. doi:10.1016/B978-0-12-819970-1.00016-5.

[4] T. R. Mancini, J. A. Gary, G. J. Kolb, C. K. Ho, Power tower technology roadmap and cost reduction plan., Tech. rep., Sandia National Laboratories (04 2011). doi:10.2172/1011644.

[5] J. Coventry, J. Pye, Heliostat cost reduction – where to now?, Energy Procedia 49 (2014) 60–70. doi:10.1016/j.egypro.2014.03.007.

[6] J. Coventry, M. Arjomandi, J. Barry, M. Blanco, G. Burgess, J. Campbell, P. Connor, M. Emes, P. Fairman, D. Farrant, F. Ghanadi, V. Grigoriev, C. Hall, P. Koltun, D. Lewis, S. Martin, G. Nathan, J. Pye, A. Qiu, W. Stuart, Y. Tang, F. Venn, J. Yu, Development of the ASTRI heliostat, AIP Conference Proceedings 1734 (2016). doi:10.1063/1.4949029.

[7] K. R. Bhargav, F. Gross, P. Schramek, Life cycle cost optimized heliostat size for power towers, in: Energy Procedia, Vol. 49, Elsevier, 2014, pp. 40–49. doi:10.1016/j.egypro.2014.03.005.

[8] A. Pfahl, M. Randt, F. Meier, M. Zaschke, C. P. Geurts, M. Buselmeier, A holistic approach for low cost heliostat fields, Energy Procedia 69 (2015) 178–187. doi:10.1016/j.egypro.2015.03.021.

[9] V. C. Thalange, V. H. Dalvi, S. M. Mahajani, S. V. Panse, J. B. Joshi, R. N. Patil, Design, optimization and optical performance study of tripod heliostat for solar power tower plant, Energy 135 (2017) 610–624. doi:10.1016/j.energy.2017.06.116.

[10] A. Pidaparthi, J. Hoffmann, Effect of heliostat size on the levelized cost of electricity for power towers, in: AIP Conference Proceedings, Vol. 1850, American Institute of Physics Inc., 2017, p. 030038. doi:10.1063/1.4984381.

[11] J. B. Blackmon, Parametric determination of heliostat minimum cost per unit area, Solar Energy 97 (2013) 342–349. doi:10.1016/j.solener.2013.08.032.

[12] F. Von Reeken, G. Weinrebe, T. Keck, M. Balz, Heliostat cost optimization study, in: AIP Conference Proceedings, Vol. 1734, American Institute of Physics Inc., 2016, p. 160018. doi:10.1063/1.4949259.

[13] C. Sansom, P. King, K. Carlisle, Design of a novel heliostat for a large-scale desalination system, SolarPACES Conference Proceedings 1 (2024) 1–8. doi:10.52825/solarpaces.v1i.691.

[14] J. P. González-López, R. A. Pérez-Enciso, C. A. Pérez-Rábago, C. A. Estrada, Development of concentrating heliostats for high temperature solar chemical Applications, SolarPACES Conference Proceedings 1 (2024) 1–8. doi:10.52825/solarpaces.v1i.644.

[15] A. Belaid, A. Filali, S. Hassani, T. Arrif, M. Guermoui, A. Gama, M. Bouakba, Heliostat field optimization and comparisons between biomimetic spiral and radial-staggered layouts for different heliostat shapes, Solar Energy 238 (2022) 162–177. doi:10.1016/j.solener.2022.04.035.

[16] P. Forman, S. Penkert, A. Pfahl, J. Schnell, P. Mark, Development of a modular concrete heliostat prototype, in: AIP Conference Proceedings, Vol. 2445, American Institute of Physics Inc., 2022. doi:10.1063/5.0086016.

[17] S. Zhang, A. M. Qwbaiban, J. Huh, T. G. Habetler, Dimension and mechanical structure design of low-cost heliostats in concentrated solar power plants, 2019 IEEE Energy Conversion Congress and Exposition (2019) 3441–3447. doi:10.1109/ECCE.2019.8912981.

[18] A. Pfahl, F. Gross, P. Liedke, J. Hertel, J. Rheinländer, S. Mehta, J. F. Vásquez-Arango, S. Giuliano, R. Buck, Reduced to minimum cost: Lay-down heliostat with monolithic mirror-panel and closed loop control, in: AIP Conference Proceedings, Vol. 2033, American Institute of Physics Inc., 2018. doi:10.1063/1.5067066.

[19] A. Zolan, E. Westphal, C. Augustine, K. Armijo, Y. Wang, J. Pye, Impact of process temperature on the cost of concentrating solar thermal industrial process heat, Solar Energy 293 (2025) 113427. doi:10.1016/j.solener.2025.113427.

[20] D. Tilley, Baseload nitrate salt central receiver power plant design abengoa solar llc, Tech. Rep. 5, Abengoa Solar LLC (2014). doi:10.2172/1165353.

[21] P. Kurup, S. Akar, S. Glynn, C. Augustine, P. Davenport, Cost update: Commercial and advanced heliostat collectors, Tech. Rep. February, NREL (2022). doi:10.2172/1847876.

[22] A. Buchroithner, G. B. Ganapathi, A. Palisoc, Estimating costs of heliostat production at high volumes based on a small-scale prototype, in: 2016 IEEE Green Energy and Systems Conference, IGSEC 2016, Vol. 2, 2016. doi:10.1109/IGESC.2016.7790061.

References

[23] J. N. Larmuth, Heliostat cost reduction methods applied to a small heliostat, Ph.D. thesis, Stellenbosch University (2015).
URL http://www.crses.sun.ac.za/files/research/completed-research/eppei/JLarmuth.pdf

[24] K. Kattke, Drop C: The drop-in, ring-of-power heliostat (final report), Tech. rep., Solar Dynamics LLC (2023). doi:10.2172/1973845.

[25] F. Téllez, M. Burisch, C. Villasente, State of the art in heliostats and definition of specifications survey for a low cost heliostat development, Tech. rep., STE-EERA (2014).
URL http://stage-ste.eu/deliverables/STAGE_STE_Deliverable_12_1.pdf

[26] A. Pfahl, J. Rheinländer, A. Krause, R. Buck, S. Giuliano, J. Hertel, K. Blume, T. Schlichting, N. Janotte, A. Ries, First lay-down heliostat with monolithic mirror-panel, closed loop control, and cleaning system, in: AIP Conference Proceedings, Vol. 2126, American Institute of Physics Inc., 2019. doi:10.1063/1.5117554.

[27] A. Pfahl, H. Bouzekri, A. Djdiaa, D. Benitez, V. Nettelroth, J. Rheinländer, A. Krause, Heliostat innovation in detail to reach challenging cost target, in: AIP Conference Proceedings, Vol. 2445, American Institute of Physics Inc., 2022. doi:10.1063/5.0086922.

[28] A. Pfahl, A. Rong, Low-cost movable heliostat, in: AIP Conference Proceedings, Vol. 2445, American Institute of Physics Inc., 2022. doi:10.1063/5.0086923.

[29] G. Augsburger, Thermo-economic optimisation of large solar tower power plants, Ph.D. thesis, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE (2013). doi:10.5075/epfl-thesis-5648.

[30] G. J. Kolb, S. A. Jones, M. W. Donnelly, D. Gorman, R. Thomas, R. Davenport, R. Lumia, Heliostat Cost Reduction Study, Tech. Rep. June, Sandia National Laboratory (2007). doi:10.1115/ES2007-36217.

[31] K. M. Armijo, M. Muller, D. Tsvankin, D. Madden, Review and gap analysis of heliostat components and controls, Journal of Solar Energy Engineering 146 (6) (2024) 061010. doi:10.1115/1.4065976.

[32] C. Augustine, A. Zolan, K. Armijo, Analysis of gaps in techno-economic analysis to advance heliostat technologies for concentrating solar-thermal power, Journal of Solar Energy Engineering 146 (6) (2024) 061002. doi:10.1115/1.4065431.

[33] G. Zhu, C. Augustine, R. Mitchell, M. Muller, P. Kurup, A. Zolan, S. Yellapantula, R. Brost, K. Armijo, J. Sment, R. Schaller, M. Gordon, M. Collins, J. Coventry, J. Pye, M. Cholette, G. Picotti, M. Arjomandi, M. Emes, D. Potter, M. Rae, HelioCon: A roadmap for advanced heliostat technologies for concentrating solar power, Solar Energy 264 (11 2023). doi:10.1016/j.solener.2023.111917.

[34] S. Mishra, J. Pohl, N. Laws, D. Cutler, T. Kwasnik, W. Becker, A. Zolan, K. Anderson, D. Olis, E. Elgqvist, Computational framework for behind-the-meter DER techno-economic modeling and optimization: REopt Lite, Energy Systems 13 (2) (2022) 509–537. doi:10.1007/s12667-021-00446-8.

[35] J. Christian, A. Moya, C. Ho, C. Andraka, J. Yuan, Probabilistic analysis to quantify optical performance and error budgets for next generation heliostats, Journal of Solar Energy Engineering, Transactions of the ASME 137 (3) (2015) 1–8. doi:10.1115/1.4029376.

[36] A. N. Yerudkar, D. Kumar, S. V. Dalvi, Vishwanath H. a nd Panse, V. R. Gaval, J. B. Joshi, Economically feasible solutions in concentrating solar power technology specifically for heliostats – A review, Renewable and Sustainable Energy Reviews 189 (PA) (2024) 113825. doi:10.1016/j.rser.2023.113825.

[37] HelioCon, Heliostat Database - HelioCon (2025).
URL https://heliocon.org/resources/plant_information_overview.html

[38] L. Li, B. Wang, J. Pye, W. Lipiński, Temperature-based optical design, optimization and economics of solar polar-field central receiver systems with an optional compound parabolic concentrator, Solar Energy 206 (May) (2020) 1018–1032. doi:10.1016/j.solener.2020.05.088.

[39] A. Steinfeld, M. Schubnell, Optimum aperture size and operating temperature of a solar cavity-receiver, Solar Energy 50 (1) (1993) 19–25. doi:10.1016/0038-092X(93)90004-8.

[40] C. K. Ho, Advances in central receivers for concentrating solar applications, Solar Energy 152 (2017) 38–56, progress in Solar Energy Special Issue: Concentrating Solar Power (CSP). doi:10.1016/j.solener.2017.03.048.

[41] J. A. Peterka, R. G. Derickson, Wind load design methods for ground-based heliostats and parabolic dish collectors, Tech. rep., Sandia National Laboratories, Albuquerque, NM (United States) (09 1992). doi:10.2172/7105290.

[42] M. J. Emes, A. Jafari, J. Coventry, M. Arjomandi, The influence of atmospheric boundary layer turbulence on the design wind loads and cost of heliostats, Solar Energy 207 (July) (2020) 796–812. doi:10.1016/j.solener.2020.07.022.

[43] S. Akar, Cost Update: Pedestal Design SunLite Heliostat Collectors, Tech. rep., National Laboratory of the Rockies (2025).

[44] R. K. Meyer, C. J. Nachtsheim, The coordinate-exchange algorithm for constructing exact optimal experimental designs, Technometrics 37 (1) (1995) 60–69. doi:10.1080/00401706.1995.10485889.

[45] W. T. Hamilton, M. J. Wagner, A. J. Zolan, Demonstrating SolarPILOT's python API through heliostat optimal aimpoint strategy use case, in: Proceedings of the ASME 2021 15th International Conference on Energy Sustainability, ES 2021, no. April, 2021. doi:10.1115/ES2021-60502.

[46] A. Pfahl, Approach to determine wind loads on small heliostats, Solar Energy 295 (2025) 113551. doi:10.1016/j.solener.2025.113551.

[47] N. Kleemeyer, A. Pfahl, Heliostat size optimization regarding component cost and yield. Under Review (2025).
URL https://elib.dlr.de/217797/

[48] A. Gamil, A. Zolan, C. Augustine, G. Zhu, K. Armijo, Techno-economic analysis on optimum size of a heliostat for high-temperature applications, SolarPACES Conference Proceedings 3 (Oct. 2025).