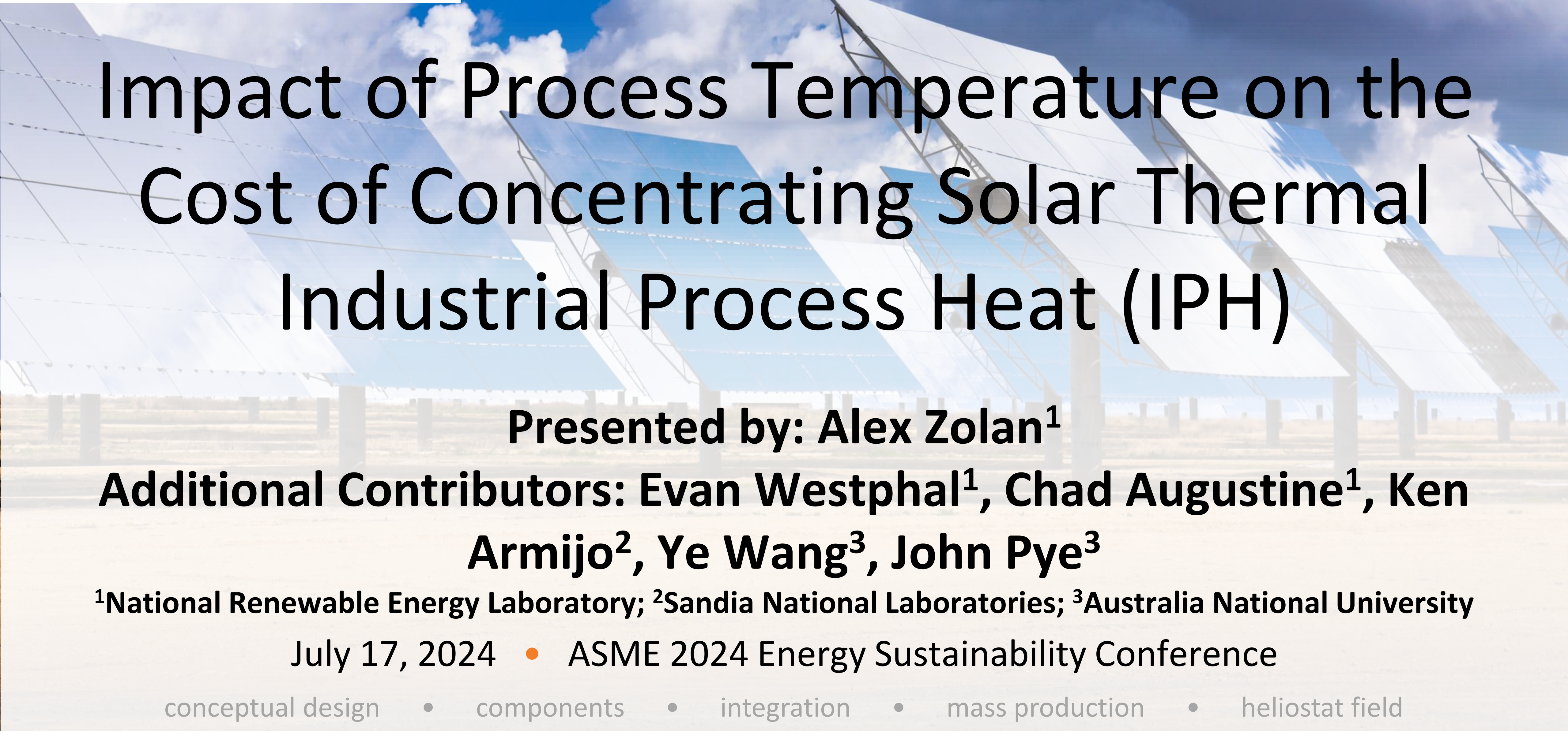
U.S. Department of Energy
HelioCon
Heliostat Consortium for
Concentrating Solar-Thermal Power



Impact of Process Temperature on the Cost of Concentrating Solar Thermal Industrial Process Heat (IPH)

Presented by: Alex Zolan[1]
Additional Contributors: Evan Westphal[1], Chad Augustine[1], Ken Armijo[2], Ye Wang[3], John Pye[3]
[1]National Renewable Energy Laboratory; [2]Sandia National Laboratories; [3]Australia National University

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conceptual design • components • integration • mass production • heliostat field

Agenda

1 **Motivation**

2 **Methodology**

3 **Results**

4 **Ongoing and Future Work**

Heliostat Consortium (HelioCon) Objectives

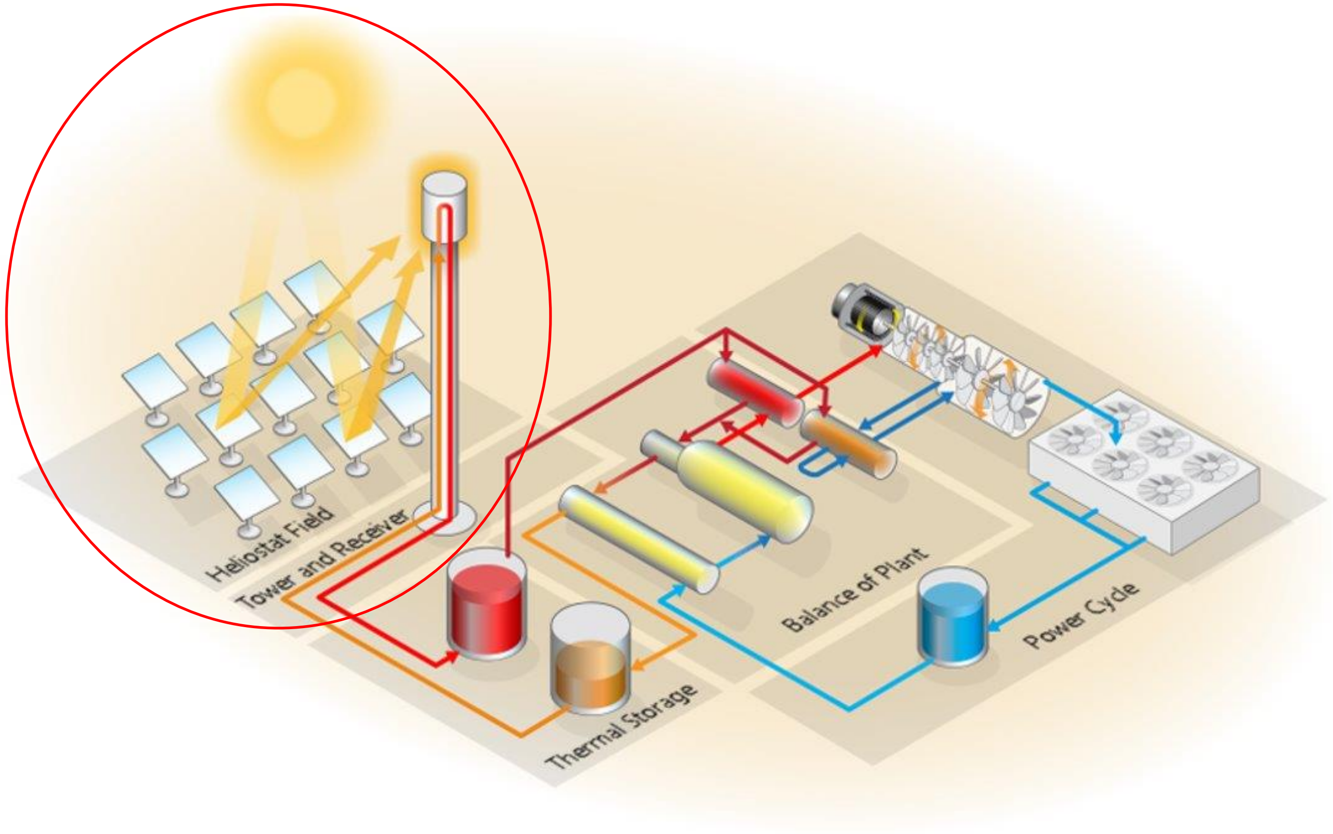
- Form U.S. centers of excellence focused on heliostat technologies to restore U.S. leadership
- Develop strategic core validation and modeling capabilities and infrastructure at DOE’s national labs (NREL and Sandia)
- Promote workforce development by integrating academia, industry, and all stakeholders

This talk focuses on work supporting the Technoeonomic Analysis (TEA) task within HelioCon


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

We attempt to address a TEA gap in the HelioCon Roadmap Study

- Identified TEA gaps:
  - Lack of a validated model for:
    - solar field O&M costs
    - **high-temperature IPH applications**
- 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 CSP model that creates and incorporates correlations for tower and receiver costs for IPH applications.**
  - Coordinate work with other HelioCon topics, perform sensitivity analysis in models, and engage industry to improve knowledge gaps.

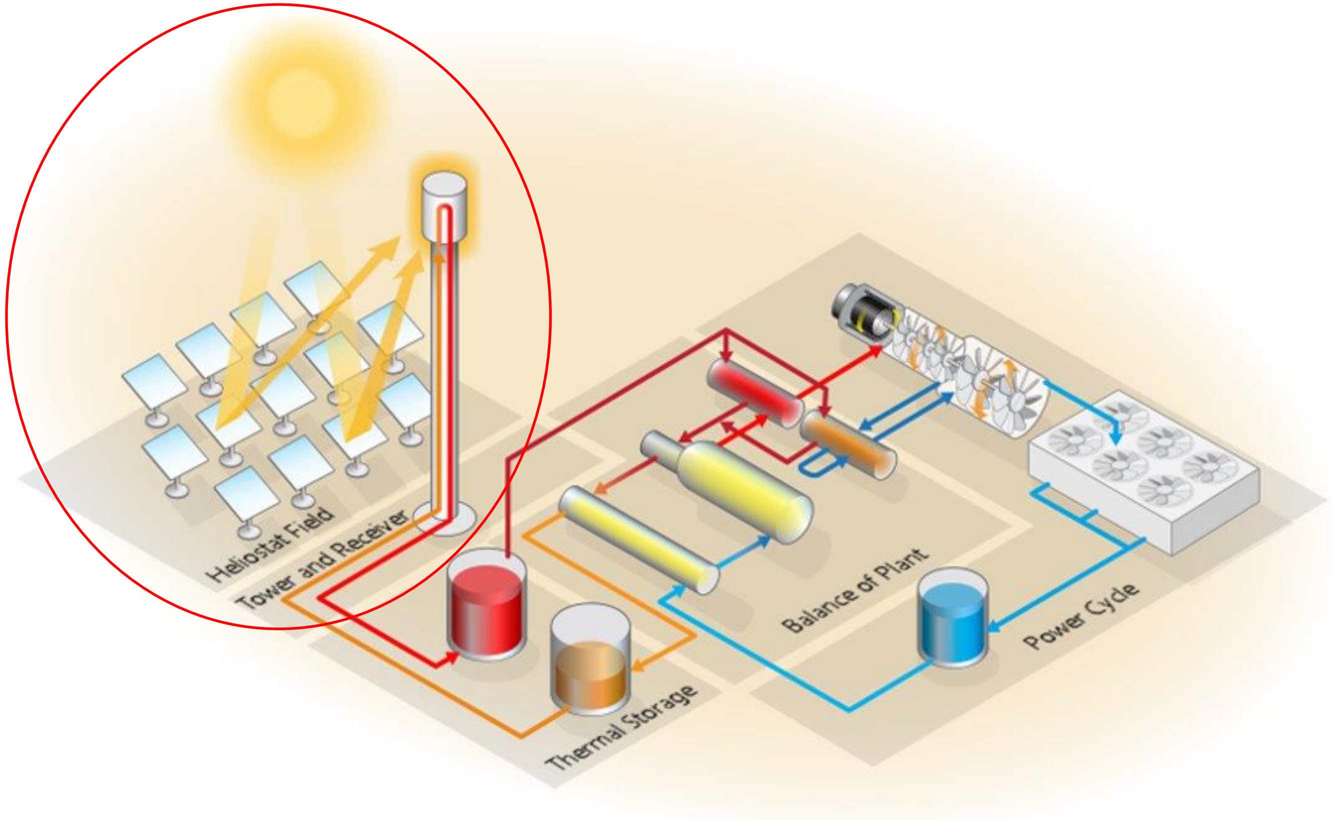


Schematic of a CSP plant; our analysis is restricted to the solar field, tower and receiver encircled above.

Image source: Cox et al. (2023)

Methodology

1. Choose SIPH process temperatures for analysis
    - 900, 1,200 and 1,550°C
2. Develop base case field layout for each process temperature
    - SolarPILOT is our modeling tool (Wagner et al. 2018)
    - Collaborating with Australia National University, using SolarTherm
3. Add cost estimates
4. Optimize concentration ratio (CR) and solar field
5. Parametric studies

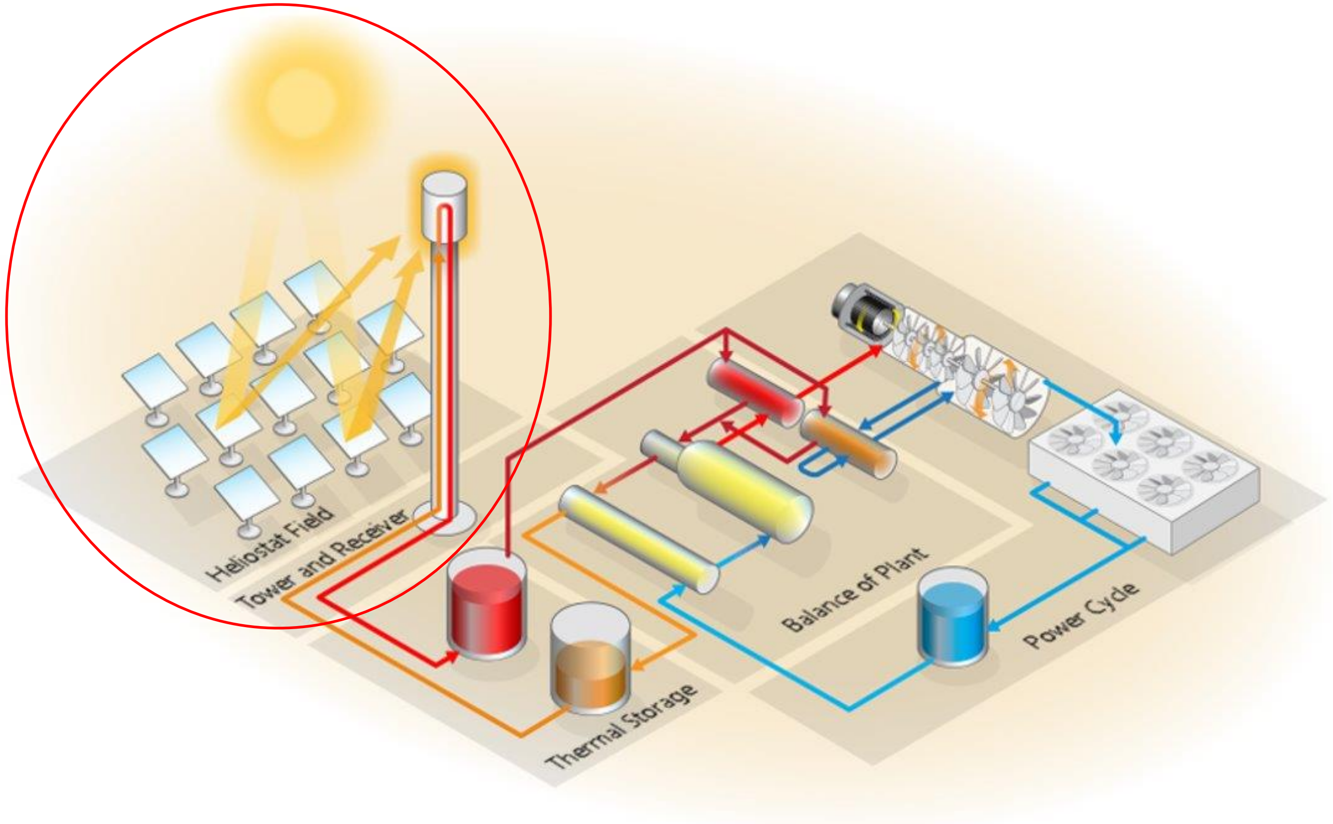


Schematic of a CSP plant; our analysis is restricted to the solar field, tower and receiver encircled above.

Image source: Cox et al. (2023)

Assumptions

- Limit analysis to field, receiver, and tower
- Assume polar field and cavity receiver are needed
- Assume blackbody radiation for heat loss from cavity receiver
- Fixed heliostat-receiver height ratio across runs (~0.7)
  - Attempt to keep spillage consistent across search
- Cost of heliostats, tower consistent with baseline HelioCon studies
- Fixed per-kW rating cost for receiver
- Our measure of heat delivery for our levelized cost of heat (LCOH) is delivery to the receiver, net of radiation loss
  - Our baseline case to calculate relative LCOH is a ~600MW$_{th}$ surround field

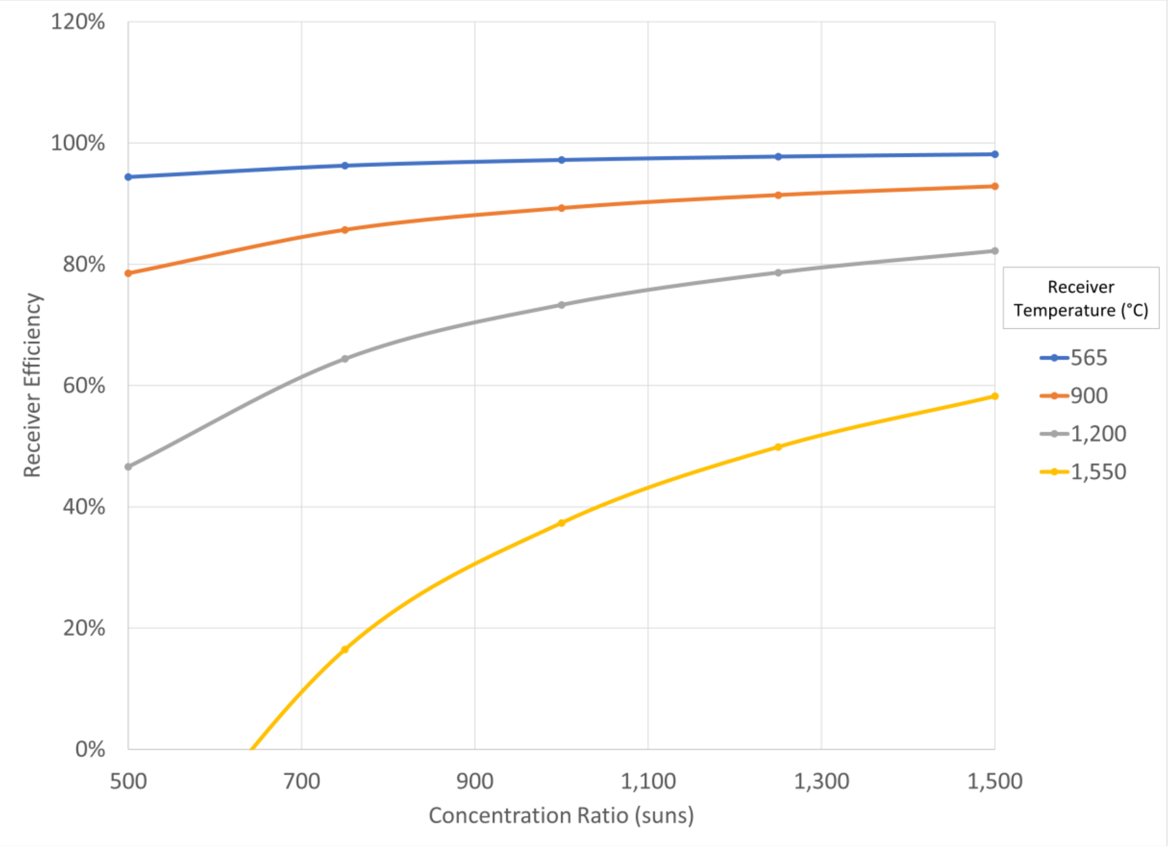


Schematic of a CSP plant; our analysis is restricted to the solar field, tower and receiver encircled above.

Image source: Cox et al. (2023)

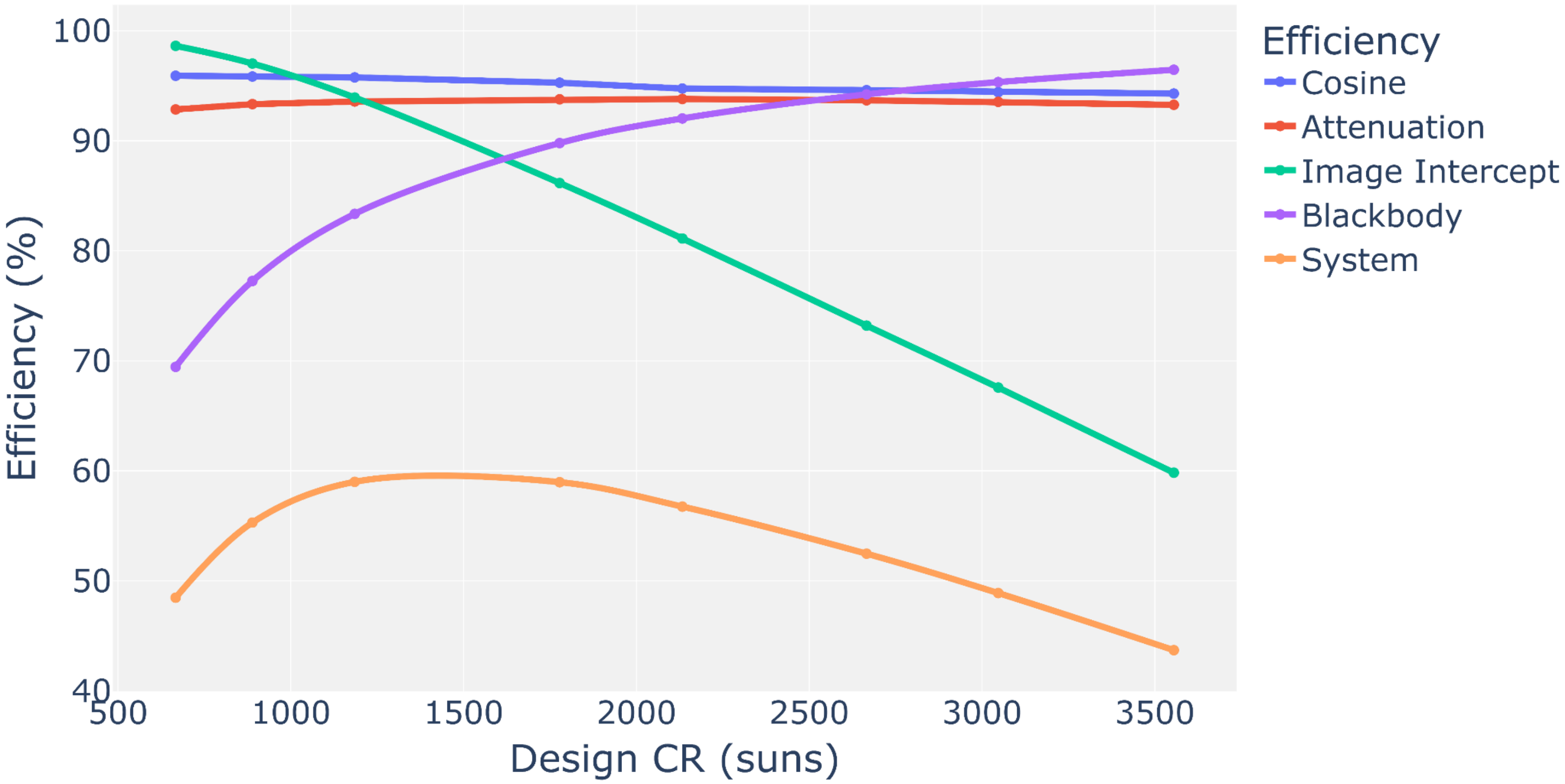
We assume blackbody radiation losses at the receiver aperture

- 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

Results: Key tradeoff when selecting a CR is between spillage and thermal (radiation) losses

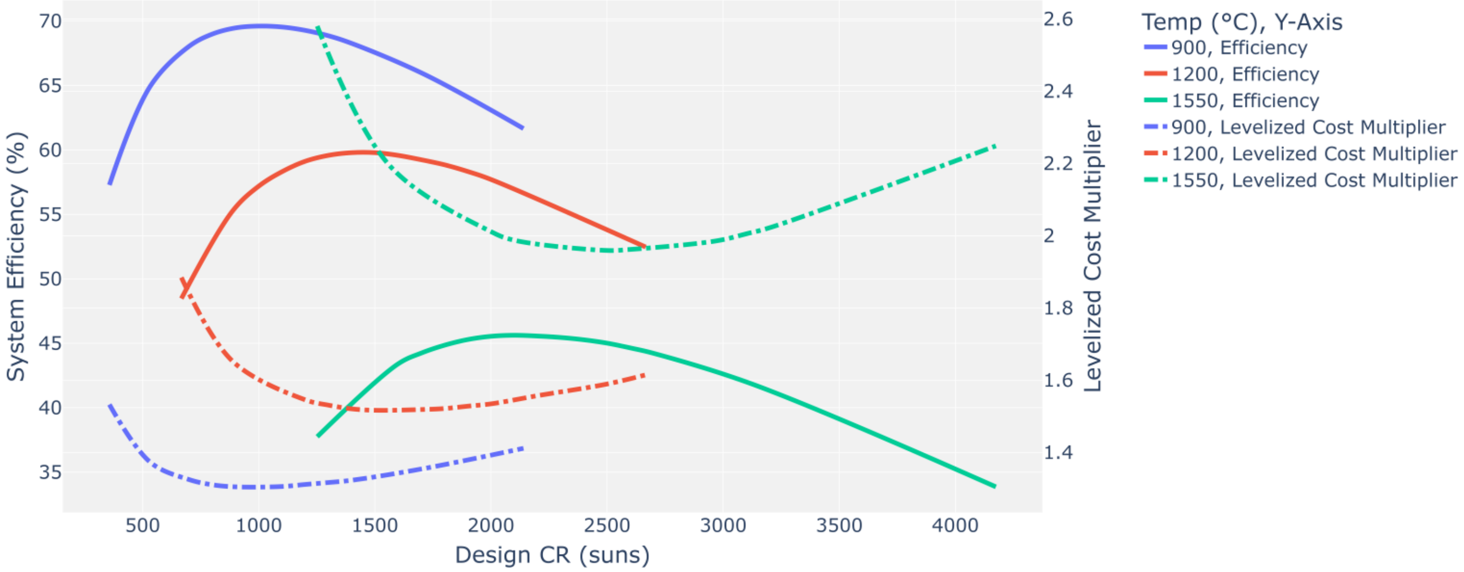


Summary of optical and thermal efficiencies as a function of CR for a case study with a 160-MW_{th} receiver operating at 1,200 °C

Results: Maximum efficiency, minimum LCOH as function of CR

Key insights:

1. Relative levelized costs increase significantly as temperature increases
2. Optimal CR depends more on the operating temperature than the objective (min LCOH vs. max efficiency)

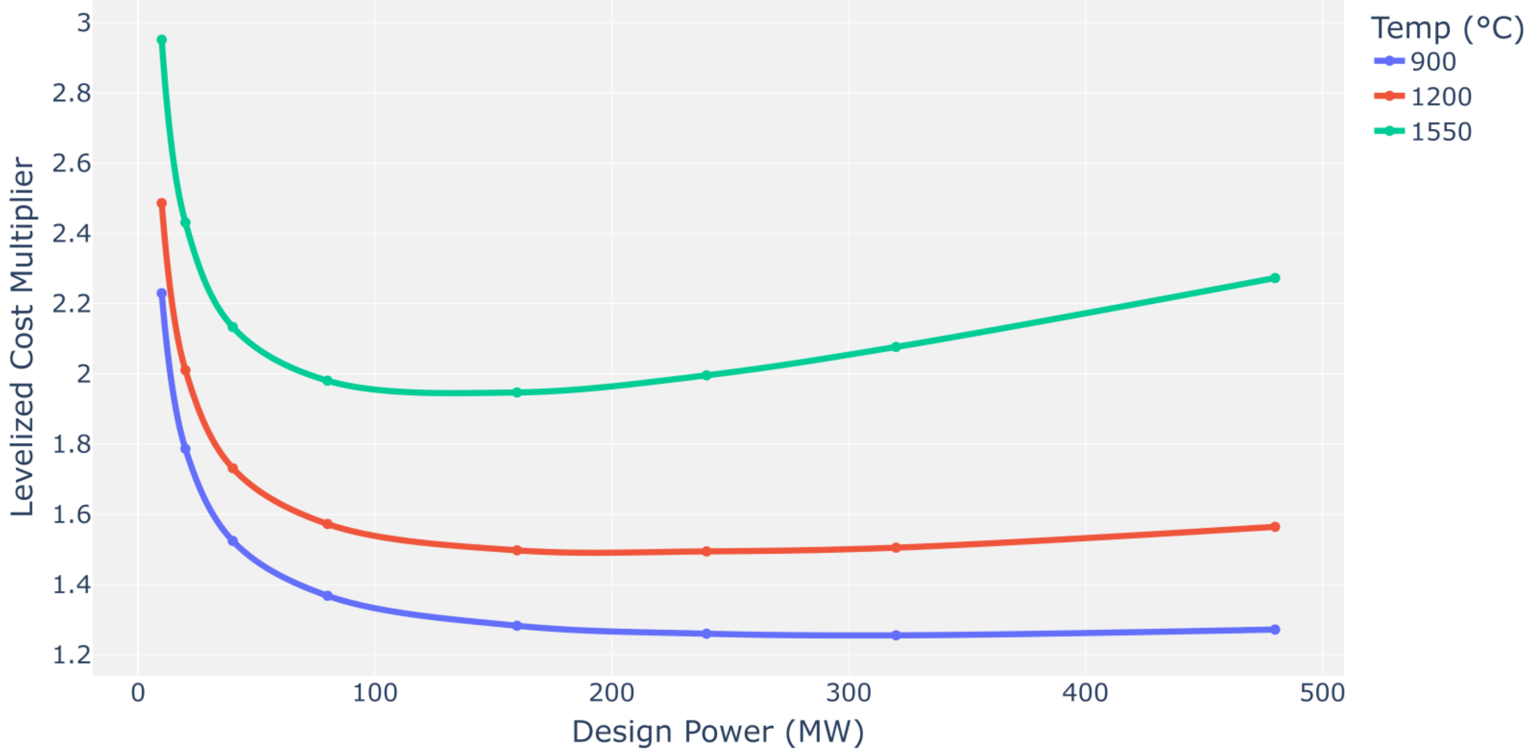


System efficiency and relative LCOH as a function of design CR for a case study with a 160-MW$_{th}$ receiver operating at 1,200 ^{o}C

Results: Minimum-cost solar field size as a function of tempratuure

Key insights:

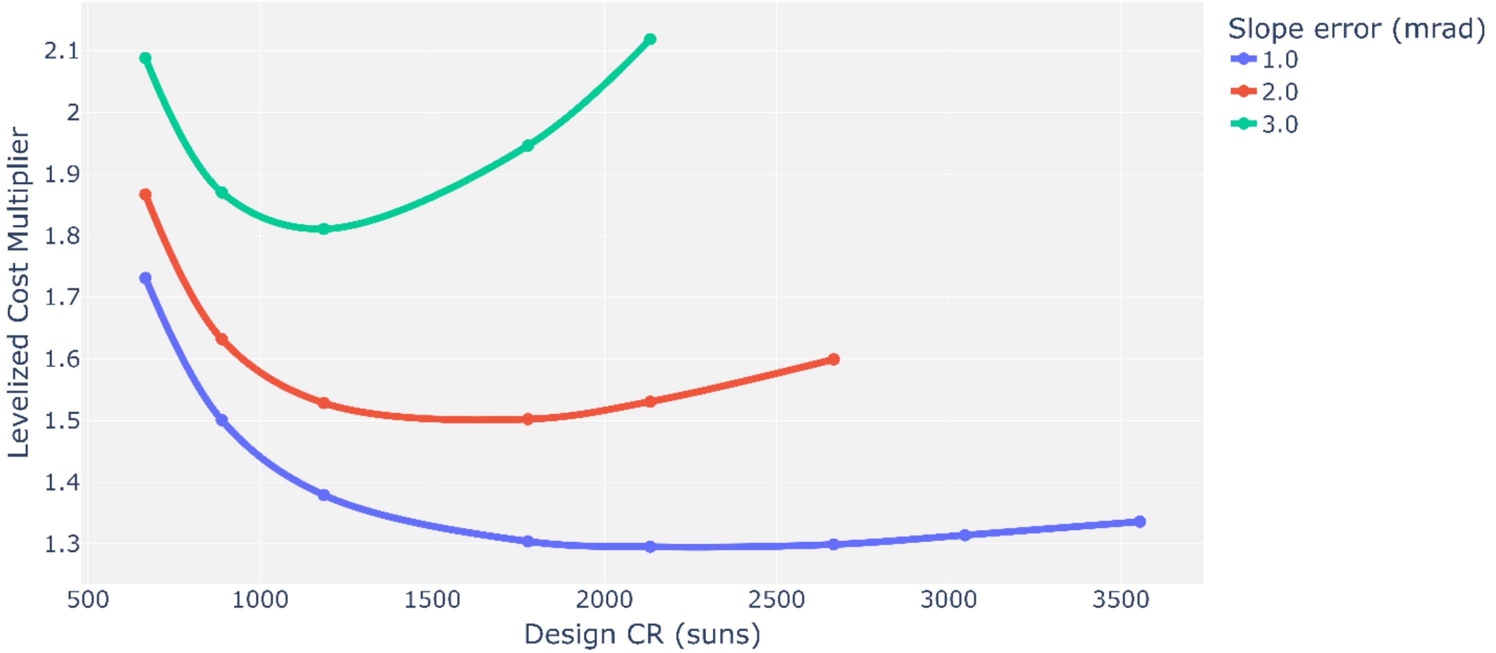
1. Optimum field size is smaller than conventional CSP plant (~800-1,000 MW_{th}) and in line with some existing IPH plant sizes
   (Lee et al., 2023)
2. Optimum size decreases as receiver temperature increases



Minimum relative LCOH obtained as a function of receiver thermal power rating

Results: Sensitivity of Heliostat Slope Error

- Varied heliostat slope error over range of 1-3 mrad
- Assumes 160-MW_{th} receiver at 1,200 °C
- Slope error impact increases as receiver target temperature increases

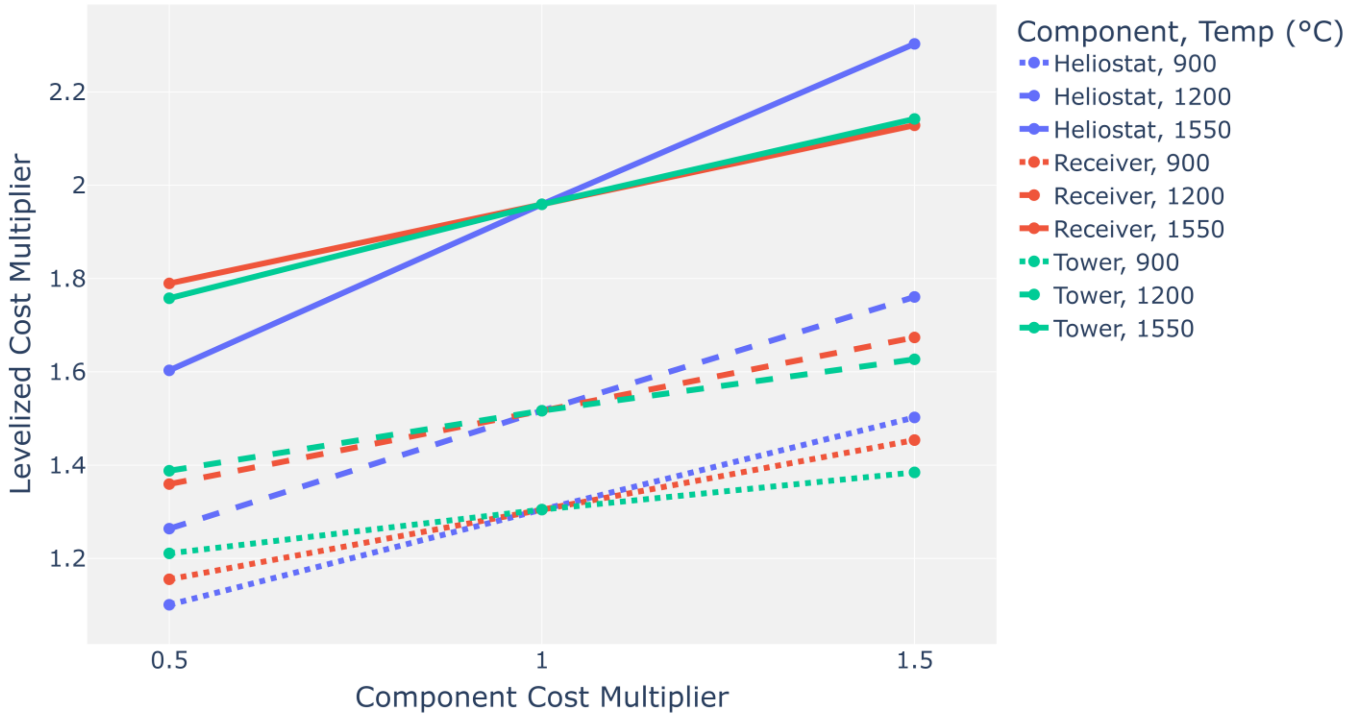


Relative LCOH as a function of CR as heliostat slope error varies, assuming a 1,200 °C receiver target temperature and a 160-MW_{th} power rating

Results: Sensitivity of Subsystem Costs

Sensitivity Analysis

- Varied the costs of the tower (\$/m), receiver (\$/m^2) and heliostat (\$/m^2) by +/-50%
- Did not see significant change in LCOH (+/-0.5 cents/kWh) despite large changes in component costs



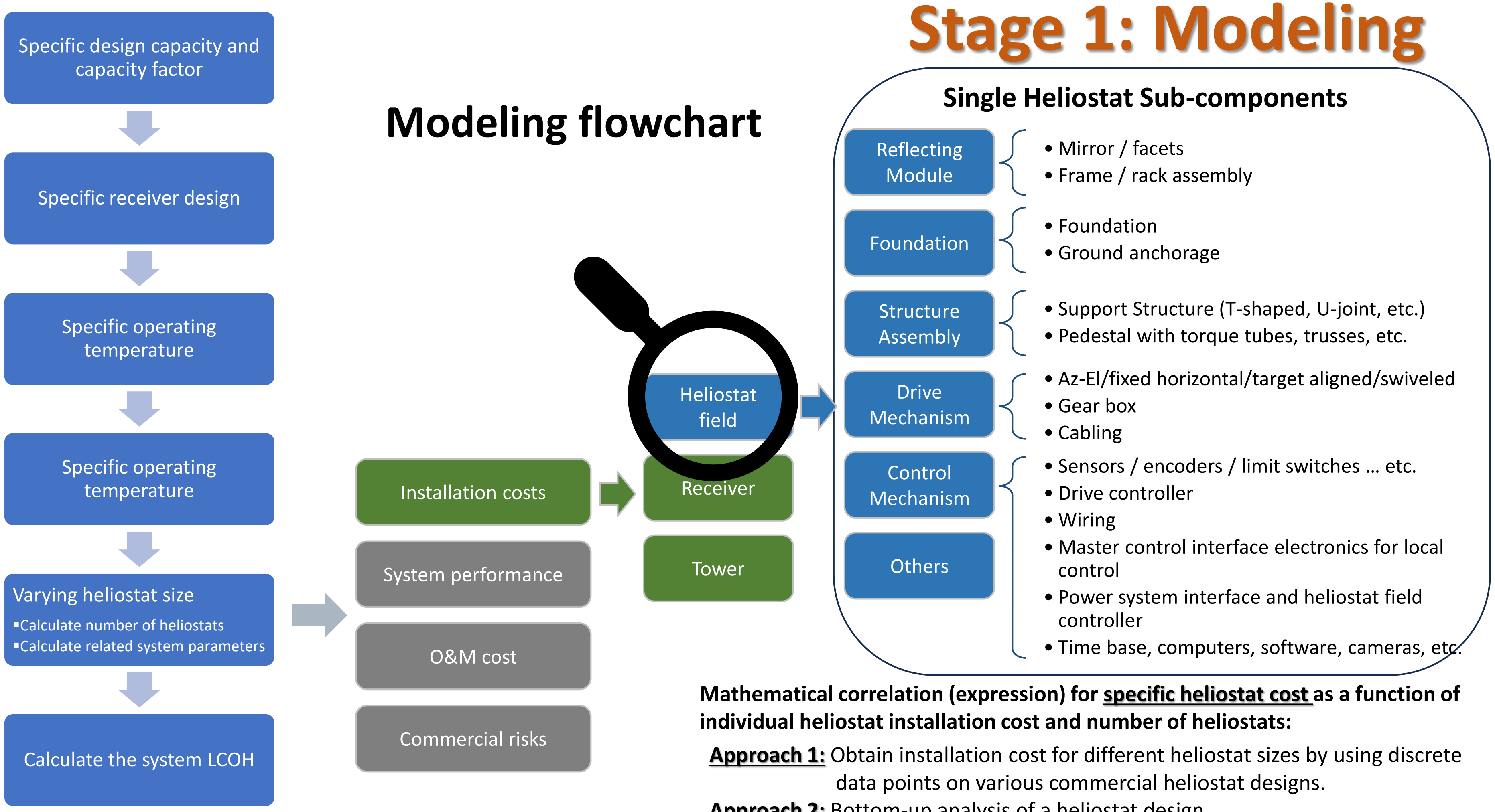
Relative LCOH as a function of subsystem cost for each temperature in our study, assuming a 160-MW$_{th}$ receiver power rating

Summary

- We present a study of solar fields and their relative levelized costs for a collection of potential IPH applications
- We demonstrate that the operating temperature has a significant impact on cost and attainable (combined optical and thermal) efficiency
- We show that the heliostat’s optical precision has a more significant impact on levelized costs, when compared to subsystem cost

Ongoing Work: Heliostat Sizing for IPH Applications

Stage 1: Modeling



Modeling flowchart

- Specific design capacity and capacity factor
- Specific receiver design
- Specific operating temperature
- Specific operating temperature
- Varying heliostat size
  - Calculate number of heliostats
  - Calculate related system parameters
- Calculate the system LCOH

Single Heliostat Sub-components

Reflecting Module	Mirror / facets Frame / rack assembly
Foundation	Foundation Ground anchorage
Structure Assembly	Support Structure (T-shaped, U-joint, etc.) Pedestal with torque tubes, trusses, etc.
Drive Mechanism	Az-El/fixed horizontal/target aligned/swiveled Gear box Cabling
Control Mechanism Others	Sensors / encoders / limit switches … etc. Drive controller Wiring Master control interface electronics for local control Power system interface and heliostat field controller Time base, computers, software, cameras, etc.

Mathematical correlation (expression) for <u>specific heliostat cost</u> as a function of individual heliostat installation cost and number of heliostats:

<u>Approach 1:</u> Obtain installation cost for different heliostat sizes by using discrete data points on various commercial heliostat designs.

<u>Approach 2:</u> Bottom-up analysis of a heliostat design.

Questions?

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References

- Zhu, Guangdong, et al. Roadmap to advance heliostat technologies for concentrating solar-thermal power. No. NREL/TP-5700-83041. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022.
- Zhu, Guangdong, et al. "HelioCon: A roadmap for advanced heliostat technologies for concentrating solar power." Solar Energy 264 (2023): 111917.
- Augustine, Chad, et al. "Analysis of Gaps in Techno-Economic Analysis to Advance Heliostat Technologies for Concentrating Solar-Thermal Power." Journal of Solar Energy Engineering 146 (2024): 061002-1.
- Cox, John L., et al. "Real-time dispatch optimization for concentrating solar power with thermal energy storage." Optimization and engineering 24.2 (2023): 847-884.
- Li, Lifeng, et al. "Temperature-based optical design, optimization and economics of solar polar-field central receiver systems with an optional compound parabolic concentrator." Solar energy 206 (2020): 1018-1032.
- McMillan, Colin, et al. Opportunities for solar industrial process heat in the United States. No. NREL/TP-6A20-77760. National Renewable Energy Lab.(NREL), Golden, CO (United States); Northwestern Univ., Evanston, IL (United States), 2021.
- Lee, Leok, et al. "Pathways to the use of concentrated solar heat for high temperature industrial processes." Solar Compass 5 (2023): 100036.
- Wagner, Michael J., and Tim Wendelin. "SolarPILOT: A power tower solar field layout and characterization tool." Solar Energy 171 (2018): 185-196.