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HelioCon
Heliostat Consortium for
Concentrating Solar-Thermal Power

# Impact of Temperature and Optical Error on the Combined Optical and Thermal Efficiency of Solar Tower Systems for Industrial Process Heat

SolarPACES Conference 2023

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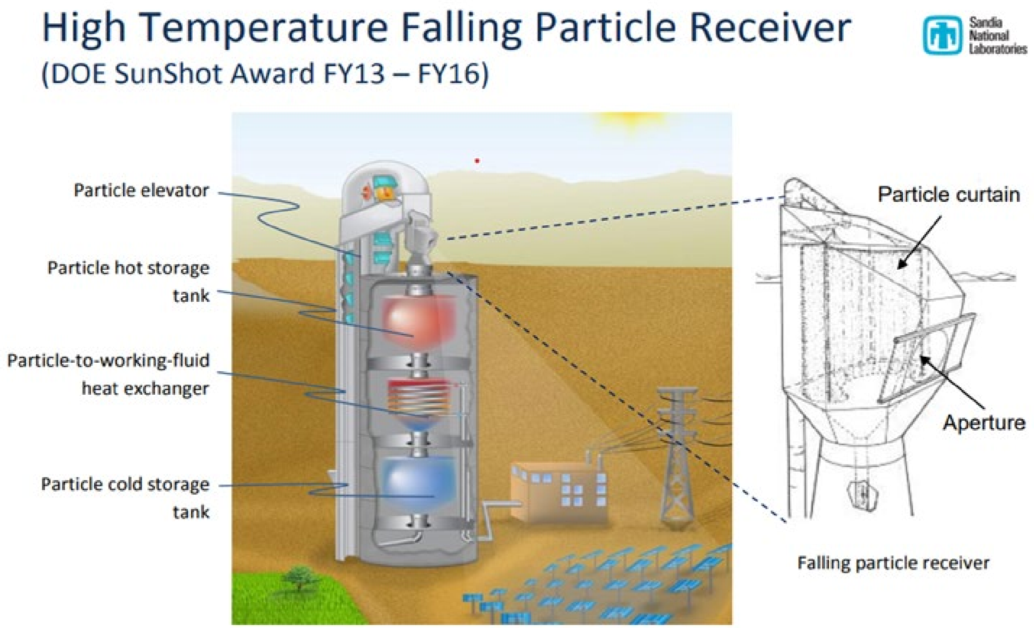
# Agenda

- Motivation
- Methodology and assumptions
  - Black-body radiation loss
  - SolarPILOT model and design search
- Results and conclusions

# Motivation and Objective

- CST power towers show promise for high-temperature industrial process heat (IPH) applications, including but not limited to:
  - Calcination (900° C)
  - Solar fuels (~1,200° C)
  - Clinker (1,550° C)
- Thermal (radiation) losses increase with temperature, reducing system efficiency
  - The high concentration ratios (CR) that increase thermal efficiency require smaller receiver targets, which leads to optical (spillage) losses
- We use the three temperatures above as case studies to explore these tradeoffs and estimate the combined optical and thermal efficiency of CST IPH plants

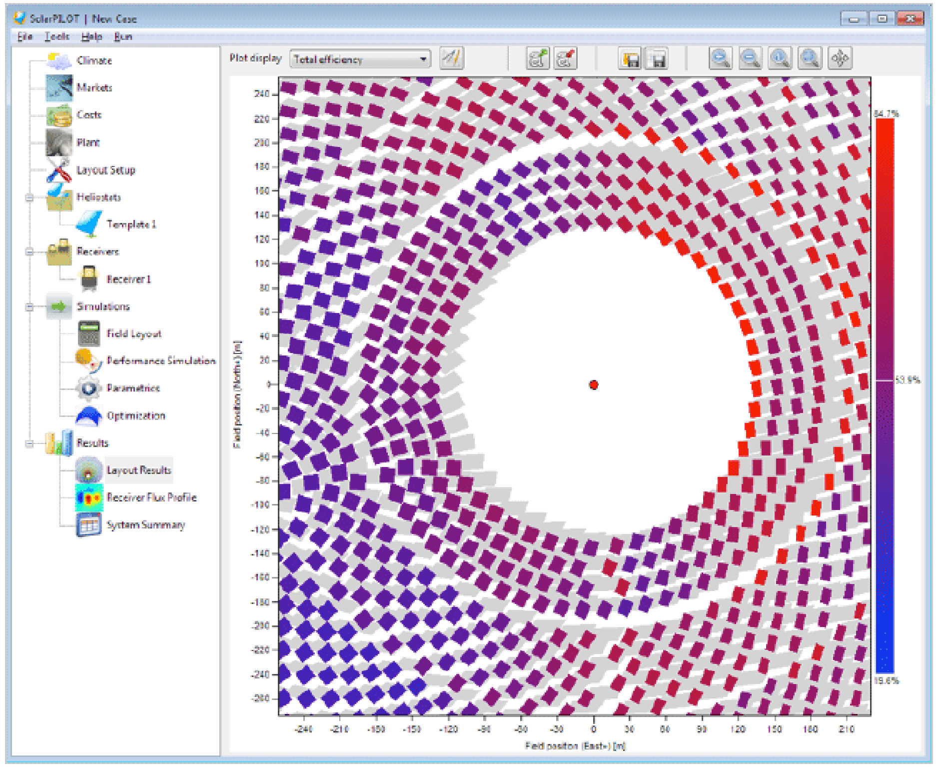


# Methodology

Using SolarPILOT, we varied tower height and receiver elevation angle to find the maximum-efficiency design with:

- Square, flat-plate receiver target
- Radiation losses only (i.e., 100% absorptance)
- Fixed heliostat/receiver width, height ratio of 0.7
- Optical error: 2 mrad slope on both *x* and *y* axes
- Zero piping loss
- Heliostat focusing type: At slant
- Heliostat aim point method: Simple aiming

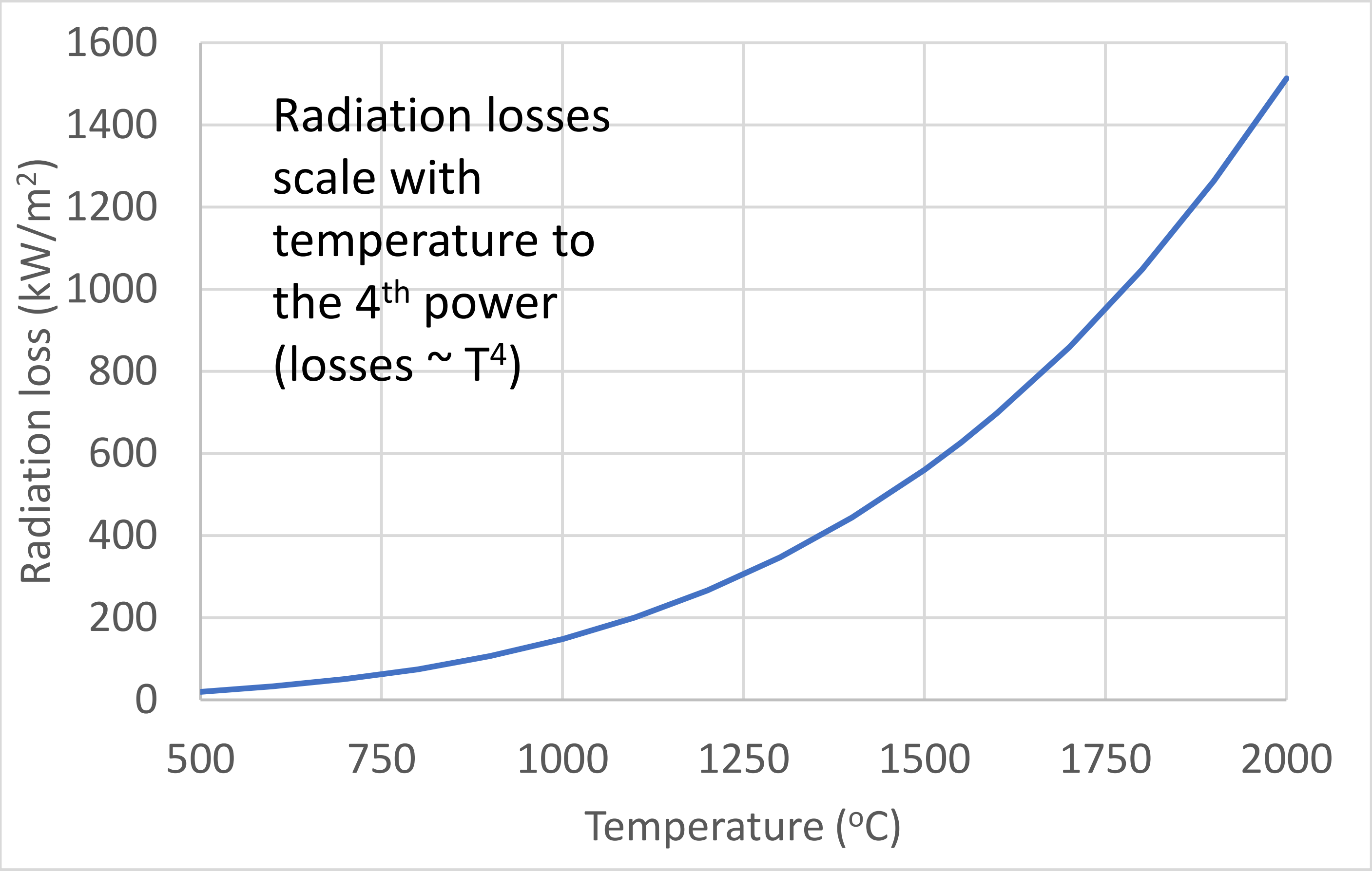
Then, we vary the CR (i.e., receiver size) to maximize system efficiency for a given temperature and thermal power rating




Example SolarPILOT layout results page
https://www.nrel.gov/csp/solarpilot.html

# Blackbody Radiation Model

- We use Stefan's Law to calculate black-body radiation losses at the receiver
- Cavity receivers would incur additional sources of loss in practice (e.g., advection, conduction, reflection)



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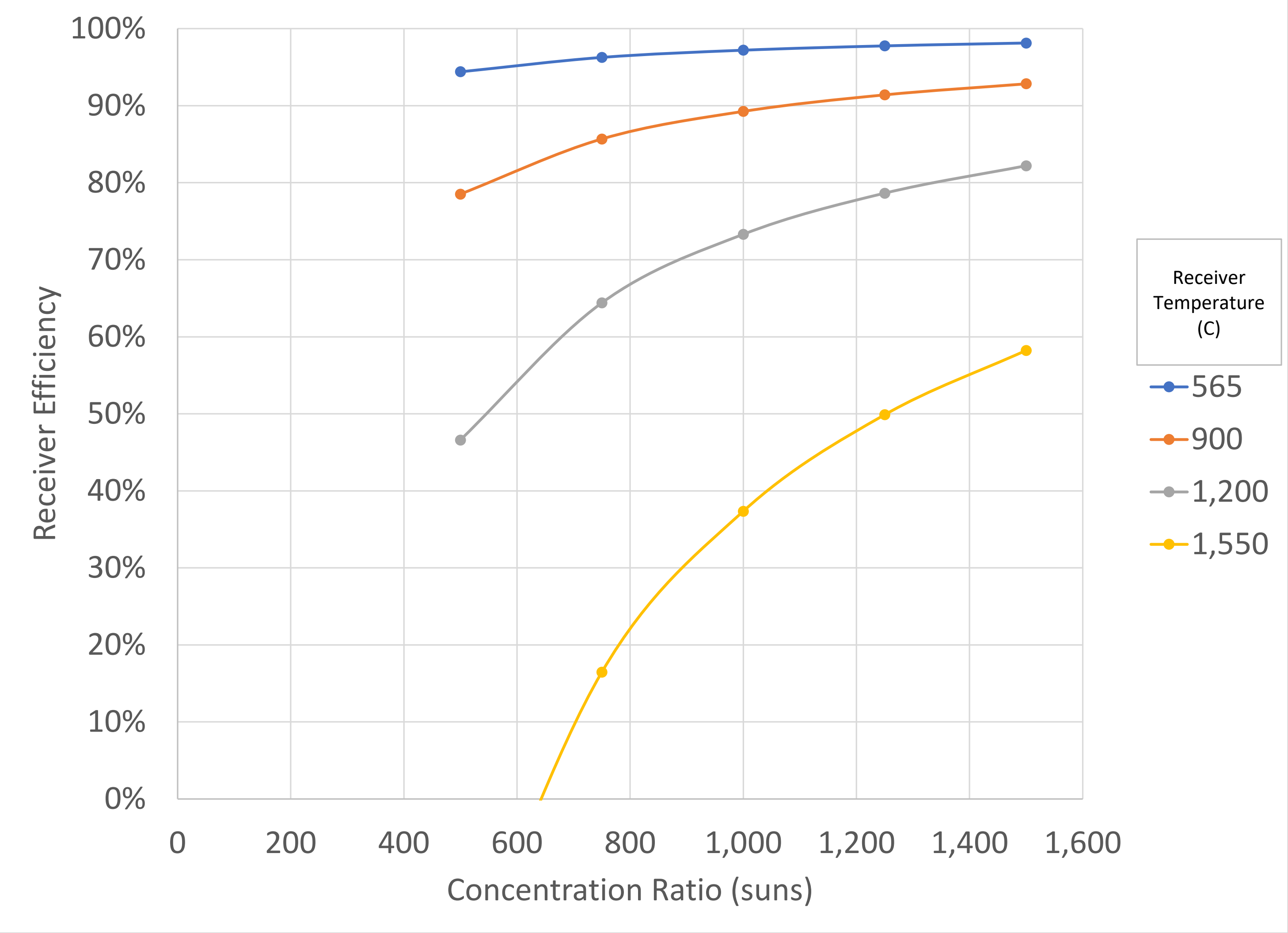
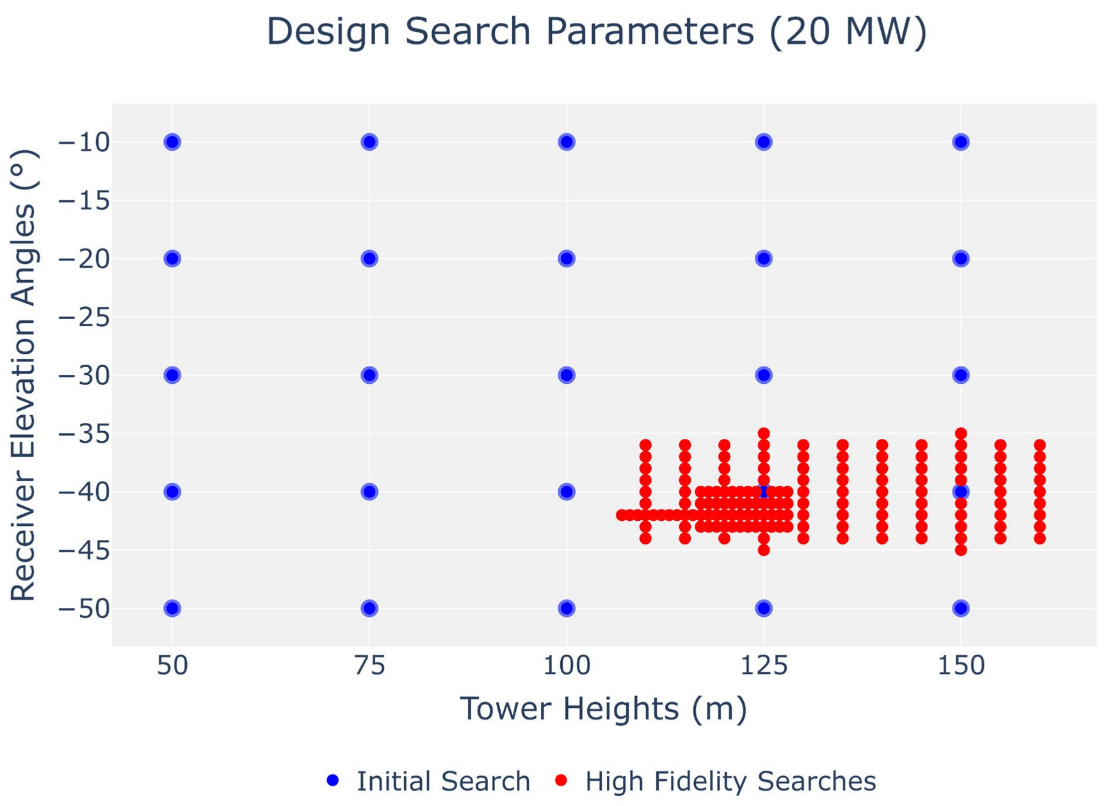
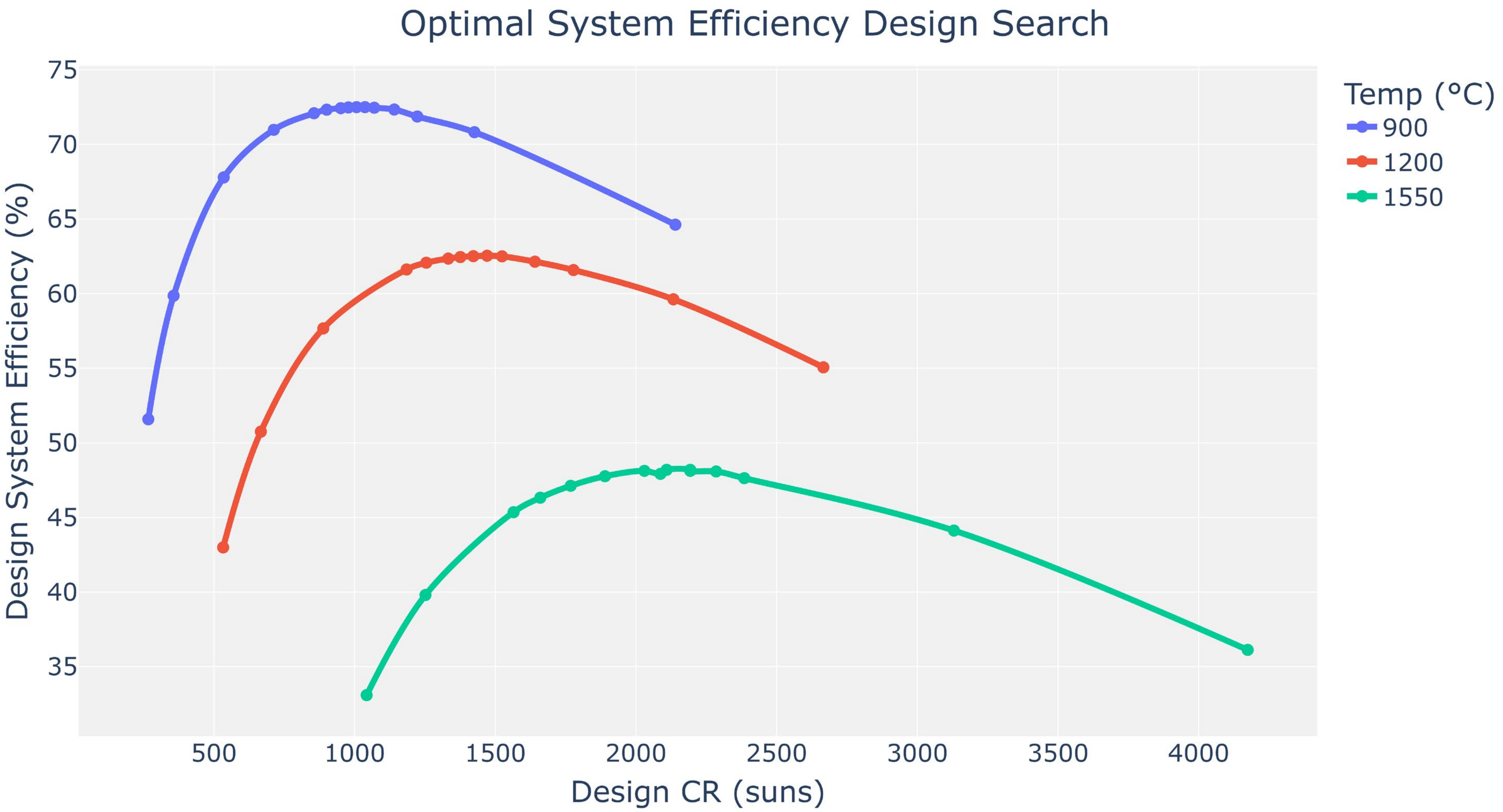


# Design Parameter Search

- Initial design parameter search of 900, 1200, and 1550°C over combinations of tower heights and receiver elevation angles for optimal design system efficiency vs design CR (intervals of 25m and 10°)
- Further searches around each maximum with intervals of 1 m and 1°

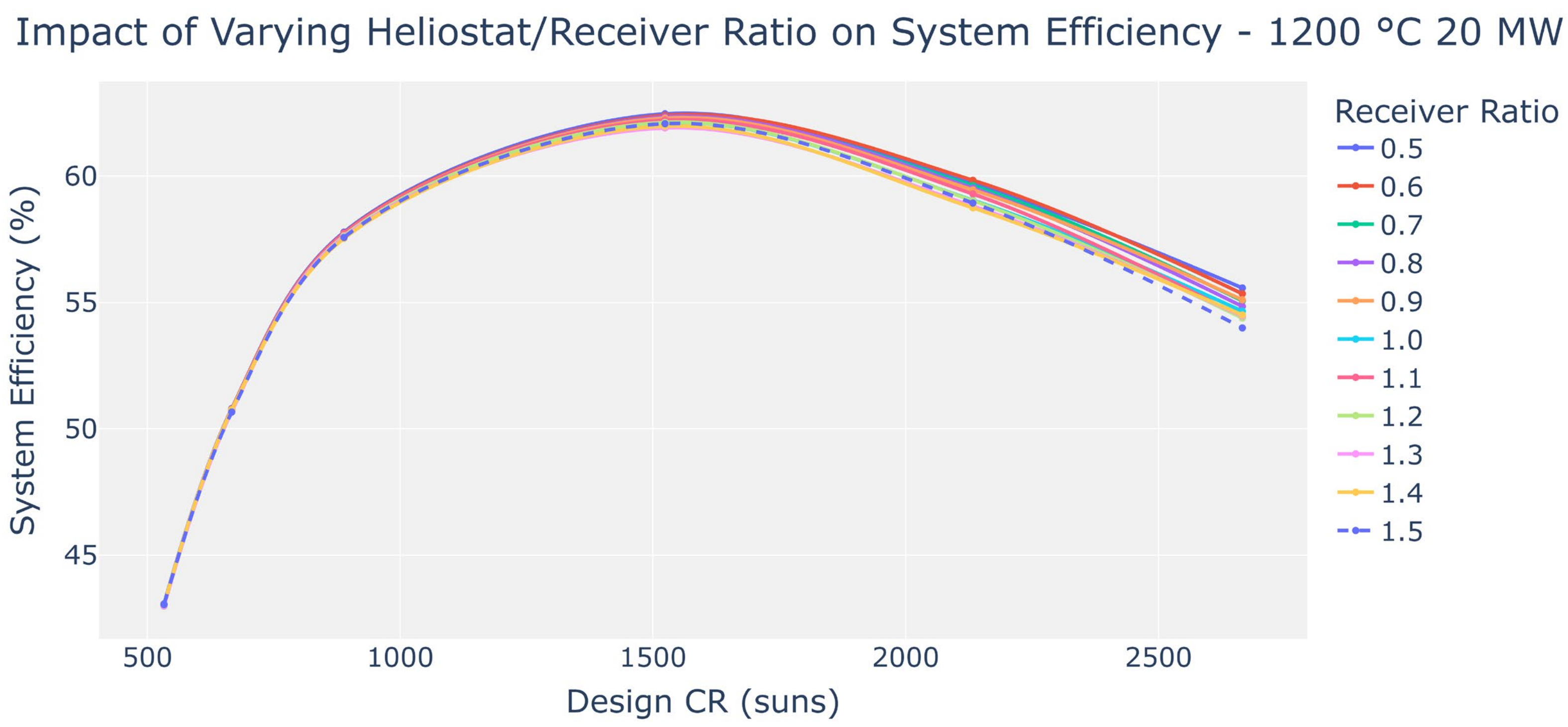


# Parameter Search Results (20 MW)

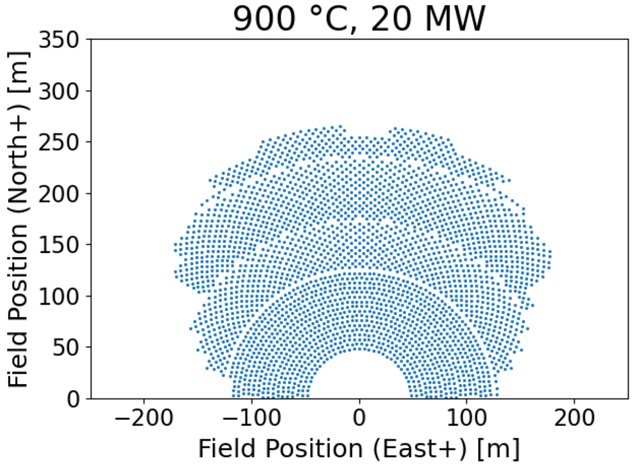


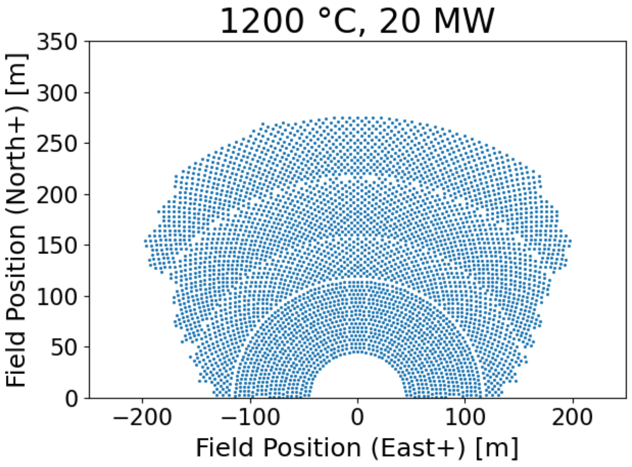
# Impact of heliostat-to-receiver size ratio on efficiency is limited

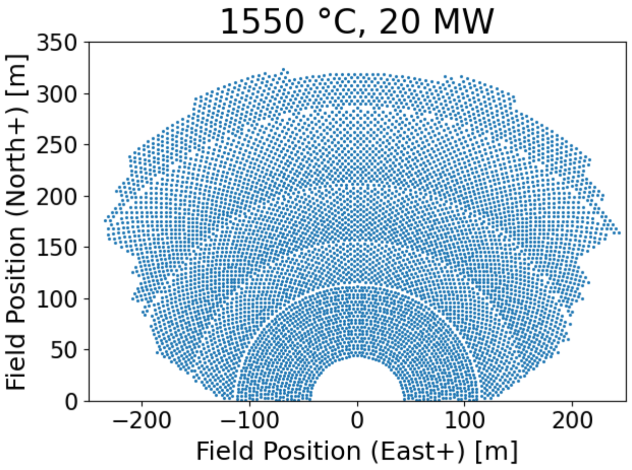
- Efficiency decreases slightly with increasing heliostat-receiver ratio
- Simplifies analysis: For a given CR, intercept efficiency does not change with field size
- The best-found design is consistent as this ratio changes
- A ratio of 0.7 is used for rest of study as a higher ratio is more computationally efficient



# Optimal Design at Each Temperature (20 MW)



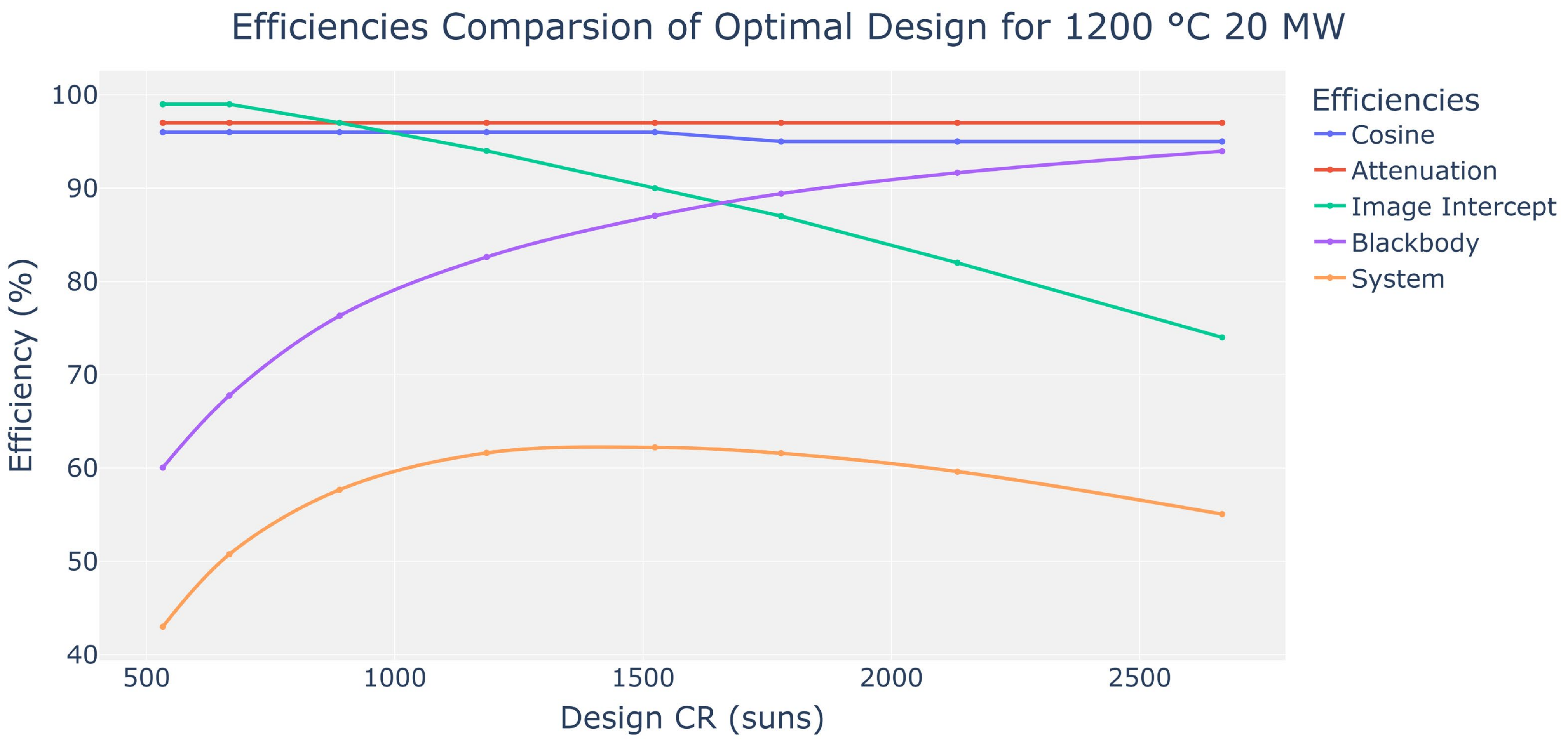




| | 900 °C | 1200 °C | 1550 °C |
|---|---|---|---|
| Receiver Size ($m^2$) | 21.50 | 16.61 | 12.76 |
| Heliostat Size ($m^2$) | 10.22 | 7.89 | 6.07 |
| Total Heliostat Area ($m^2$) | 29,794 | 34,531 | 44,713 |
| Tower Height (m) | 121 | 113 | 110 |
| Receiver Elevation Angle | -41 | -42 | -41 |
| Solar Field Optical Efficiency (%) | 81 | 76 | 67 |
| Total System Efficiency (including receiver) | 72.5 | 62.54 | 48.19 |

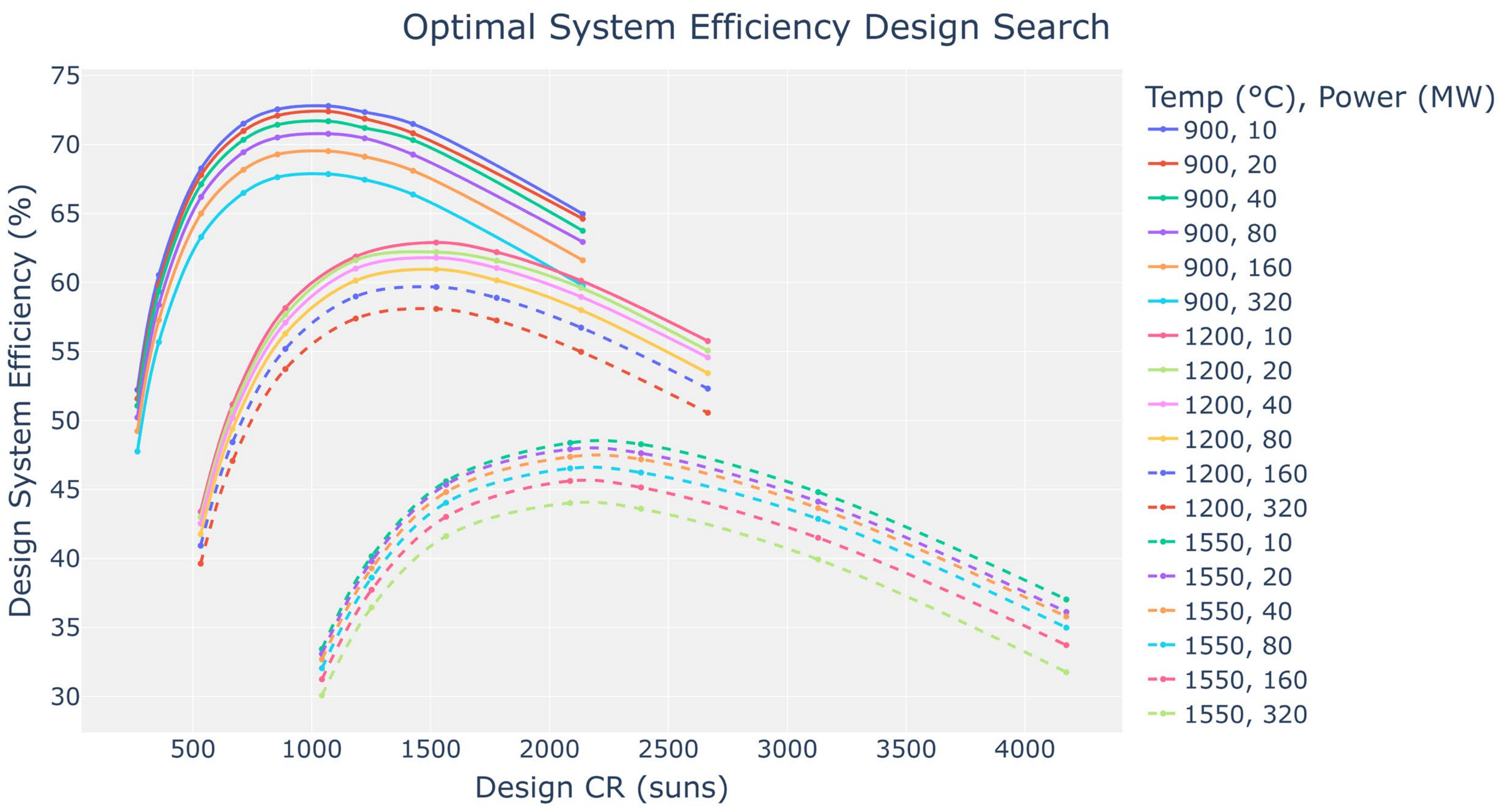
*Fields were designed and optimized for solar noon on the Spring Equinox. Future work will incorporate annual simulations.*

# Key tradeoff: radiation vs. spillage losses

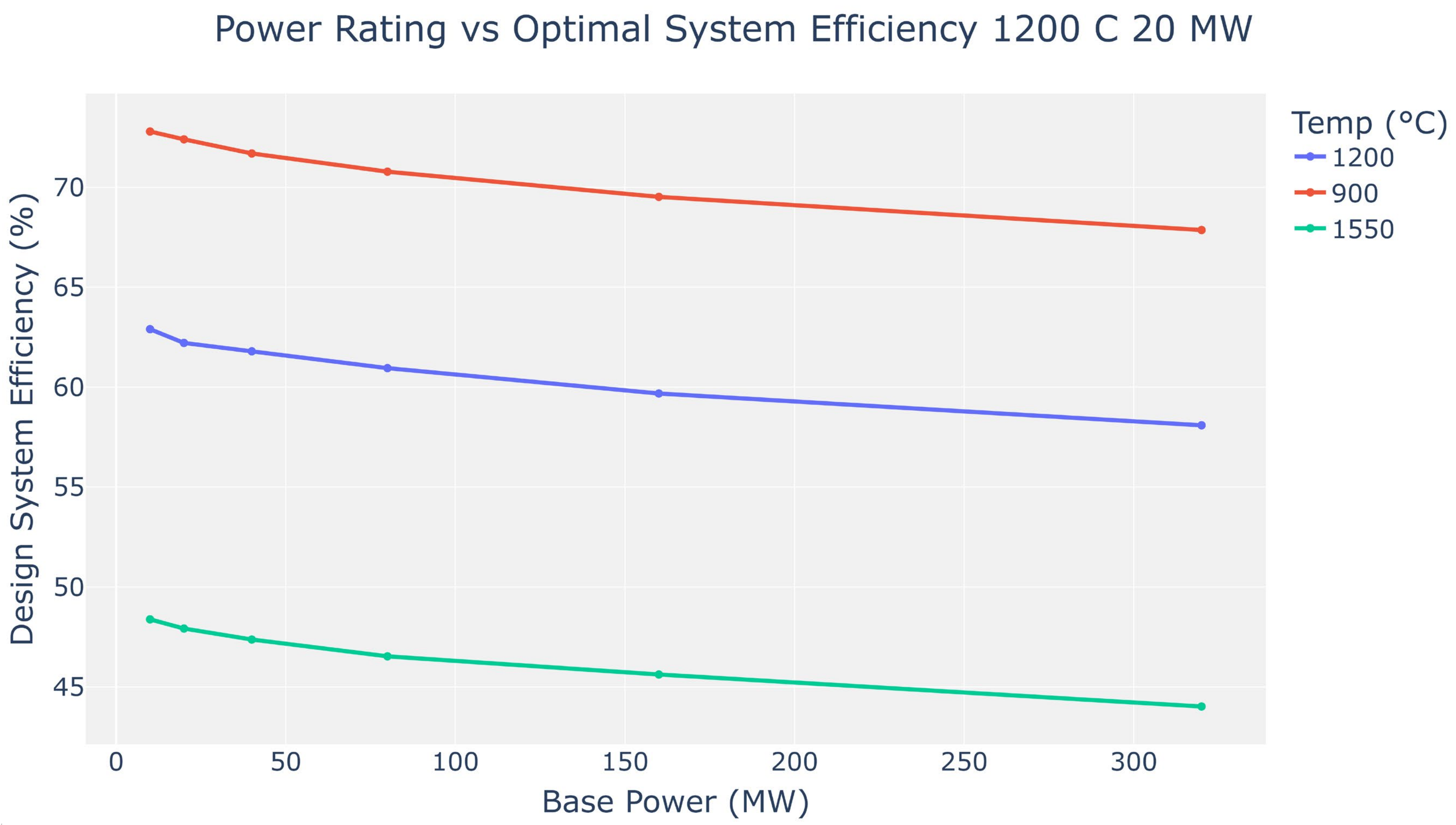


# Optimal CR is consistent as plant size changes

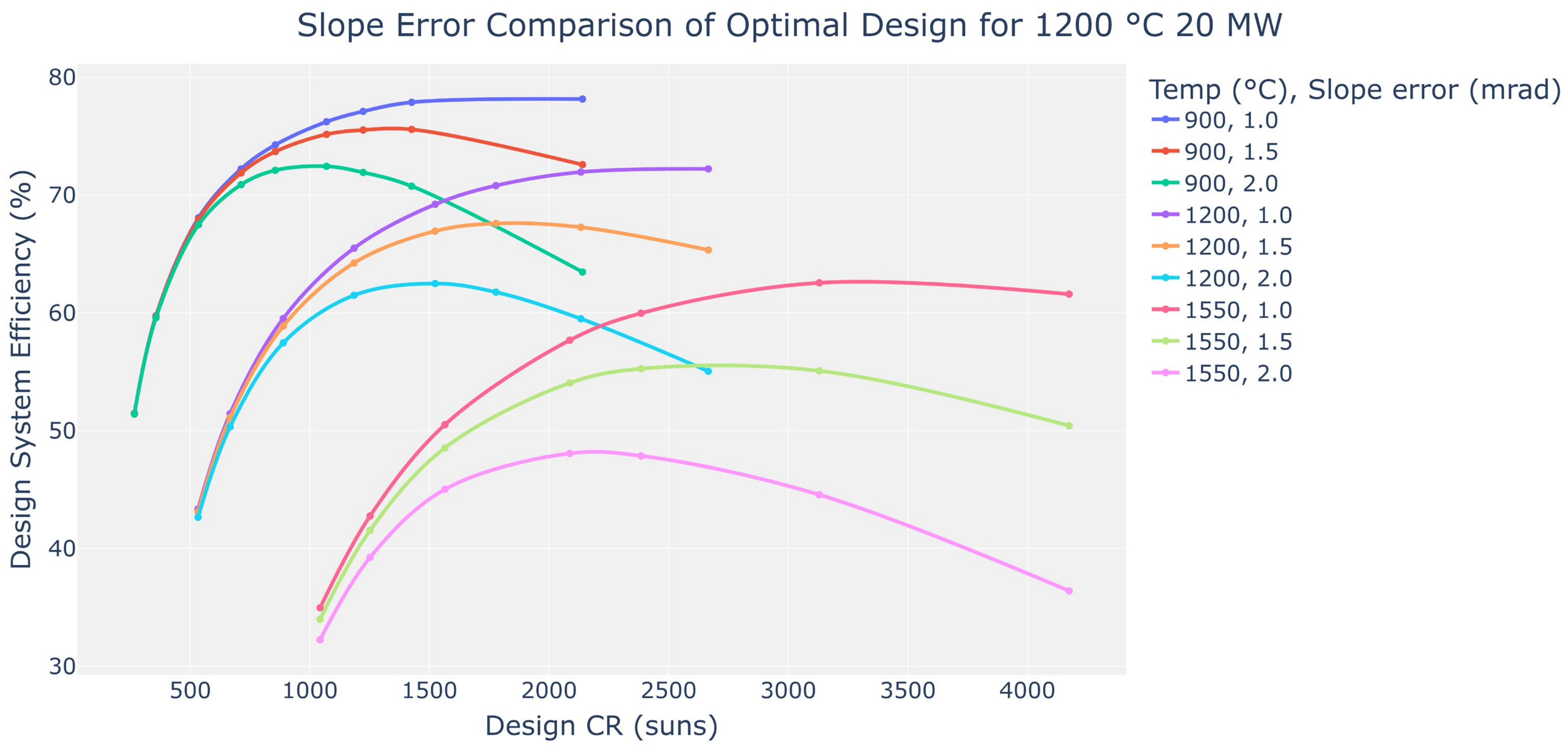
- Further design search to explore impact of varying power rating on optimal system efficiency
- Optimal tower height scales up with power rating, optimal receiver elevation angle remains the same



# System efficiency decreases almost linearly as receiver power rating increases



# Improvements to optical error increase both system efficiency and the optimal CR



# Key Insights

- Radiation losses at elevated temperatures (900+ °C) much higher than those at electricity generation temperatures
  - Developers must keep this in mind when designing high-temperature SIPH projects
- Fixing the heliostat-to-receiver height ratio simplifies the analysis by removing a variable
  - Results show that intercept efficiency constant for given CR and heliostat-to-receiver ratio
- The key efficiency tradeoff for high-temperature CST IPH plants is between (thermal) radiation and (optical) spillage losses
  - For a given receiver power rating, a higher solar concentration ratio (more flux) increases the receiver efficiency but also results in a smaller receiver target, increasing spillage losses
- While increasing the receiver power rating reduces efficiency, the most efficient concentration ratio remains consistent as plants increase in size
- Future work will investigate:
  - Levelized costs using varied cost functions for the tower and receiver and annualized production
  - The impact of additional sources of loss at the receiver and black-body vs. gray-body assumptions
  - The impact of practical design constraints (maximum flux, tower height, etc.)

# Thank You!

**www.nrel.gov**

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