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Sandia National Laboratories

Thermal Performance of Commercial Falling Particle Receivers at Different Scales

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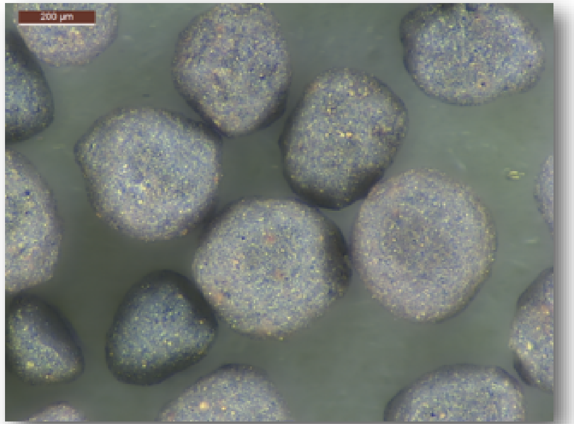
Concentrating Solar Power and Particles

Particle technology is a leading candidate to couple with next-generation concentrating solar power (CSP) systems

Advantages of particles in CSP:

- Able to achieve high temperatures (>800°C)
- Low parasitics (gravity driven)
- Low cost heat transfer medium
- Efficient storage
- Direct irradiation (absence of flux limitations)
- No trace heating is necessary

Sandia National Laboratories has been researching particles for CSP technologies for decades



Yue, L., et al. (2019)

Falling Particle Receivers

Falling particle receivers (FPRs) are <u>one type</u> of particle receiver

- Cavity-type receivers where particles are released in a curtain and fall via gravity past the beam of concentrated light

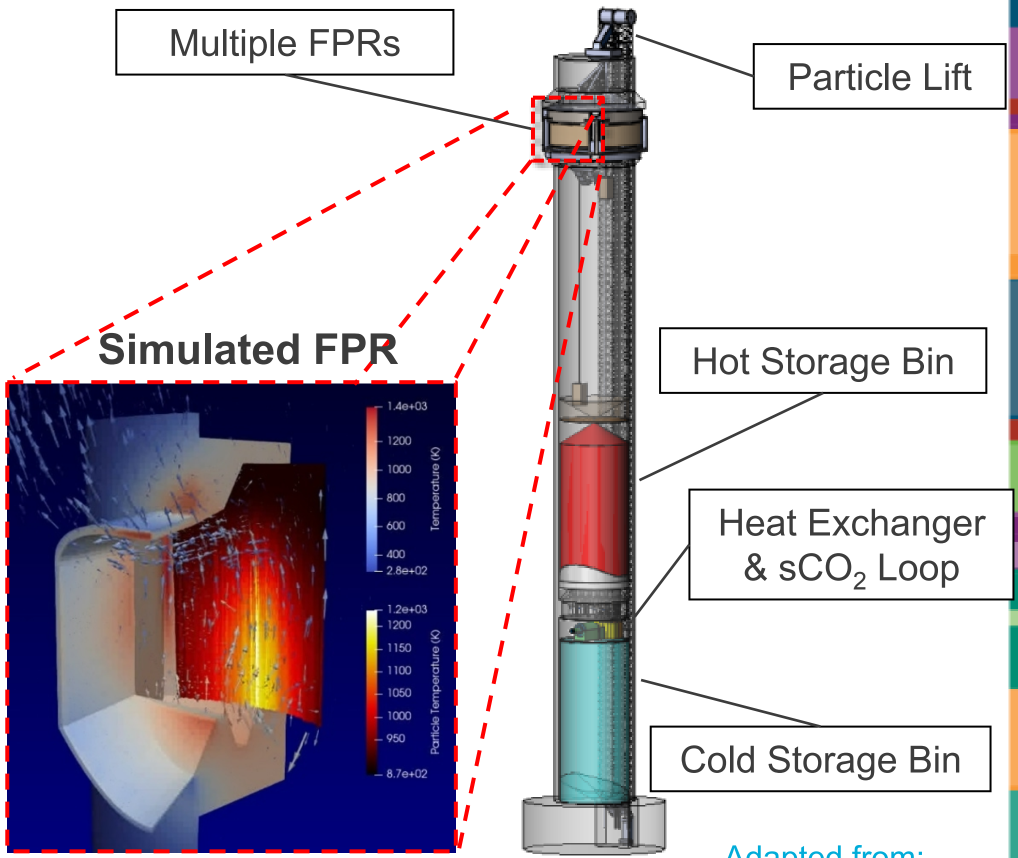
Advantages of FPRs:

- Direct irradiance of the particles (absence of flux limitations)
- Experimental evidence of high temperatures (> 800°C)
- Low parasitics; only a single slide gate for control
- Conceptually simple and inexpensive

Disadvantages of FPRs:

- High advective losses through the aperture
- Open aperture increase susceptibility to wind

Candidate, Vertically Integrated, Utility-scale, Particle CSP Facility with Multiple FPRs

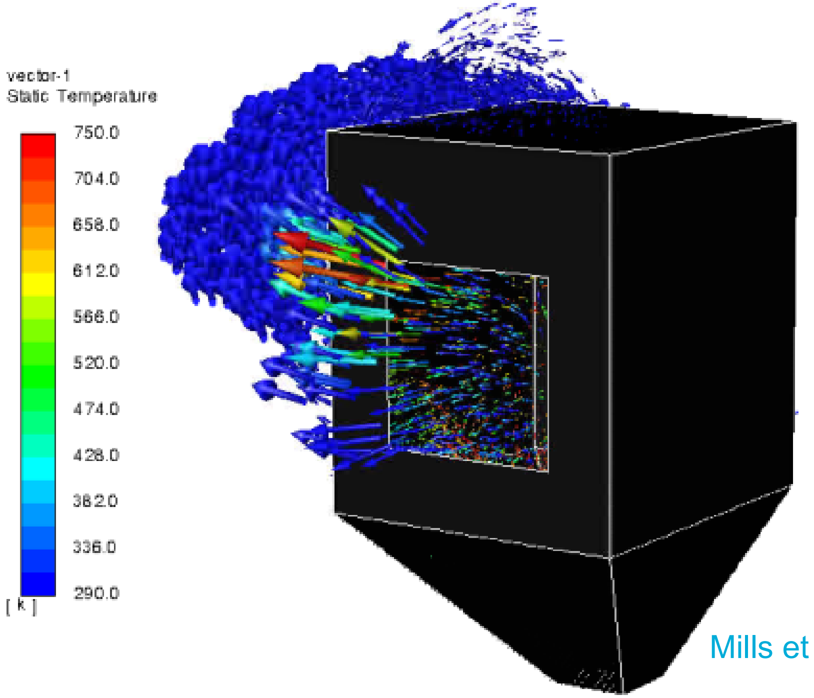


Adapted from: SAND2021-14614

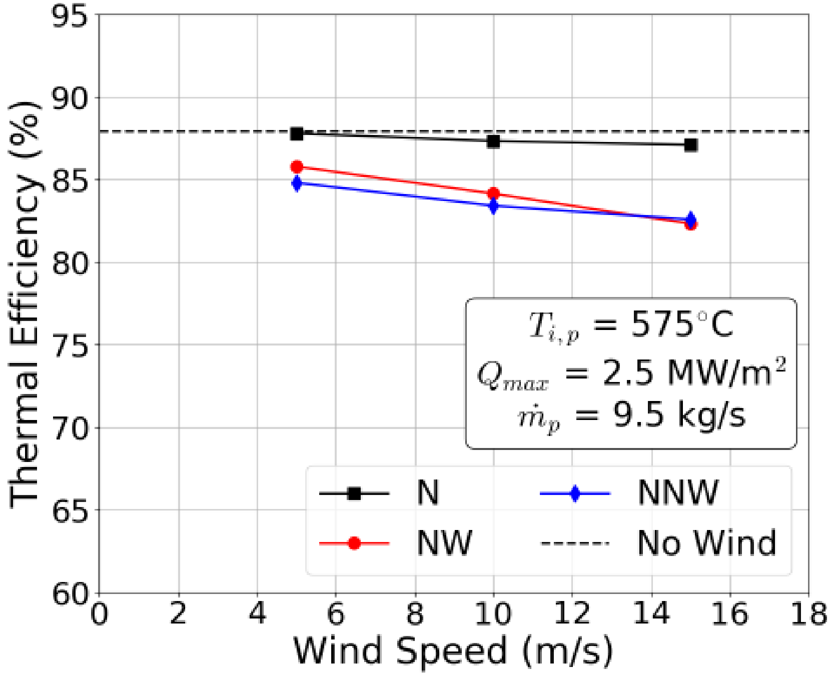
Motivation

For a utility-scale FPR, the **thermal efficiency** is highly affected by the environment

- Wind can significantly increase advective losses from the receiver cavity



Mills et al. (2019)



Mills et al. (2020)

Technoeconomic analysis requires accurately predicting the efficiency throughout a typical year

Predicting a FPR's thermal efficiency is computationally expensive

Objectives and Methodology

Develop models for the FPR thermal efficiency in all relevant environmental conditions that can be leveraged in technoeconomic analysis

Methodology:

1. Develop sophisticated models of candidate, utility-scale FPRs at different sizes
2. Parametrically simulate the thermal performance under a range of relevant conditions
   - Receiver size, particle temperature, particle mass flow rate, incident radiative power, wind conditions
3. Use data to fit correlations of the FPR thermal efficiency that are computationally inexpensive

Computational Model

Used a Lagrangian-Eulerian CFD model coupled with a discrete ordinates (DO) radiation model (ANSYS Fluent®)

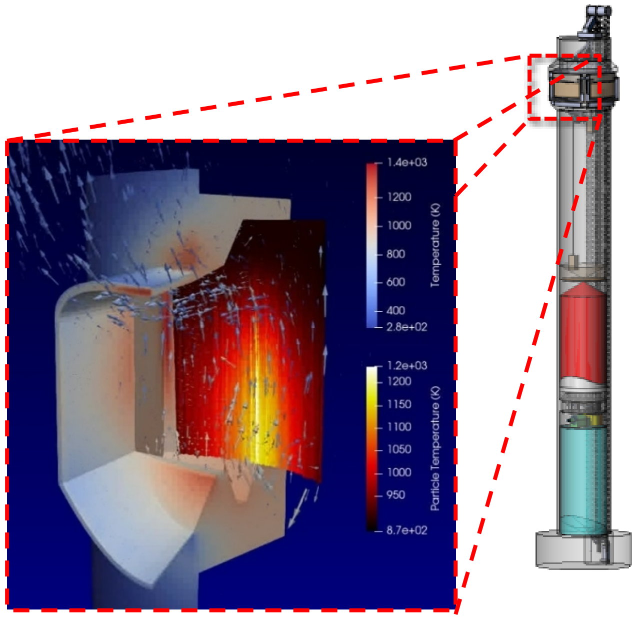
- Two-equation RANS turbulence model; realizable k-ε
- Spherical particles: CARBO HSP (350 μm nominal diameter)

Cavity design based on proposed utility-scale, “north-facing” FPR designs and lessons learned in the G3P3 project

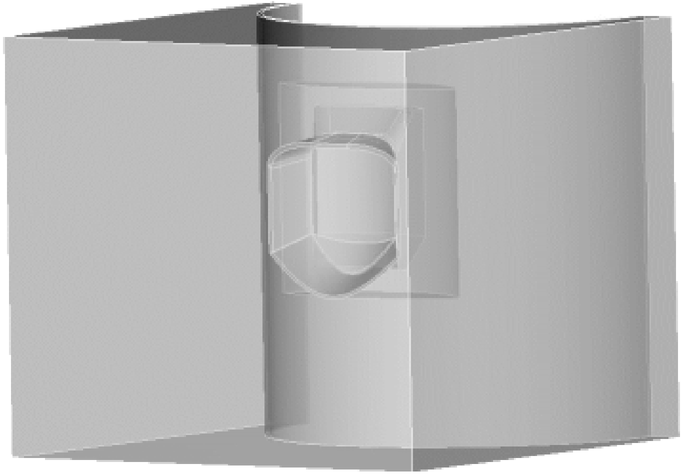
- 3 receiver sizes; aperture area: **25, 144, 324 m²**
- Varying: radiative power Q, particle temperature T, and particle mass flow rate $\dot{m}$

Boundary conditions are assigned based on wind

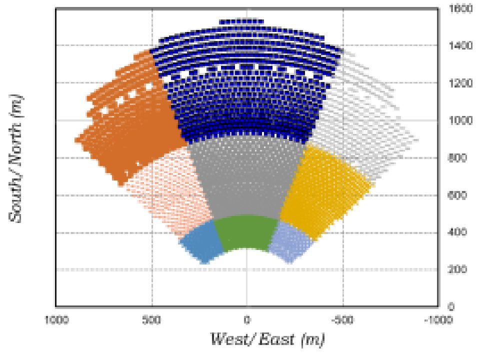
- Wind from **N (360°) to SW (225°)** and speeds up to **15 m/s**
- 5% and 10 for turbulent intensity and viscosity ratio



Computational Domain

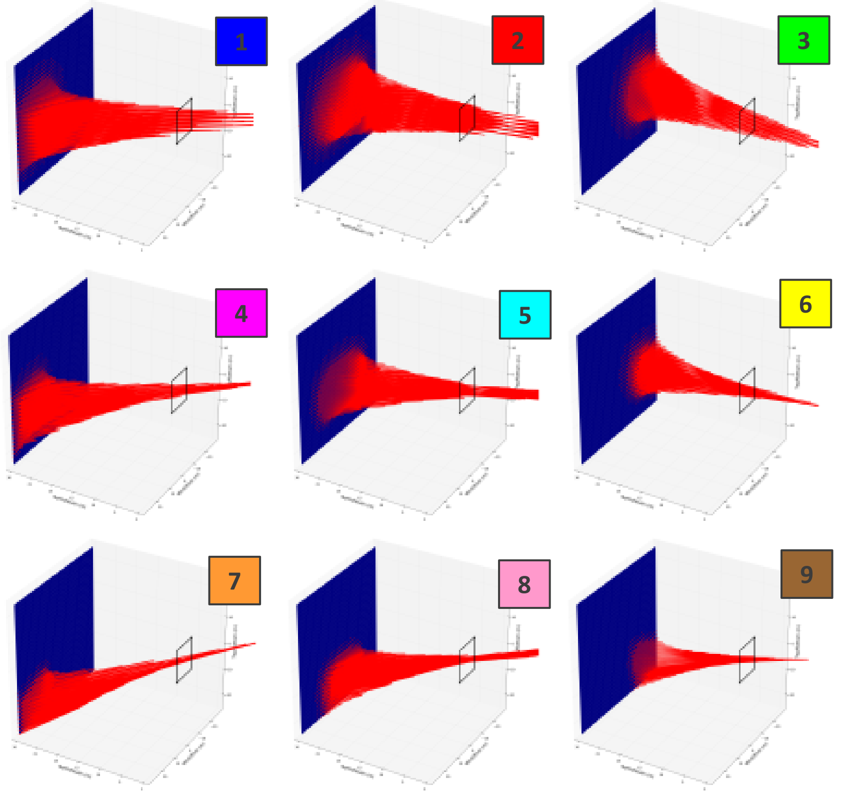


Radiation Modeling



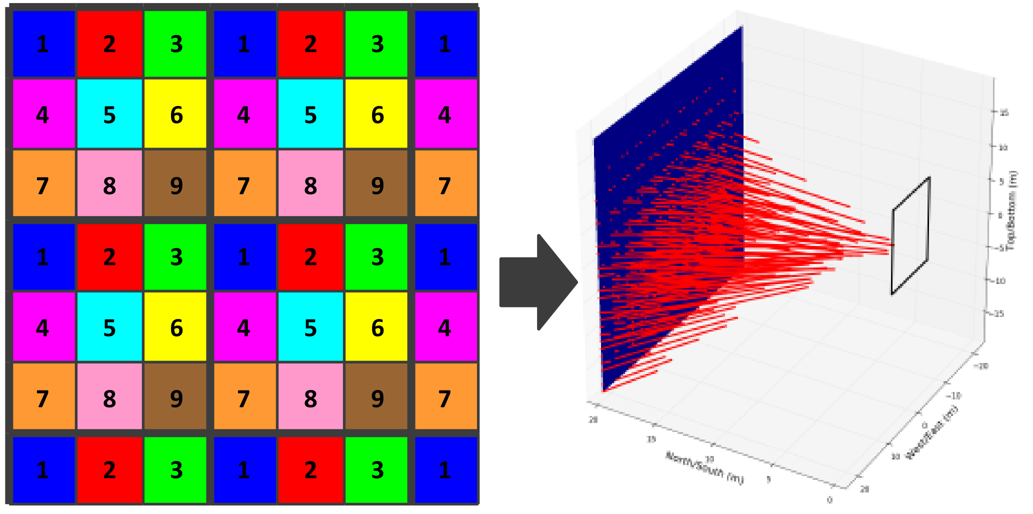
Non-grey DO model:

- Three bands: 0–2.5, 2.5–4.5, 4.5–100 μm
- All incident radiation entered in the smallest band



To generate a realistic radiative BC for simulations, a compatible heliostat field generated with SolarPILOT:

1. Field was divided into nine zones
2. Ray-tracing simulations performed for each zone
3. Analytical correlations: intensity and directionality
4. Faces on north surface corresponded to a zone
5. Intensity was scaled proportionally to match the targeted flux from SolarPILOT

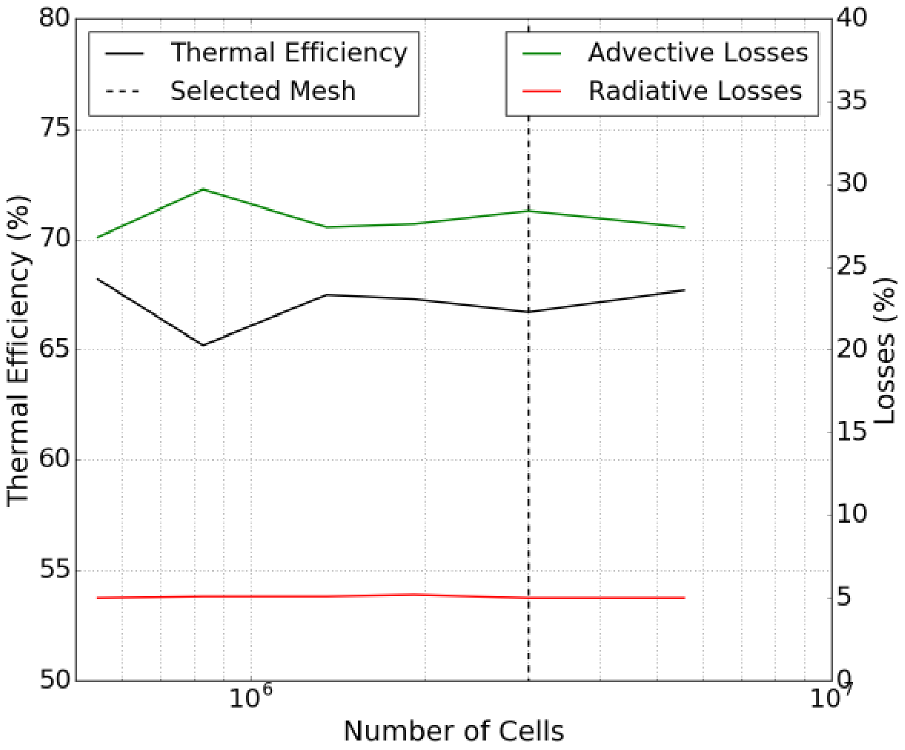


Mesh Convergence Study

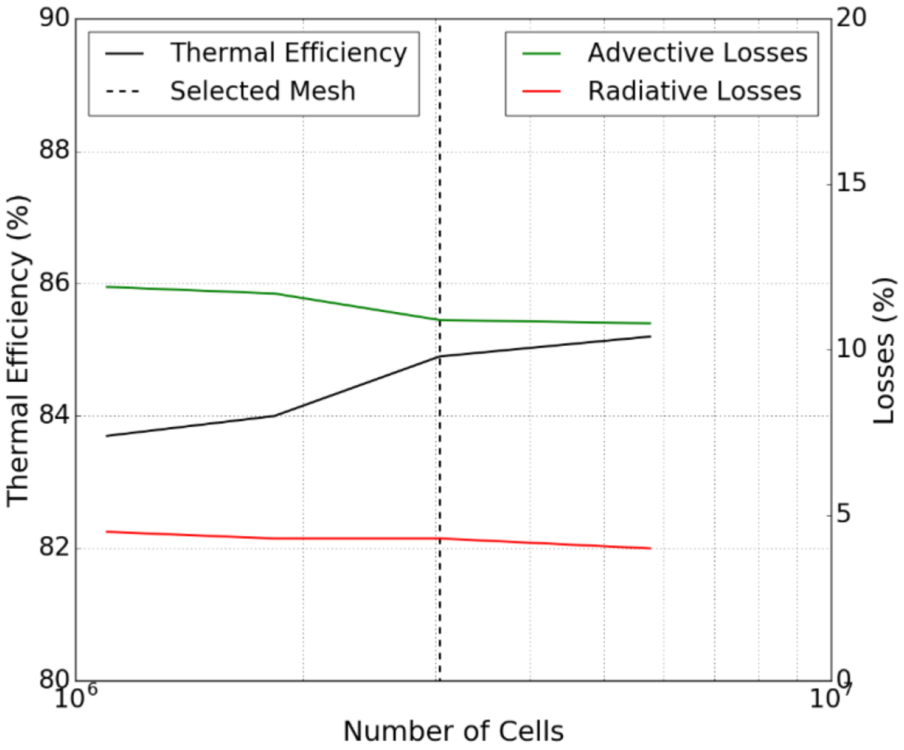
To ensure adequate mesh sizing for all FPR sizes (25 to 324 m^2), a mesh convergence study was performed for the largest receivers

- Approximately **3 million cells** were sufficient to reasonably converge

144 m^2 aperture FPR; NW wind; 10 m/s



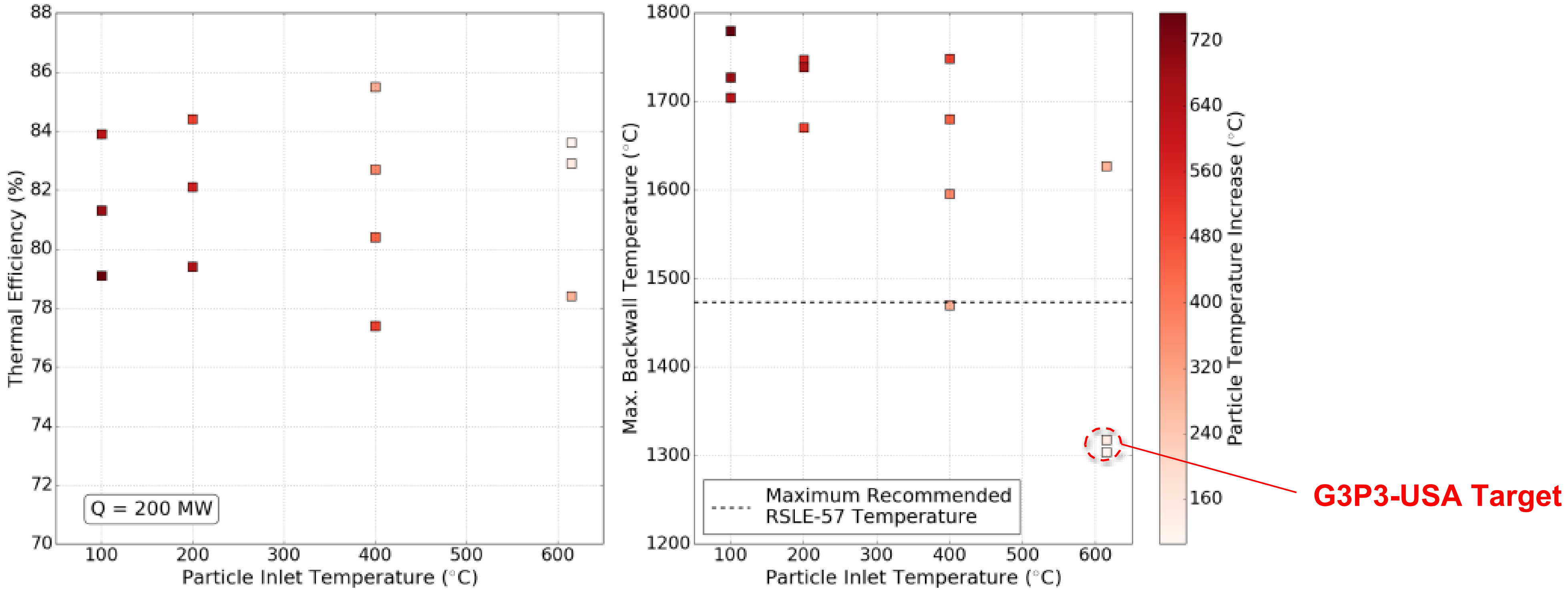
324 m^2 aperture FPR; quiescent conditions



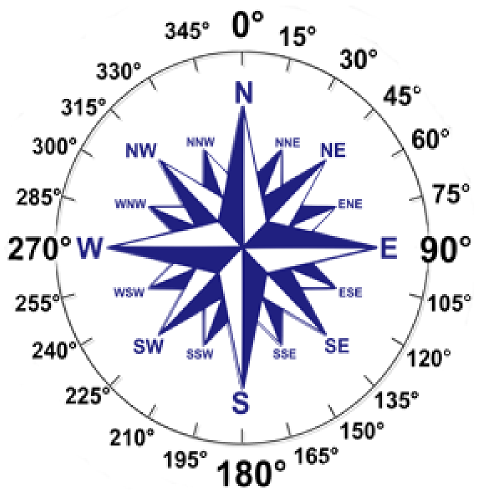
Thermal Efficiency with Particle Temperature

Particle T_i and T_o were varied to determine the effect on efficiency η

- **144 m² FPR, $Q = 200$ MW;** varied $\dot{m}$ to achieve targeted T_o in **quiescent conditions**
- Efficiency is relatively insensitive to the particle temperature
- Higher ΔT corresponds to a higher cavity back wall temperature

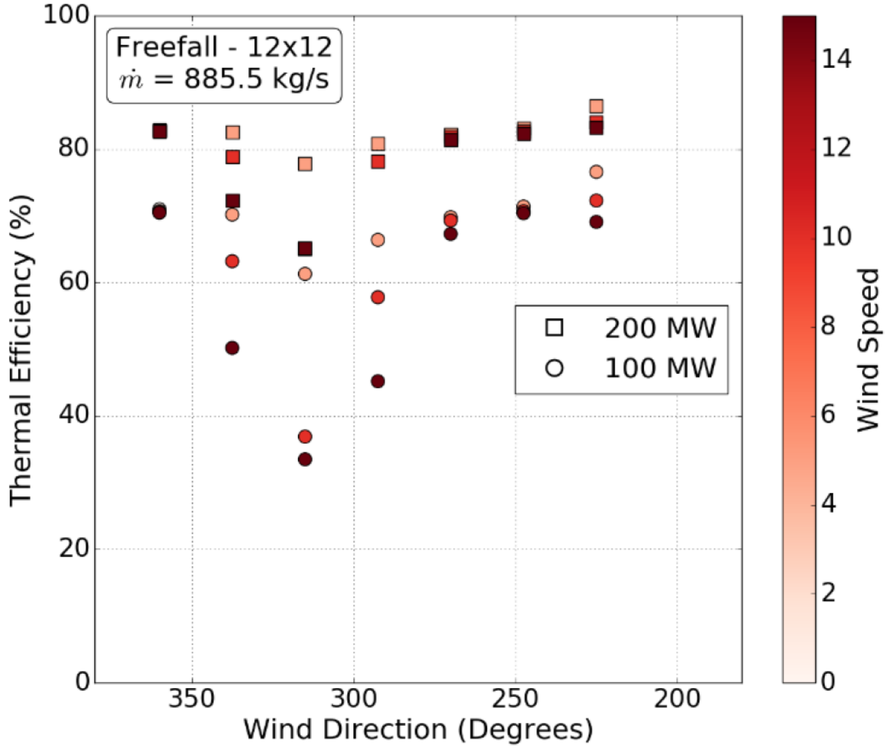


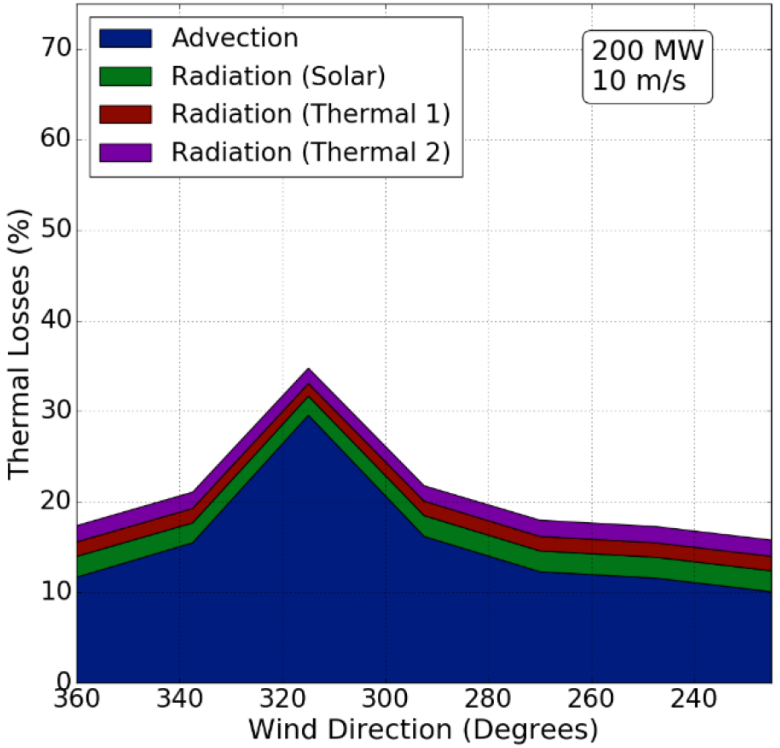
Thermal Efficiency with Wind



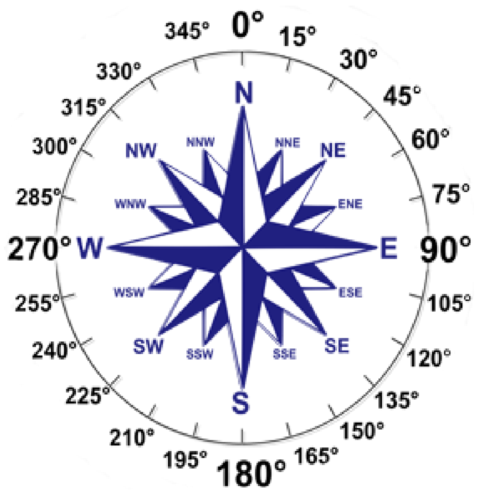
The effect of wind on the thermal efficiency η was quantified

- **144 m² FPR**, $Q = 100\text{–}200$ MW, $\dot{m} =$ **885.5 kg/s**, $T_i =$ **615°C**, $\Delta T =$ **160°C**
- Winds from the **NNW to WNW** showed the lowest efficiency
- Advective losses are the primary contribution to decreased thermal efficiency from wind



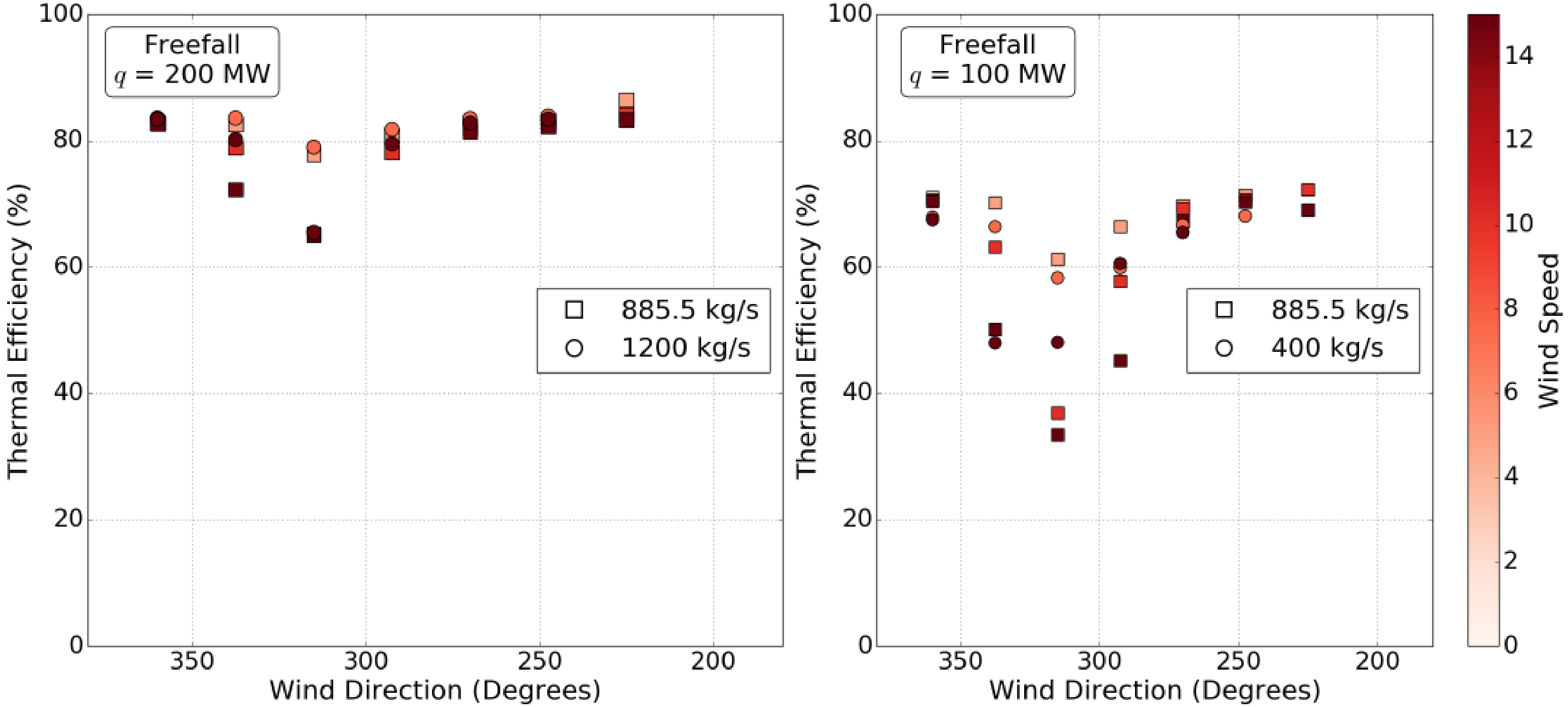


Thermal Efficiency with Mass Flow Rate



The effect of mass flow rate on the thermal efficiency η was quantified

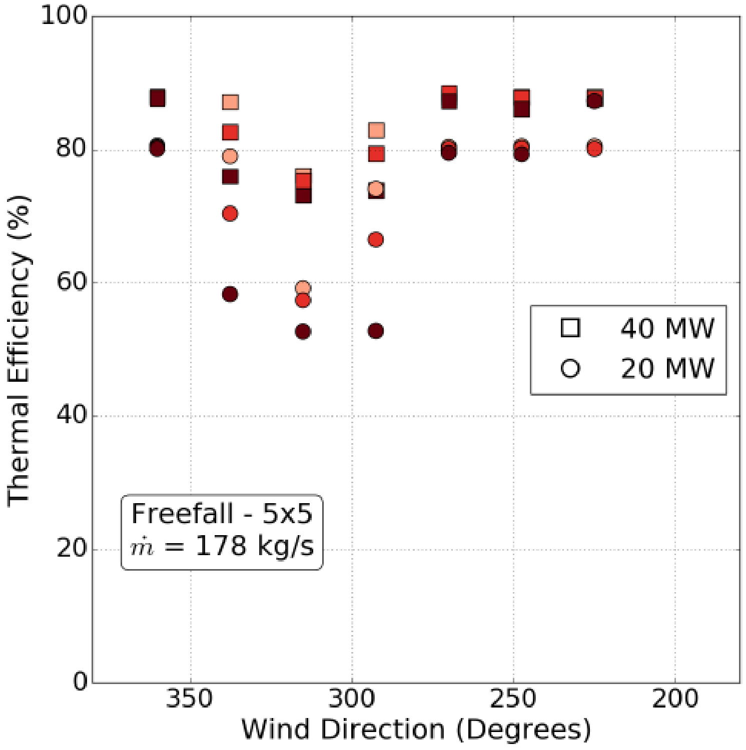
- **144 m² FPR,** $Q = 100\text{–}200$ MW, $\boldsymbol{T_i} =$ **615°C,** $\Delta \boldsymbol{T} =$ **160°C**, varied $\dot{m}$
- Efficiency is less affected by the particle mass flow rate
- At relatively low incident radiative powers, the effect is more pronounced

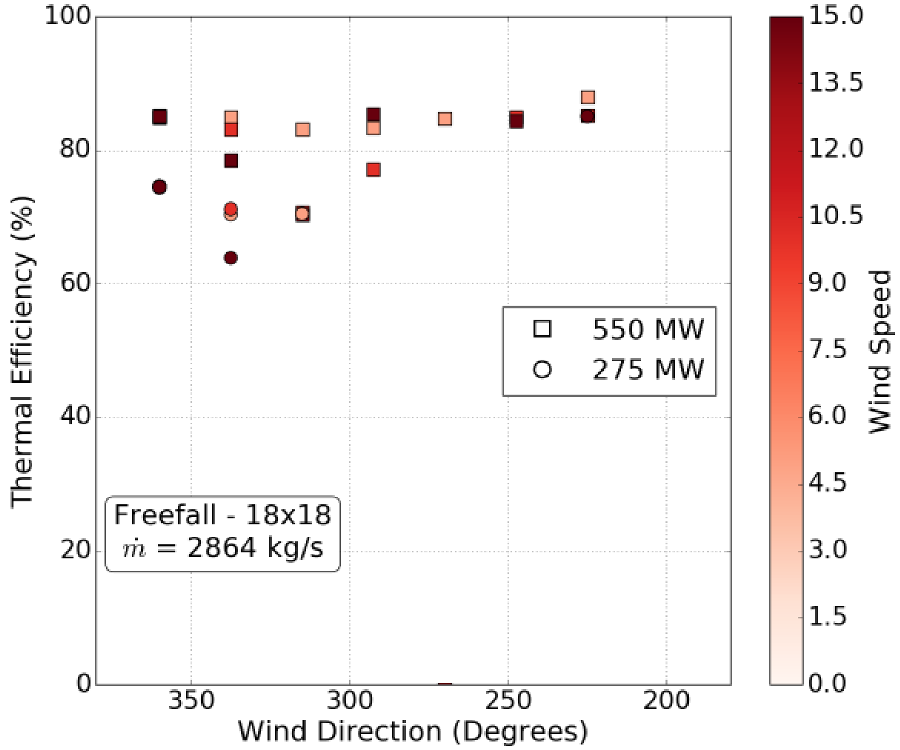


Thermal Efficiency with Receiver Scale

The receiver size (25 and 324 m^2) was varied for different wind conditions

- Values for $\boldsymbol{Q}$ and $\dot{\boldsymbol{m}}$ were adjusted to appropriate match the scale; $\boldsymbol{T_i} = \mathbf{615°C}$, $\boldsymbol{\Delta T} = \mathbf{160°C}$
- Similar results were found among all three FPR scales
- The average incident radiative flux $\boldsymbol{q''}$ was more relevant than the scale





Size (m^2)	Q (MW)	q'' (MW/m^2)	η^* (%)
25	20	0.8	80.6
25	40	1.6	88.0
144	100	0.69	71.0
144	200	1.39	82.9
324	275	0.85	74.6
324	550	1.70	84.9

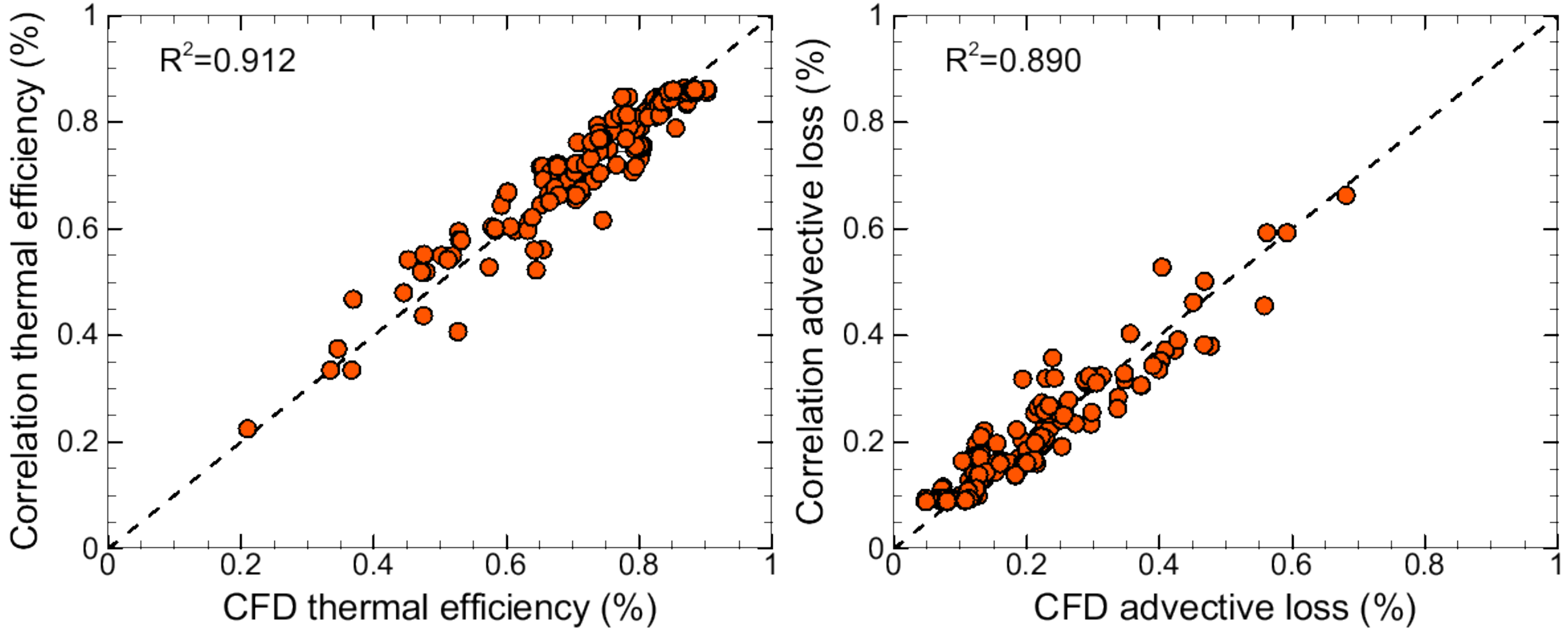
***Quiescent Conditions**

Correlation Development

- Incident solar power ($\boldsymbol{Q}$), wind speed ($\boldsymbol{U_w}$), wind direction ($\boldsymbol{\theta_w}$), and aperture area ($\boldsymbol{A_p}$)
- Correlation function: $A + B\tilde{q} + C\tilde{q}^2 + D\tilde{q}U_w\Theta + E{U_w}^2\Theta$

$$\text{where} \quad \Theta = \frac{(180-|\theta_w-180|)^F}{H}\exp\left[-\left(\frac{180-|\theta_w-180|}{G}\right)\right] \quad \text{and} \quad \tilde{q} = e^{-Q/A_p}$$

- A similar correlation has been develop for multistage, utility-scale FPRs (J. B. Lee's presentation)



	Efficiency		Advective Losses	
A				
B	0.8481	0.0993	0.9351	0.0021
C	0.2498	-0.1899	-0.0560	0.1166
D	-1.0116	0.7733	-0.5519	0.2940
E	-7.9429×10^{-5}	8.0952×10^{-5}	-6.4055×10^{-5}	7.1750×10^{-5}
F				
G	-1.4575×10^{7}	1.6878×10^{7}	-3.1344×10^{-6}	2.7996×10^{-6}
H	5.5	5.5	5.0	5.0
	7.5	7.5	9.1	9.1

Summary and Conclusions

A parametric study was executed to quantify the efficiency of utility scale FPRs subject to **anticipated operating and environmental conditions**

- Varied: receiver size, particle inlet and outlet temperature, particle mass flow rate, incident radiative power, and wind conditions

The most relevant parameters to the thermal efficiency included the wind direction, wind speed, and average incident flux

A new correlation was developed for utility-scale FPRs to inform technoeconomic models of the particle-based CSP facilities

Acknowledgements

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Questions?