Gas-Particle System: LCOE Analysis and System Design Optimization

2021 GEN3 Workshop

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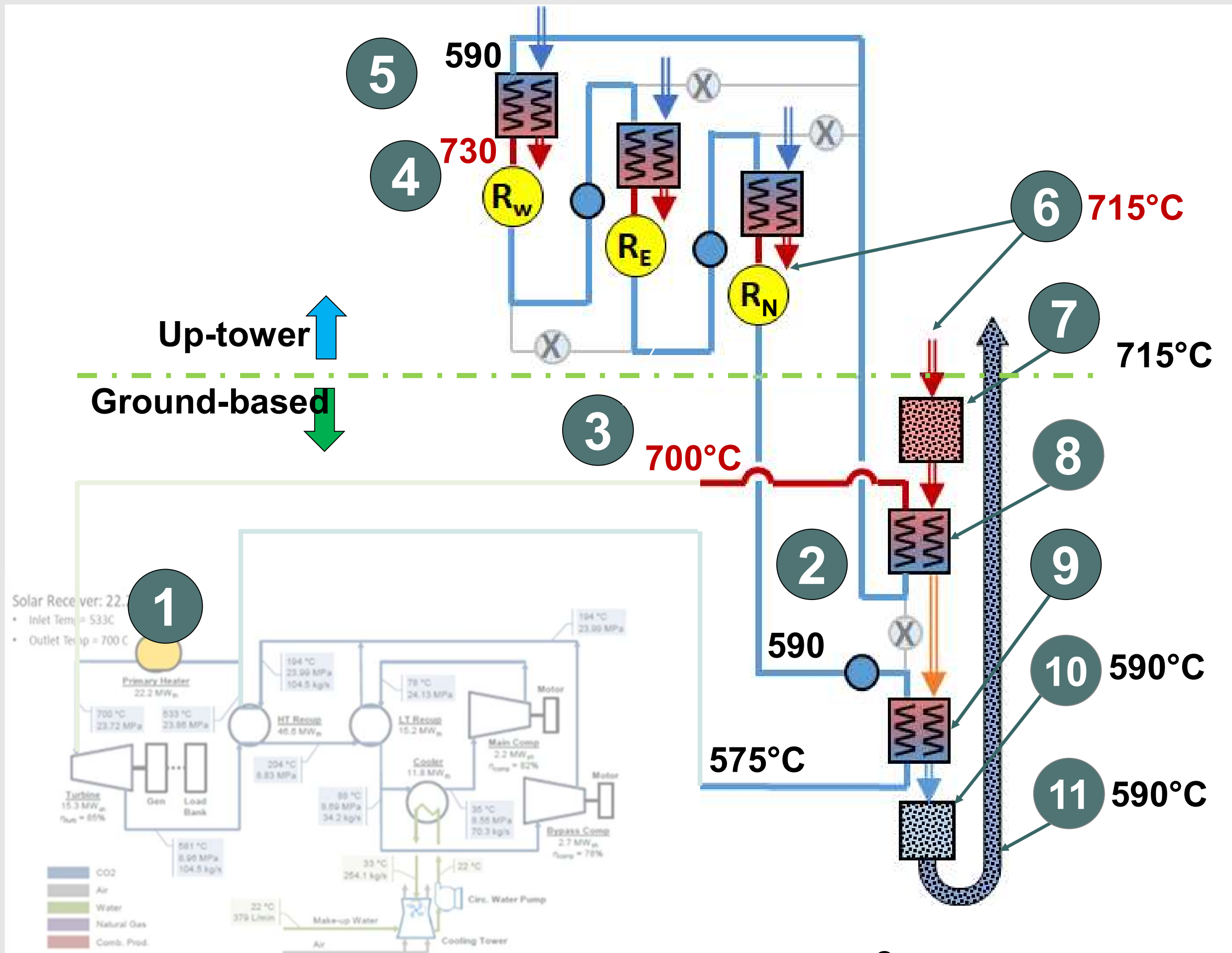
Baseline Gen3 System (Baseload)

1. RCBC sCO_2 power block
2. Low temp. high press. sCO_2 piping
3. Low temperature flow valves
4. TES charging receivers
5. TES charging heat exchangers
6. TES low pressure particle shaft
7. TES hot particle storage silo
8. High temp. TES discharge heat exchanger
9. Low temp. TES discharge heat exchanger
10. TES cold particle storage silo
11. TES particle lift

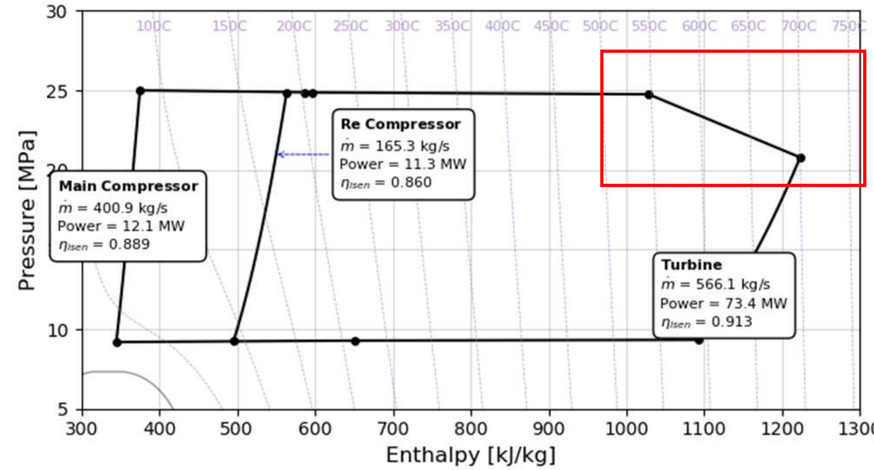
- Mass flow is dictated by power block
- Heat input is constrained by peak allowable receiver material temp.
- Control parameters shown in red

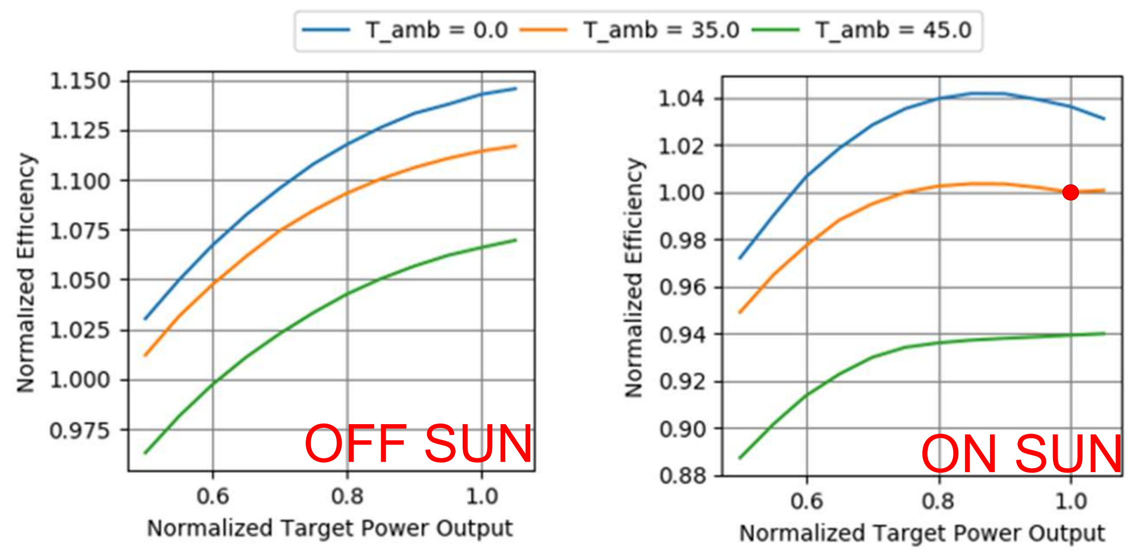


Modeling sCO2 cycle integrated w/ receiver

- Direct integration w/ CO2 receiver causes large ΔP (~15%) in design cycle
  - Compressor ΔP ~15% > Turbine ΔP
- Off-sun ΔP significantly smaller (<1%)
  - Compressor ΔP ~=Turbine ΔP
- Balancing turbomachinery to achieve higher efficiencies off-sun requires active cycle control
  - Modeling inventory control
  - May be able to reduce required inventory w/ compressor shaft speed control
- Higher off-sun efficiencies can result in unintuitively higher annual capacity factors

https://github.com/NREL/SAM/blob/develop/samples/CSP/sco2_analysis_python_V2/example/User_Guide.pdf





Design Optimization Methodology

- 11 optimization variables identified
- 24 key functions and correlations dependent on these variables were developed
- Incorporate all variables and functional relationships into SAM
- Develop wraparound code for optimization
  - Because of their non-continuous nature, 4 basic configurations formed the basis of the analysis:
    - **Particle Transport**: Skip Hoist, Bucket Elevator
    - **Field Layout**: North Field, Surround Field

FUNCTIONS AND CORRELATIONS	
Baseline System Availability	%
Receiver Efficiency	%
Receiver Pressure Drop	%
Receiver Specific Cost	$\$/kW_t$
TES Heat Exchanger Cost	$/UA
TES Heat Exchanger DP	%
Power Block Efficiency	%
Power Block Cost	$\$/kW_e$
Tower Cost	$/m
Foundation Cost	$/m
Permitting Cost (Height)	$/m
Permitting Cost (Power)	$\$/kW_e$
Permitting Cost (O&M)	$/yr
Media Transport Power	kW_e
Media Transport Cost	$
Media Transport Availability	%
Balance of TES System Cost	$
Solar Field Efficiency	%
Solar Field Area	m^2
Solar Field Cost	$\$/m^2$
Riser/Down-Comer Cost	$
EPC Costs	$
O&M Labor Costs	$/yr
O&M Non-Labor Costs	$/yr

OPTIMIZATION VARIABLES	
Cycle design gross power	MW
Solar multiple	-
Tower height	m
Design-point DNI	W/m2
Receiver absorber height	m
Tube outer diameter	in
Riser pipe diameter	m
Down-comer pipe diameter	m
Hours full-load storage	hours
Charge HX approach temp.	deg C
Discharge HX approach temp.	deg C

Design Optimization Process

Goal: find set of design parameters that minimize LCOE

Many random starting points used in parallel to identify global optimum

Initial random guess for design variables “$\underline{x}$”

Enforce variable constraints on guesses to ensure simulation stability

Calculate remaining physical plant design from optimization variables

Simulate annual performance w/ “SAM”

Calculate costs (including O&M)

Calculate LCOE w/ single owner model

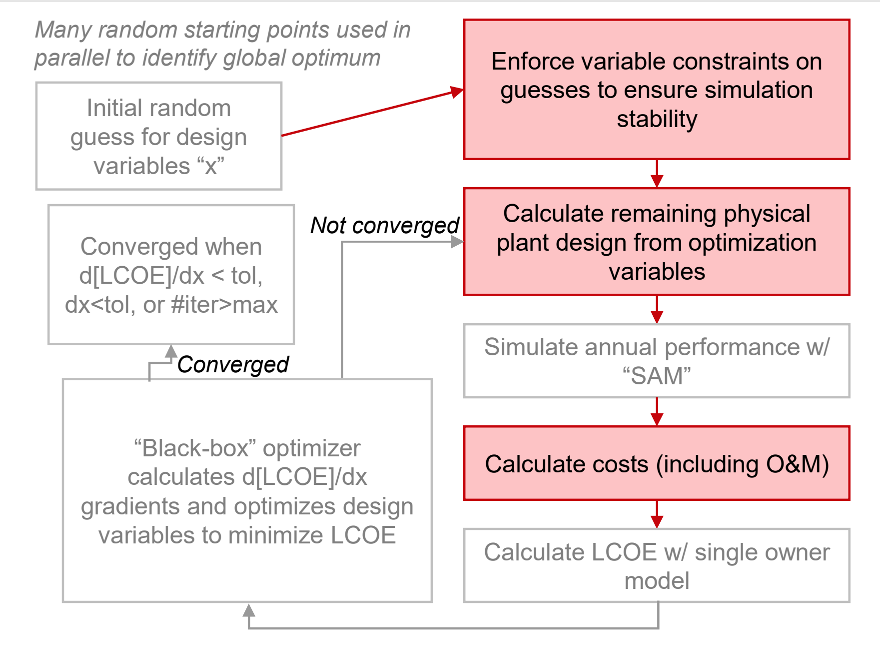
“Black-box” optimizer calculates d[LCOE]/d$\underline{x}$ gradients and optimizes design variables to minimize LCOE

Not converged

Converged

Converged when d[LCOE]/d$\underline{x}$ < tol, d$\underline{x}$<tol, or #iter>max

Variables and Constraints



Design Parameter	Units	Lower bound	Upper bound
Cycle design gross power	MW	50	120
Solar multiple	-	2.2	3.2
Tower height	m	50	200
Design-point DNI	W/m2	650	1200
Receiver absorber height	m	2	7
Tube outer diameter	in	0.25	0.375
Riser pipe inner diameter	m	0.3	0.75
Down-comer pipe inner diameter	m	0.3	0.75
Hours full-load storage	hours	4	20
Charge HX approach temp.	deg C	10	40
Discharge HX approach temp.	deg C	10	40

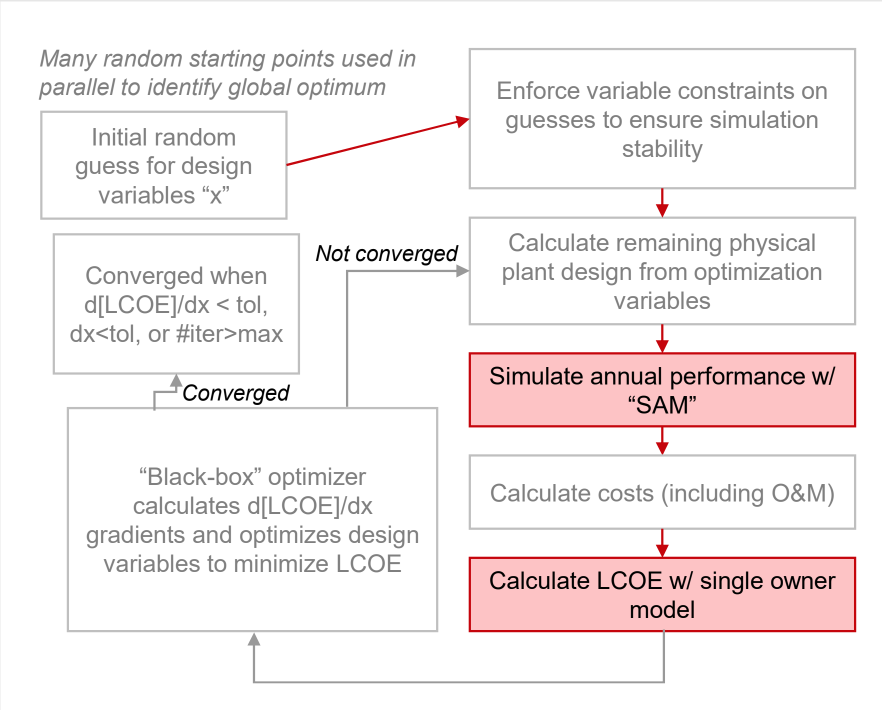
Constrained guess values

- Solar multiple (< max total receiver thermal power); Tube outer diameter; Riser/down-comer pipe diameter

Calculated design information

- Receiver dimensions, field size, optical and thermal efficiency, pressure drop; Cycle inlet temperature and efficiency; Physical size of TES
- Solar field and receiver lookup tables specific to tower height, thermal rating
- Capital costs

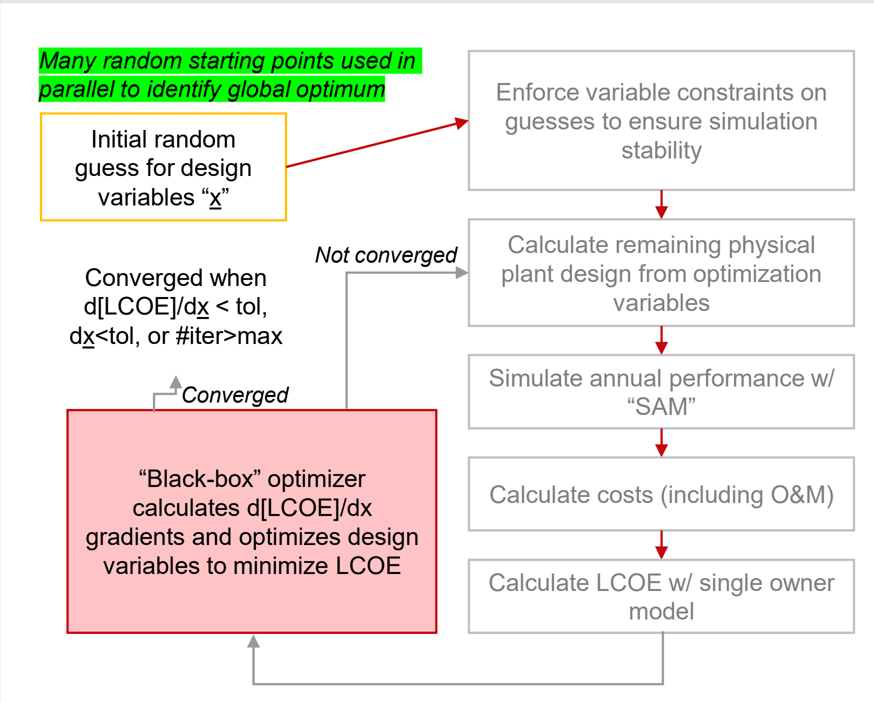
Objective Function Evaluation



Annual Simulation

- Implement detailed component model behavior with multi-dimensional lookups / reduced order models
  - Field optical efficiency vs solar position, tower height, power rating
  - Receiver thermal efficiency and pressure loss vs inlet temperature and mass flow rate
  - Cycle off-design performance
- Leverage SAM's annual simulation framework to control TES and startup/shutdown operations
- Use SAM's single-owner financial model to calculate LCOE

Moving Through the Design Space



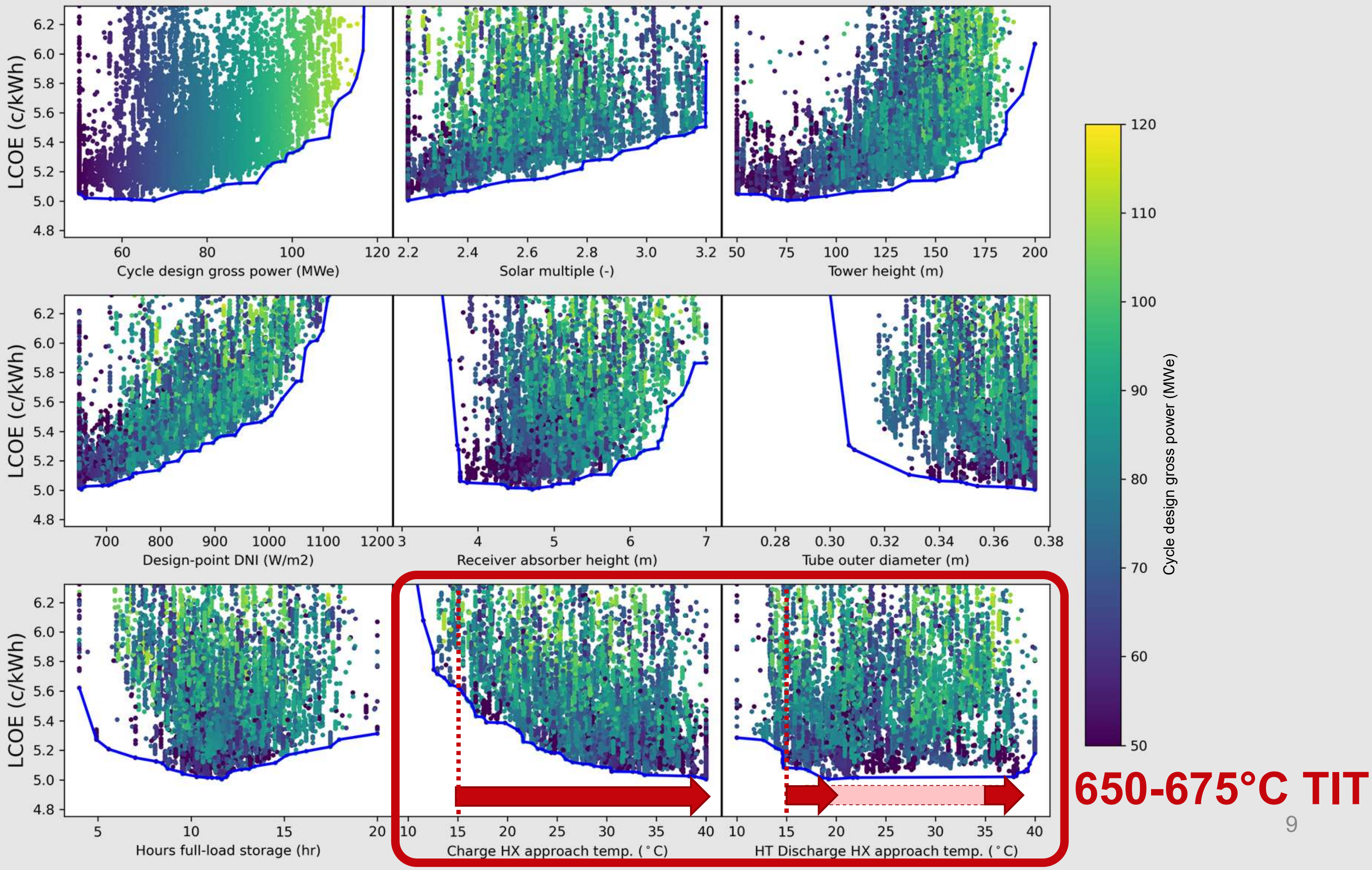
"Black-box" optimizer

- Objective function derivatives not explicitly known
- Local nonlinear optimization (SLSQP)
- Custom objective penalty function to maintain minimum receiver heights as function of receiver power and tube diameter

Random starting points

- Design optimization is nonlinear and non-convex, so need to try optimization from a large number of random starting points
- Approach generates lots of data to plot design parameter relationships

Baseload Configuration Pareto Fronts



Baseload Optimal Design

Design variable	Units	Optimal Value
Cycle design gross power	MW	83.0
Solar multiple	-	2.2
Tower height	m	110.7
Design-point DNI	W/m2	650
Receiver absorber height	m	4.34
Tube outer diameter	in	0.375
Riser pipe inner diameter	m	0.40
Down-comer pipe inner diameter	m	0.40
Hours full-load storage	hours	11.4
Charge HX approach temp.	deg C	31.0
Discharge HX approach temp.	deg C	23.3

Metric	Units	Value	MSPT (G2)
Annual energy	kWh	574,104,722	571,782,107
Capacity factor	%	87.7	63.1
LCOE (real)	c/kWh	5.03	
Subsystem and total costs:			
Site improvement	$M	15.1	
Heliostats	$M	113.3	
Tower	$M	10.7	
Receiver	$M	6.0	
Storage	$M	67.2	
Power block	$M	49.8	
Charge HX	$M	27.2	
Discharge HX	$M	12.3	
Riser	$M	4.2	
Downcomer	$M	4.3	
Contingency	$M	21.3	
Net capital cost	$M	387.6	
OM lifetime total	$M	156.6	
Analysis period	year	30	
Annual average performance:			
Field efficiency	%	41.0	51.7
Receiver efficiency	%	82.0	82.8
Cycle efficiency	%	49.6	40.2
Cycle on-sun efficiency	%	47.4	38.7
Cycle off-sun efficiency	%	51.7	41.9

- Field efficiency: Low heliostat cost, Low tower height
- Receiver efficiency: Aided by lower max. operating temperature
- Cycle efficiency: 4.3% vs 2.8% gain mostly due to reduced cycle pressure drop (MSPT efficiency result does not include salt pump parasitic)

Design Optimization – Peaker

Plant modifications for “peaker” operation

- *Indirect* configuration moves CO_2 through receiver with hot circulator
  - Removes riser and downcomer
- Combines low- and high- temperature discharge heat exchanger
- Designs cycle for much smaller pressure drop across heat input
- Plant controller forces cycle off whenever price multiplier is <= 0
- Redesigning receivers to operate in parallel rather than in series should improve peaker performance
  - Dispatch optimization would help maximize production at most valuable hours

Gen3 System (Peaker)

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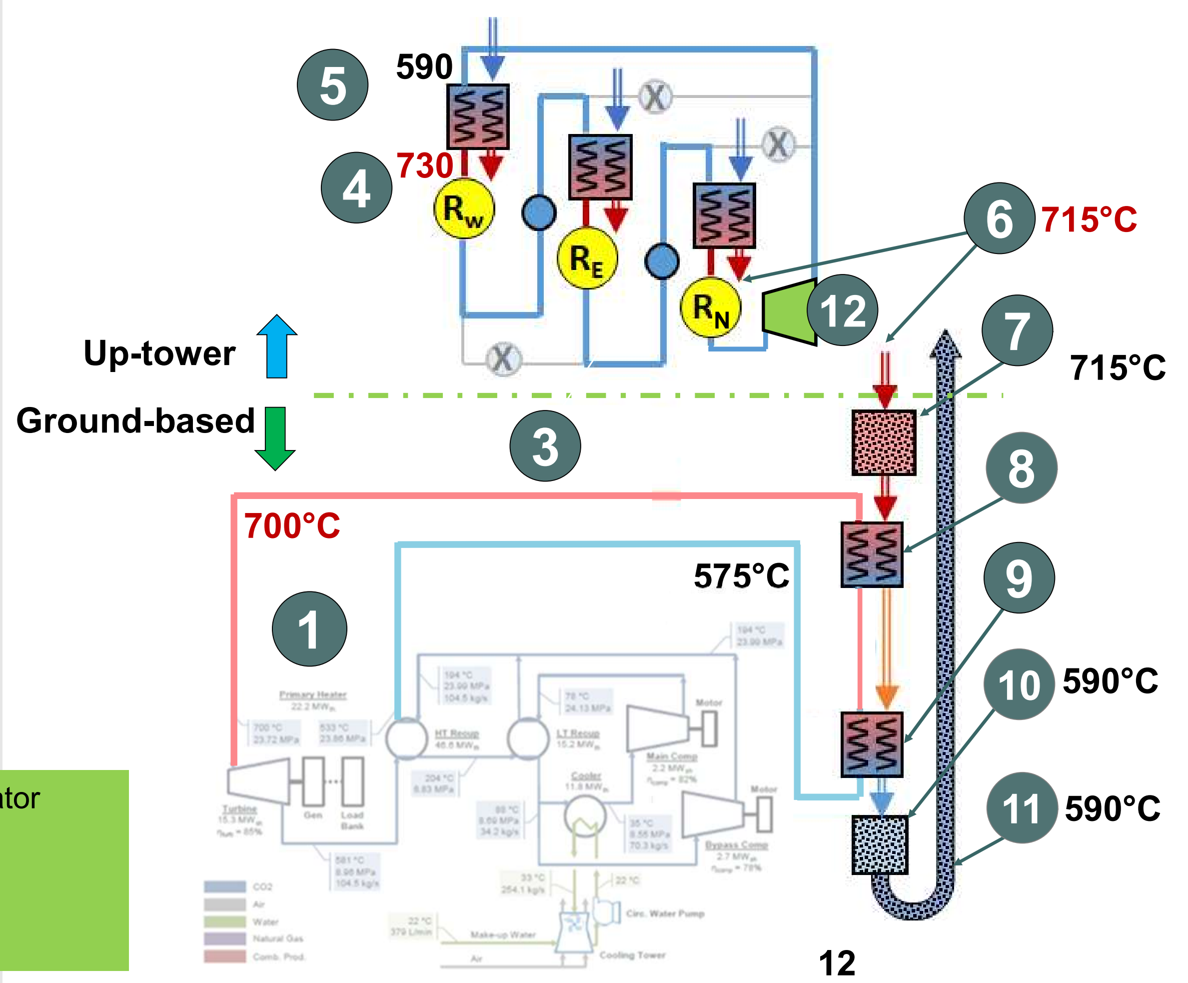
12. sCO_2 Circulator



- Receiver flow is dictated by circulator
- Heat input is constrained by peak allowable receiver material temp.
- Control parameters shown in red

Peaker Optimal Design

Design variable	Units	Optimal value
Cycle Power [MWe]	MWe	65
Solar Multiple	-	1.5
Hours of TES [hr]	hr	15.6
Receiver Height [m]	m	3.3
Tube OD [in]	in	0.375
Charge HX dT [C]	C	40
Discharge HX dT [C]	C	30
Tower Height [m]	m	70
DNI Design [W/m2]	W/m2	760

Results		
Metric	Units	Value
Unweighted annual energy	kWh	207,919,349
Capacity factor unweighted	%	40.573
Capacity factor weighted	%	113.455
LCOE (real)	c/kWh	2.83
PPA price (year 1)	c/kWh	3.403
Annual circulator energy	kWh	7,077,800
TOD1 capacity factor	%	-3.201
TOD2 capacity factor	%	97.64
TOD3 capacity factor	%	79.667
TOD4 capacity factor %	%	0

Uncertainty Analysis

- Estimated input uncertainty based on variety of sources
  - Phase 2 testing
  - Brayton TES manufacturing roadmap
  - Vendor cost estimates
  - Engineering judgment
- Assumed normal distributions on all parameters, symmetric behavior
- Performed stochastic sampling with large (N=1000) population
  - Corresponding 90% CI for population mean is $\pm$0.02 c/kWh
- Evaluated using annual performance simulation model

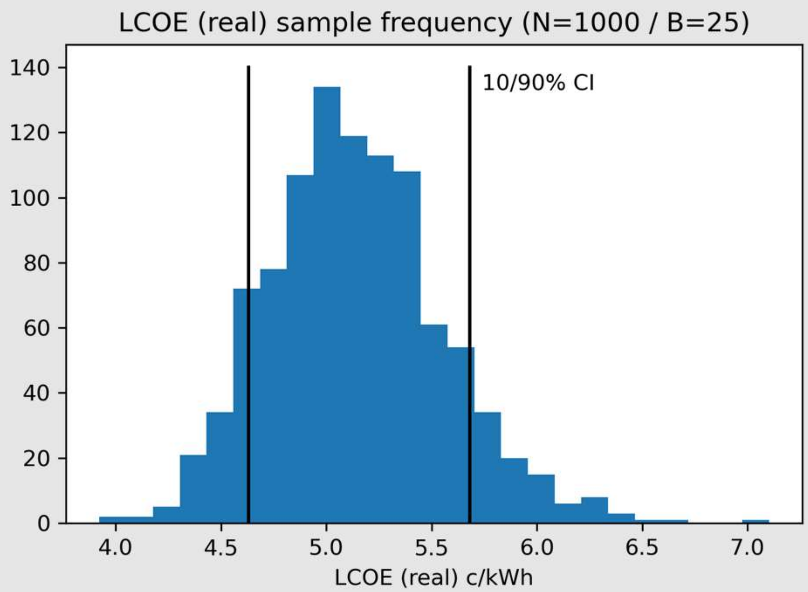
1σ standard deviation, Fraction of nominal value

LCOE Input	1-sigma estimate
Receiver thermal efficiency	0.028
Receiver pressure drop	0.318
Receiver Cost	0.3
TES HX Performance	0.15
TES Cost	0.3
Realized nominal cycle efficiency	0.055
Riser/Downcomer Specific Cost	0.3
Tower Cost	0.15
Particle Lift Cost	0.3
Particle Lift Efficiency	0.05
Particle Lift Availability	0.02
Particle Storage Cost	0.25
EPC Cost	0.10
O&M Cost	0.25

Uncertainty analysis results

Table (right) shows metrics describing system performance and cost. Shown are the nominal (mean) ***value****, the values bounding the 10 & 90% range, and the population standard deviation (1σ).*

Histogram (bottom) of the population's LCOE values, with N=1000 samples grouped into B=25 bins.



Metric	Units	Value	P10/P90	Stdev
Annual energy	kWh	574,104,722	[538,675,705 - 583,952,180]	3.4%
Capacity factor	%	87.7	[82.3 - 89.2]	3.4%
LCOE (real)	**c/kWh**	**5.03**	**[4.63 - 5.68]**	**8.2%**
Subsystem and total costs:				
Site improvement	$k	15,107	[14,644 - 15,613]	2.6%
Heliostats	$k	113,300	[109,834 - 117,101]	2.6%
Tower	$k	10,741	[8,841 - 12,804]	14.4%
Receiver	$k	5,960	[3,831 - 8,343]	29.8%
Storage	$k	67,246	[47,920 - 86,292]	22.0%
Power block	$k	49,827	-	-
Charge HX	$k	27,219	[16,353 - 37,102]	29.9%
Discharge HX	$k	12,280	[7,373 - 16,739]	29.9%
Riser	$k	4,230	[2,560 - 5,836]	29.8%
Downcomer	$k	4,315	[2,611 - 5,954]	29.8%
Contingency	$k	21,268	[19,613 - 22,950]	6.0%
Net capital cost	$k	387,588	[357,526 - 417,599]	5.9%
OM lifetime total	$k	156,567	[107,184 - 207,741]	25.2%
Analysis period	year	30		
Annual average performance				
Field efficiency	%	41		
Receiver efficiency	%	82		
Cycle efficiency	%	49.6		
Cycle on-sun efficiency	%	47.4		
Cycle off-sun efficiency	%	51.7		

Thank you!

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