



Concentrating Solar Power: Current Cost and Future Directions

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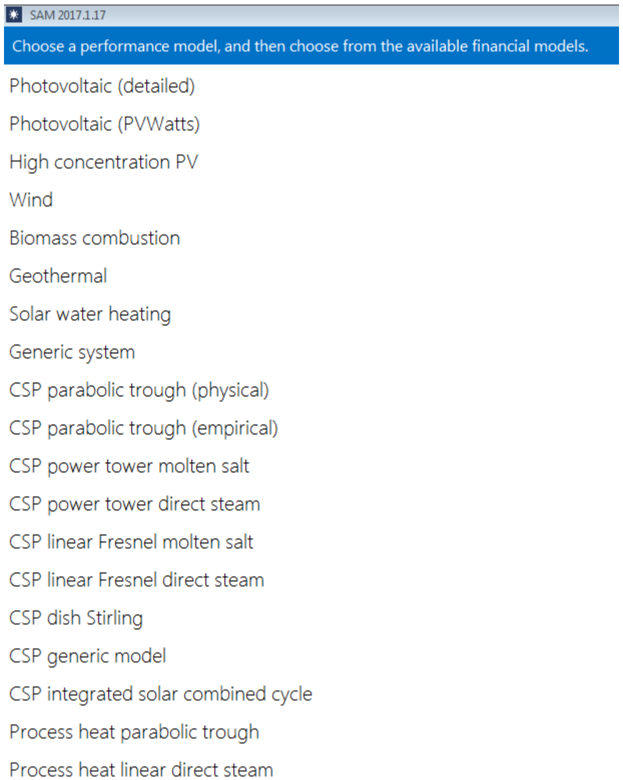
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

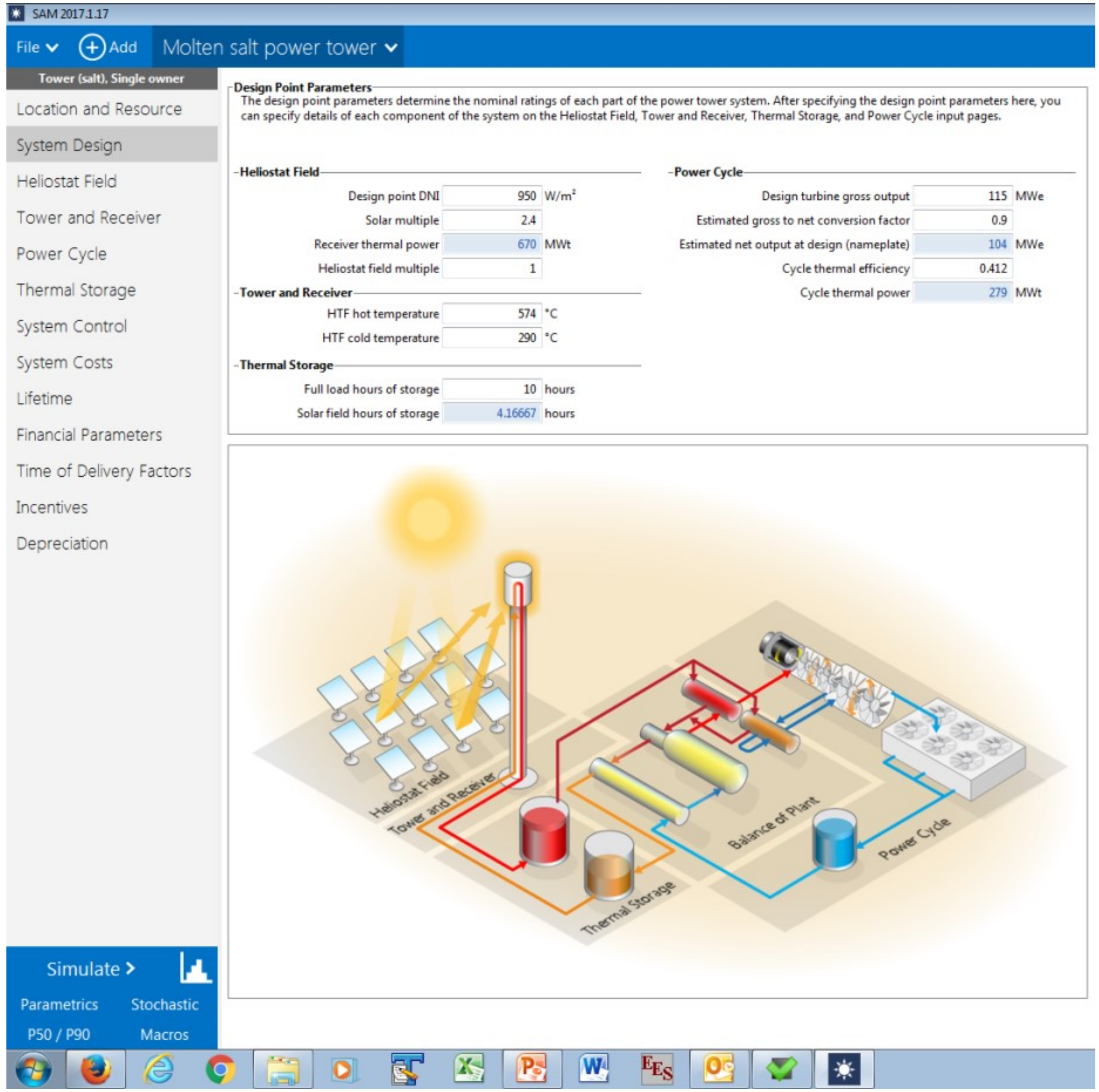
Topics

- NREL’s System Advisor Model (SAM)
- CSP costs
- CSP research directions
  - Molten salts and other heat storage media
  - Advanced power cycles
  - Plant configuration and value optimization

SAM https://sam.nrel.gov/

The System Advisor Model (SAM) is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry.





NREL 2016 CSP Cost Survey

- Questioned CSP developers and stakeholders regarding the current cost of CSP
- Values used to keep SAM's cost inputs up-to-date
- Separate sections for power tower, parabolic trough, and linear Fresnel systems

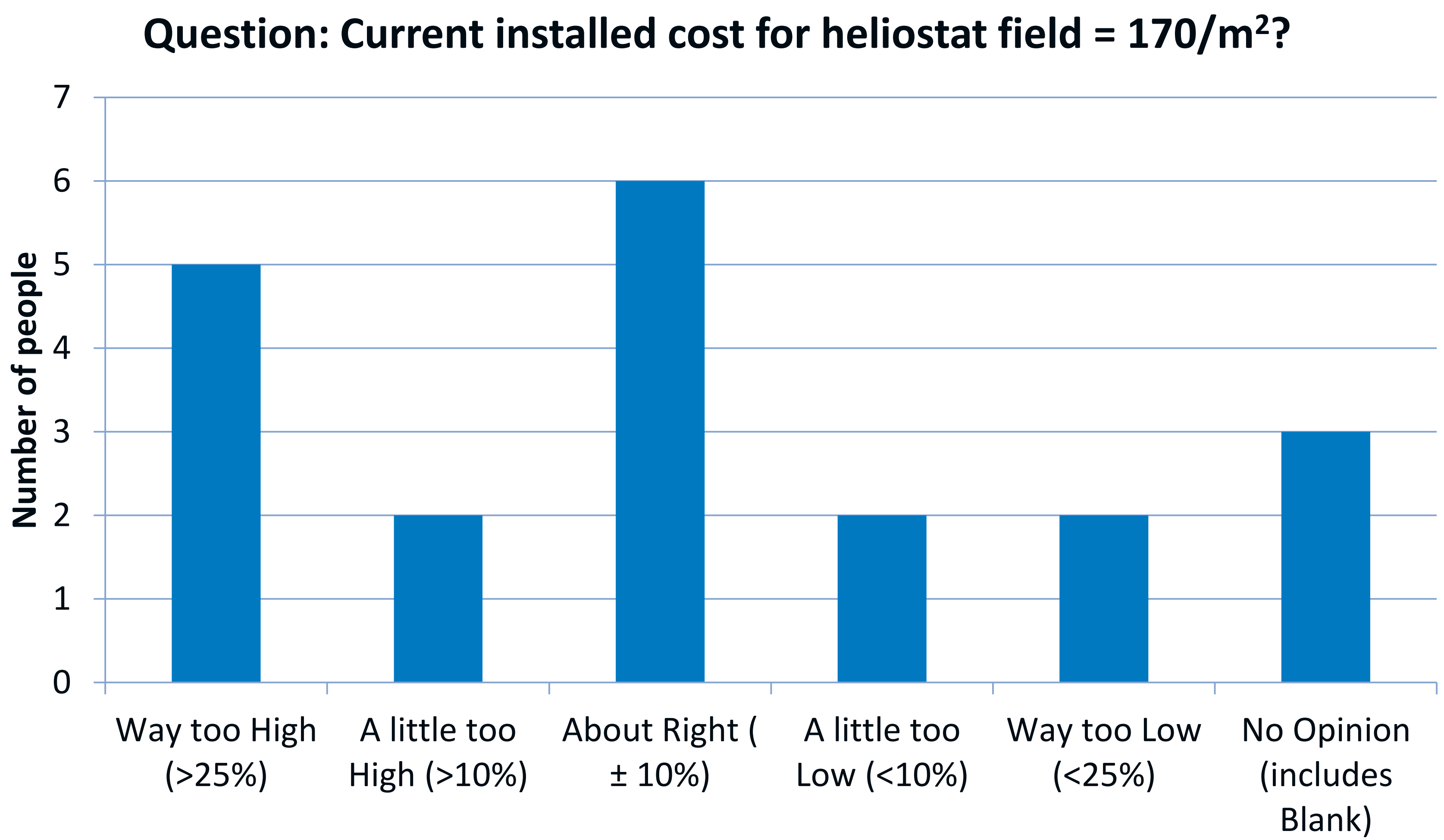
Survey	Number of respondents	Total questions	Questions with ≥ 3 responses
Power Tower	20*	32	32 (100%)
Parabolic Trough	20*	26	15 (58%)
Linear Fresnel	0	29	0

* The 20 respondents were not all the same for each technology

SAM Changes: Power Towers

Power Tower (Molten Salt and DSG)		SAM 2016	SAM 2017	Responses	Comments/Justification
Site Improvements	$/m2	16	no change	11	
Heliostat Field	$/m2	170	145	17	Wide variability in responses
Tower cost formula			no change	11	
Receiver cost formula				10	Reduce DSG by about 10%, MS by lesser amount
Receiver reference cost (MS)	$	110,000,000	103,000,000		
Receiver cost scaling exponent		0.7	no change		
Receiver reference cost (DSG)	$	55,402,800	48,800,000		
Receiver cost scaling exponent		0.7	no change		
Thermal energy storage	$/kWh-t	26	24	11	
Power cycle	$/kWe	1190	1100	12	
Balance of plant	$/kWe	340	no change	11	
Contingency	%	7	no change	15	
EPC & Owners Cost	%	11	13	13	
Sales Tax	%	5	no change	13	5% applied to 80% of direct costs
O&M Fixed cost by capacity (MS)	$/kW-yr	66	no change	7	
O&M Fixed cost by capacity (DSG)	$/kW-yr	50	55	6	
Variable cost O&M (both)	$/MWh	4	3.5	10	
Property Tax	%	0	no change	7	reviewers recommend 0-1.2%, but left at 0% to match other SAM models
Insurance	%	0.5	no change	7	
Min. turbine operation	%	25	20	10	
Max. turbine over design	%	105	no change	12	

Heliostat Field Cost



- New SAM value = $\$145/m^2$

CSP Costs: SAM 2016 vs. SAM 2017

SAM Model with default values	Total Overnight Installed Cost ($/kW)		
	SAM 2016.03.14	SAM 2017.01.17	% change
Physical Trough (6 h thermal storage)	6,705	6,065	-9.5%
Molten Salt Tower (10 h thermal storage)	7,365	6,800	-7.7%
Direct-Steam Tower (no thermal storage)	4,710	4,170	-11.5%

- Costs assume construction in the southwest region of the United States
- Applying SunShot financial assumptions (see *On the Path to SunShot*, NREL/TP-5500-65688, 2016), the lowest levelized cost of energy corresponds to the molten salt power tower with a value of approximately 110 USD/kWh.

SunShot CSP Gen3 Technology Roadmap

Collector Field

- Cost <$75/m^2
- Concentration ratio >50
- Operable in 35-mph winds
- Optical error <3.0 mrad
- 30-year lifetime

	Molten Salt	Falling Particle	Gas Phase
Receiver *Cost < $150/kWth* *Thermal Efficiency > 90%* *Exit Temperature > 720°C* *10,000 cycle lifetime*	• Similarities to prior demonstrations • Allowance for corrosive attack required	• Most challenging to achieve high thermal efficiency	• High-pressure fatigue challenges • Absorptivity control and thermal loss management
Material & Support *Cost < $1/kg* *Operable range from 250°C to 800°C*	• Potentially chloride or carbonate salt blends; ideal material not determined • Corrosion concerns dominate	• Suitable materials readily exist	• Minimize pressure drop • Corrosion risk retirement
Thermal Storage *Cost < $15/kW$_{th}$* *99% energetic efficiency* *95% exergetic efficiency*	• Direct or indirect storage may be superior	• Particles likely double as efficient sensible thermal storage	• Indirect storage required • Cost includes fluid to storage thermal exchange
HTF to sCO_2 Heat Exchanger	• Challenging to simultaneously handle corrosive attack and high-pressure working fluid	• Possibly greatest challenge • Cost and efficiency concerns dominate	• Not applicable

Supercritical CO_2 Brayton Cycle

- Net thermal-to-electric efficiency > 50%
- Power-cycle system cost < $900/kW$_e$
- Dry-cooled heat sink at 40° C ambient
- Turbine inlet temperature ≥ 700°C

Molten Salt Options for Higher Temperature Operation

Salt	Melting Point (C)	Maximum Temp (C)	Heat Capacity (J/g-K)	Density (kg/L)	Viscosity (cP)	Relative $\rho * C_p$ (-)
Solar Salt ($NaNO_3/KNO_3$)	220	~600	1.55	1.71	1.0	1.00
KNO_3	334	~650?	1.39	1.78	-	0.93
$KCl/MgCl_2$	426	>900	1.1	1.97	1.9	0.82
$KCl/NaCl/MgCl_2$	385	>900	1.1	1.94	1.6	0.81
$ZnCl_2/KCl/NaCl$	199	>800	0.92	2.08	4.5	0.72
$Na_2CO_3/K_2CO_3/Li_2CO_3$	398	~800	1.83	1.99	8.3	1.37

Physical properties estimated/measured near 600°C for comparison

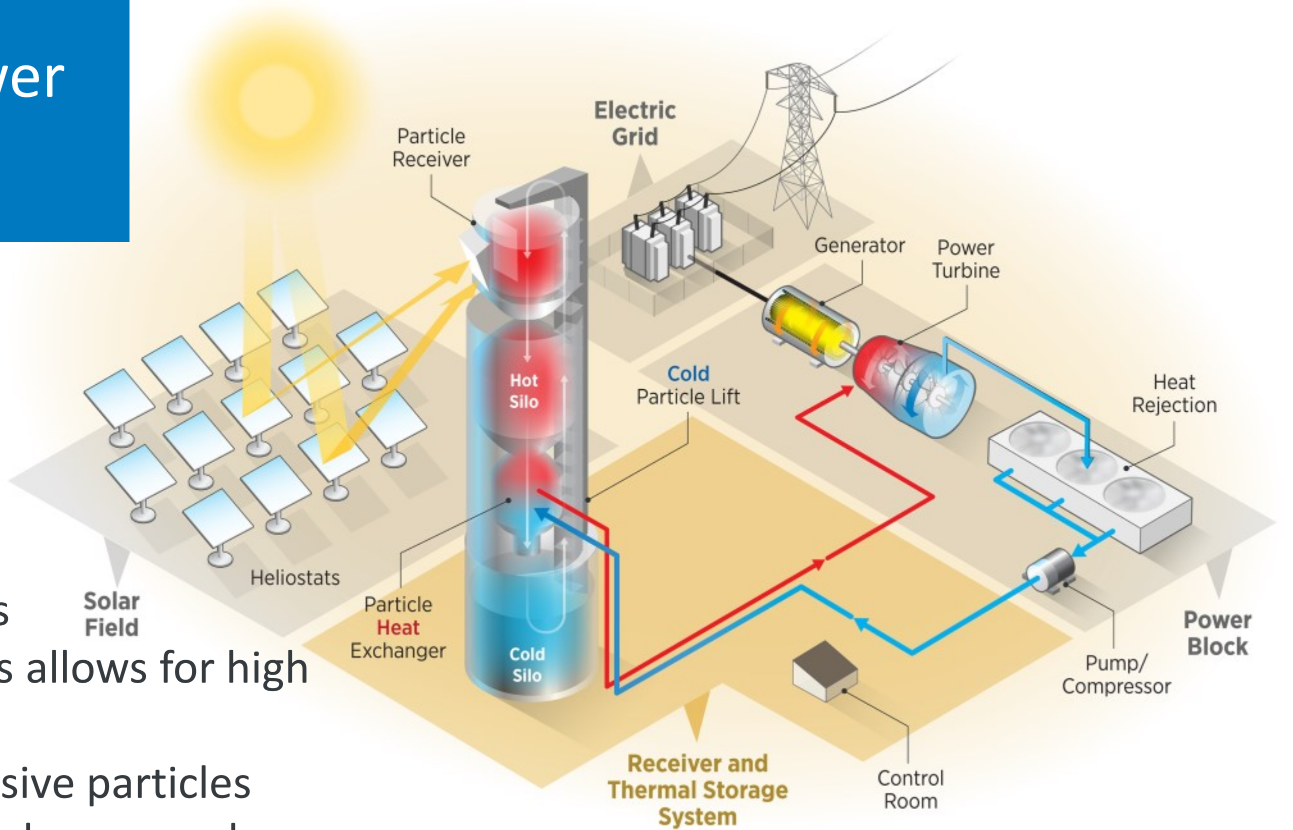
Data sources:
- Solar salt: SQM solar thermal salts factsheet
- Mg chlorides: ORNL/TM-2006/69; Serrano-Lopez et al. (2013); Gowtham Mohan et al. (2017 submitted)
- Zn chlorides: University of Arizona (private correspondence)
- Carbonates: An et al. (2016)

New Molten Salt Benefits/Challenges

Salt	Primary Benefit vs Solar Salt	Primary Challenges
KNO_3	• Slightly better thermal stability (600-650ºC)	• Slightly higher T_{mp} • Slightly higher cost
$KCl/MgCl_2$	• Lower salt cost • Better thermal stability	• Higher T_{mp} • Lower $\rho*C_p$ (i.e., larger tanks) • Corrosion
$KCl/NaCl/MgCl_2$	• Lower salt cost • Better thermal stability	• Higher T_{mp} • Lower $\rho*C_p$ • Corrosion
$ZnCl_2/KCl/NaCl$	• Slightly lower T_{mp} • Better thermal stability	• Lower $\rho*C_p$ • Corrosion • Measureable vapor pressure • Slightly higher salt cost
$Na_2CO_3/K_2CO_3/Li_2CO_3$	• Higher $\rho*C_p$ (smaller tanks) • Better thermal stability	• Higher T_{mp} • Corrosion • High salt cost (Li_2CO_3)

➢ Laboratory testing indicates Cl corrosion can be controlled if high purity is maintained in the salt melt

Falling Particle Power Tower Systems



Advantages

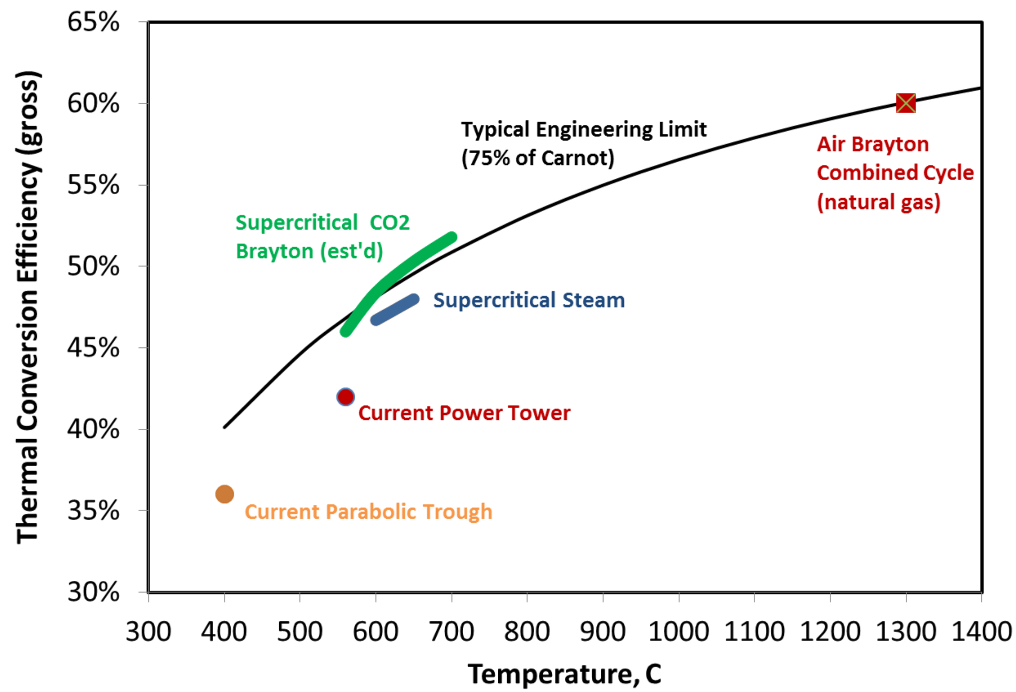
- No freezing concerns
- No trace heating
- Thermally stable particles
- Direct heating of particles allows for high flux/concentration ratios
- Direct storage of inexpensive particles
- Particle handling, heat exchange, and storage techniques well established

Challenges

- Less established within CSP industry
- Particle durability, attrition (dust emission)
- Receiver efficiency via convective/radiative and particle losses
- Increase particle/wall heat transfer
- Particle-to-sCO_2 heat exchanger at 700ºC, 20 MPa

CSP Power Cycle Development

- The supercritical-CO_2 Brayton cycle promises higher efficiency and lower installed cost versus to existing superheated steam cycle
- $100 million cost-shared project is to build and demonstrate a 10 MW_e system in Texas
- Cycle performance gains are more pronounced at higher temperatures; U.S. DOE program is targeting 700ºC turbine inlet temperature

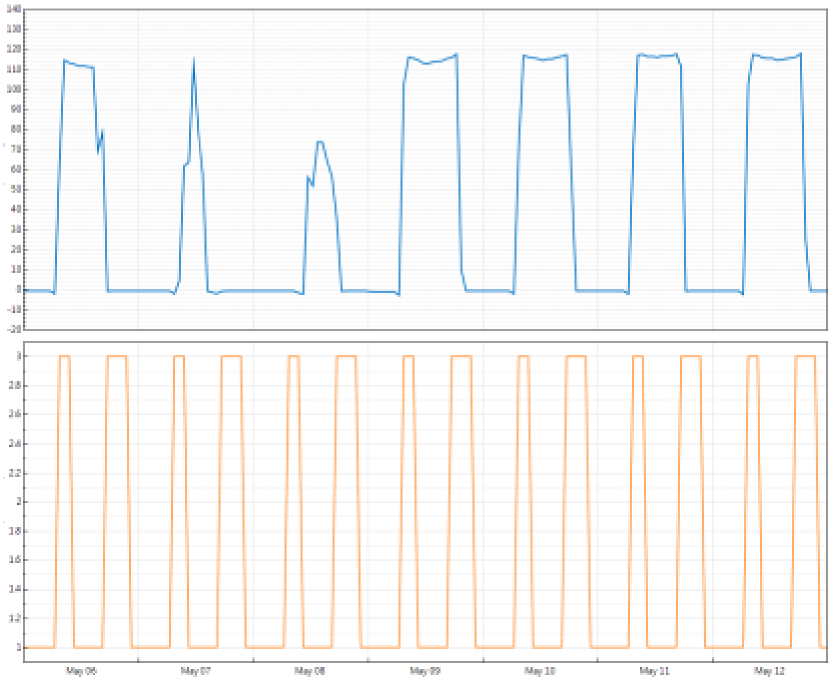


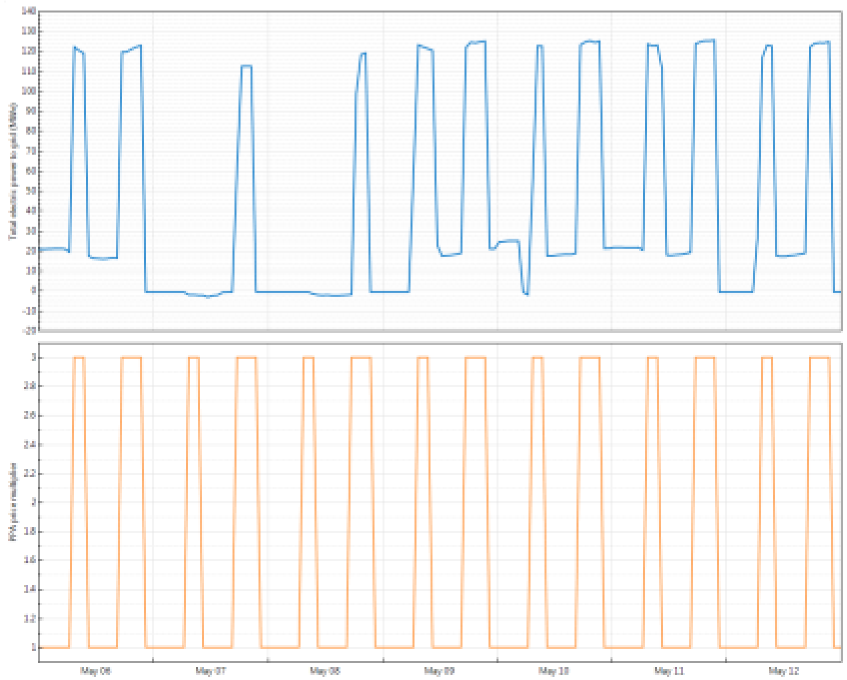
System Operation/Dispatch Optimization

Simple | **Optimized**

Power to Grid

Price signal





Metric	Simple	Optimized
Annual energy (year 1)	301,600 MWh	289,300 MWh
Levelized Cost of Energy (real)	11.9 ¢/kWh	12.4 ¢/kWh
Power Purchase Agreement price (year 1)	9.6 ¢/kWh	5.9 ¢/kWh

- Despite lesser generation, optimized dispatch produces greater value as indicated by a lower acceptable PPA price
- Matching CSP system design and dispatch to grid demand is essential

Thank you!

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sCO$_2$ Cycle Development under STEP

DOE's "STEP" project will demonstrate a 10 MW$_e$ sCO$_2$ recompression cycle

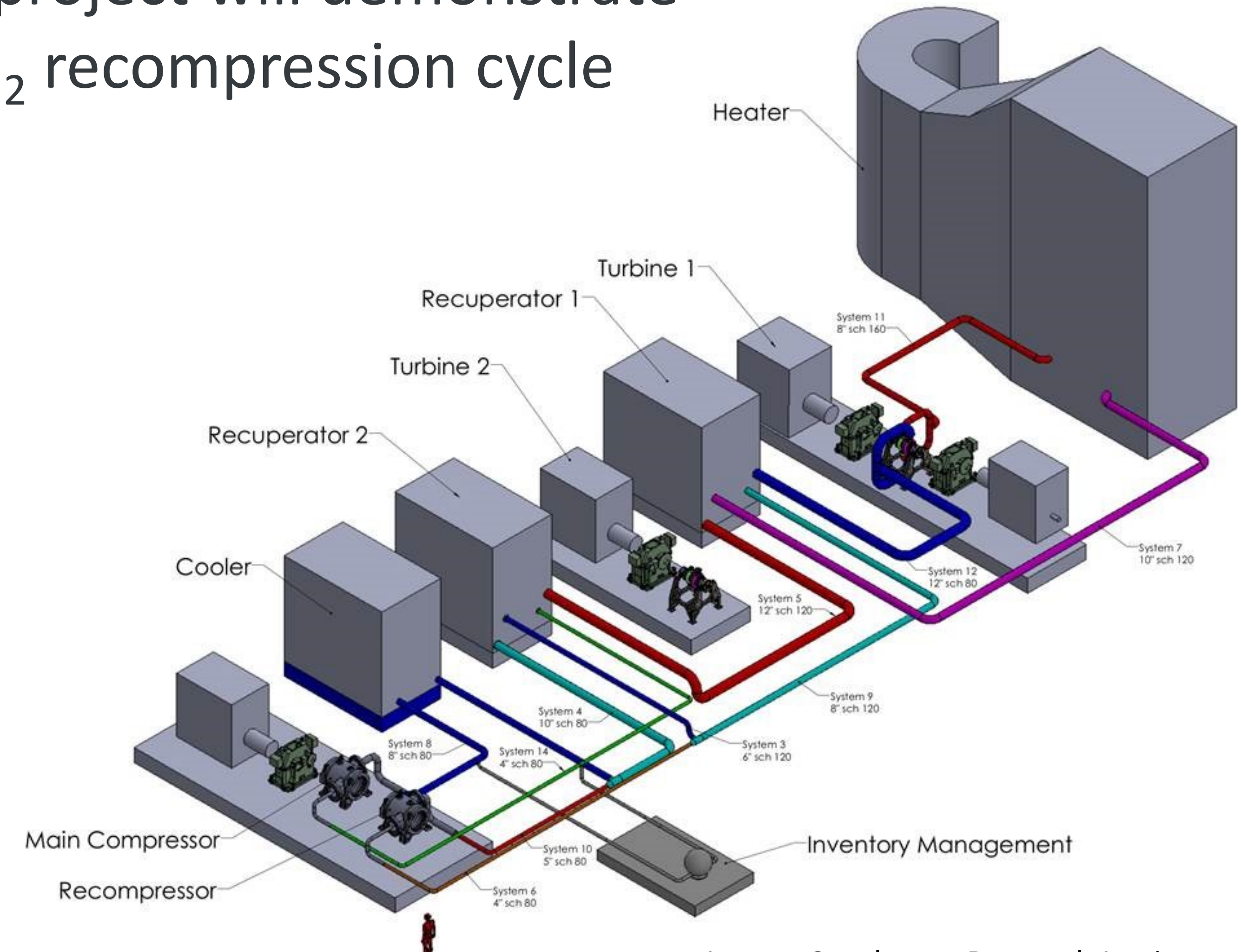


Image: Southwest Research Institute

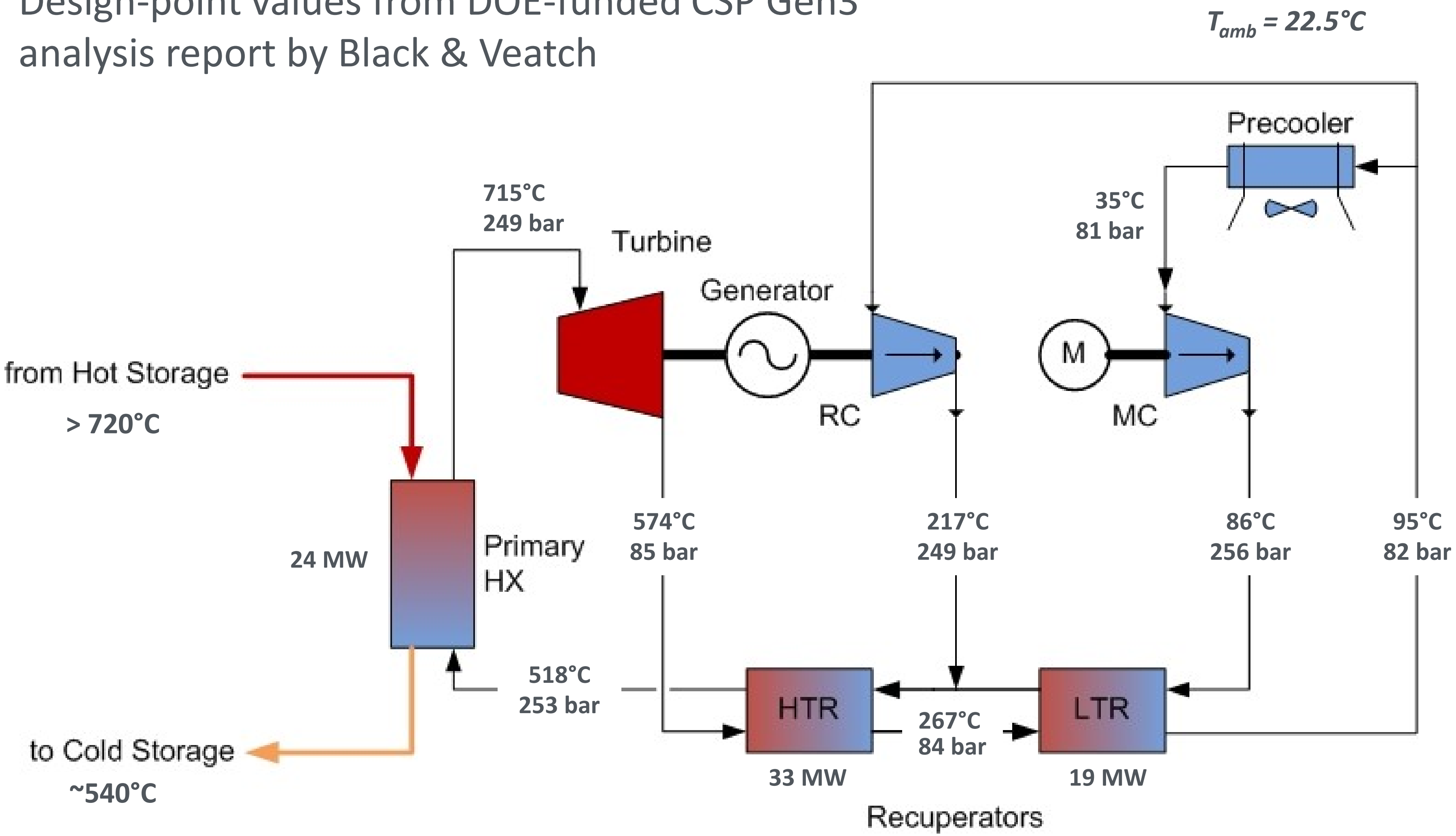
Supercritical
Transformational
Electric
Power

STEP Test Facility Attributes and Objectives

- 10 MW_e sCO_2 recompression Brayton cycle
- Turbine inlet temperature of 700°C
- Demonstrate pathway towards an overall power cycle efficiency of 50% or greater
- Reconfigurable and can monitor and characterize primary components or subsystems (turbomachinery, heat exchangers, recuperators, bearings, seals, etc.)
- Demonstrate steady state, transient load following, and limited endurance operation.
- Capable of test campaigns to assess critical component degradation mechanisms to assess component life and cost

sCO_2 Recompression Cycle

Design-point values from DOE-funded CSP Gen3 analysis report by Black & Veatch



Note: SunShot CSP plants are assumed to be dry cooled, so a higher design-point ambient temperature is likely.