# Pathways to cost competitive CSP via sc-$CO_2$ power cycles

Supercritical $CO_2$ Power Cycles Symposium; March 2016

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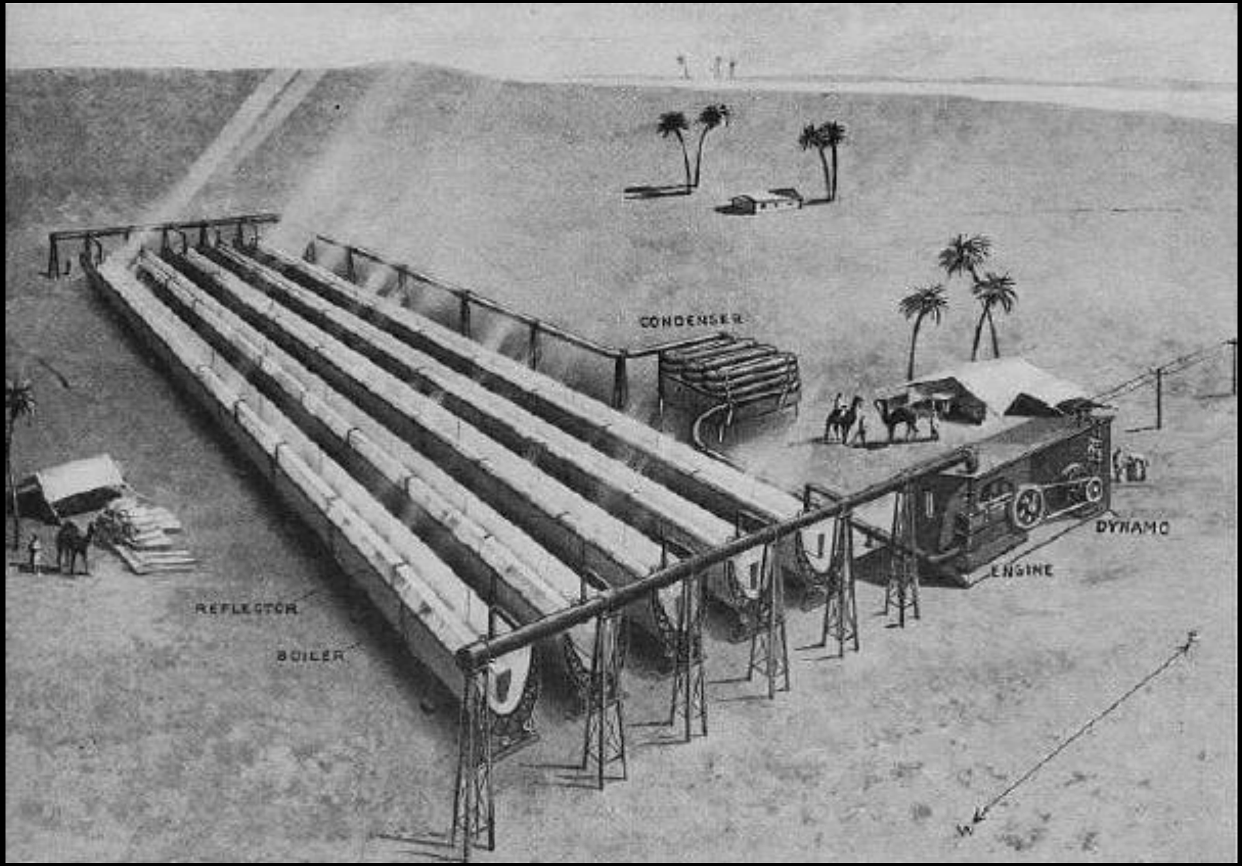
# Talk Objectives

- Brief CSP History
- Present technoeconomic metrics aligned with cost competitive CSP
  - What do these metrics mean for the power cycle?
  - What do these metrics mean for the rest of a CSP plant?
- Provide overview of technology development for third generation CSP
  - Focus on heat transfer fluid (HTF) specific pathways

# CSP: A Brief Technology History




Ragheb, M. "Solar thermal power and energy storage historical perspective." *University of Illinois at Urbana-Champaign* (2011).

Aerial View of Solana Power Block and Thermal Energy Storage

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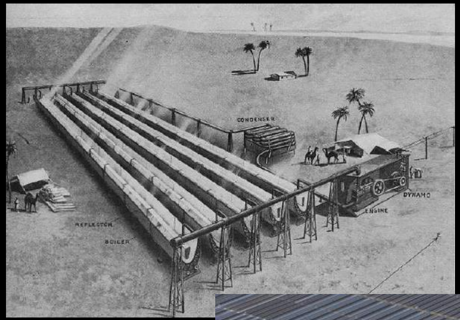
# CSP: A Brief Technology History

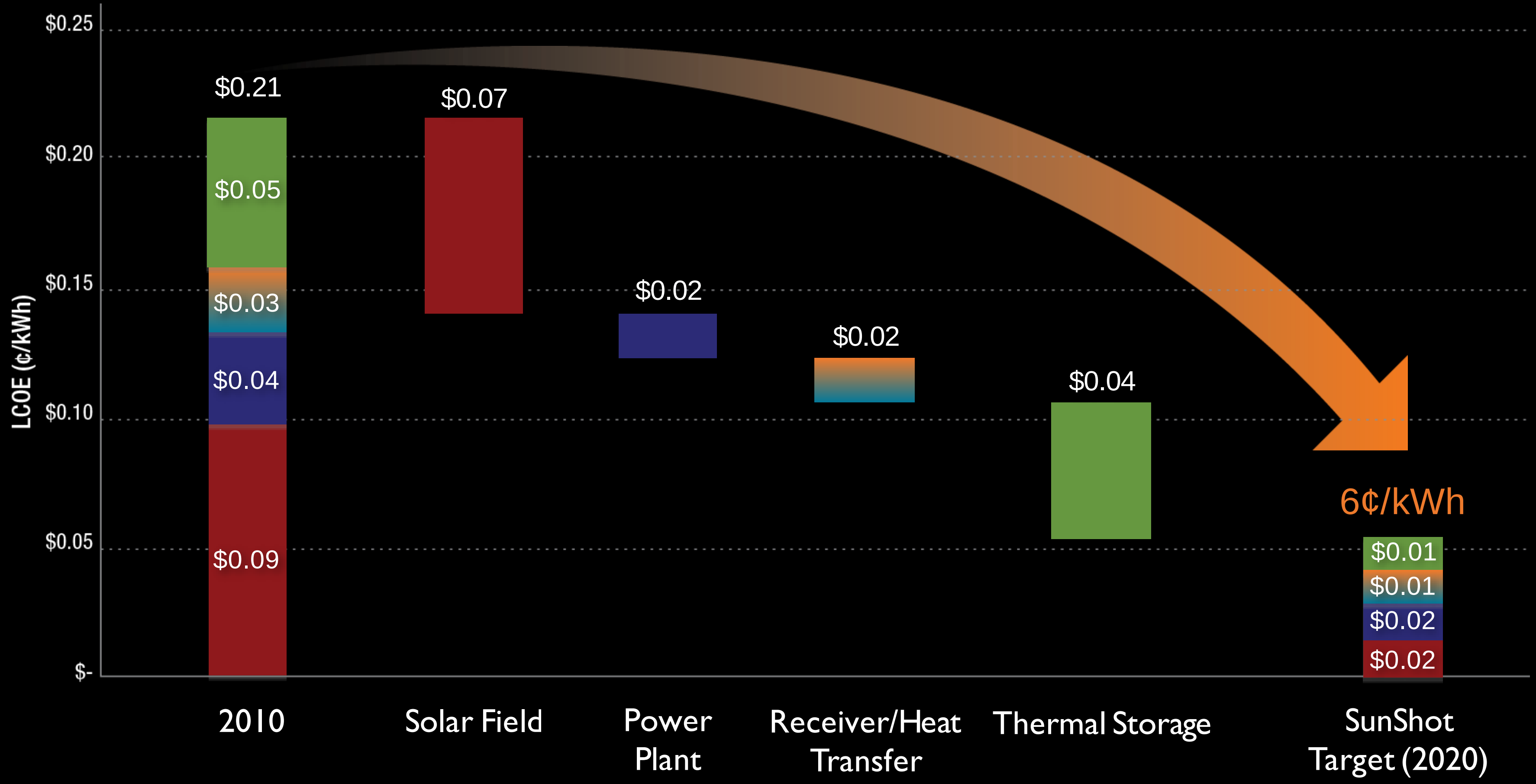
- From steam heat generation to power generation
- Collector/Receiver options have expanded
- Storage has been added
- Heat transfer fluid has evolved
- Power cycle: Rankine





Images: 1913 Maadi Egypt station, Solana, Crescent Dunes, Man Diesal & Turbo steam turbine

# SunShot CSP Cost Objective

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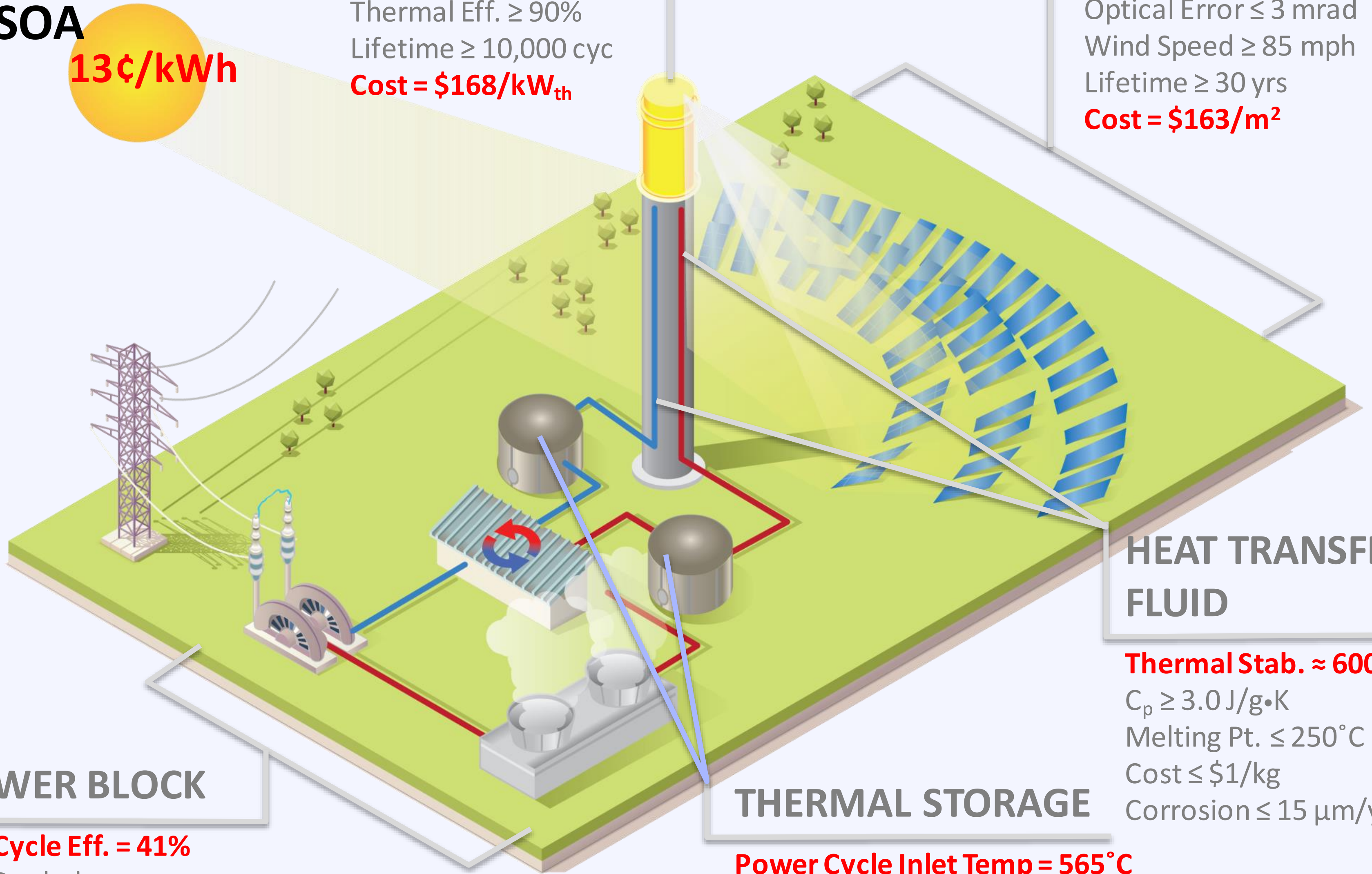
# Current Commercial SOA

**13¢/kWh**



## RECEIVER

**HTF Exit Temp = 565˚C**
Thermal Eff. ≥ 90%
Lifetime ≥ 10,000 cyc
**Cost = $168/$kW_{th}$**

## SOLAR FIELD

Optical Error ≤ 3 mrad
Wind Speed ≥ 85 mph
Lifetime ≥ 30 yrs
**Cost = $163/$m^2$**

## HEAT TRANSFER FLUID

**Thermal Stab. ≈ 600˚C**
$C_p$ ≥ 3.0 J/g•K
Melting Pt. ≤ 250˚C
Cost ≤ $1/kg
Corrosion ≤ 15 µm/yr

## THERMAL STORAGE

**Power Cycle Inlet Temp = 565˚C**
Energy Eff. ≥ 99%
Exergy Eff. ≥ 95%
**Cost = $23/$kWh_{th}$**

## POWER BLOCK

**Net Cycle Eff. = 41%**
Dry Cooled
**Cost = $1,540/$kW_e$**

***Highlighted values are based on current commercial deployments***

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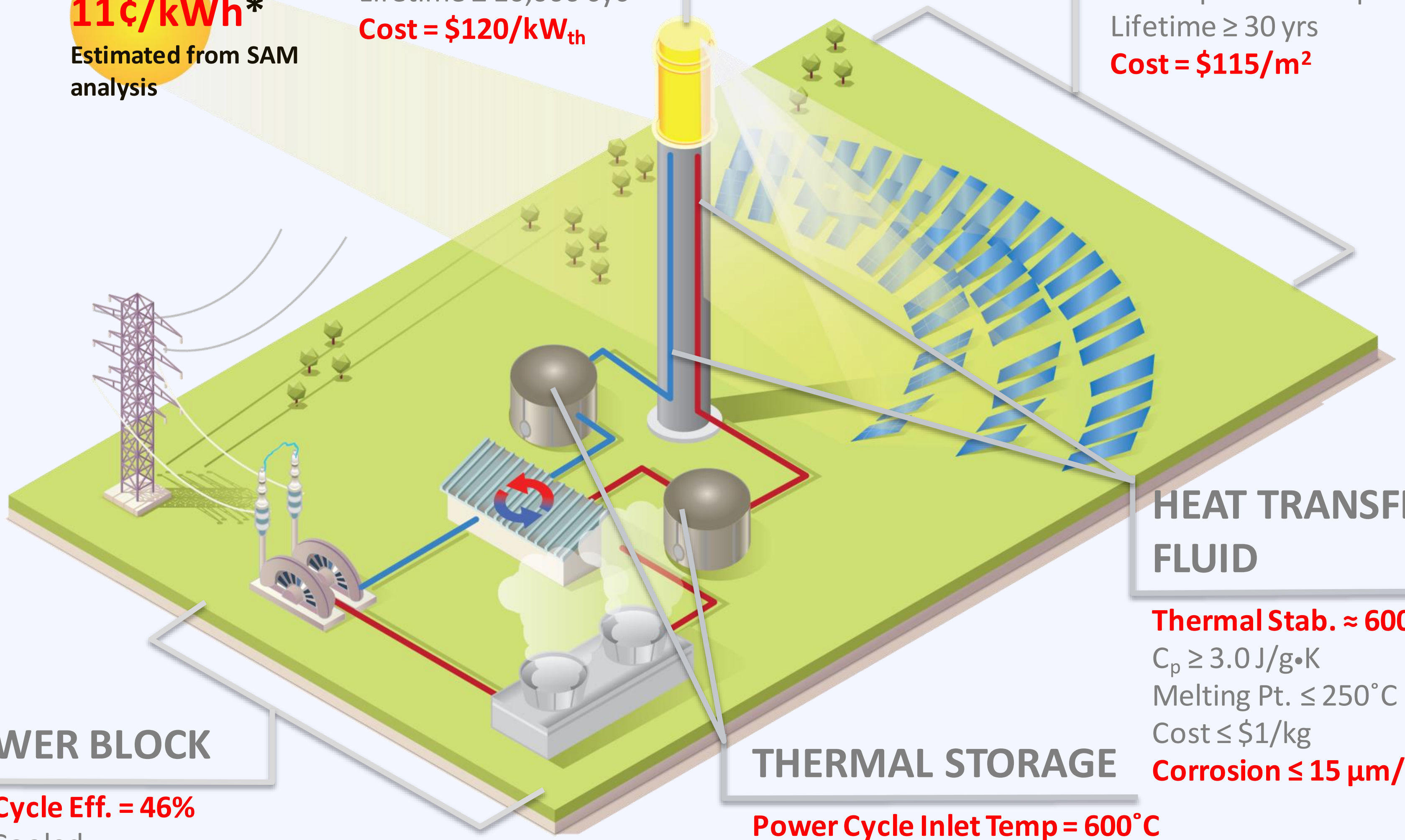
# DOE CSP Portfolio

**11¢/kWh***
**Estimated from SAM analysis**



## RECEIVER

**HTF Exit Temp = 600˚C**
Thermal Eff. ≥ 90%
Lifetime ≥ 10,000 cyc
**Cost = $\$120/\text{kW}_{th}$**

## SOLAR FIELD

Optical Error ≤ 3 mrad
Wind Speed ≥ 85 mph
Lifetime ≥ 30 yrs
**Cost = $\$115/\text{m}^2$**

## HEAT TRANSFER FLUID

**Thermal Stab. ≈ 600˚C**
$C_p \geq 3.0$ J/g•K
Melting Pt. ≤ 250˚C
Cost ≤ $1/kg
**Corrosion ≤ 15 µm/yr**

## POWER BLOCK

**Net Cycle Eff. = 46%**
Dry Cooled
**Cost = $\$1{,}270/\text{kW}_e$**

## THERMAL STORAGE

**Power Cycle Inlet Temp = 600˚C**
Energy Eff. ≥ 99%
Exergy Eff. ≥ 95%
**Cost = $\$23/\text{kWh}_{th}$**

***Highlighted values are based on successful completion of current projects***

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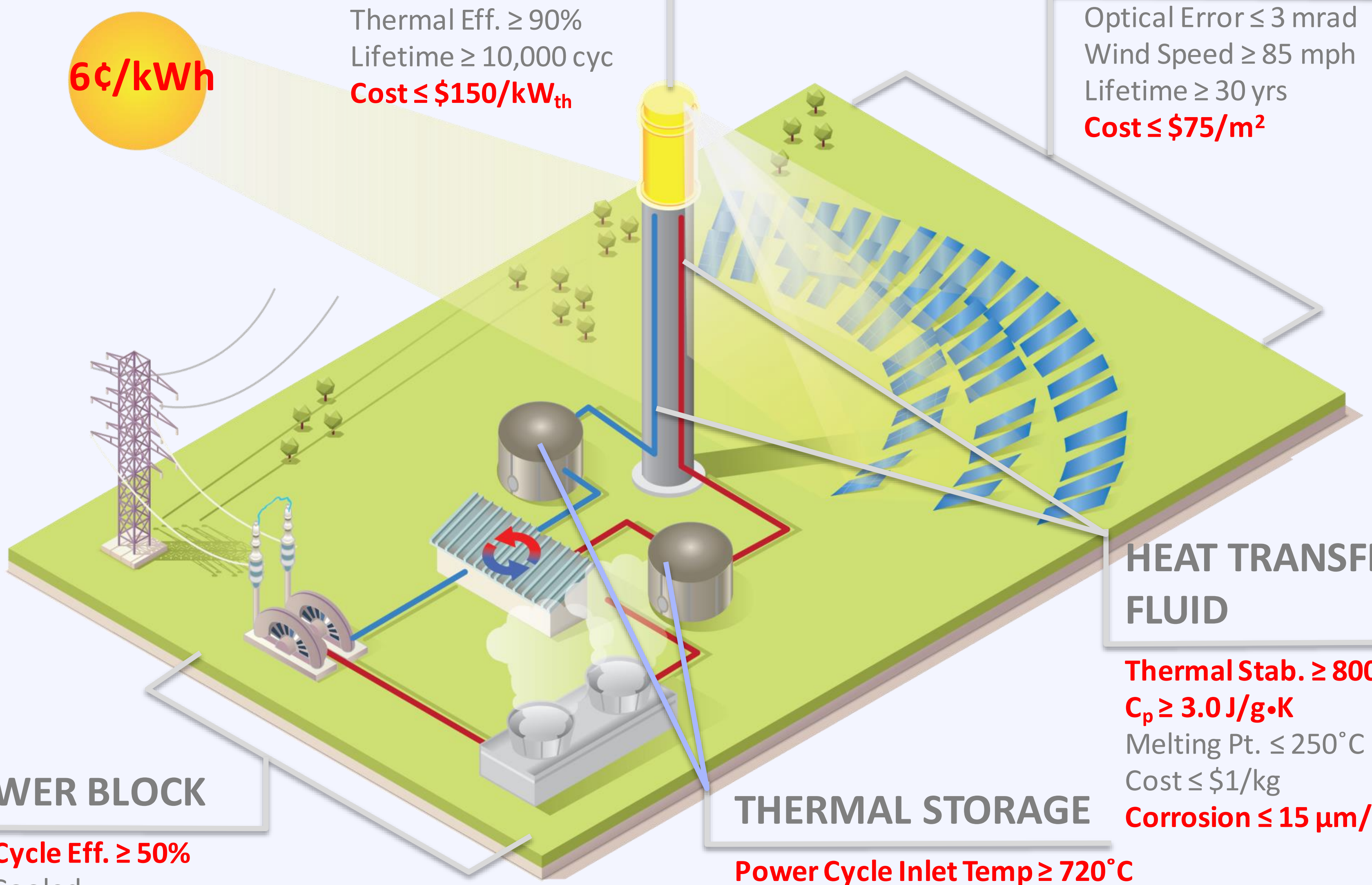


***Highlighted targets are notable challenges***

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# What Temperature makes sense for CSP?

$$\eta = 1 - \frac{T_C}{T_H}$$

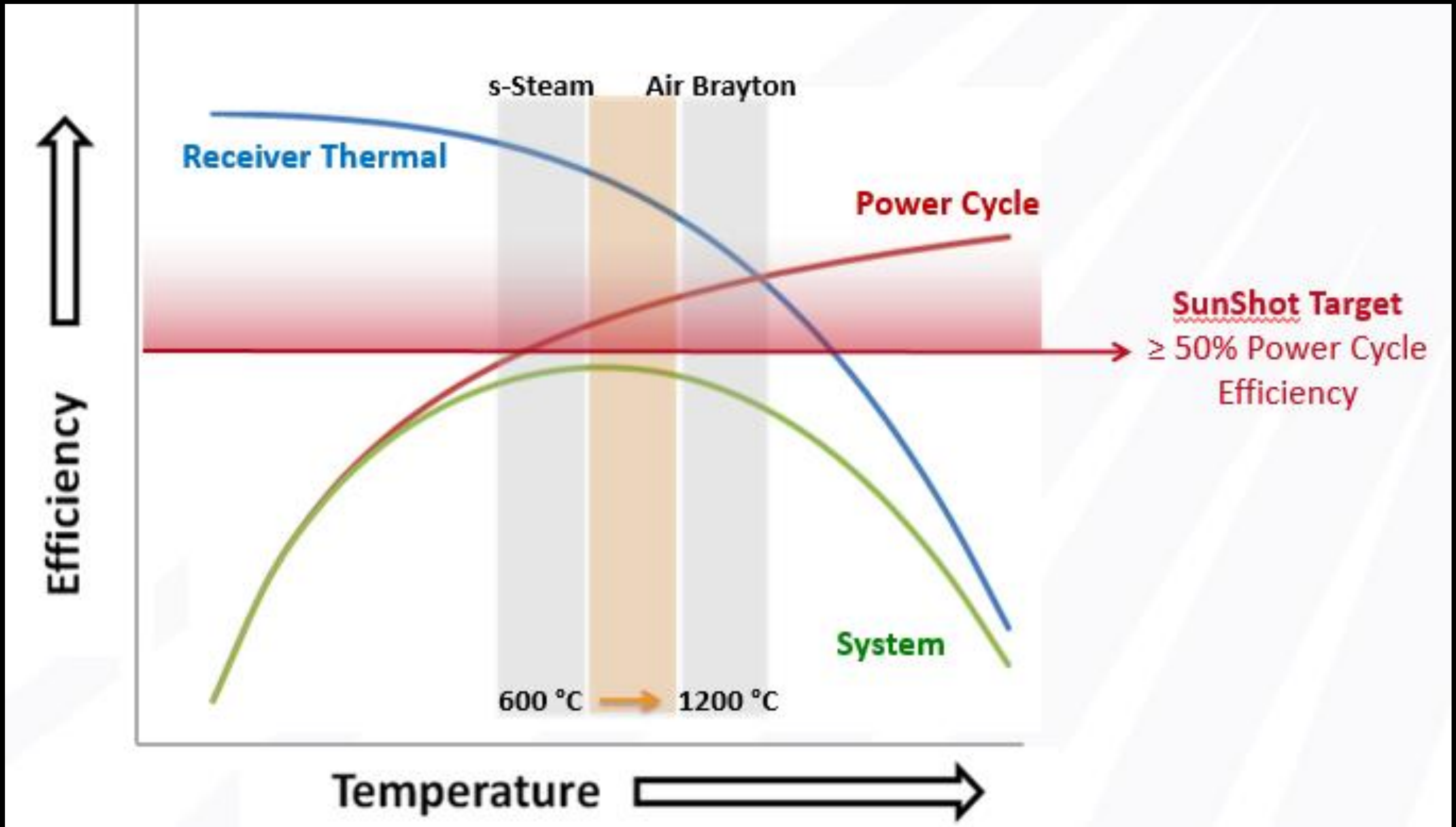
Increasing cycle efficiency requires higher temperatures

$$q = \sigma T^4 A$$

Increasing temperature causes greater radiative losses

# Third Generation CSP: 720 C

- Tradeoff between Carnot efficiency and radiation
- Price targets can be achieved near 700 C
- HTF, TES, Receiver, and material transport must be redesigned for this temperature regime
- Increased power block efficiency decreases size of the CSP plant




**First Generation:**
Thermal or organic HTF operating at 390 C, trough dominate; Steam Rankine Cycle

**Second Generation:**
Solar Salt HTF operating at 565 C; often doubles as TESM; towers and troughs; Steam Rankine Cycle

**Third Generation:**
To be determined HTF and TESM; demands increased efficiency power cycle

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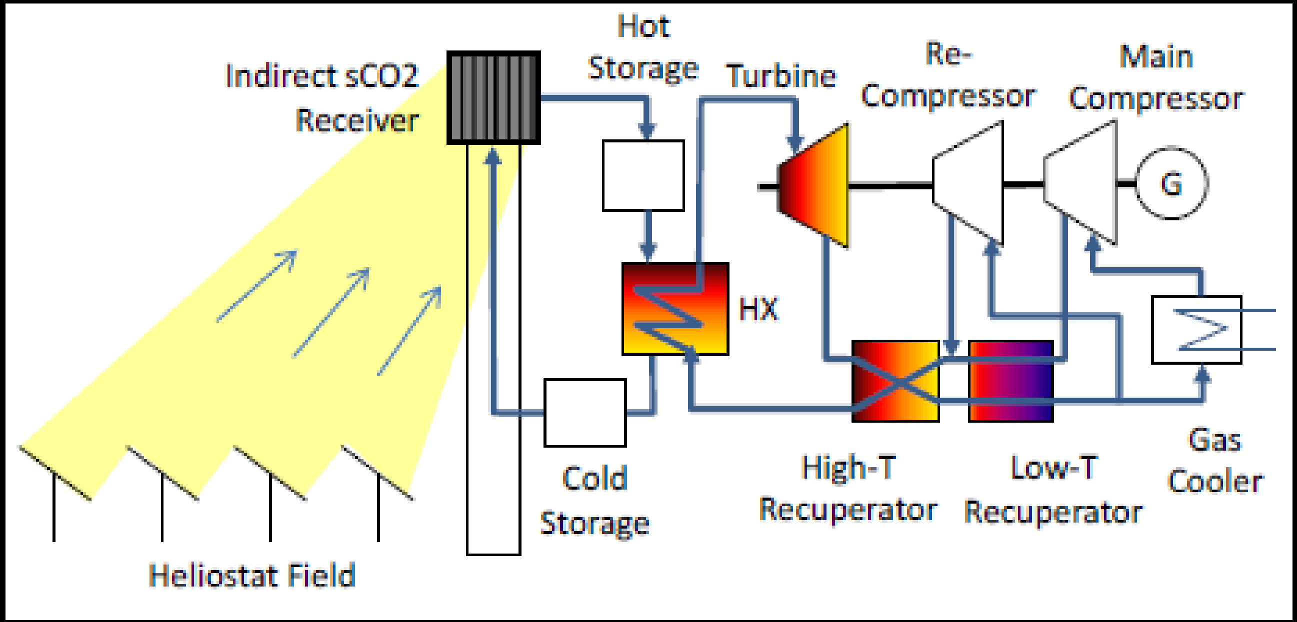
# Cost Metric




| | SCBC [20] | | RCBC [20] | CCBC [21] | CBI[22] |
|---|---|---|---|---|---|
| *Net Power (MWe)* | 100 | 100 | 100 | 133 | 100 |
| *Efficiency (%)* | 16 | 46 | 46 | 28 | 51 |
| $T_{max}$(C) | 700 | 700 | 700 | 600 | 700 |
| $P_{max}$(MPa) | 20 | 20 | 20 | 27.6 | 15 |
| $P_{min}$(MPa) | 6.4 | 8.0 | 7.3 | 8.5 | 2.6 |
| $P_{int}$(MPa) | N/A | N/A | N/A | N/A | 5.0 |
| $T_{comp,min}$(C) | 55 | 55 | 55 | 37 | 35 |
| $\eta_{comp}$(%) | 90 | 90 | 90 | 85 | 90 |
| $\eta_{exp}$(%) | 90 | 90 | 90 | 90 | 90 |
| $f_{rec}$ or $f_{cascaded}$(%) | N/A | N/A | 11.5 | 47.5 | 40 |
| $\Delta T_{HTF,min}$(C) | 25 | 25 | 25 | 25 | 25 |
| $T_{air,min}$(C) | 30 | 30 | 30 | 30 | 30 |
| $\Delta T_{HTR}$(C) | 540 | 172 | 170 | 518 | 159 |
| $\dot{C}_{HTF}$(MW/K) | 1.39 | 1.53 | 1.27 | 0.919 | 1.21 |
| $\dot{q}_{HTF}$(MWth) | 623 | 220 | 216 | 449 | 192 |
| *Heater ($/kWe)* | 381 | 212 | 322 | 370 | 292 |
| *Recuperation ($/kWe)* | 0.00 | 243 | 244 | 160 | 259 |
| *Cooling ($/kWe)* | 545 | 85 | 154 | 763 | 350 |
| *Compression ($/kWe)* | 423 | 230 | 147 | 110 | 74 |
| *Expansion ($/kWe)* | 136 | 128 | 135 | 180 | 120 |
| *Total ($/kWe)* | 1,485 | 898 | 1,002 | 1,583 | 1,095 |

Clifford K Ho, Matthew Carlson, Pardeep Garg, and Pramod Kumar; Cost and Performance Tradeoffs of Alternative Solar-Driven S-CO2 Brayton Cycle Configurations; ASME 2015 9th International Conference on Energy Sustainability

# Turbomachinery Technology Gaps

- Rotordyanamic considerations
  - Real gas effects
  - Bearing and seal coefficients at high pressure w/ real gas effects
  - Coupling mass for small rotors
- Structural dynamics
  - Blade-wake interactions heightened by high fluid density
  - Shift in structural response with gas density
- Materials
  - Impact of high inlet temperatures and pressures on materials selection
  - Stress associated with high rotational speeds
- Off design operations
  - – Surge and stall maps
  - – Operation near critical point
- Sub-components
  - – Dry gas seals and leakage rates
    - Incorporation of real gas effects in prediction codes
  - – Bearings
    - Limited high DN bearings
    - Selection between oil, magnetic, and gas bearings for sealed applications
  - – Non-metallic seals
    - Explosive decompression of polymer/elastomeric materials

Fundamental designs and component technologies differ for machines under 10 MW

# SunShot sc-$CO_2$ Cycle Portfolio Highlights

| Primary Heater (HTF to $CO_2$ heat exchanger) | | | | |
|---|---|---|---|---|
| 2015 SunLamp | 2015 Apollo | 2012 National Lab R&D | 2012 SunShot, 2015 Apollo | 2012 SunShot, 2015 Apollo |
| Sandia National Laboratorie; Australian National University | PURDUE UNIVERS; The University of Wisconsin Madison; Georgia Institute of Technology | NREL National Renewable Energy Laboratory | Brayton Energy LLC; SRNL Savannah River National Laboratory | OSU Oregon State University |
| Particle to $CO_2$ | Salt to $CO_2$ | Direct $CO_2$ Receiver | $CO_2$ Rec. +TCES | Direct $CO_2$ Receiver |

| Turbomachinery | | | |
|---|---|---|---|
| 2012 SunShot | 2013 Predicts | 2015 Apollo | 2015 Apollo |
| SwRI; GE; TharEnergy | GE; SwRI | SwRI; Samsung; Samsung Techwin | GE; SwRI |
| Turboexpander | Bearings / Seals | Compander | Compression |

| Heat Exchangers | Corrosion | | Technoeconomics |
|---|---|---|---|
| 2015 Apollo | 2015 SunLamp | Various Awards | 2015 SunLamp |
| The University of Wisconsin Madison | Oak Ridge National Laboratory | The University of Wisconsin Madison | NREL National Renewable Energy Laboratory |
| Regenerator | | | Sys. Advisory Model |

# Technology development to support third generation CSP

## Collector Field

- Cost < \$75/m²
- Concentration ratio > 50
- Operable in 35 mph winds
- Optical error < 3.0 mrad
- 30 year lifetime

| | Receiver | Material & Transport | Thermal Storage | HTF to sc-$CO_2$ Heat Exchanger |
|---|---|---|---|---|
| | *Cost < \$150/kW$_{th}$*<br>*Thermal Eff. > 90%*<br>*Exit Temp > 720˚C*<br>*10,000 cycle lifetime* | *Cost < \$1/kg*<br>*Operable range from 250˚C to 800˚C* | *Cost < \$15/kWh$_{th}$*<br>*99% energetic efficiency*<br>*95% exergetic efficiency* | |
| **Direct sc-CO2** | • High pressure fatigue challenges<br>• Absorptivity control and thermal loss management | • Minimize pressure drop<br>• Corrosion risk retirement | • Indirect storage required<br>• Cost includes fluid to storage thermal exchange | • Not applicable |
| **Liquid** | • Similarities to prior demonstrations<br>• Allowance for corrosive attack required | • Potentially chloride salt, ideal material not determined<br>• Corrosion concerns dominate | • Direct or indirect storage may be superior | • Challenging to simultaneously handle corrosive attack and high pressure working fluid |
| **Falling Particle** | • Most challenging to achieve high thermal efficiency | • Suitable materials readily exist | • Particles likely double as efficient sensible thermal storage | • Possibly greatest challenge<br>• Cost and efficiency concerns dominate |

## Super Critical CO2 Brayton Cycle

- Net thermal to electric efficiency > 50%
- Power cycle system cost < \$900/kW$_e$
- Dry cooled heat sink at 40˚C ambient
- Turbine inlent temperature near 720˚C

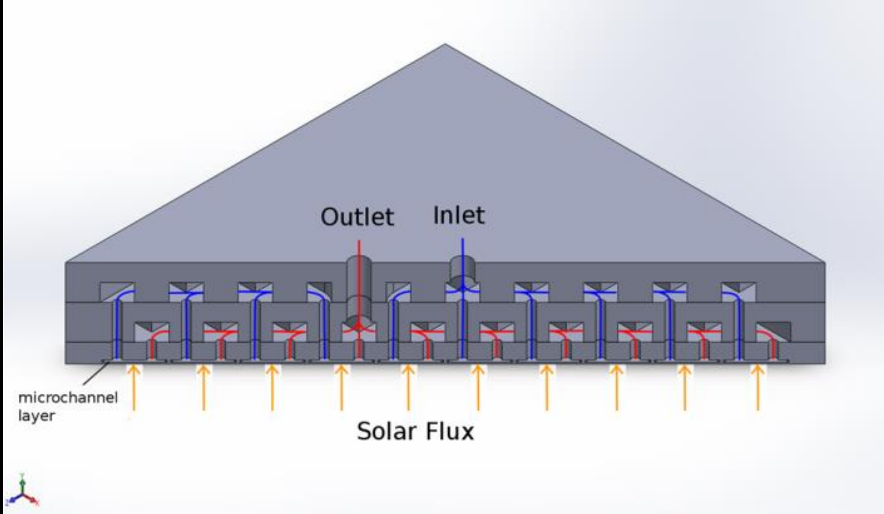
# SunShot CSP Receiver Portfolio: Novel Receivers

| Falling Particle | | | |
|---|---|---|---|
| 2012<br>CSP SunShot R&D<br>NREL<br>Zhiwen Ma | 2012, 2015<br>SunShot R&D, SunLamp<br>Sandia National Laboratories<br>Cliff Ho | 2012<br>BRIDGE<br>University of Colorado Boulder<br>Christine Hrenya | 2012<br>CSP SunShot R&D<br>San Diego State University<br>Fletcher Miller |

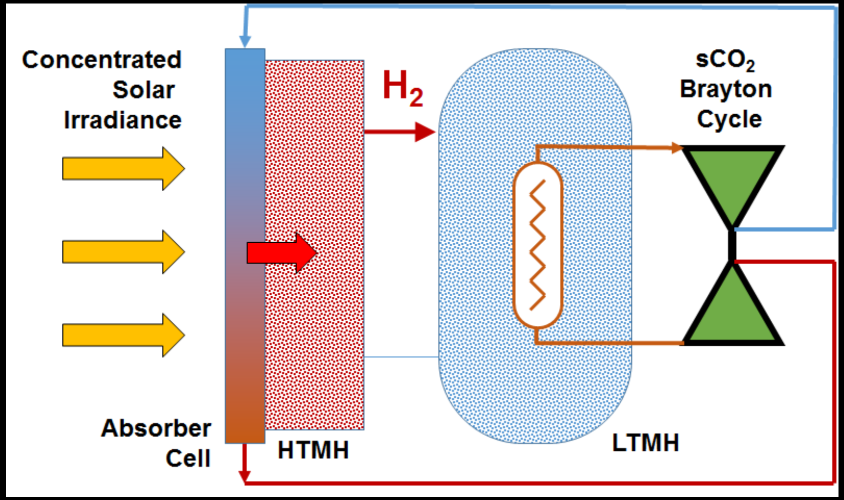
| Supercritical $CO_2$ | | |
|---|---|---|
| 2012, 2015<br>SunShot R&D, Apollo<br>BraytonEnergy<br>Shaun Sullivan | 2012<br>National Lab R&D<br>NREL<br>Michael Wagner | 2012, 2015<br>National Lab R&D, Apollo<br>OSU Oregon State University<br>Kevin Drost |

| Molten Salt | | | High Temperature Heat Pipe |
|---|---|---|---|
| 2012<br>SunShot R&D<br>NORWICH Technologies<br>Joel Stettenheim | 2010<br>Baseload<br>ABENGOA SOLAR<br>Bruce Kelly | 2015<br>Apollo<br>SOLARRESERVE®<br>David Wait | 2012, 2015<br>National Lab R&D, SunLamp<br>Los Alamos National Laboratory Est. 1943<br>Stephen Obrey |

# Direct $sCO_2$ Pathway




Oregon Statue University Microchannel Receiver Concept




Brayton Energy's Integrated Receiver, TES, Power Cycle Concept

## Key Advantages

- Simplifies and reduces plant size
- Comparable steam plants commercially operating
- Significant research and design progress made at 650C

## Remaining Technology Gaps

- Separate thermal energy storage
- Pressure drop and material survival at the receiver at > 720C
- Corrosion concerns at maximum temperatures

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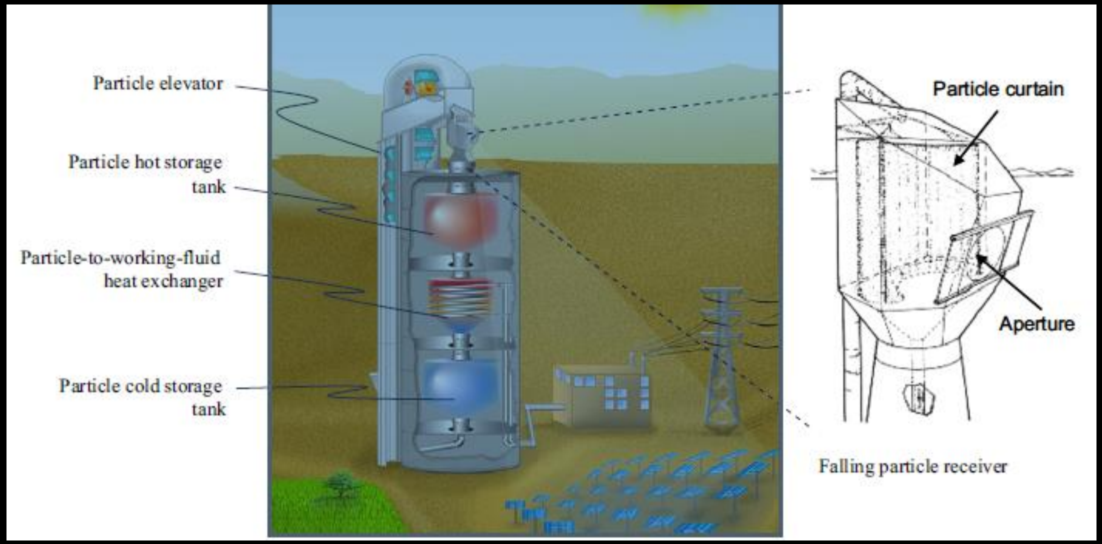
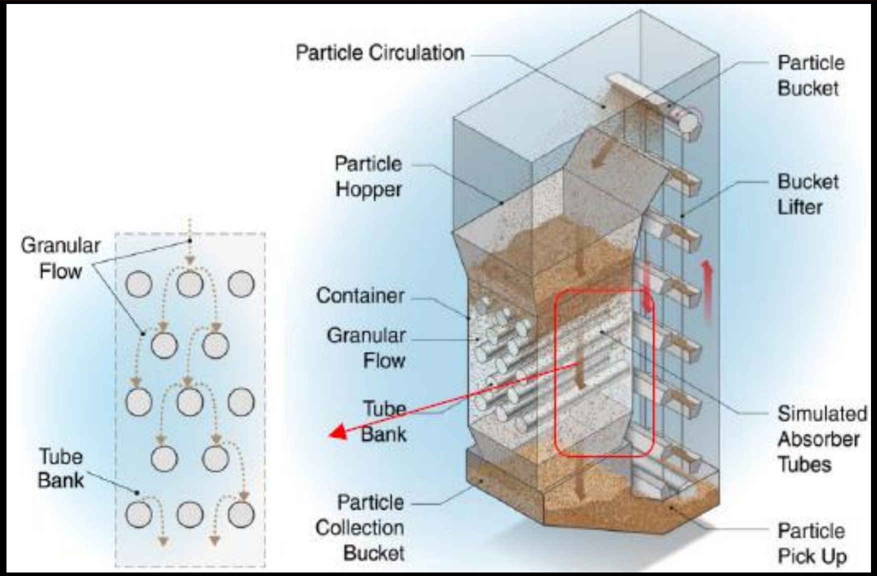
# Falling Particle Technology Path




Ho, Clifford K., and Brian D. Iverson. "Review of high-temperature central receiver designs for concentrating solar power." *Renewable and Sustainable Energy Reviews* 29 (2014): 835-846.




Ma, Z., et al. "Development of a concentrating solar power system using fluidized-bed technology for thermal energy conversion and solid particles for thermal energy storage." *Energy Procedia* 69 (2015): 1349-1359

## Key Advantages

- Material survival
- Direct Thermal Energy Storage

## Remaining Technology Gaps

- Proving high efficiency heat exchangers "on sun" (Both receiver and HTF to $CO_2$)
- Material handling

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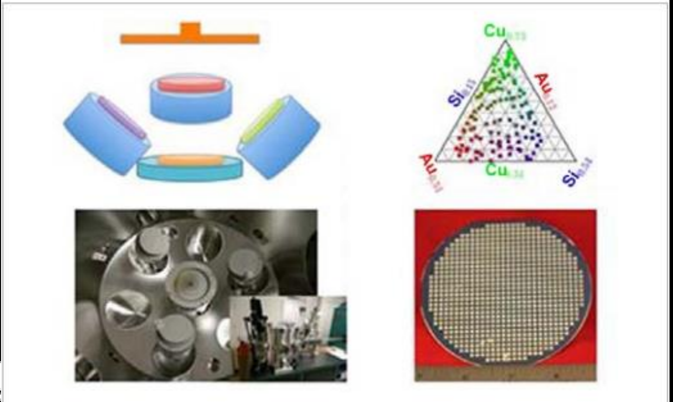
# Liquid HTF Pathway

## 2012 MURI HOT Fluids awards

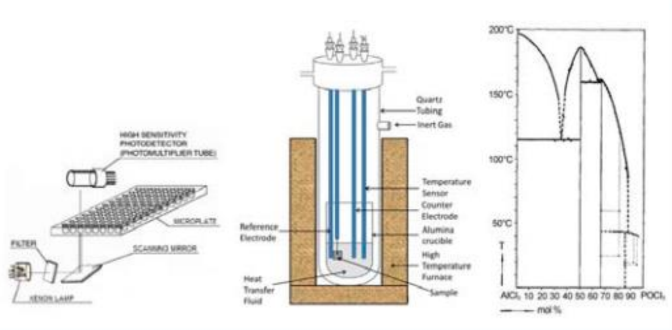
THE UNIVERSITY OF CALIFORNIA, LOS ANGELES
THE UNIVERSITY OF CALIFORNIA, BERKELEY
YALE UNIVERSITY

| | |
|---|---|
| PROGRAM: | 2012 Multidisciplinary University Research Initiative (MURI): High Operating Temperature (HOT) Fluids |
| LOCATION: | California; Connecticut |
| AWARD AMOUNT: | Up to $5 million |
| PROJECT TERM: | 2012–2017 |



THE UNIVERSITY OF ARIZONA
ARIZONA STATE UNIVERSITY
GEORGIA INSTITUTE OF TECHNOLOGY

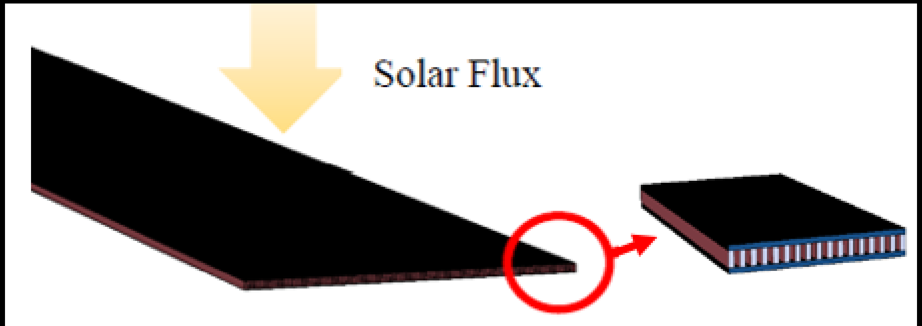
| | |
|---|---|
| PROGRAM: | 2012 Multidisciplinary University Research Initiative (MURI): High Operating Temperature (HOT) Fluids |
| LOCATION: | Arizona; Georgia |
| AWARD AMOUNT: | Up to $5.5 million |
| PROJECT TERM: | 2012–2017 |



- Identify liquids operable from 200-800C
- Thermophysical and cost values aligned with SunShot price goal
- Fluid and container pipping able to survive for 30 year life
- Greatest technical gap: **Corrosion**

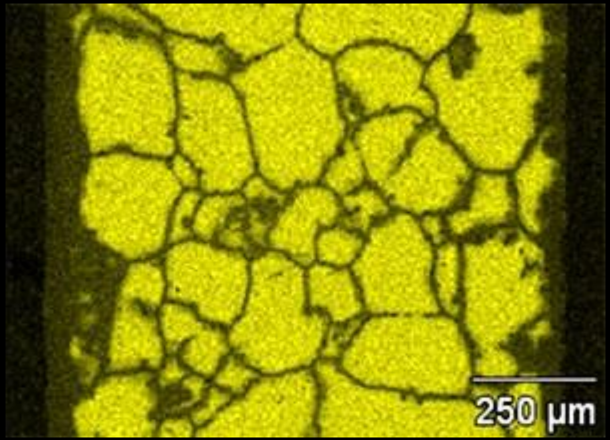
# Liquid HTF Pathway

## Solar Reserve: Ceramic Receiver




- Monolithic absorber employing microchannel flow and absorptive coating
- Demonstrate 10,000 cycle survival

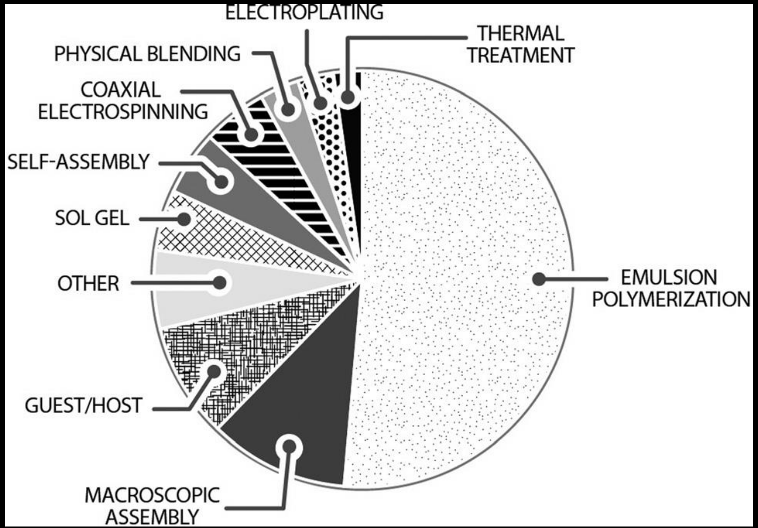
## Corrosion Investigations: NREL, SRNL

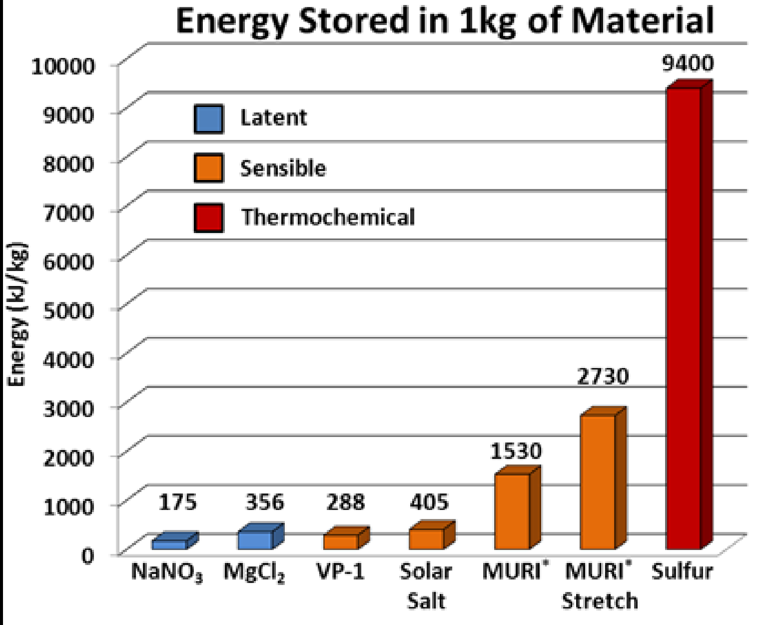



- Rapidly screen and mitigate corrosion in chloride salts contained within superalloys above 700 C
- Develop control practices such as protective coatings and material healing additives

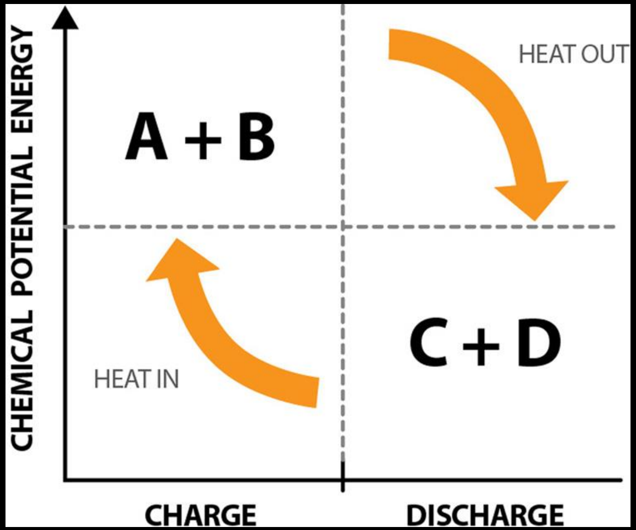
# Thermal Energy Storage

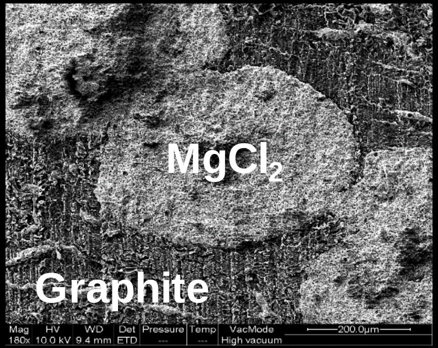
## Phase Change

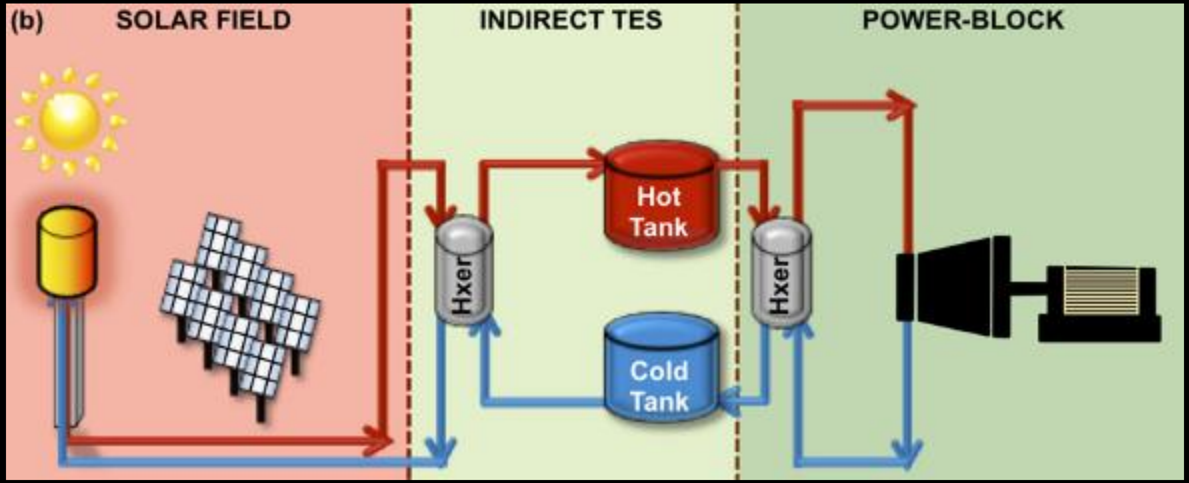



## Chemical

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Stekli, Joseph, Levi Irwin, and Ranga Pitchumani. "Technical challenges and opportunities for concentrating solar power with thermal energy storage." *Journal of Thermal Science and Engineering Applications* 5.2 (2013): 021011

# Pathways to cost competitive CSP via sc-$CO_2$ power cycles

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