CSP with Storage is Solar Energy On-Demand
CSP is Deployed Worldwide

- **4.8 GW** CSP deployed globally
- **1.8 GW** CSP deployed in the U.S.
- **0.4 GW** CSP deployed in the U.S. with storage

Since 2016 CSP’s share of electricity generation:
- 1% of California
- 2% of Spain
CSP: Flexible Designs for an Evolving Grid

‘Peaker’
(≤6 hours of storage)

‘Intermediate’
(9 hours of storage)

‘Baseload’
(≥12 hours of storage)

By choosing the size of the solar field and thermal energy storage, the same CSP technology can be configured to meet evolving demands of the future grid
2030 Levelized Cost of Electricity Targets

- **PEAKER** (<6 hours of storage):
  - 2010 CSP Cost: 21¢
  - 2017 CSP Cost: 18.4¢
  - 2030 CSP Goal: 10¢

- **BASELOAD** (>12 hours of storage):
  - 2017 CSP Cost: 10.3¢
  - 2030 CSP Goal: 5¢
CSP Program Technical Targets

**Collector Field**
- Optical Physics
- Structural design and dynamics
- Manufacturing and automation
- Sensors and control

**Receivers**
- Optical properties
- Coatings
- High temperature materials
- Chemistry
- Heat Transfer, Fluid Mechanics

**TES and HTF**
- Chemistry
- High temperature materials
- Materials Science
- Heat Transfer, Fluid Mechanics

**Power Block**
- High temperature materials
- Turbomachinery
- Manufacturing and automation
- Sensors and control

---

**O&M TARGET**

- $40/kW-yr plus $3/MWh

**5¢/kWh**

**SOLAR FIELD**

- Cost ≤ $50/m²
- Lifetime ≥ 30 yrs
- Annual Efficiency ≥ 55%
- Concentration Ratio ≥ 1000 Suns

**RECEIVER**

- Thermal Efficiency ≥ 90%
- Lifetime ≥ 10,000 cyc
- Cost ≤ $150/kWₘ
- Exit Temp ≥ 720°C

**POWER BLOCK**

- Net Cycle Efficiency ≥ 50%
- Dry Cooled
- Cost ≤ $900/kWₑ

**THERMAL STORAGE**

- Energy Efficiency ≥ 99%
- Exergetic Efficiency ≥ 95%
- Cost ≤ $15/kWₑ
- Power Cycle Inlet Temp ≥ 720°C
CSP Program Technical Targets

**O&M TARGET**
$40/kW-yr plus $3/MWh

**RECEIVER**
- Thermal Efficiency ≥ 90%
- Lifetime ≥ 10,000 cycles
- Cost ≤ $150/kW
- Exit Temp ≥ 720°C

**SOLAR FIELD**
- Cost ≤ $50/m²
- Lifetime ≥ 30 yrs
- Annual Efficiency ≥ 55%
- Concentration Ratio ≥ 1000 Suns

**HEAT TRANSFER MEDIUM**
- Thermally Stable ≥ 800°C
- Compatible with Rec. Performance

**POWER BLOCK**
- Net Cycle Efficiency ≥ 50%
- Dry Cooled
- Cost ≤ $900/kW

**THERMAL STORAGE**
- Energy Efficiency ≥ 99%
- Exergetic Efficiency ≥ 95%
- Power Cycle Inlet Temp ≥ 720°C

**Competitive Programs**
- $15M Desalination (2017)
- $15M FY19-21 National Lab Call (2017)
- $9M COLLECTS (2016)
- $29M CSP SuNLaMP (2015)
- $14M SolarMat II (2014)
- $10M CSP: ELEMENTS (2014)
- $1.1M SunShot Incubator (Recurring)
- $4M PREDICTS (2013)
- $2M SolarMat (2013)
- $10M CSP-HIBRED (2013)
- $10M SunShot MURI (2012)
- $56M CSP SunShot R&D (2012)
- $0.5M BRIDGE (2012)
- $62M CSP Baseload (2010)
A Pathway to 5 Cents per KWh for Baseload CSP

2017 Real LCOE (U.S. Cents/kWh)

- 2017 Baseline: 10.3¢
- Low Cost Solar Field ($50/m²) and Site Improvement ($10/m²): 2.3¢
- Low Cost Power Block and BOP ($900/kWe): .9¢
- High Efficiency Power Cycle (50% net)*: 1.1¢
- Low Cost TES ($15/kWh), Receiver ($120/kWe), O&M ($40/kWe-yr): 1¢
- SunShot 2030 CSP Goal: 5¢

*Assumes a gross to net conversion factor of 0.9
Pathways to Achieving 2030 SunShot Goals

All lines represent 5¢/kWh LCOE in a typical Southwestern U.S. climate

*Baseload power plant is defined as a CSP plant with greater than or equal to 12 hours of storage
Pathways to Achieving SunShot 2030 Goals

All lines represent 10¢/kWh LCOE in a typical Southwestern U.S. climate

- 40 Yr Life
- Power Block Costs Achieve $700/kWe
- O&M Costs Reduced to $30/kW-yr
- Baseline 2030 Peaker Scenario

*Peaker power plant is defined as a CSP plant with less than 6 hours of storage

energy.gov/solar-office
Gen3 CSP: Raising the Temperature of Solar Thermal Systems

\[ \eta = 1 - \frac{T_C}{T_H} \]

<table>
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<tr>
<th>Thermal Pathway</th>
<th>Primary Challenges</th>
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<td>Reliable corrosion management with advanced molten salts</td>
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<td>Solids</td>
<td>High-efficiency transfer of heat in and out of particles</td>
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<td>Gas</td>
<td>Integrating low-density gases with cost-effective thermal energy storage</td>
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</table>

**Gen3 System Innovation**

- **Concentrated Sunlight**
- **Receiver**
- **Storage**
- **Heat Exchanger**
- **Power Cycle**
Generation 3 Concentrating Solar Power Systems Funding Opportunity

- Total federal funds available: $62,000,000
- Full Applications were received in January, 2018
- Selections expected to be announced in May of 2018
### SETO sCO₂ Power Cycle Portfolio by Category

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<tr>
<th>CATEGORY</th>
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<td>Development of an Integrally-Geared sCO₂ Compander</td>
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<td>Development of High Efficiency Expander and 1 MW Test Loop</td>
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<td>Physics-Based Reliability Models for sc-CO₂ Turbomachinery Components</td>
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<td>Lifetime Model Development for Supercritical CO₂ CSP Systems</td>
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<td>sCO₂ Corrosion and Compatibility with Materials</td>
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<td><strong>Other Components</strong></td>
<td>Development and Testing of a Switched-Bed Regenerator</td>
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<td>sCO₂ Power Cycle with Integrated Thermochemical Energy Storage</td>
<td>Echogen Power Systems</td>
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<td><strong>Technoeconomics</strong></td>
<td>Cycle Modeling, Integration with CSP, and Technoeconomics</td>
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<td><strong>Primary Heat Exchanger</strong></td>
<td>High Flux Microchannel Direct sCO₂ Receiver</td>
<td>Oregon State</td>
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<td></td>
<td>High-Temperature Particle Heat Exchanger for sCO₂ Power Cycles</td>
<td>SNL</td>
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<td></td>
<td>Robust, Cost-Effective Molten Salt HXer for 800°C Operation with sCO₂</td>
<td>Purdue</td>
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<td></td>
<td>Solar Receiver with Integrated Thermal Storage for sCO₂</td>
<td>Brayton Energy</td>
</tr>
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</table>
SETO sCO₂ Power Cycle Portfolio - Turbomachinery

Development of High Efficiency Expander and 1 MW test loop – SunShot (2012)

Physics-Based Reliability Models for sc-CO₂ Turbomachinery Components— PREDICTS (2013)


SETO sCO₂ Power Cycle Portfolio – Corrosion and Components

**Lifetime Model Development for Supercritical CO2 CSP Systems – SuNLaMP (2015)**

**Development and testing of a switched-bed regenerator – CSP: APOLLO (2015)**

sCO₂ corrosion and compatibility with materials – various awards


Cycle modeling, integration with CSP, and technoeconomics – SuNLaMP (2015)
**SETO sCO₂ Power Cycle Portfolio – Primary Heat Exchanger**

**High-Temperature Particle Heat Exchanger for sCO2 Power Cycles – SuNLaMP (2015)**

**Robust, Cost-Effective Molten Salt HXer for 800 °C Operation with sCO₂ – CSP: APOLLO (2015)**

**High Flux Microchannel Direct sCO₂ Receiver – CSP: APOLLO (2015); SunShot (2012)**

**Solar Receiver with Integrated Thermal Storage for sCO2 – CSP: APOLLO (2015); SunShot (2012)**

**Direct sCO₂ Receiver Development – LPDP (2012)**

[energy.gov/solar-office](http://energy.gov/solar-office)
Optimizing the Supercritical CO\textsubscript{2} Brayton Cycle for Concentrating Solar Power Application

Rajgopal Vijaykumar, Matthew L. Bauer, Mark Lausten, and Abraham M. Shultz

950 L’Enfant Plaza Washington D.C. 20024 United States Department of Energy

Questions?

Avi Shultz

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Program Manager (Acting), CSP
CSP Program Technical Targets

**Collector Field**
- Optical Physics
- Structural design and dynamics
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Next Generation CSP will Leverage Next Generation Power Cycles

\[ \eta_{\text{Cycle}} = 1 - \frac{T_C}{T_H} \quad \text{vs.} \quad Q_{\text{Radiative}} \propto T^4 \]

Supercritical CO\(_2\) is a dense, compressible fluid:

- Compact turbomachinery
- Good compatibility with dry cooling
- Fewer loss mechanisms and parasitics