Gen3 Particle Pilot Plant (G3P3) – Next Generation Concentrating Solar Thermal Power

PRESENTED BY
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Outline

- Introduction to concentrating solar thermal power (CSP)
- Challenges with CSP and intro to Gen 3
- Gen 3 Particle Pilot Plant overview
What is Concentrating Solar Power (CSP)?

Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle.
What is Concentrating Solar Power (CSP)?

CSP uses concentrated heat from the sun as an alternative heat source for the power cycle.
CSP and Thermal Energy Storage

- Concentrating solar power uses mirrors to concentrate the sun’s energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining
Growing Need for Large-Scale Energy Storage

~10,000 MWh is required to power a large city (e.g., Los Angeles or New York) for one hour.

Battery data from U.S. Energy Information Administration (June 5, 2018)
CSP data from [https://solarpaces.nrel.gov/projects](https://solarpaces.nrel.gov/projects)

<table>
<thead>
<tr>
<th>Energy Storage Capacity (MWh)</th>
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<tr>
<td>1,800</td>
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<tr>
<td>1,600</td>
</tr>
<tr>
<td>1,400</td>
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<td>1,200</td>
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<tr>
<td>200</td>
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<tr>
<td>100</td>
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- Large-Scale Battery Storage (~100 plants in U.S.)
- Crescent Dunes CSP Plant (molten-salt storage)
- Solana CSP Plant (molten-salt storage)
Timeline of CSP Development

1970’s

- National Solar Thermal Test Facility
  - 6 MWₜ, Albuquerque, NM, Est. 1976

1980’s - 1990’s

- Solar One and Solar Two
  - 10 MWₑ, Daggett, CA
  - 1980’s - 1990’s
- Stirling Energy Systems
  - 1.5 MWₑ, AZ, 2010
- SEGS, 1980’s
  - 9 trough plants
  - 354 MWₑ, CA

2000’s

- PS10/20,
  - steam, Spain,
  - 2007-2009
- Gemasolar, molten salt,
  - 19 MWₑ, Spain, 2011
- Ivanpah,
  - steam, 377 MWₑ, CA, 2014
- Crescent Dunes, molten salt,
  - 110 MWₑ, NV, 2015

SunShot

- 2011 -
Global Concentrating Solar Power Plants

No recent CSP development in the U.S.
Outline

• Introduction to concentrating solar thermal power (CSP)
  - Challenges with CSP and intro to Gen 3
  - Gen 3 Particle Pilot Plant overview
Challenges Facing CSP

Cost
- CSP is \( \sim \$0.07 - \$0.10 / \text{kWh} \) (levelized cost of energy)
- Solar PV and wind are \( \sim \$0.02 - \$0.04 / \text{kWh} \) (no storage)
- Levelized cost of battery systems > \( \sim \$0.10 / \text{kWh} \)*

Policies/mandates
- Meeting renewable portfolio standards driven by “lowest bid”
- States and policies have generally not valued storage (no need for > 4 hours)

“Bankability” (reliability/risk)
- High up-front capital costs for CSP (no fuel cost)
- CSP and thermal storage for process-heat is nascent; few demonstrations
- Perceived reliability issues (Crescent Dunes), need for backup fuels (Ivanpah), safety issues (“vaporizing” birds)

Why Now?
Higher penetrations of intermittent renewables require economical longer-duration energy storage \( \Rightarrow \) CSP & thermal storage

Why Now?
Need to decarbonize heating sector

*For \( \sim \) 4 hrs of daily use

https://www.nature.com/articles/s41467-019-09988-z
Challenges with Current State-of-the-Art CSP

• Current state-of-the-art CSP uses molten salt as storage media
  ◦ Decomposes at temperatures ~600 °C
  ◦ Freezes at ~200 °C
  ◦ Requires expensive trace heating everywhere the salt touches

• Need higher temperatures to reduce costs
  ◦ More efficient power cycles (supercritical CO₂ Brayton Cycles >700 °C)
  ◦ Air Brayton Combined Cycles (>1000 °C)
  ◦ Thermochemistry & Solar Fuels (>1000 °C)

Need higher-temperature CSP systems (>700 °C)
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Gen 3 CSP Program (FY19 – FY24)

Achieve higher operating temperatures (>700 °C) for greater efficiency and lower LCOE ($0.05/kWh_e)

- Brayton Energy
  - Gas Phase Pathway
  - 18 months
    - FY19 - FY20

- NREL
  - Liquid Phase Pathway
  - 6 months
    - FY20

- Sandia
  - Solid Phase Pathway
  - 3 years
    - FY21 - FY23

Risk Mitigation:
- Receiver
- Storage
- Heat exchanger
- Particles, Lift

Phase 1

Phase 2
- G3P3
- Integrated System Design
- DOE Downselection (March 2021)

Phase 3
- G3P3 Test and Operation

18 months FY19 - FY20

6 months FY20

3 years FY21 - FY23
**Introduction to the Team**

<table>
<thead>
<tr>
<th>Role</th>
<th>Team Members</th>
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<tbody>
<tr>
<td>PI / Management</td>
<td>• Sandia National Labs (PI, PMP, financial, facilities)</td>
</tr>
</tbody>
</table>
| R&D / Engineering     | • Sandia National Laboratories  
                          • Georgia Institute of Technology  
                          • King Saud University  
                          • German Aerospace Center  
                          • CSIRO  
                          • U. Adelaide  
                          • Australian National University  
                          • CNRS-PROMES |
| Integrators / EPC     | • EPRI  
                          • Bridgers & Paxton / Bohannan Huston |
| CSP Developers        | • SolarDynamics                                                             |
| Component Developers / Industry | • Carbo Ceramics  
                          • Solex Thermal Science  
                          • Vacuum Process Engineering  
                          • FLSmidth  
                          • Materials Handling Equipment  
                          • Allied Mineral Products  
                          • Matrix PDM |
| Utility               | • Saudi Electric Company                                                   |
Background and Introduction

High-Temperature Particle-Based CSP

Particle elevator
Particle hot storage tank
Particle-to-working-fluid heat exchanger
Particle cold storage tank

Particle curtain
Aperture
Falling particle receiver
Background and Introduction

High-Temperature Particle-Based CSP

Particle elevator
Particle hot storage tank
Particle-to-working-fluid heat exchanger
Particle cold storage tank

Falling particle receiver
Particle curtain
Aperture

National Solar Thermal Test Facility
Sandia National Laboratories
Background and Introduction

Higher temperatures (>1000 °C) than molten nitrate salts

- Direct heating of particles vs. indirect heating of tubes
- No freezing or decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles
Gen3 Particle Pilot Plant (G3P3)

- Next-Generation High-Temperature Falling Particle Receiver

Gen 3 Particle Pilot Plant
- ~1 - 2 MW_t receiver
- 6 MWh_t storage
- 1 MW_t particle-to-sCO_2 heat exchanger
- ~300 - 400 micron ceramic particles (CARBO HSP 40/70)

Brantley Mills, SNL
K. Albrecht, SNL
Gen 3 Particle Pilot Plant (G3P3) Integrated System

National Solar Thermal Test Facility (NSTTF), Albuquerque, NM
<table>
<thead>
<tr>
<th>Parameter</th>
<th>G3P3-USA</th>
<th>G3P3-KSA</th>
</tr>
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<tbody>
<tr>
<td>Receiver</td>
<td>$\sim 2 \text{ MW}_t$</td>
<td>6 - 7 $\text{ MW}_t$</td>
</tr>
<tr>
<td>Solar multiple</td>
<td>$\sim 2$</td>
<td>$\sim 2$</td>
</tr>
<tr>
<td>Particles</td>
<td>CARBO HSP 40/70</td>
<td>Silica sand or Carbobead</td>
</tr>
<tr>
<td>Receiver</td>
<td>Multi-stage, 775°C, $\Delta T=160^\circ$C</td>
<td>Obstructed flow; up to 1000°C, $\Delta T=400^\circ$C</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>1 $\text{ MW}_t$ duty; shell-and-plate; 20-25 MPa $s\text{CO}_2$</td>
<td>$\sim 3$ $\text{ MW}_t$ duty; shell-and-tube; 400 kPa air</td>
</tr>
<tr>
<td>Particle Lift</td>
<td>Bucket elevator</td>
<td>Skip hoist</td>
</tr>
<tr>
<td>Power block</td>
<td>$\sim 1$ $\text{ MW}_t$ $s\text{CO}_2$ flow loop</td>
<td>1.3 $\text{ MW}_e$ Air Brayton turbine/generator (Aurelia A1300)</td>
</tr>
</tbody>
</table>
Particle Receiver R&D

Brantley Mills, Reid Shaeffer, Lindsey Yue
G3P3-USA Receiver Design Evolution

Feature evaluation

- NSTTF 1 MW\textsubscript{th} FPR
- Hood/Tunnel
- Quartz Half Shells
- Active Air Flow
- Multistage
- Optimized Cavity

Reduced volume with SNOUT

Design refinement

- Receiver Chimney
- Ray Tracing Analysis

2020

Optimized G3P3 FPR

Design Challenges
- Low thermal efficiency
- Sensitivity to wind

FPR = Falling particle receiver

Pathway
- Wind Evaluation
- Ground Testing
- On-sun Testing
- Model Validation
StAIR (Staggered Angle Iron Receiver) Testing

Drawing of “stairs” in receiver cavity

StAIRS create a more uniform and opaque particle curtain for increased solar absorptance

Particle flow over two-stair configuration (5 - 10 kg/s)
On-Sun Testing at Sandia

On-sun testing of particle receiver with StAIRs and reduced volume
Particle Sampling
Particle Storage R&D

Jeremy Sment

Key Partners:

Tulsa University and King Saud University
Storage Design Evolution

Initial Design

Feature 1: Form Factor

Feature 2: Floor Design

Feature 3: Mass Flow vs. Funnel Flow

Feature 4: Refractory Insulation Layers

Baseline Design

Funnel-flow bin is expected to yield less heat loss and wall erosion than conventional mass-flow bin
Particle Heat Exchanger R&D

Presented by Kevin Albrecht

Key Partners:
Particle Heat Exchanger

Solex Thermal Science

https://www.solexthermal.com/our-technology/cooling/
High-T, High-P Particle-to-sCO2 Heat Exchanger

100 kW particle-to-sCO2 heat exchanger

Integration of heat exchanger and sCO2 flow loop in tower

~100 kW sCO2 flow loop

On-sun testing of integrated system with falling particle receiver
G3P3-USA Heat Exchanger Design Evolution

SuNLaMP 100 kW Prototype

Initial G3P3 Concept

Current G3P3 Concept

Design Challenges:
- High pressure drop
- Low heat transfer coefficient
- \(\text{sCO}_2\) flow maldistribution
- Particle flow nonuniformity
- Particle-side instrumentation
- Heat exchanger edge effects
- High heat loss
- Difficult to manufacture

Design Improvements:
- Closer plate spacing (HTC)
- Remove plate nozzles
- Single outlet cone
- Heat exchanger edge effects
- No particle case

Design Challenges:
- High pressure drop
- Large material wastage
- Substantial \(\text{sCO}_2\) external pipe
- Large thermal mass (startup)
- Sharp change in material thickness

Design Improvements/Future Work:
- Commercial scale technoeconomics
- Limited ramp rate

Achieved ~300 W/m\(^2\)-K overall heat-transfer coefficient with low pressure drop (0.4%)
CSP Outlook
U.S. Investment in CSP R&D

• DOE Gen 3 CSP (~$70M)
  o Develop next generation high-temperature solar-thermal power generation (FY19 – FY23)

• DOE TESTBED/Heliogen
  o $39M DOE, $30M cost share FY20 – FY24
  o Solarized supercritical CO₂ power cycle with thermal storage; solar fuels
  o Sandia is a key partner

• DOE Annual Lab and FOA calls
  o ~$30M - $60M per year in CSP and solar thermal R&D
Global Investments in Particle-Based CSP

• International CSP Partners
  • Australian Solar Thermal Research Institute (ASTRI)
    • CSIRO, Australian National University, U. Adelaide
  • Saudi Electricity Company / King Saud U.
  • DLR – German Aerospace Center
    • Process heat (HiFlex – Barilla, drying of pasta using heated particles, Foggia, Southern Italy)

Millions being invested globally in Sandia & CSP

DLR and Sandia received a $1.5M DOE Technology Commercialization Fund award
G3P3 Summary

• Significant advantages
  ◦ Direct heating of particles
    ◦ Wide temperature range (sub-zero to >1000 °C)
    ◦ Inexpensive, durable, non-corrosive, inert
  ◦ Demonstrated ability to achieve >700 °C on-sun with hundreds of hours of operation

• Gaps and risks
  ◦ Extended operation of integrated system over wide range of conditions
  ◦ Heat loss (receiver, storage, heat exchanger, lift)
  ◦ Particle-to-working-fluid heat transfer
  ◦ Thermomechanical stresses in heat exchanger and storage tanks
  ◦ Materials erosion
Economical carbon-free electricity production with large-capacity, long-duration energy storage.

Why particle-based CSP?

The future of CSP
Acknowledgments

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DOE Project Managers: Matthew Bauer, Vijay Rajgopal, Shane Powers, Levi Irwin, Andru Prescod, Mark Lausten, Avi Shultz
Backup Slides
Summary

- Renewables require energy storage for increased penetration
- Concentrating solar power provides utility-scale electricity AND energy storage for dispatchability when it is most needed
  - Cost of CSP with storage is currently cheaper than photovoltaics with large-scale battery storage
Current $1 \text{ MW}_t$ and $20 \text{ kW}_t$ Heat Exchanger Design and System Integration

G3P3 Heat Exchanger System Integration

20 kW Heat Exchanger Test Stand

Model and manufacturing development is being led by $20 \text{ kW}_t$ geometry followed by application to $1 \text{ MW}_t$ geometry.