Gen3CSP

Bringing together the people and the pieces for an INTEGRATED CSP SYSTEM
Gen3 CSP Summit

Dr. Avi Shultz, Program Manager

August 25, 2021

energy.gov/solar-office
Solar Energy Technologies Office (SETO) Overview

MISSION

We accelerate the advancement and deployment of solar technology in support of an equitable transition to a decarbonized energy system by 2050, starting with a decarbonized power sector by 2035.

WHAT WE DO

**Advance solar technology** and drive soft cost reduction to make solar **affordable** and **accessible** for all Americans

Enable solar to **support grid reliability** and pair with storage to provide new options for **community resilience**

Support **job growth**, **manufacturing**, and the **circular economy** in a wide range of applications
## Roadmap to Success: 8-10 Year Strategy

### Top Priorities

1. **Accelerate solar deployment and associated job growth** by opening new markets, providing workforce training, growing U.S. manufacturing, reducing environmental impacts, and **putting a focus on environmental justice**.

2. Enable inverter-based technologies to provide essential grid services and black start capabilities while demonstrating the **reliable, resilient and secure operation of a 100% clean energy grid**.

3. **Reduce hardware and soft costs** of solar electricity for **all Americans** to enable an affordable carbon-free power sector by 2035.

4. **Support a decarbonized industrial sector** with advanced concentrating solar-thermal technologies and develop affordable renewable fuels produced by solar energy.

### Key Goals by 2030

**Acceleration**
- Enable 5x faster deployment (60 GW\(_{AC/yr}\))
- 65% of the solar hardware installed in U.S. was made or assembled in U.S.

**Reliability & Resiliency**
- Demonstrate reliable operation of a grid with 75% inverter-based generation by 2025

**Costs**
- $0.02/kWh for utility-scale photovoltaics
- $0.05/kWh for concentrating solar power
- 100% of energy consumers can choose solar without increasing energy costs by 2025

**Net Zero Emissions Energy Sector**
- $0.02/kWh for solar process heat at a range of temperatures by 2025
Affordable grid storage for clean power – any time, anywhere

Reduce storage costs by 90% from a 2020 Li-ion baseline...

...in storage systems that deliver 10+ hours of duration...

...in 1 decade
Significant Storage Cost Decreases Required

Business-as-usual Projections of Storage Price Decreases (10-hour system)

2020
$162/kWh Li Capex → 30¢-35¢/kWh LCOS

2030 Goal:
$10-$35/kWh Capex → 5¢/kWh LCOS

90% Lower Capex

2030 BAU Est.
$97/kWh Li Capex → 22¢/kWh LCOS

Other battery chemistries

10¢-20¢/kWh LCOS gap between business-as-usual improvements and LDSS target

Other Thermal and Chemical Technologies

LCOS = Levelized Cost of Storage, or the cost of moving a kilowatt-hour of energy from one time period to another
Li batteries were 99% of grid storage being deployed in 2020: IHS, Grid-Connected Energy Storage Market Tracker, 1 February 2021
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Concentrating Solar-Thermal Power Status and Goals

The goal for SETO’s CSP research is to achieve $0.05/kWh for dispatchable CSP with >12 hours of thermal energy storage (TES), with a 50% thermal-to-electric power cycle efficiency at a turbine inlet temperature of > 700 °C

Where we are now:
- Modeled LCOE of $0.098/kWh for a U.S. plant with 14 hours of TES
- 1.7 GW CSP deployed in the U.S., 6.3 GW globally
- 5.1 GW of global deployment is parabolic trough, 1.2 GW is tower
- 45% of global tower capacity and 34% of trough capacity has 6 or more hours of storage
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Priority R&D Topics:

• Designing and piloting ‘Gen3 CSP’ high-temperature (> 700 °C) thermal transport systems
• Lowering the installed cost of highly autonomous heliostats
• Enhancing the performance and reliability of CSP plants
• Developing solar thermal systems and components for solar-driven industrial processes

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Progress and Goals: 2030 LCOE Goals

The office’s 2030 cost targets for CSP baseload (≥12 hours of storage) plants will help make CSP competitive with other dispatchable generators.

*Levelized cost of energy (LCOE) progress and targets are calculated based on average U.S. climate and without the ITC or state/local incentives. The residential and commercial goals have been adjusted for inflation from 2010-18.
Applications of Solar-Thermal Energy

- Solar Electricity
- Renewable Fuel
- POWER to grid
- FUEL SYNTHESIS REACTOR
- Industrial Process Heat
- POWER from grid
- STEAM GENERATOR
- COLD TANK
- HOT TANK
Solar Thermal for Decarbonization of Industrial Process Heat

Thermally-Driven Industrial Processes:
• Desalination
• Enhanced Oil Recovery
• Agriculture and Food Processing
• Fuel and Chemicals Production
• Mining and Metals Processing

Priority Research Areas:
• Reduce the levelized cost of heat, with thermal energy storage, in temperature ranges of high priority to industrial processes
• Improve the thermal efficiency of solar-thermal-coupled processes
• Develop long-duration, thermochemical storage of solar energy (i.e. solar fuels and chemical commodities)

SETO Goals by 2025:
• Define system concepts and key components for solar process heat for carbon-emissions-intensive, high-heat-demand industries
• Define system concepts and key components for producing fuels from CSP
CSP Funding Portfolio

Non-Profit Research Institute, 8%
For-Profit Company, 36%
University, 24%
National Laboratory, 32%

~$185M over ~100 Active Projects

For full research portfolio, visit: energy.gov/eere/solar/concentrating-solar-power
A Pathway to 5 Cents per KWh for Baseload CSP

2018 Baseline

- Low Cost Solar Field ($50/m²) and Site Improvement ($10/m²): 9.8¢
- Low Cost Power Block and BOP ($900/kWe): 2.1¢
- High Efficiency Power Cycle (50% net): 0.7¢
- Low Cost TES ($15/kWh), Receiver ($120/kWt), O&M ($40/kWe-yr): 1.1¢
- Total: 5¢

*Assumes a gross to net conversion factor of 0.9

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Next Generation CSP will Leverage Next Generation Power Cycles

Advantages of the sCO$_2$ Brayton Cycle:
- Higher Efficiency (50% at ~720 °C)
- Compact Components
- Smaller Turbine Footprint (by a factor > 10)
- Reduced Power Block Costs
- Amenable to Dry Cooling
- Scalability (< 100 MW) with high efficiency
- Operational Simplicity

Ongoing Research Focus
- Improvements in Expander Design – particularly dry gas seal performance
- Improvements in compressor efficiency and reduction in compression power – especially near dome
- Improvements in Manufacturing
  - Casting or novel manufacturing processes for casing
  - 3D printing or other Novel manufacturing for blades, rotor and bearings
- Integration of compressor and expander into one single casing, drive train; elimination of seals
• Integrated demonstration of a sCO₂ cycle power block heated by thermal energy storage at 5 MWe scale
• Provide operational experience of the sCO₂ Brayton cycle for utilities, operators, and developers.
• Public-private partnership cost-shared with $39 million DOE funding and >$31 million private investment
Gen3 CSP

Bringing together the people and the pieces for an INTEGRATED CSP SYSTEM
Three waves of Gen3 relevant funding

Competitive Programs

- $9M COLLECTS (2016)
- $29M CSP SuNLaMP (2015)
- $1.4M 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)
- $30M ARRA (2009)
- $35M Thermal Storage (2008)
Generation 3 CSP Technology

- Annual Average Efficiency 50%
- Receiver ≥ 90% η
- Power Cycle ≥ 50% η

**SOLAR FIELD ASSUMPTIONS**
- $75/m^2$

**RECEIVER / TOWER**
- $150/kW_{th}$
- Thermal Efficiency ≥ 90%

**THERMAL ENERGY STORAGE**
- $15/kWh_{th}$
- Energetic Efficiency: >99%

**PRIMARY HEAT EXCHANGER**
- $150/kW_{th}$
- Power Cycle Inlet: >700°C

**POWER CYCLE ASSUMPTIONS**
- $600 / kW_e$
- Design Point Turbine inlet: 715°C / 250 bar

- Gen 3 CSP >700 °C
Gen3 Pathway Development

- Black and Veatch cost study for a 10MW power plant using chloride salt or particles for heat transfer media
- Series of workshops developing potential Gen3 pathways with CSP R&D community
- Commissioned NREL/SNL to draft technical report on gaps and status of 700 C + Heat transfer media for integrated test
Gen3 Pathway Challenges

- High temperature thermal transport systems were immature for the ~10 MW scale
- Small Brayton cycle $\Delta T$ has strong effect on TES cost
- High temperature piping going up and down the tower can be a cost breaker
- Significant uncertainty in any high-flux receiver performance, especially with transients
Gen3 CSP: Solar Thermal Transport Systems > 700 °C

**Total federal funds awarded in 2018:**
$85,000,000 over 25 projects in 3 Topics:
- **Topic 1:** Integrated, multi-MW test facility
- **Topic 2A:** Individual Component Development
- **Topic 2B** and **National Lab Support:** Cross-cutting Gen3 Research and Analysis
Gen3 CSP: Solar Thermal Transport Systems > 700 °C

$25 million was available for one of the Topic 1 pathways to construct and operate the ‘Phase 3’ test facility.
Gen3 CSP: Raising the Temperature of Solar Thermal Systems

Executive Summaries of Phase 1/2 accomplishments are available at: https://bit.ly/gen3-summit-2021
‘Gas’ Gen3 CSP Pathway

**TOPIC 1**

- Brayton Energy

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**PHASE 1**

- Integrated Solids System
  - Component Level Design and Testing
  - System Design

**PHASE 2**

- Integrated Liquids System
  - Component Level Design and Testing
  - System Design

**PHASE 3**

- Integrated Gas System
  - Component Level Design and Testing
  - System Design

- Tower and Solar Field Design
  - Component Level Design and Testing
  - System Design

- Down-Selection to One Path

- Integrated System Construction and Testing

- Particle TES and Heat Exchanger
State of the technology – Gas Pathway

- Mass flow is dictated by power block
- Heat input is constrained by peak allowable receiver material temp.
Related Gas Pathway Accomplishments

**High-Temperature fluid circulator development**

Mohawk Innovative Technologies, Inc

EPRI - 740H Seam Welded Pipe

Idaho NL, Argonne – Creep/fatigue characterization and receiver design

**Material Metrology and Characterization**

Oak Ridge – sCO₂ Corrosion Lifetime Model Development

U. Tulsa – Development of GEN3 Durability Life Models
Liquid Gen3 CSP Pathway

TOPIC 1

- National Renewable Energy Laboratory

Integrated System Design

PHASE 1 | PHASE 2 | PHASE 3

Integrated Solids System | Component Level Design and Testing | System Design |
Integrated Liquids System | Component Level Design and Testing | System Design | Down-Selection to One Path |

Molten Chloride Tank Design

Component Design and Prototyping
State of the technology – Liquid Pathway

Mass Ratio: 45 MgCl\textsubscript{2}, 39 KCl, 16 NaCl

The salt is a chemical... for which you must keep water out.

Electrochemical real-time monitoring of salt health

‘Dirty Salt’ esp. H\textsubscript{2}O

‘Clean Salt’ – no H\textsubscript{2}O
State of the technology – Liquid Pathway

Salt or Sodium in the Receiver?

Salt: Lower thermal conductivity and higher freeze point resulted in higher materials-level risks, tighter operating constraints.

Sodium: Higher thermal conductivity resulted in lower materials-level risks, more forgiving operating constraints.
State of the technology – Liquid Pathway

Sodium/Salt Heat Exchanger

Challenge
800C compatibility between Sodium and high nickel alloys is not well known

Challenge
Salt vapor pressure is much higher than expected
Related Liquid Pathway Accomplishments

Chloride salt purification, handling, and characterization

Oak Ridge, Savannah River, NREL, RPI, et al

Novel Heat Exchanger Design and Materials

Purdue U. – Melt infiltration synthesis of ceramic/metal composites

Argonne – Additive manufacturing of SiC/Si HXers

Pump and Valve Component Development

Sandia, Flowserve – High-temperature Liquid Valve Design

MIT, Purdue, Flowserve
Solid Particle Gen3 CSP Pathway

TOPIC 1

• Sandia National Laboratories

Receiver Design and Modelling

Integrated Solids System
Component Level Design and Testing
System Design

Integrated Liquids System
Component Level Design and Testing
System Design

Integrated Gas System
Component Level Design and Testing
System Design

Down-Selection to One Path

Integrated System Construction and Testing

PHASE 1  PHASE 2  PHASE 3

Particle – sCO2 Heat Exchanger
Contributors: VPE and Solex

Thermal Energy Storage (Particle Silo)
Contributors: Allied Mineral Products and Matrix PDM
State of the technology – Solid Pathway

R&D and design of major components

Ho, Clifford K. Gen 3 Particle Pilot Plant (G3P3): Integrated High-Temperature Particle System for CSP (2020 SETO Peer Review poster). OSTI ID 1770059

Critical Advancements
• Substantial development of wind tolerant open particle receiver
• Robust understanding of high temperature particle handling, heat transfer, flow, and lifetime
• Sustained effort to demonstrate greater than 300 W/m² K moving packed bed particle to sCO₂ HX
• Original conceptual design of 100 MW system and components
• Compatible with 5¢/kWh LCOE target

Remaining Challenges: • Robust receiver operation and scale up; • Heat Exchanger performance and cost improvement; • TES and particle media cost reduction; • High Temperature Skip Hoist
Related Solid Particle Pathway Accomplishments

**Particle Receiver Characterization**

- Sandia/UNM – Characterization of Convective and Particle Losses

**Particle Flow Characterization**

- Georgia Tech (Loutzenhiser) – Advanced Characterization of Particulate Flow

**Material Metrology and Testing**

- UCSD (Chen) - Modulation Photothermal Radiometry (MPR)
- Laser Flash
- 3-omega
- Georgia Tech (Yee) – Thermophysical Properties Database of Gen3 CSP Materials
- U. Tulsa – Development of GEN3 Durability Life Models
Review Process / Selection Criteria

1. Critical technology risks addressed to advance and succeed in Phase 3.

2. Project management and technical capabilities of the awardees to accomplish Phase 3 activities. Preparation for construction.

3. Merit of future (100 MW scale) Gen 3 System to achieve LCOE targets and the likelihood of market adoption.

4. Extent to which the proposed Phase 3 activities will de-risk technology concerns.

5. Extent to which the proposed Phase 3 results will de-risk commercial adoption of Gen3 CSP.
Pathway Selection: Gen 3 Particle Pilot Plant (G3P3)


Image from Hany Al-Ansary – King Saud University
Solid Pathway Strengths

- System simplicity for construction, operation, and reliability
- Wide operating range and opportunity for further temperature increases
- Potential relevance to other solar thermal applications

Future Needs for Gas and Liquid Pathways

**Gas**

- Design of robust, high-thermal-efficiency receivers for high-flux applications, continue testing to validate
- Continued development of particle-to-gas heat exchangers
- Particle TES design could benefit a wide variety of future applications using indirect HTFs
- System designs needed to minimize parasitics (pressure drop)

**Liquid**

- Chloride salt is a promising low-cost TES media for multiple applications
- TES tank development and chloride corrosion detection and control needs to be scaled up and validated
- Na receivers integrated with nitrate salt TES may lead to future adoption of chlorides
- Currently available materials impose significant flux limitations on indirect receivers due to thermomechanical property limitations
Particle System Research Opportunities

- Alternate receiver designs may be needed for thermochemical applications where controlled environments are needed
- Particle cost and performance improvement are significant sensitivities to LCOE
- Particle handling and flow control needs to be cost effective and reliable
- Scaling up – system architectures and components need to be optimized and tested at MW-scale, potentially as part of the G3P3 system
- Significant opportunities to improve heat exchanger cost and performance
- Direct receivers and particle TES couple well with large cycle ΔT – can particle systems be optimized to use full temperature range down to ambient?
- Beyond electricity – long duration energy storage, and solar thermochemical applications
Gen3 Summit Goals

• Dissemination of Gen3 pathway designs and project conclusions
  • Project summaries available on our website: https://bit.ly/gen3-summit-2021

• Discussion of remaining gaps and research opportunities
  • Moderated panel discussions, webex chat and Q&A
# Gen3 CSP Summit Agenda – Wednesday, August 25

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<thead>
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<th>Time (ET)</th>
<th>Session</th>
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<tr>
<td>11:00AM–12:00PM</td>
<td>SETO Introduction and Overview of the Gen3 CSP Program</td>
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<td><em>Avi Shultz, Program Manager, CSP, Solar Energy Technologies Office</em></td>
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<tr>
<td>12:00PM–1:00PM</td>
<td>Track A: High-Temperature Nickel-Based Alloys</td>
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<td>Track B: Solid Particle Receivers</td>
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<tr>
<td>1:00PM–1:30PM</td>
<td>Parallel Session Discussion</td>
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<td>1:30PM–2:00PM</td>
<td>Break</td>
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Gen3 CSP Summit Agenda – Wednesday, August 25

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<tr>
<td>2:00PM–3:00PM</td>
<td>Gen3 CSP Liquid Pathway</td>
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<tr>
<td>3:00PM–4:00PM</td>
<td>Track A: High-Temperature Nickel-Based Alloys</td>
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<td>Track B: Solid Particle Characterization and Handling</td>
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<tr>
<td>4:00PM–4:30PM</td>
<td>Parallel Session Discussion</td>
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## Gen3 CSP Summit Agenda – Thursday, August 26

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<td>11:00AM–12:00PM</td>
<td>Gen3 CSP 'Gas' Pathway</td>
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<tr>
<td>12:00PM–1:00PM</td>
<td>Track A: Additive Manufacturing of Gen3 CSP Components</td>
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<td>Track B: Metrology and Characterization of High-Temperature Media and</td>
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<td>Materials</td>
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<td>2:00PM–3:00PM</td>
<td>Gen3 CSP Solid Particle Pathway</td>
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<tr>
<td>3:00PM–4:00PM</td>
<td>Track A: Solid Particle Heat Exchangers</td>
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<td></td>
<td>Track B: Components for Molten Chloride Systems</td>
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<td>4:00PM–4:30PM</td>
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QUESTIONS?

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