CSP Program Summit 2016

**Brayton Energy**

HIGH-EFFICIENCY LOW-COST SOLAR RECEIVER FOR USE IN A SUPERCRITICAL CO\textsubscript{2} RECOMPRESSION CYCLE

**SRNL**

LOW-COST METAL HYDRIDE THERMAL ENERGY STORAGE SYSTEM FOR CSP SYSTEMS

**Brayton Energy** and **SRNL**

SOLAR RECEIVER WITH INTEGRATED THERMAL STORAGE FOR A SUPERCRITICAL CO\textsubscript{2} POWER CYCLE

Shaun Sullivan
Brayton Energy

Dr. Ragaiy Zidan
Savannah River National Lab.
### HIGH-EFFICIENCY LOW-COST SOLAR RECEIVER FOR USE IN A SUPERCritical CO$_2$ RECOMPRESSION CYCLE

<table>
<thead>
<tr>
<th><strong>PROJECT NAME</strong></th>
<th>High-Efficiency Low-Cost Solar Receiver for use in a Supercritical CO$_2$ (sCO$_2$) Recompression Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FUNDING OPPORTUNITY</strong></td>
<td>DE-FOA-0000595 SunShot Concentrating Solar Power (CSP) R&amp;D</td>
</tr>
<tr>
<td><strong>PRINCIPAL INVESTIGATOR</strong></td>
<td>Shaun Sullivan</td>
</tr>
<tr>
<td><strong>LEAD ORGANIZATION</strong></td>
<td>Brayton Energy, LLC</td>
</tr>
<tr>
<td><strong>PROJECT DURATION</strong></td>
<td>36 months</td>
</tr>
<tr>
<td><strong>PROJECT BUDGET</strong></td>
<td>$ 3,150,316</td>
</tr>
</tbody>
</table>
“... to design and build hardware solutions for sustainable, efficient energy systems through applied research, revolutionary innovation, sound engineering, and dedicated partnerships with our clients.”

• A private Advanced Energy R&D firm
• Located in Hampton, NH
  • About 50 miles north of Boston
• Turbomachinery solutions
  • Power systems
  • Biomass
  • UAVs
  • Transportation
• CSP components
• High-temperature compact heat exchangers
• Advanced system modeling and analysis
• Energy storage solutions (thermal, CAES)
Overview

- In its 2012 SunShot Vision Study, the DoE identified high-efficiency sCO$_2$ power cycles as an enabling technology critical to achieving the 6¢/kWh LCOE goal.

- At that time, there was no existing receiver technology for transferring absorbed solar energy directly into sCO$_2$.
  - Challenging operating conditions (>700 °C, 25 MPa)
sCO₂ Receiver Technology

- Fully-welded pressure boundary ensures sealing
- Individually tested for quality control
- Customizable fin geometry
- Small hydraulic diameters, densely-packed fins, and thin walls enhance heat transfer
- Brazed or diffusion (TLP*) bonded fins react high internal pressure, acting as tension support members while enhancing heat transfer.
- Thin structures reduce thermal stresses, enabling long fatigue lives

*Transient liquid phase (TLP)
Mechanical Design, Performance, & Validation Testing

- Cold Burst Tests: > 100 MPa
- Creep and Fatigue Testing
  - 800 C, 140 MPa max.
- Colburn Modulus $j$
- Friction Factor
Low-Cost Quartz Tube Window

- Low-Cost Commodity Tubes
- Reduces Radiation Losses
  - Transparent to visible light
  - Opaque to infrared radiation
- Impedes Convection Losses
- 5% (6 pt.) performance benefit
Solar Receiver

- Cylindrical
  - 4 m Diameter
  - 4 m Height
- 20 MW$_{th}$ Design Heat Rate
  - Designed for sCO$_2$ Engines currently under development
Program Results

<table>
<thead>
<tr>
<th>PERFORMANCE METRIC</th>
<th>SUNSHOT TARGET</th>
<th>BRAYTON TARGET</th>
<th>BRAYTON RESULTS</th>
<th>EXTERNAL RECEIVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver Creep Life</td>
<td>n/a</td>
<td>&gt; 90,000 hours</td>
<td>60,000 hours</td>
<td>&gt; 90,000 hours</td>
</tr>
<tr>
<td>Receiver Fatigue Life</td>
<td>≥ 10,000 cycles</td>
<td>≥ 10,000 cycles</td>
<td>≥ 100,000 cycles</td>
<td>≥ 10,000 cycles</td>
</tr>
<tr>
<td>Receiver Cost</td>
<td>≤ $150/kW_th</td>
<td>≤ $120/kW_th</td>
<td>$98/kW_th</td>
<td>≤ $150/kW_th</td>
</tr>
<tr>
<td>HTF Exit Temperature</td>
<td>≥ 650 °C</td>
<td>≥ 750 °C</td>
<td>750 °C</td>
<td>715 °C</td>
</tr>
<tr>
<td>Receiver Efficiency $\eta_{thermal}$</td>
<td>n/a</td>
<td>≥ 95%</td>
<td>94.9%</td>
<td>(partner defined)</td>
</tr>
<tr>
<td>Receiver Efficiency $\eta_{annualized}$</td>
<td>≥ 90%</td>
<td>≥ 92%</td>
<td>93.1%</td>
<td>(partner defined)</td>
</tr>
<tr>
<td>System Efficiency Gain</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>≥ 15.00%</td>
</tr>
<tr>
<td>Quartz Window Benefit</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>≥ 2.00%</td>
</tr>
</tbody>
</table>

- Meets or exceeds all technical and cost goals of program
  - High Performance, Long Life (creep + fatigue), Low Cost
- 30% (10+ pts.) System Efficiency (receiver + cycle) gain as compared to state-of-the-art CSP Steam Cycle
- Tailored to be compatible with the sCO₂ engine cycles currently under development through the SunShot program
sCO2 Heat Exchangers
sCO\textsubscript{2} Heat Exchangers

- Industry-leading design:
  - High Effectiveness
  - Compact, less weight
  - Lower-cost

- Low-cost modular panel solar receivers for high-efficiency engine configurations
- Low-cost compact high-temperature heat exchangers and recuperators for high-efficiency power cycles
- Low-cost compact high-temperature working fluid (sCO\textsubscript{2}) to molten salt heat exchangers
# LOW-COST METAL HYDRIDE THERMAL ENERGY STORAGE SYSTEM FOR CSP SYSTEMS

<table>
<thead>
<tr>
<th><strong>PROJECT NAME</strong></th>
<th>Low-Cost Metal Hydride Thermal Energy Storage System for CSP Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FUNDING OPPORTUNITY</strong></td>
<td>SunShot Lab Proposal Development Process (LPDP), Concentrating Solar Power (CSP) Subprogram</td>
</tr>
<tr>
<td><strong>PRINCIPAL INVESTIGATOR</strong></td>
<td>Ragaiy Zidan, Ted Motyka</td>
</tr>
<tr>
<td><strong>LEAD ORGANIZATION</strong></td>
<td>Savannah River National Laboratory</td>
</tr>
<tr>
<td><strong>PROJECT PARTNERS</strong></td>
<td>Curtin University</td>
</tr>
<tr>
<td><strong>PROJECT DURATION</strong></td>
<td>36 months</td>
</tr>
<tr>
<td><strong>PROJECT BUDGET</strong></td>
<td>$ 1,873,333</td>
</tr>
</tbody>
</table>
• Located at the Savannah River Site (SRS), Aiken SC
• Newest National Laboratory (11yrs) but with > 60 years of R&D as a Federal Lab
  • ~ 900 Staff
• Multi-Program Laboratory
  • >60% of funding from non-SRS customers
• Core Capabilities
  • Chemical Processing/Separation
  • Materials Science
  • Hydrogen/Tritium
  • Environmental Science
Metal Hydride Based Thermal Energy Storage for Concentrating Solar Power Plants

• Objective:
  • Evaluate and demonstrate a metal hydride-based Thermal Energy Storage (TES) system for use with a Concentrating Solar Power (CSP) system.

• Why metal hydrides:
  • Metal hydrides (MH) have a unique ability to deliver low-cost, high capacity and energy efficient TES systems for CSP applications.
  • New higher capacity and lower cost metal hydride materials have recently become available.
  • SRNL’s unique approach, based on integration of modeling and hydride material development, has been applied to help solve this challenge.
Metal Hydride CSP Schematic

Energy Storage Density for Several Metal Hydride Materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy Storage Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molten salt</td>
<td>153 kJ/kg</td>
</tr>
<tr>
<td>Phase change mat’l (NaNO₃)</td>
<td>282 kJ/kg</td>
</tr>
<tr>
<td>CaH₂</td>
<td>4934 kJ/kg</td>
</tr>
<tr>
<td>LiH</td>
<td>8397 kJ/kg</td>
</tr>
<tr>
<td>TiH₂</td>
<td>1900 – 2842 kJ/kg</td>
</tr>
<tr>
<td>NaMgH₃</td>
<td>1721 – 2881 kJ/kg</td>
</tr>
<tr>
<td>Mg₂FeH₆</td>
<td>2090 kJ/kg</td>
</tr>
<tr>
<td>MgH₂</td>
<td>2814 kJ/kg</td>
</tr>
</tbody>
</table>

Metal Hydrides

Thermal Energy Storage is based on Reversible Chemical Reactions
SunShot CSP TES Targets

• TES system techno-economic targets:
  • charging time of less than 6h,
  • volumetric energy density $\geq 25\text{kWh}_{\text{th}}/\text{m}^3$,
  • cycle life demonstrates $\leq 5\%$ degradation in thermal capacity over 1000 exercises with a plausible and valid pathway to less than 1% degradation
  • operating temperature $\geq 650 \, ^\circ\text{C}$
  • exergetic efficiency $\geq 95\%$.
  • cost estimation must demonstrate a viable path to TES cost of $15/\text{kWh}_{\text{th}}$. 
Metal Hydride TES Project Period 1

- SRNL and partner Curtin University collected and evaluated material property data for over 20 MH candidates.
- Three potential pairs of materials were selected as the most promising materials capable of meeting many of the DOE SunShot targets. These material pairs included:
  - 1) Mg$_2$FeH$_6$/NaMgH$_3$-NaAlH$_4$ (SAH),
  - 2) TiH$_{1.72}$ – TiXY and
  - 3) CaH$_2$ – TiXY(where X & Y are typically Fe, Mn).
- None of the existing pairs of materials could meet all of the DOE targets.

The challenge therefore for Periods 2 and 3 were to either modify or develop a new lower cost, higher temperature materials and systems that could meet or exceed the DOE Targets


Period 2/3 Material Development, Characterization and Performance Accomplishments

- Na$_3$AlH$_6$ with additives was identified as leading low-cost LTMH pairing material over NaAlH$_4$
- A variety of HTMHs were investigated for TES applications. These include MgH$_2$, Mg$_2$FeH$_6$, NaMgH$_3$, TiAl, NaMgH$_2$F.
- Thermal and kinetic properties of the above materials were measured including enthalpy, entropy, bulk density, hydrogen capacity, activation energy, thermal conductivity, etc.
  - A low cost metal hydride capable of reversibly storing ~ 2 wt. % hydrogen at 750 °C was demonstrated for the first time. This material is currently the most promising high temperature metal hydride material discovered for TES applications at high temperatures (> 650 °C) which is capable of meeting DOE cost targets.

Period 2/3 System Modeling & Techno-Economic Analysis Accomplishments

- A screening analysis tool was developed to evaluate the performance of the MH based TES system against targets. The screening criteria included: system cost, system exergetic efficiency, volumetric efficiency, operating temperature.

- A TES system model was developed to model the coupled MH pairs. The model is a lumped parameters transient model that incorporates mass and energy balance equations along with the kinetics of the two materials.

- A detailed Finite-Element based model was developed to evaluate the detailed behavior of the MH system, highlighting the gradients inside the reactor. The model includes mass, energy and momentum balance as well as the kinetics of the MH materials.

A statistical cost methodology was developed and applied showing that the newly developed composite CaH$_2$/Si based material can achieve a cost of ~16 $/kWhth under selected conditions.

An integrated TES system model was developed in MatLab® and was integrated into a Trnsys® program, to simulate an overall solar plant.

The detailed MH model was used to simulate the behavior of modified LTMH material (Na$_3$AlH$_6$) and to compare the obtained results with experimental data.

MH pairing was examined and modeled using the previously developed system model both as separate MHs and as paired materials.
## Metal Hydride TES Project Overall Accomplishments

<table>
<thead>
<tr>
<th></th>
<th>State of the art before SunShot project:</th>
<th>End of SunShot project:</th>
<th>SunShot targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES system (High T matl – Low T matl)</td>
<td>MgH$_2$-MmNi$_5$</td>
<td>Ca$_2$Si-Na$_3$AlH$_6$</td>
<td></td>
</tr>
<tr>
<td>Cost ($/kWh$_{th}$)</td>
<td>200</td>
<td>24.9, down to 16.1 based on statistical evaluations as per SunShot</td>
<td>15</td>
</tr>
<tr>
<td>Exergetic efficiency (%)</td>
<td>72</td>
<td>93</td>
<td>95</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>Lower than 500</td>
<td>650-750</td>
<td>650</td>
</tr>
<tr>
<td>Volumetric density (kWh/m$^3$)</td>
<td>270</td>
<td>193</td>
<td>25</td>
</tr>
</tbody>
</table>

Components and material were considered, approaching DOE targets

Metal Hydride TES Project Summary

• With DOE support during this project, SRNL has quickly become a world leader in this technology.
• SRNL has applied for a potentially transformational patent and had 6 peer-reviewed papers published in this area.
• With its partner CU, SRNL initiated an International Energy Agency (IEA) working group for MH TES technology and has helped create significant international research interest and excitement in this area.
• SRNL has also received considerable interest from several solar system design and installation firms, including United Sun Systems and Brayton Energy.
• SRNL has received additional funding to continue its MH TES development from Brayton Energy as well as through a special Laboratory Directed Research and Development Initiative.
### Solar Receiver with Integrated Thermal Storage for a Supercritical Carbon Dioxide Power Cycle

<table>
<thead>
<tr>
<th><strong>Project Name</strong></th>
<th>Solar Receiver with Integrated Thermal Storage for a Supercritical Carbon Dioxide Power Cycle</th>
</tr>
</thead>
</table>
| **Funding Opportunity**| DE-FOA-0001186  
CSP: Advanced Projects Offering Low LCOE Opportunities (APOLLO) |
| **Principal Investigator** | Shaun Sullivan |
| **Lead Organization**   | Brayton Energy, LLC |
| **Project Partners**    | Savannah River National Laboratory Greenway Energy, Inc. |
| **Project Duration**    | 39 months |
| **Project Budget**      | $3,295,953 |
• Founded in 2006
• Clean Energy & Energy Storage
  • Fuel Cell System Development & Deployment
  • H₂ Storage Material Electrochemical Scale-up
  • Fuel Reforming and Purification
  • Battery Research
  • Betavoltaics & Tritium Research
  • Bioelectrochemical Sensors
• Electrochemical Engineering Research Focus
Roadmap to Low-Cost CSP

• Couple the design of critical technologies:
  - Low-Cost High-Efficiency Solar Receiver
  - High-Temperature Energy-Dense TES
  - High-Efficiency Recompression sCO₂-Brayton Cycle Engine

• Adopt demonstrated enabling technologies:
  - Commercial Wind Turbine Tower Technology
  - Low-Cost High-Performance sCO₂ Heat Exchangers
  - Economic Modular Heliostat Designs

• Employ a High-Impact Nominal Operating Profile
  - 10 MWₑ for 8 hrs. during day
  - 10 MWₑ for 4 hrs. at night
Metal Hydride

- Characteristics for this Application:
  - Approximately isothermal (HTMH: 715 to 745 °C) operation
  - Moderately High Pressure (1.5-3.0 MPa)

- HTMH Volume:
  - Interacts directly with receiver and engine cycle
  - Approx. 160 m³ of material
    - A cylinder with Diameter = 5.8 m, Height = 5.8 m

- UP-TOWER MOUNTING OF TES SYSTEM POSSIBLE
Operational Overview

• During the day, concentrated solar energy is absorbed by receiver and is:
  • Transferred to the sCO\textsubscript{2} to run the engine directly, and/or
  • Conveyed into the HTMH, where:
    1. Chemical bonds are broken, generating H\textsubscript{2}
    2. The H\textsubscript{2} flows from the HTMH to the LTMH
    3. The H\textsubscript{2} bonds with the LTMH, storing the energy

• At night, H\textsubscript{2} is released from the LTMH and flows into the HTMH, where it bonds exothermically; the released heat is transferred into the sCO\textsubscript{2} to run the engine.
Program Summary

- Solar Receiver
- Thermal Transport
- sCO₂-to-Glycol Heat Exchanger
- Hydrogen Transport
- High-Temperature Recuperator
- Low-Temperature Recuperator

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>sCO₂ Turbine Inlet Temp.</td>
<td>715 °C</td>
</tr>
<tr>
<td>sCO₂ Cycle Rated Power</td>
<td>10 MWₑ</td>
</tr>
<tr>
<td>TES Energetic Efficency</td>
<td>99%</td>
</tr>
<tr>
<td>TES Exergetic Efficency</td>
<td>95%</td>
</tr>
<tr>
<td>TES Storage Capacity</td>
<td>80 MWhₘ</td>
</tr>
<tr>
<td>TES Discharge Duration</td>
<td>4 hours</td>
</tr>
<tr>
<td>Operating Life</td>
<td>90,000 hrs</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>10k cycles</td>
</tr>
<tr>
<td>LCOE</td>
<td>$0.06/kWₘ</td>
</tr>
</tbody>
</table>
Thank You!

Integrated Modular CSP Incorporating Up-Tower Receiver, Engine, and Thermal Energy Storage

Up-Tower $\eta = 50\%$ sCO$_2$ Brayton Engine
Low-Cost Brayton Energy sCO$_2$ Receiver
Up-Tower Integrated HTMH TES
Eliminates Ground-Level Infrastructure
Minimizes Working Fluid Inventory
Eliminates Heat Transfer Fluid
Commercial Wind Turbine Tower
Commercial e-Solar Type Heliostat Field
Ground-Level LT MH TES
Ground-Level Dry Cooling
Truck/Highway-Transportable
Entirely Factory-Assembled
Electrical Interconnect Only

6¢/kWh

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