Integrated Solar Thermochemical Reaction System for the High Efficiency Production of Electricity

SunShot
Concentrating Solar Power
Program Review 2013
April 23, 2013

Awardee:	Pacific Northwest National Laboratory
PI / Presenter:	Robert S Wegeng
Subcontractors:	Oregon State University, Barr Engineering, Diver Solar LLC and Infinia Technology Corporation
CRADA Partner:	SolarThermoChemical LLC
Project Start Date:	February 19, 2013

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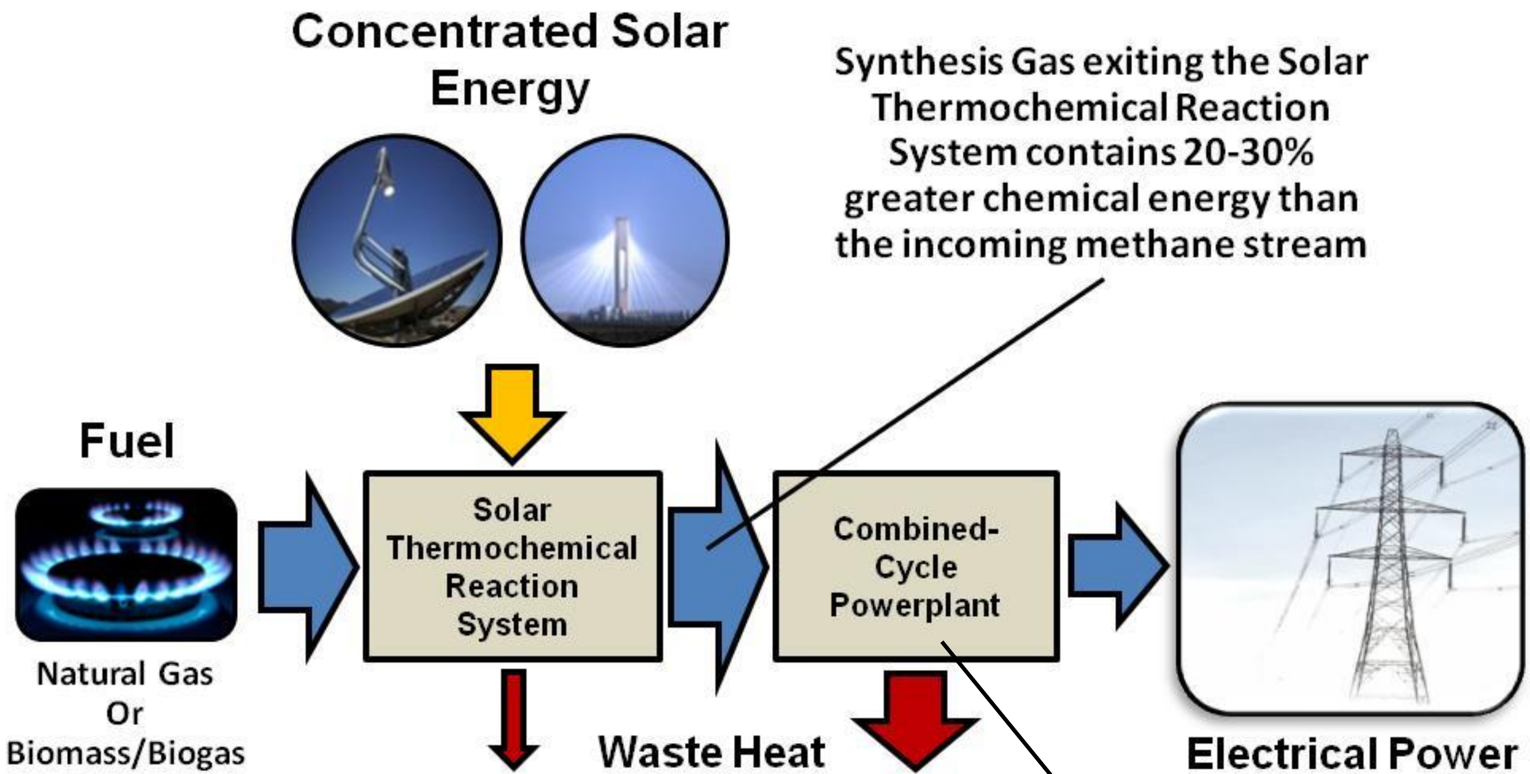
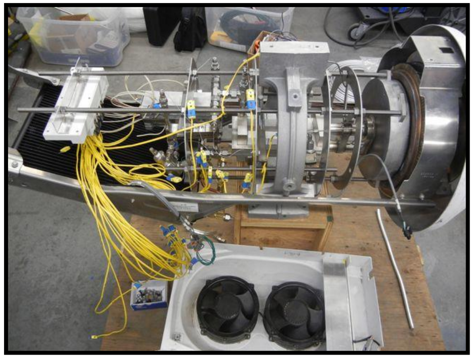
Project Approach

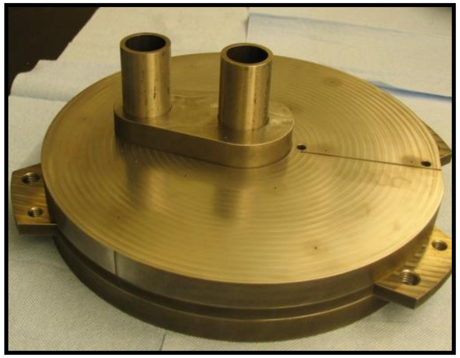
We can readily project meeting the SunShot goal of 6 ¢/kWh by 2020

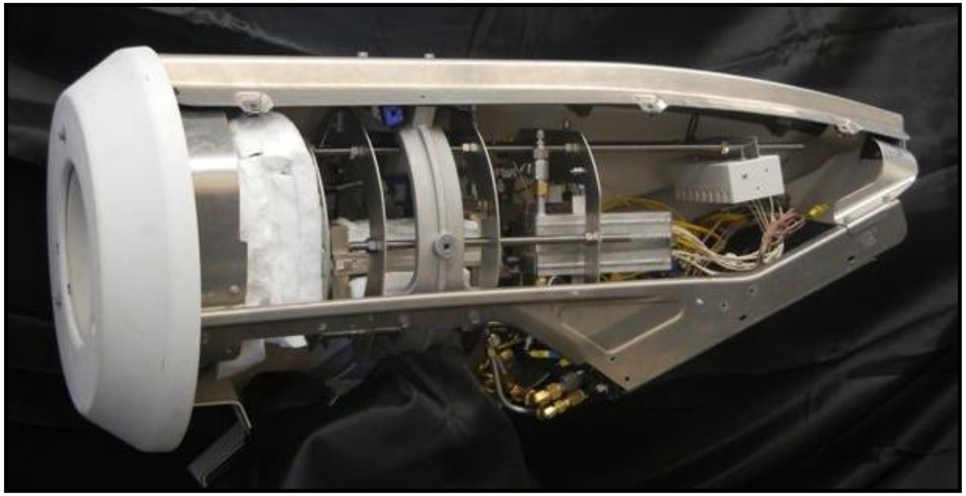


Combined-Cycle Powerplants are already proven technologies/systems

Core Technology
Micro- and Meso-channel Reactors and Heat Exchangers
Process-Intensive Components and Systems: High Efficiencies







Methane Steam Reforming: $CH_4 + H_2O \rightarrow CO + 3H_2$

Outline

- Introduction
  - Project Approach
  - Core Technology
- Outline
- Previous Work
  - By Others
  - By Our Project Team (Key Technical Results)
- Project
  - Project Goals and Objectives
  - Project Description
  - Reactor and High Temperature Heat Exchanger
  - Challenges and Barriers for Development and Commercialization
- Significance of Results
- Summary and Conclusions
- Publications

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Previous Work by Others

Solar-to-Chemical Energy Conversion Efficiencies Exceeding 50%

Sandia 1980s

- Solar CO_2 reforming of methane in a direct catalytic absorption reactor; with a 3.5 kW_s concentrator; maximal thermal and chemical efficiencies of 79.8% and 55.5%

Weizmann Institute of Science and DLR 2000s

- Solar steam reforming of methane; 400 kW_s

Sandia and DLR 1990s

- Solar CO_2 reforming of methane; 150 kW_s concentrator; chemical efficiency of 54%

DLR and CIEMAT 1990s

- Solar steam reforming of methane; 170 kW_s; highest methane conversion at 93%

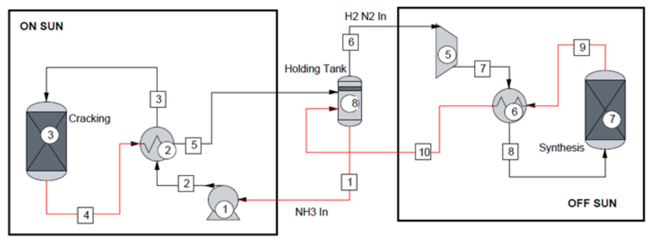
DOE Hydrogen Program 2000s

- Several solar water-splitting investigations

Key Technical Results, Analyses, Accomplishments and Breakthroughs to Date

Previous Project Phase 1: Evaluations of Chemical Cycles for Solar Thermochemical Energy Storage

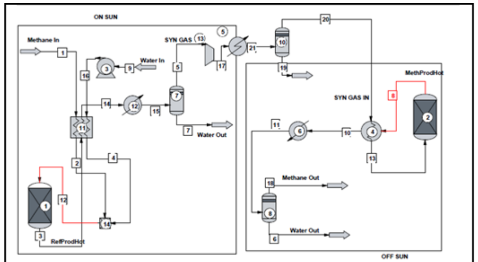
- Previous project was focused on thermochemical energy storage for dish-Stirling power systems
- ChemCad Simulations were used to assess multiple thermochemical cycles
- Chemistries incorporating methane reforming and methanol synthesis were identified as providing the highest potential roundtrip efficiencies
- Open cycles performed better than closed cycles



Closed Cycle: Ammonia Decomposition and Resynthesis

$NH_3 \rightarrow N_2 + H_3$ (On-Sun)

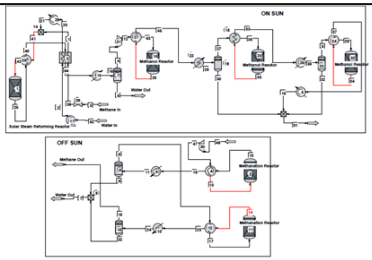
$N_2 + H_3 \rightarrow NH_3$ (Off-Sun)



Closed Cycle: Hydrocarbon Conversion (Methane to Syngas to Methane)

$CH_4 + H_2O \rightarrow CO + 3H_2$ (On-Sun)

$CO + 3H_2 \rightarrow CH_4 + H_2O$ (Off-Sun)

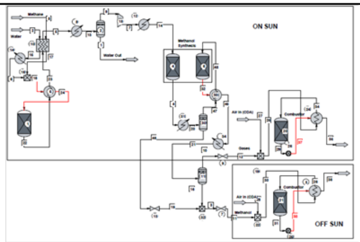


Closed Cycle: Hydrocarbon Conversion (Methane to Syngas to Methanol to Methane)

$CH_4 + H_2O \rightarrow CO + 3H_2$ (On-Sun)

$CO + 3H_2 \rightarrow CH_3OH + H_2$ (On-Sun)

$CH_3OH + 3H_2 \rightarrow CH_4 + H_2O$ (Off-Sun)



Open Cycle: Hydrocarbon Conversion (Methane to Syngas to Methanol with Combustion)

$CH_4 + H_2O \rightarrow CO + 3H_2$ (On-Sun)

$CO + 3H_2 \rightarrow CH_3OH + H_2$ (On-Sun)

$CH_4 + CO + H_2 + O_2$ (Air) $\rightarrow CO_2 + H_2O$ (On-Sun)

$CH_3OH + O_2$ (Air) $\rightarrow CO_2 + H_2O$ (Off-Sun)

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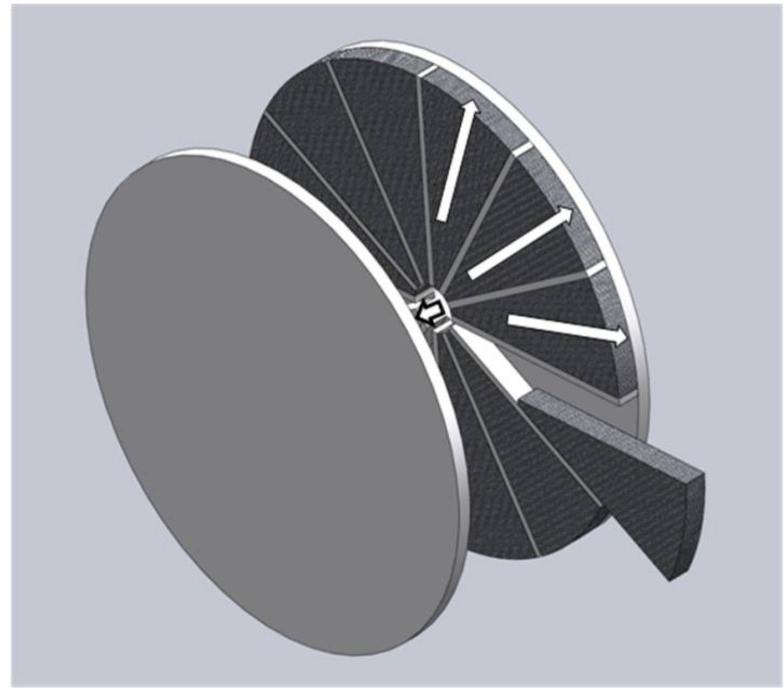
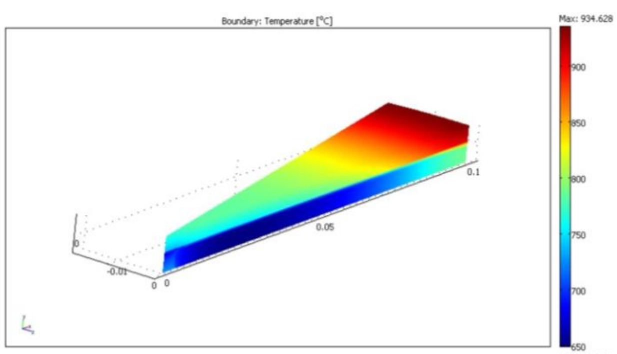
Key Technical Results, Analyses, Accomplishments and Breakthroughs to Date

Previous Project Phase 2: Proof-of-Principle Demonstration of a Solar Methane Reforming Reactor (TRL3)

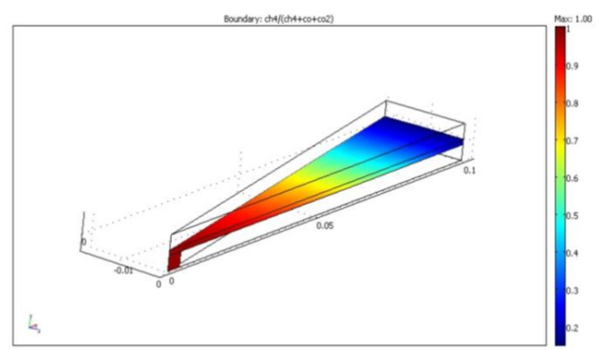
Reactor Design

- For the solar reforming reactor, various conceptual approaches were identified
- 3-D reacting flow simulations were generated using Comsol Multiphysics
- A radial flow geometry was selected for the first proof-of-principle reactor





Temperature profile



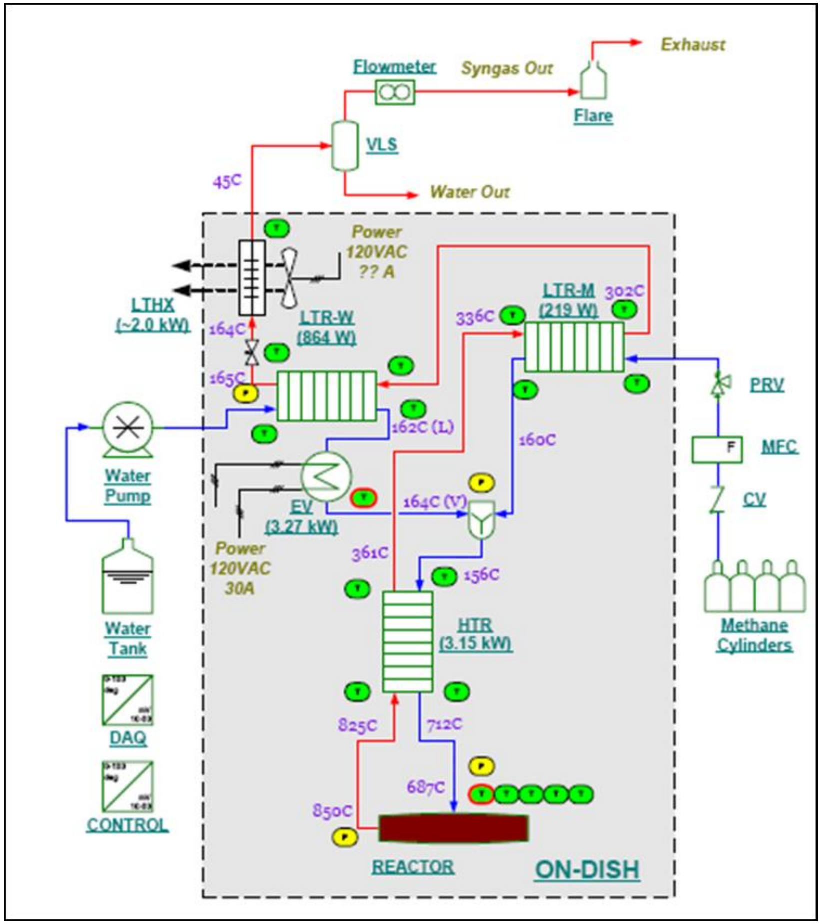
Methane conversion profile

Key Technical Results, Analyses, Accomplishments and Breakthroughs to Date

Previous Project Phase 2: Proof-of-Principle Demonstration of a Solar Methane Reforming Reactor (TRL3)

System Design

- ChemCad simulations were used to specify the other components for the reaction system and determine the requirements for the solar reforming reactor
- The demonstration system was sized for an Infinia Power Dish III solar concentrator
- Available microchannel heat exchangers were identified, from other projects, that could reasonably be incorporated within the system
- Since methanol production was part of the cycle, but not included in the experiment, and electrical resistance heater was added to simulate the heat from methanol synthesis



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Key Technical Results, Analyses, Accomplishments and Breakthroughs to Date

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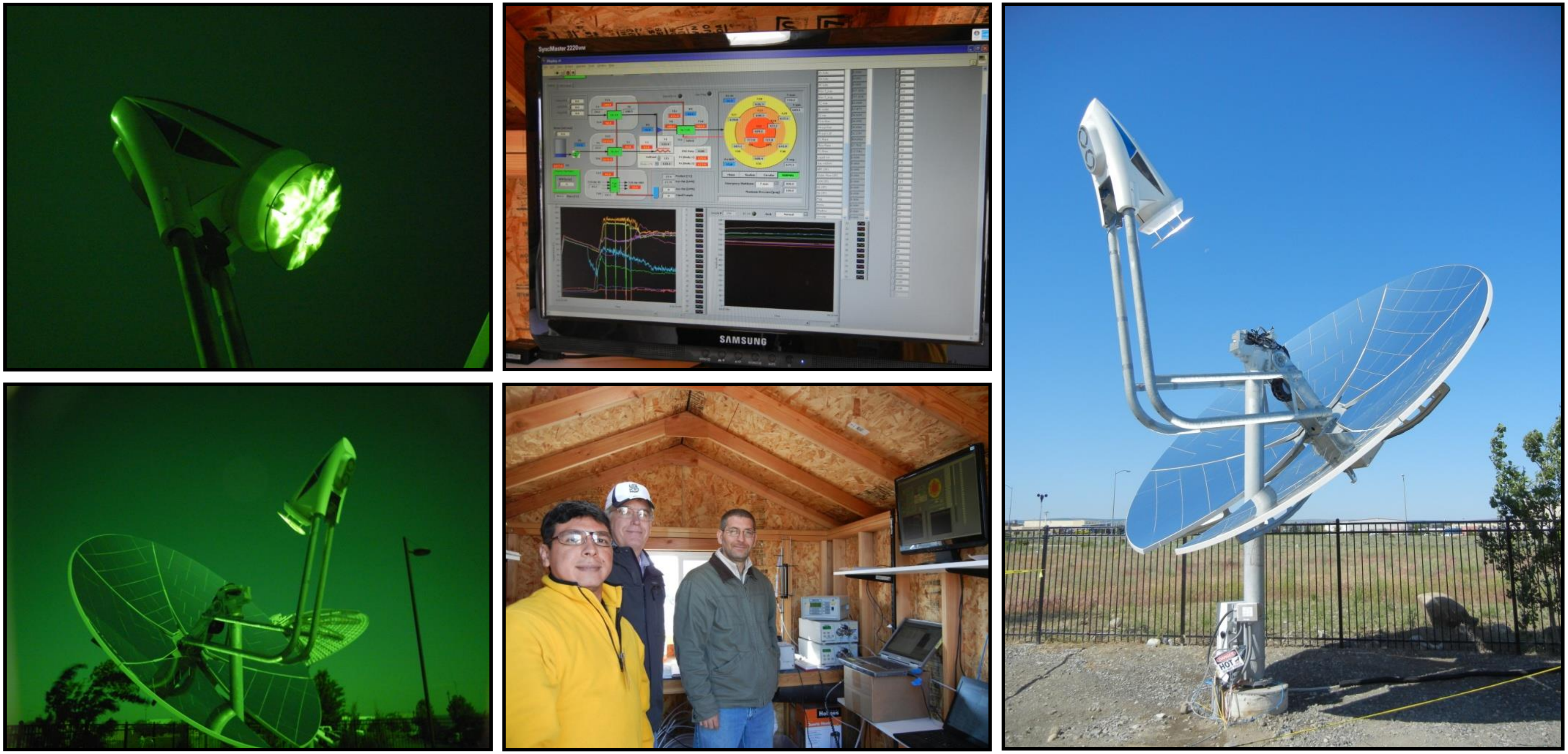

Preliminary Results for Solar Methane Reforming:

>90% Methane Conversion

63 ± 4% Solar-to-Chemical Energy Conversion Efficiency

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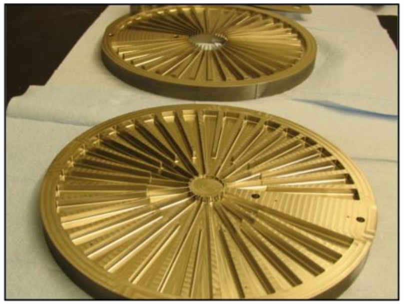
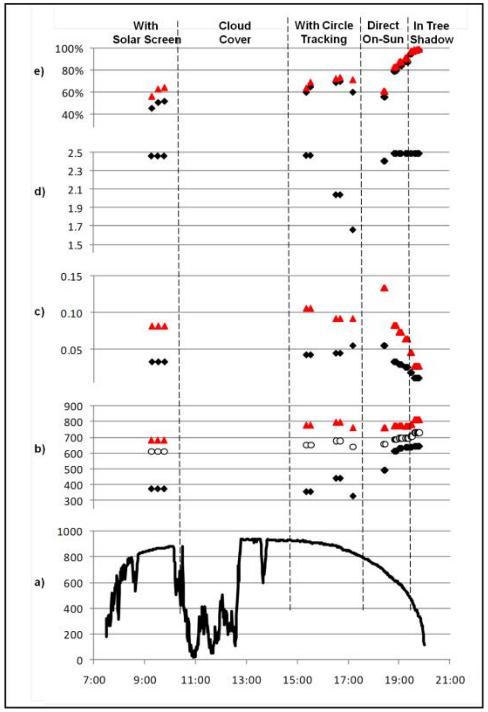
Key Technical Results, Analyses, Accomplishments and Breakthroughs to Date

Previous Project Phase 2: Proof-of-Principle Demonstration of a Solar Methane Reforming Reactor (TRL3)



On-Sun Testing of TRL 3 Prototype

On-sun testing achieved 63 ± 4% solar-to-chemical energy conversion efficiency with high methane conversion



Summary of data from first day of shakedown testing with steam reforming.

Legend:

a) Direct Normal Incidence (DNI) Solar Energy (watts/m^2);

b) Reactor Temperatures (C; ◆ – inlet temperature; ○ – outlet temperature; ▲ – average of reactor surface thermocouples);

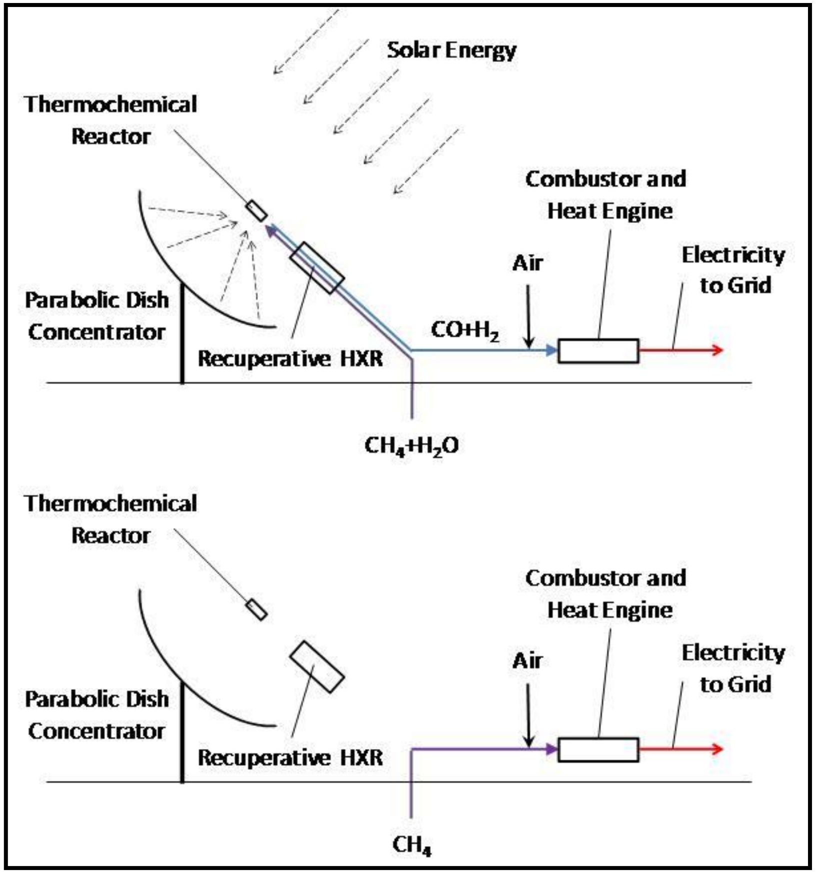
c) Mass Flow Rates of Reactants (moles/sec; ◆ – methane; ▲ – water);

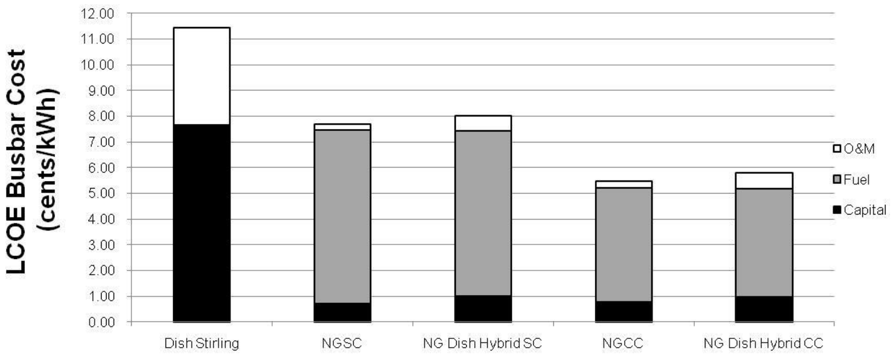
d) Steam:Carbon ratio;

e) Conversion (◆ – actual methane conversion; ▲ – approach to equilibrium conversion)

Current SunShot Project

Solar Thermochemical Augment for Hybrid Solar/Natural-Gas Powerplant





- Efficient conversion of solar energy to electricity
- High capacity factors (>90+%)
- Reduced CO_2 emissions
- Competitive Levelized Cost of Electricity (LCOE); accelerated approach to grid parity for solar concentrators

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SunShot Project Goals and Objectives

Project Goal

- Advance the technology of solar thermochemical reaction systems from Technology Readiness Level (TRL) 3 to TRL 6 in support of electricity production from solar energy at a Levelized Cost of Electricity (LCOE) no greater than 6¢/kWh

Project Objectives

- Improve the performance of the Solar Thermochemical Reaction System:
  - Increase solar-to-chemical energy conversion efficiency from ~63% to 74-75%
  - Increase the solar thermochemical augment from about 20% to as much as 28%
- Reduce the manufactured costs for critical components (e.g., micro- and meso-channel reactors and heat exchangers)
- Perform end-to-end demonstration of solar thermochemical power generation using a solar reforming system and a combustion gas turbine

SunShot Project Description
Current and Future Work Planned

Phase I: On-Sun Critical Component Testing

- On-Sun Testing of Improved Reaction System (TRL4)
- Preliminary Evaluations of Manufacturing Methods for Reactors and Heat Exchangers, including Process-Based Manufacturing Cost Models and Volume-Cost Curves

Phase II: On-Sun Demonstration of High Performance Subsystem

- Improve the performance of the Solar Thermochemical Reaction System, advancing to TRL5

Validate Manufactured Costs through Technology Development Vehicles (TDVs) and Process Development Vehicles (PDVs)

Phase III: On-Sun Demonstration of Design-for-Manufacturing (DFM) System

- Develop full range of operational characteristics for high fidelity (TRL6) reaction system, designed for mass production

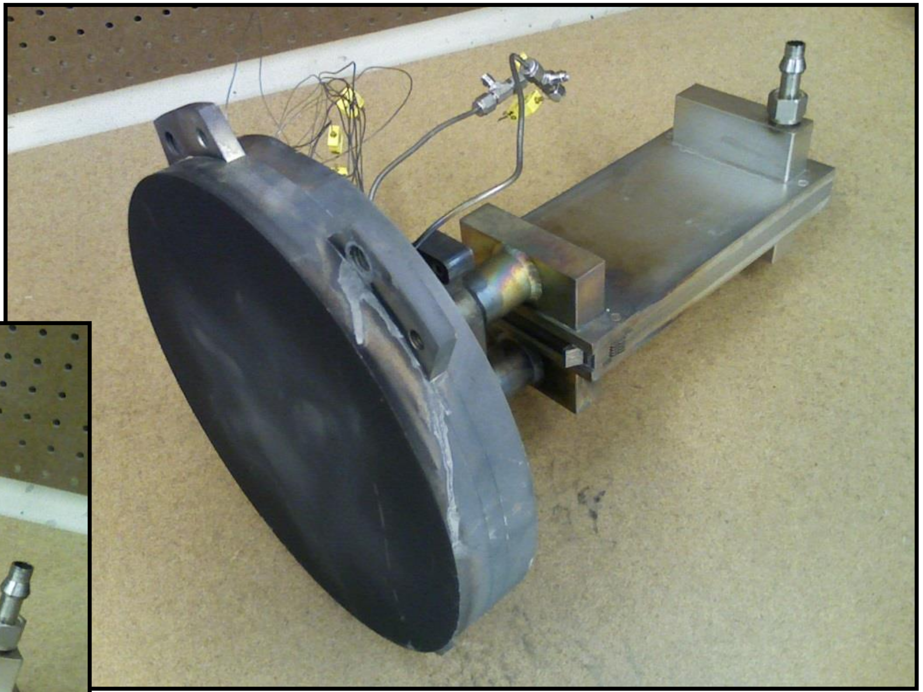
SunShot Project Description
Current and Future Work Planned

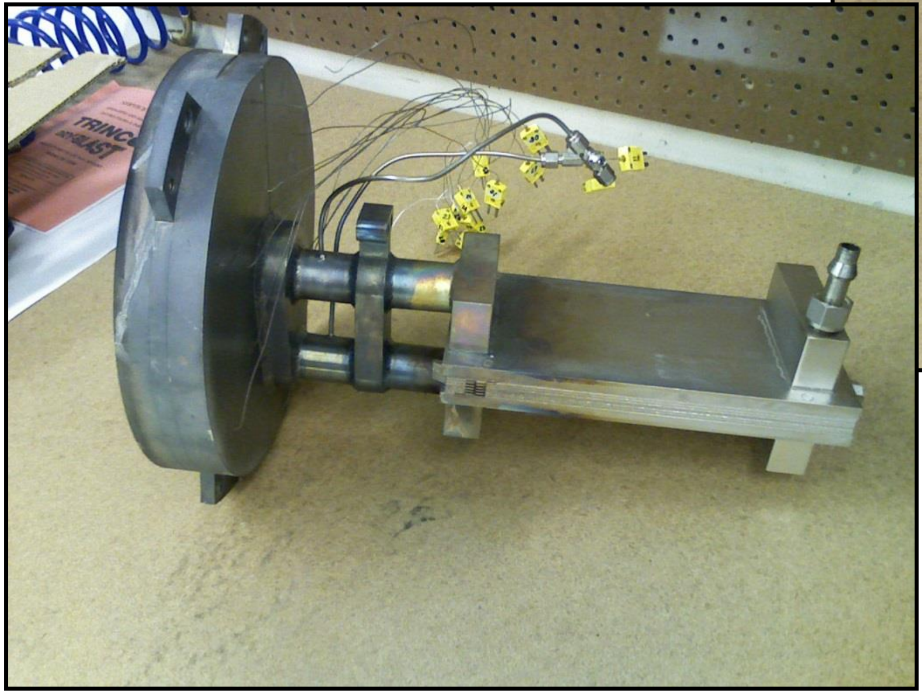
Three-phase project also includes:

- Establishment of Solar Concentrator Test Stand at PNNL
- LCOE Cost Modeling
- Catalyst Investigations
- Commercialization Planning (led by STC LLC)
- End-to-end demonstration of the solar thermochemical reaction system with power generation using a combustion gas turbine

TRL 3 Solar Reactor and High Temperature Microchannel Recuperative Heat Exchanger

The integration of microchannel heat exchangers provides a compact, process-intensive system for insertion within the heat drive





Highly effective recuperation is critical to high efficiency solar-to-chemical energy conversion!

Challenges and Barriers
For Development and Commercialization

Development: Achieving 6¢/kWh LCOE, without subsidies, requires parallel thrusts in two, highly integrated areas:

- Demonstrating high solar-to-chemical energy conversion efficiency within the thermochemical reaction system
  - Highly effective thermal integration
  - High temperature operation (which creates material requirements)
- Developing low-cost, mass-production methods for micro- and meso-channel process technology
  - Forming and joining processes
  - High equipment utilization

Commercialization:

- Initial field demonstrations at prospective sites
- Establishing limited and eventually full-scale mass production capabilities for all elements of the value-chain

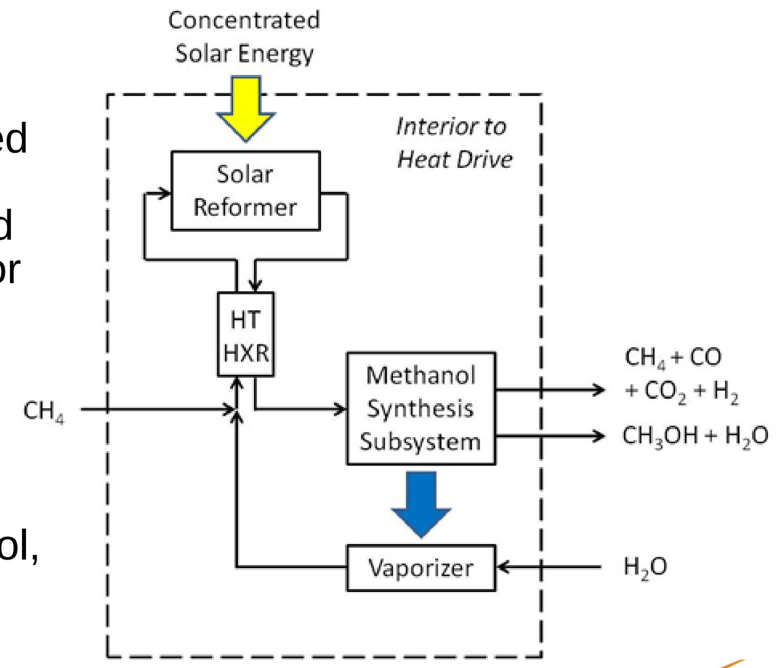
Significance of Results
Implications if we are successful

Implications for Power Generation

- Potential for hybrid solar/natural-gas power generation at reasonable costs, with potentially higher "cost targets" for concentrator systems (dish and central receivers)
- As an approach that is complementary to conventional CSP systems, hybrid solar power generation can help advance the establishment of CSP manufacturing infrastructure

Implications for Other Applications

- Many chemical process systems currently are based on combusting a fuel in order to drive endothermic chemical operations (reactions, separations); hybrid solar power systems are a possible starting point for integrating concentrating solar power into chemical plants
- Syngas, the product of our Solar Thermochemical Reaction System, is the preferred feedstock for many chemical processes, including the production of chemicals and transportation fuels (e.g., methanol, synthetic crude oil)
- Because chemical products have different value propositions and different supply-demand characteristics, some of these applications will also have higher "cost targets" for concentrator systems



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Summary and Conclusions

- Current project – started two months ago – builds upon previous success with a "low-fidelity" (TRL3) prototype system that achieved high solar-to-chemical energy conversion efficiency (63 ± 4%)
- New project has two, highly integrated parallel tracks that are designed to lead to hybrid solar/natural-gas power generation at reasonable costs (i.e., 6 ¢/kWh by 2020)
  - Aggressively improving solar-to-chemical energy conversion efficiency, perhaps to as high as 74-75%
  - Developing mass-production methods for micro- and meso-channel reactors and heat exchangers
- Together with our cost-share/CRADA partner, STC LLC, our aim is to bring the technology to commercialization in just a few years
- Additional applications include the production of chemicals and transportation fuels, including potential co-production with electricity

Publications

Previous Publications:

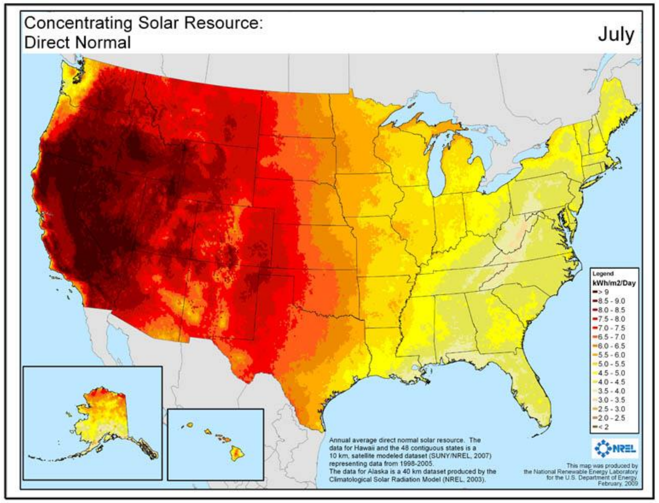
- Wegeng RS, DR Palo, RA Dagle, PH Humble, JA Lizarazo-Adarme, S Krishnan, SD Leith, CJ Pestak, S Qiu, B Boler, J Modrell, and G McFadden. 2011. "Development and Demonstration of a Prototype Solar Methane Reforming System for Thermochemical Energy Storage – Including Preliminary Shakedown Testing Result." Presented at the 2011 International Energy Conversion Engineering Conference, July 2011
- Krishnan S, DR Palo, and RS Wegeng. 2010. "Cycle Evaluations of Reversible Chemical Reactions for Solar Thermochemical Energy Storage in Support of Concentrating Solar Power Generation Systems." Presented at the International Energy Conversion Engineering Conference, August 2010.
- Humble PH, DR Palo, RA Dagle, and RS Wegeng. 2010. "Solar Receiver Model for an Innovative Hybrid Solar-Gas Power Generation Power Cycle." Presented at the International Energy Conversion Engineering Conference, August 2010.
- Wegeng, RS, WE TeGrotenhuis and JC Mankins, 2007. "Solar Thermochemical Production of Fuels", 2007 International Energy Conversion Engineering Conference, July 2007

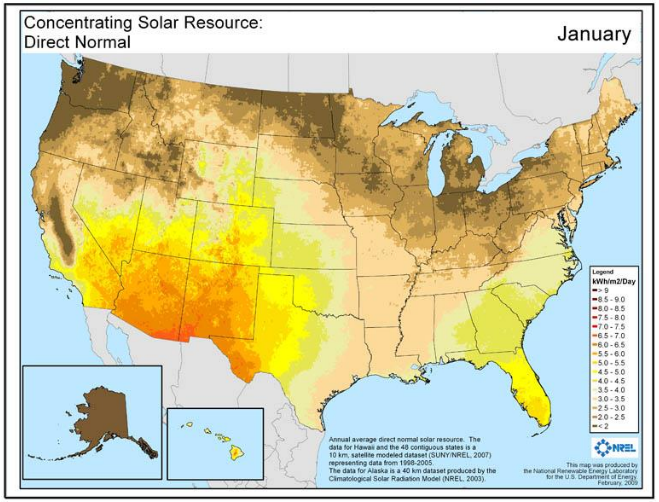
Planned Publications (Submissions Underway):

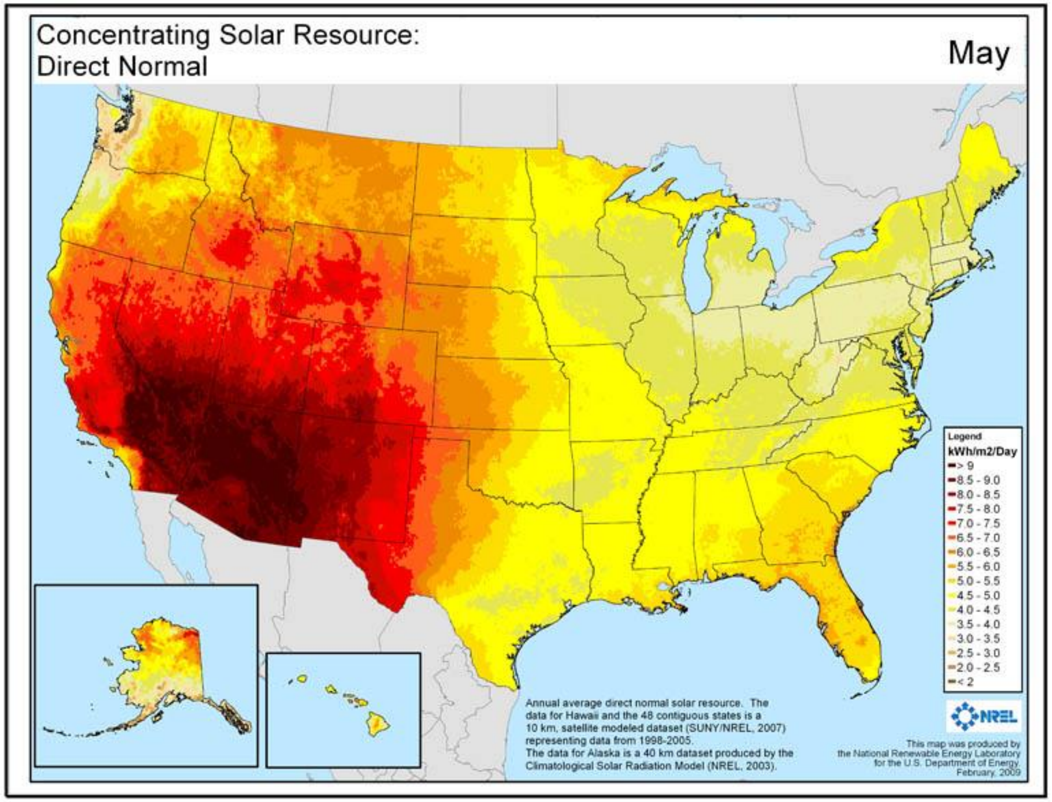
- ASME Sustainability Conference, July 2013
- IECEC July 2013
- Solar PACES 2013 (2 abstracts submitted)

Discussion

Solar Resource – Direct Normal Insolation







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