Supercritical Carbon Dioxide Power Cycle: Next Generation Power

Rocky Mountain AIChE
March 19, 2013

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NREL’s Areas of Research

Efficient Energy Use
- Vehicle Technologies
- Building Technologies
- Industrial Technologies

Renewable Resources
- Wind and water
- Solar
- Biomass
- Geothermal

Energy Delivery and Storage
- Electricity Transmission and Distribution
- Alternative Fuels
- Hydrogen Delivery and Storage

2100 employees (full-time and contract)
2012 budget $405 million
Presentation Outline

• US and World Energy Resources

• Introduction to Concentrating Solar Power (CSP)

• Supercritical CO$_2$ Power Cycle
  • General attributes
  • Applications
US Electricity Sources

U.S. Electric Sector Net Generation

- Coal: 48% in 2008, 38% in 2012
- Natural gas: 21% in 2008, 27% in 2012
- Nuclear
- Petroleum

U.S. Renewable Generation

- Total RE
- Solar: 0.2%
- Geothermal: 0.5%
- Municipal Waste: 0.5%
- Biomass: 1.2%
- Wind: 3.2%
- Hydropower: 7.5%

Solar is Growing

Thursday, March 14, 2013 2:25 PM MT Extra

Study: Solar industry saw record year in 2012, with 3,313 MW of solar PV installed

By Michael Copley

Declining costs for solar panels and installed solar-power systems have helped the U.S. solar industry leapfrog from its spot as one of the most expensive power sources to one of the cheapest. Solar is also the fastest-growing energy source in the U.S. and a leading source of new electricity that increasingly is capable of competing with conventional

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Saudi Arabia Plans $109 Billion Boost for Solar Power

By Wael Mahdi - Nov 22, 2012 9:53 AM MT

Saudi Arabia plans to produce electricity from its first nuclear plant by 2020 and begin operating a solar farm by 2015, said an official at the agency developing the country's renewable energy program.

The country will start work on its first solar-power facility early next year, which may take as much as 24 months to complete, Khalid Al-Suliman, vice president at the King Abdullah City for Atomic and Renewable Energy, told the state-owned Saudi Press Agency.

Al-Suliman said the project will get underway once the government approves his agency's plan for renewable energy. He told the press agency yesterday that he expects to receive official approval early next year.

Saudi Arabia, which is tapping renewable energy as a way to free more crude oil for export, is planning for $109 billion in investment to create a solar industry that generates a third of the nation's electricity by 2032.

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China to Boost Solar Power Goal 67% as Smog Envelops Beijing

By Bloomberg News - Jan 30, 2013 4:39 AM MT

China plans to increase its goal for solar-power installations in 2015 by 67 percent to reduce reliance on fossil fuels blamed for greenhouse gases and as smog in Beijing reached record hazardous levels this month.

The world's biggest emitter of carbon-dioxide plans to raise the solar target to 35 gigawatts by 2015 from 21 gigawatts set last year, boosting demand for manufactures that suffer from slowing sales in Europe, Shi Dinghuan, the counselor of China's State Council and the president of Chinese Renewable Energy Society, said today by phone.

"We've got more pressure to save energy and reduce emissions as smog worsens due to pollution," he said. China will use renewable energy to cut coal consumption and support the domestic industry amid U.S. and Europe anti-dumping charges against Chinese solar products, Shi said.

Sources: Bloomberg.com, SNL Energy
Total recoverable reserves are shown for the finite resources. Yearly potential is shown for the renewables. Values in Terawatt-years. (Perez & Perez, 2009.)
Torresol Energy 20 MW Gemasolar  
Seville, Spain
Power Towers under Construction: BrightSource 392 MW Ivanpah, California
Power Towers under Construction: SolarReserve 110 MWe Crescent Dunes, Nevada

Fast Facts:
• 10 hours of thermal energy storage
• 195-m tall tower
• 600 construction jobs; 45 permanent jobs
• 1600-acre site
• Hybrid cooling

Looking down at the storage tank foundations
Value of CSP with Thermal Energy Storage

[Graph showing solar DNI and net power over time of day]
Supercritical CO₂ Brayton Cycle

Density and Heat Capacity

Pressure = 8 MPa
Yoo, 2012

$T_c = 31.1^\circ C$
$\rho_c = 73.8$ bar
Open Brayton Power Cycle

Air in

Turbo-expander

Compressor

Work out

Exhaust to atmosphere

Combustion chamber (heat in)
Closed Brayton Power Cycle

Diagram showing the components of a closed Brayton power cycle:
- Combustion chamber (heat in)
- Turbo-expander
- Compressor
- Work out
- Compressor Precooler
- Recuperators

The diagram illustrates the flow of the cycle, starting with the combustion chamber, moving through the turbo-expander and compressor, and ending with the work output.
Brief History of the Closed Brayton Cycle (CBC)

1939  First commercial CBC at Escher Wyss in Zurich (2 MW, air)
1949  Air CBC efficiency greater than contemporary steam cycles
1956-1977 Ravensburg air CBC accumulates 120,000 hrs operation at average 91% availability
1967  Feher catalogs candidate supercritical fluids for use in CBC
1968  Angelino proposes s-CO$_2$ power cycles including the “recompression” cycle
2006  Dostal rekindles interest in s-CO$_2$ CBC by examining its use for Gen IV nuclear power plants
2009  Sandia National Labs builds 250 kW recompression cycle at Barber-Nichols in Arvada, CO
2012  Echogen Power Systems designs 7 MW s-CO$_2$ system for waste heat recovery
2012  SunShot funds testing of ~10 MW high-temp s-CO$_2$ turbine
Attractive features of s-CO$_2$ Brayton Cycle

- Simpler cycle design than steam Rankine
- Higher efficiency than steam Rankine
- High density working fluid yields compact turbomachinery
- Optimum turbine size 10 to 300 MWe
- Low-cost, low toxicity, low corrosivity fluid
- Thermally stable fluid at temperatures of interest to CSP (550C to 750C)
- Single phase reduces operational complexity
“Simple” s-CO$_2$ Brayton Cycle

Recuperated s-CO$_2$ Brayton Cycle

S-CO$_2$ Power Turbine

Generator

Main Compressor

Precooler

Primary Heat Exchanger

Recuperator

Carbon Dioxide

![Diagram of the recuperated s-CO$_2$ Brayton cycle with a T-s diagram showing the cycle's operation at various pressures and temperatures.](image-url)
### S-CO₂ Brayton has Potential in Multiple Markets

<table>
<thead>
<tr>
<th>Power Sector</th>
<th>Why?</th>
<th>Who?</th>
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</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>Good match to Gen IV sodium fast reactor designs</td>
<td>Sandia, Argonne, INEL</td>
</tr>
<tr>
<td>Fossil</td>
<td>Next generation coal plants with oxy-fuel combustion and CO₂ capture</td>
<td>NETL, Pratt &amp; Whitney Rocketdyne (PWR)</td>
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<tr>
<td>Marine Power</td>
<td>Compact and fast responding turbomachinery</td>
<td>Knolls and Bettis Atomic Power Labs</td>
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<tr>
<td>Waste Heat Recovery</td>
<td>Simple cycle design with high efficiency</td>
<td>Echogen, Dresser-Rand</td>
</tr>
<tr>
<td>Solar</td>
<td>Allows for higher conversion efficiency in high-temperature power towers</td>
<td>NREL, PWR</td>
</tr>
<tr>
<td>Grid Electricity Storage</td>
<td>Reversible cycle: heat pump / power turbine</td>
<td>ABB</td>
</tr>
</tbody>
</table>
Oxy-Fuel Combustion and CCS Application

S-CO2 Turbomachinery Technology Development for Power Plant Applications, Pratt & Whitney Rocketdyne, RD11-159
Oxy-Fuel Direct Combustion Application
Nuclear Power Applications

- Under investigation by Generation IV nuclear power researchers in US, Europe and Asia
- Applicable to multiple Gen IV reactor concepts

“The SunShot Initiative will spur American innovations to reduce life costs of solar energy and re-establish U.S. global leadership in this growing industry.”
U.S. Energy Secretary Steven Chu
February 2011

- DOE’s SunShot Initiative aims to make solar electricity cost-competitive with conventional forms of energy before 2020.
- Reducing the costs of utility, commercial and residential installations by approximately 75% could enable widespread deployment of solar energy.
- Coordination among the DOE Solar Program, Office of Science, and ARPA-E.
Maximizing efficiency requires maintaining good collection efficiency while moving to higher conversion temperatures.
Power Cycle Options for CSP

- Current Parabolic Trough
- Current Power Tower
- Supercritical Steam (commercial for coal)
- S-CO2 Brayton (recompression)
- Typical Engineering Limit (75% Carnot)
- Air Brayton Combined Cycle (commercial for NG)

Graph showing thermal conversion efficiency and power tower range against temperature.
Dry-cooled, recompression cycle with reheat coupled to high-temp molten salt power tower to achieve SunShot goal of 50% gross cycle efficiency.
Demonstrating s-CO$_2$: Pilot Test Catch-22

An optimized 20 kW prototype s-CO$_2$ turbine is ¼” diameter and spins at 1,500,000 rpm.

A manufacturable s-CO$_2$ prototype turbine of 6” diameter spinning at 20,000 rpm produces 10 MW and requires a ~$20M support facility.

Objectives:

1. Design, fabricate and validate a s-CO$_2$ Brayton cycle that is capable of operation at up to 700°C and dry cooling conditions
2. Validate and map power turbine and compressor performance
3. Simulate advanced CSP/s-CO$_2$ system performance and estimate LCOE to meet SunShot goals

Echogen’s EPS100 process skid
s-CO$_2$ Brayton Cycle Research Needs

- Corrosion and materials compatibility data at high T, P
- Long-term testing of recuperators
- Design and validation of primary heat exchangers; understanding of s-CO$_2$ / HTF interactions
- Validation of power turbine bearings, seals, stop-valves
- Cycle models of transient operation, start/stop, off-design operation
- Demonstration of cycle operations and equipment durability
Thank you!

For more information:
http://www.nrel.gov/csp/
http://maps.nrel.gov/
http://solareis.anl.gov/

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NREL’s trough module test facility
Support slides
Why 10 MWe Scale?

- 10 MW is the minimum size that allows use of commercial design technologies

<table>
<thead>
<tr>
<th>Feature</th>
<th>0.3</th>
<th>1.0</th>
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<th>10</th>
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<th>100</th>
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<td><strong>Turbine Speed/Size</strong></td>
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<td>Single stage</td>
<td>75,000 / 5 cm</td>
<td>30,000 / 14 cm</td>
<td>10,000 / 40 cm</td>
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<td>Dry Lift Off</td>
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<td>Single Shaft</td>
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</table>

**Specialty/Lab technology**

**Commercial technology**
# CSP Plant Characteristics

<table>
<thead>
<tr>
<th>CSP Design and primary Heat Transfer Fluid</th>
<th>2010 Oil Trough</th>
<th>2013 Salt Tower</th>
<th>Supercrit. Steam</th>
<th>Air Brayton Cycle</th>
<th>S-CO$_2$ Brayton Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Data:</td>
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<tr>
<td>Turbine MW$_e$ (Range)</td>
<td>50-125</td>
<td>20-110</td>
<td>400+</td>
<td>0.3-200</td>
<td>10-150</td>
</tr>
<tr>
<td>Receiver T/P (°C/bar)</td>
<td>391/100</td>
<td>565/140</td>
<td>610/250</td>
<td>1300/30</td>
<td>700/250</td>
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<tr>
<td>Power Cycle Gross Effic.</td>
<td>0.38</td>
<td>0.42</td>
<td>0.47</td>
<td>0.40</td>
<td>0.50</td>
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<tr>
<td>Thermal Storage Options</td>
<td>Oil, Salt</td>
<td>Molten salt</td>
<td>Molten salt</td>
<td>Ceramic blocks</td>
<td>Molten salt</td>
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<tr>
<td>Cost:</td>
<td></td>
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</tr>
<tr>
<td>LCOE (cents/kWh, no ITC)</td>
<td>19</td>
<td>15</td>
<td>11</td>
<td>&lt;10?</td>
<td>&lt;10?</td>
</tr>
</tbody>
</table>

LCOE = levelized cost of electricity  
ITC = investment tax credit
Journal Publications on s-CO$_2$ Brayton Cycle
Solar Potential in the Southwest

Solar Potential in Southwest US:
6,900 GW (6x current US generation capacity)
16 million GWh (4x current US annual electricity consumption)

Assumptions:
DNI Solar Resource ≥ 6.75 kWh/m2/day
Plant footprint = 5 acres/MW
Annual capacity factor = 27%

Map represents land that has no primary use today, excludes land with slope > 1% and excludes known environmentally or culturally sensitive lands.
Thermal Inertia

Comparison of power output from large CSP and PV plants located within 50 km of each other.

figure 10. Comparison of short-term variations in PV (red) and solar thermal (blue)

Projects List from SEIA

http://www.seia.org/map/majormap.php
Unsubsidized CSP Trough and Tower Costs

Assumed location is Daggett, CA
# Solar Energy Potential

## Energy Potential vs. Global Annual Energy Consumption

<table>
<thead>
<tr>
<th>Fossil fuels</th>
<th>Renewables</th>
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</thead>
<tbody>
<tr>
<td>Global reserves/resources</td>
<td>Global energy potential per year</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td>348</td>
<td>2850</td>
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<tr>
<td>155</td>
<td></td>
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<tr>
<td>60</td>
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</table>

### Energy Potential/Global Annual Energy Consumption

<table>
<thead>
<tr>
<th>Energy potential</th>
<th>Thereof conventionally utilizable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserves/Resources</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Coal**: ~135,000 EJ
- **Natural gas**: ~60,400 EJ
- **Crude oil**: ~23,000 EJ

### Global energy demand 2006: ~470 EJ

<table>
<thead>
<tr>
<th>Energy potential (amount of energy p. a.)</th>
<th>Technologically utilisable (state of the art)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solar radiation</strong>: ~1,111.500 EJ</td>
<td>~1.482 EJ</td>
</tr>
<tr>
<td><strong>Wind energy</strong>: ~78.000 EJ</td>
<td>~195 EJ</td>
</tr>
<tr>
<td><strong>Biomass</strong>: ~7.800 EJ</td>
<td>~156 EJ</td>
</tr>
<tr>
<td><strong>Geothermal</strong>: ~1.950 EJ</td>
<td>~390 EJ</td>
</tr>
<tr>
<td><strong>Hydro/tide power</strong>: ~1.170 EJ</td>
<td>~78 EJ</td>
</tr>
</tbody>
</table>

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University of Twente, Netherlands, [http://www.utwente.nl/mesaplus/nme/Introduction/](http://www.utwente.nl/mesaplus/nme/Introduction/)