Bulk Energy Storage using a Supercritical CO₂ Waste Heat Recovery Power Plant

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Outline: \( \text{SCO}_2 \) Bulk Energy Storage
One of Many \( \text{SCO}_2 \) Transformational Power Systems

- List of Transformational \( \text{SCO}_2 \) Power Systems
- Energy Storage and the Electric Grid
- Pure Bulk Energy Storage \( \text{SCO}_2 \) Concept (Hermle, ABB)
- Bulk Energy Storage for Power Peaking using WHR Concepts
- Charging Cycle Description
- Discharge Cycle Description
- Energy Storage & Power Peaking Operation
- Economic Benefit
- Summary and Conclusions
Transformational \( \text{SCO}_2 \) Power Systems

1. Oxy-Combustion Direct Injection + CCS (Eff > 50%)
2. Oxy-Combustion Indirect Heating + CCS (Eff > 43%)
3. Single Cycle High Efficiency Fossil Fuel Combustion (~50%, > ~150 MW\(_e\))
4. Advanced Nuclear Reactor High Efficiency (45% - 50%, TIT > ~600 C)
5. Concentrated Solar Power (>50% with TIT > ~750 C)
6. Integrated Gas Turbines & \( \text{SCO}_2 \) Power Systems (\( \text{SCO}_2 \) Bottoming + Others)
   - Distributed Generation (5-20 MWe): Smartgrid (~48%-50% \( \text{SCO}_2 \) Combined Cycle)
   - Marine Propulsion, Other Priority Applications
7. Waste Heat Recovery Plants (Eff ~ 25% @ 510 C)
8. USC Pulverized Coal Plant Upgrades (Topping Cycles or Other)
9. Energy Storage and Power Peaking (RT Eff =55-60%, 4 hrs, 50-100 MWe)
10. Combined Cooling, Heat, and Power + CHP, CCP
11. Heat Pump / Refrigeration (Cooling + Heating is favored by \( \text{CO}_2 \) EOS)

Focus

Key to Achieving these Technologies: Multiple Successful Demonstration \( \text{SCO}_2 \) Power Systems
The Power Peaking with Bulk Energy Storage - Addressing the Energy Storage Problem

• 150 Hours at Peak Usage
  Costs you ~20% of your Electric Bill
• Off-Peak versus On-Peak = Critical Peak Cost  10 X
• 2% of Power usage Costs 20%

• \( \text{SCO}_2 \) Bulk Energy Storage Offers
  • Site Independent Storage
  • 10-100 MWe for 4-5 hours
  • Little Competition

• Other Benefits
  • Better Grid Stability
  • Lower Distribution Costs
  • Less Use of Inefficient Plants
  • Better use of Capital Assets
Bulk Thermal Energy Storage
J. Hermle (ABB), SCO₂ Power Cycle Symposium 2011, Boulder Co.

Key Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Performance in Charging Cycle</td>
<td>4.51</td>
</tr>
<tr>
<td>Efficiency in Discharge</td>
<td>13.35%</td>
</tr>
<tr>
<td>Heat Added/Removed to/from Water HX</td>
<td>179895 kWh</td>
</tr>
<tr>
<td>Heat Removed/Added from/to the Ice</td>
<td>139989 kWh</td>
</tr>
<tr>
<td>Round Trip Efficiency (no additional losses)</td>
<td>60.2%</td>
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<tr>
<td>Round Trip Efficiency with 3% losses</td>
<td>56.7%</td>
</tr>
<tr>
<td>Maximum CO₂ Temp Charging</td>
<td>119°C</td>
</tr>
<tr>
<td>Maximum CO₂ Temp Discharging</td>
<td>116°C</td>
</tr>
<tr>
<td>Minimum CO₂ Temp Charging</td>
<td>-2.7°C</td>
</tr>
<tr>
<td>Minimum CO₂ Temp Discharging</td>
<td>0°C</td>
</tr>
</tbody>
</table>

\[ \eta_{Round-Trip} = COP_{Heat Pump} \times \eta_{Thermal} = 100\%_{(Ideal)} \]

Site Independent Bulk Energy Storage
Footprint = City Block
50-100 MWₑ for ~4 hours
Unlimited Cycles, Target \( RT_{eff} = 60\% \)

Reference: Round Trip Efficiency
Batteries: \( = 70\% \), 600 cycles
Pumped Hydro \( = 70\% \)
Ice Energy Storage for SCO\textsubscript{2} Power Peaking

- Goal: More Efficient use of Capital Assets (SCO\textsubscript{2} Hardware) than Orig. Concept
  - Orig Concept Operates 4 hrs/day
  - This Concept Operates 24 / 7 / 365
- Avoids Flow Direction Reversal
- Avoids Flow Rate Doubling
- Uses larger dT in HXs
- Provides Bulk Energy Storage as Ice
- Uses Waste Heat from Gas Turbine
  - No Hot Water Storage Tanks
- Maintain: Site Independence
  - No Dams or Caves
  - Foot Print: ~City Block for 50-100 MW\textsubscript{e}
- Maximize Dispatchable Power (profit)
- SCT Patented Process
Charging Cycle, \( \text{SCO}_2 \) Heat Pump

\[ T_{\text{evap}} = -5 \, ^\circ\text{C}, \quad T_{\text{max}} = 86 \, ^\circ\text{C} \]

\[ P_{\text{evap}} = 30.5 \, \text{bar}, \quad P_{\text{max}} = 91.3 \, \text{bar} \]

Net \( \text{COP}_{\text{Refr}} = 2.69 \) exp-valve / COP = 3.34 turbo-exp

Mass Flow Rate = 50 kg/s-valve / 48 kg/s-turbo-exp

\( Q_{\text{Refrig}} = 8445 \, \text{kW} = 2401 \, \text{Refr.-Ton} \)
SCO₂ with Waste Heat Recovery

Normal Operating WHR Cycle : Water-Air Cooling (20 hrs)
Discharge Cycle: Ice Cooling (4 hrs)

Waste Heat 39.4 MW\textsubscript{th}, @ 538 C

1. Waste Heat 39.4 MW\textsubscript{th}, @ 538 C
2. Split Flow with Preheating, Typical Cycle for Waste Heat Recovery (ORCs)
3. Compressor Inter-recuperation (SCT Patented)
4. Water-Air Cooling versus Ice-Cooling†
WHR Brayton Cycle and the Ice-Rankine Cycle

- Lower Heat Rejection Temperature due to Ice Melting
  - Increases Cycle Efficiency 31.7% – 34.5%
  - Increases Combustion Efficiency 44.7% – 68%
  - Lower Turbine Back Pressure Increases Pwr$^+$ 5.58 MW$_e$ – 9.25 MW$_e$ + 66%

*Additional Turbomachinery stages may be required for larger P ratio.*
Power Peaking Operation

Power Produced and Consumed over 24 Hour Period

- **Brayton WHR Power (kWe)**
- **Ice-Rankine Power (kWe)**
- **Elect. Pwr to Make Ice (kWe)**

**Dispatchable Power Round Trip Efficiency**: 148%-183%

**Excess Dispatchable Power Round Trip Efficiency**: 58.6% – 73%

9.25 MWe for 4 Hours using 2.5 MWe for Ice Generation over 8 hrs
Economics

• Addressed in a Companion Paper
  – Presented in the Poster Session (William Scammel)

• Major Results
  – Primary benefit is from the conversion of Waste Heat to Electricity
  – ROI for WHR ~3 years
  – Given the assumed pricing structure (Peak Cost at 2-4 X Off-Peak)
    • Additional Benefit is due to Ice-Energy Storage (~8% / year)

• Other Benefits not studied
  – Demand Peak Reductions
  – Spinning Reserve Benefit
  – Grid Stability improvements
  – Need to Work with a Utility to fully understand the Peaking Benefit
    • Will vary by location throughout the country
Summary and Conclusions

- **SCO\textsubscript{2}** Power Systems Promise Transformational Power Systems
- **SCO\textsubscript{2}** Offer Methods for Bulk Energy Storage
- Power Peaking with Ice-Energy Storage Plant was Described using Waste Heat Recovery
- System Proposed was designed to make maximum use of capital assets 24 hours per day

- System
  - Produces Ice using a **SCO\textsubscript{2}** Heat Pump during off-peak, (8 hrs, 2.5 MWe)
  - **SCO\textsubscript{2}** Power Cycle using water or air cooling: off-peak (20 hrs, 5.5 MWe)
  - Power Cycle is switched to Ice Melting for Peak Power (4 hrs, 9.2 MWe)

- Excess Round Trip Efficiency \(58.6\% - 73\%\)
- Dispatchable Round Trip Efficiency \(148\% - 183\%\)
- **Improved Economics due to** (ROI < 3 yrs)
  - Waste Heat Recovery (primary economic benefit)
  - Ice-Energy Storage (secondary economic benefit)