Concentrating Solar Power and Thermal Energy Storage

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Outline

- Problem Statement
- What is Concentrating Solar Power (CSP)?
- Thermal Storage Options and Challenges
- Summary
Problem Statement

- Current renewable energy sources are intermittent
  - Causes curtailment or negative pricing during mid-day
  - Cannot meet peak demand, even at high penetration

- Available energy storage options for solar PV & wind
  - Large-scale battery storage is expensive
    - $0.20/kWh_e - $1.00/kWh_e
  - Compressed air and pumped hydro – geography and/or resource limited

Source: California Independent System Operator

The “Duck Curve”
Need

- Renewable energy technology with reliable, efficient, and inexpensive energy storage

  Concentrating solar power (CSP) with thermal energy storage
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What is Concentrating Solar Power (CSP)?

Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle.
What is Concentrating Solar Power (CSP)?

CSP uses concentrated heat from the sun as an alternative heat source for the power cycle.
CSP and Thermal Energy Storage

- Concentrating solar power uses mirrors to concentrate the sun’s energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- Hot fluid can be stored as thermal energy efficiently and inexpensively for on-demand electricity production when the sun is not shining
Commercial CSP Plants
Ivanpah Solar Power Tower
California (near Las Vegas, NV)

http://news.nationalgeographic.com

392 MWe direct-steam power tower plants in Ivanpah, CA. 170,000 heliostats. Opened February 2014
1st commercial power tower (19 MW) in the world with 24/7 dispatchable energy production (15 hours of thermal storage using molten salt). Commissioned in May 2011.
Crescent Dunes
Tonopah, Nevada

Solana Generating Station

280 MW parabolic trough plant
Phoenix, AZ (Gila Bend)
Started 2013

6 hours of molten-salt storage
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Types of Thermal Energy Storage

- **Sensible (single-phase) storage**
  - Use temperature difference to store heat
  - Molten salts (nitrates, carbonates, chlorides)
  - Solids storage (ceramic, graphite, concrete)

- **Phase-change materials**
  - Use latent heat to store energy (e.g., molten salts, metallic alloys)

- **Thermochemical storage**
  - Converting solar energy into chemical bonds (e.g., decomposition/synthesis, redox reactions)
Sandia Research in Thermal Energy Storage

Corrosion studies in molten salt up to 700 C in “salt pots”

Ceramic particle storage and heating with falling particle receiver

Component testing with molten-salt test loop

Thermochemical particle storage with reduction/oxidation of perovskites

Latent phase-change material storage in dish engines
Particle Receiver Designs – Free Falling
On-Sun Tower Testing

Over 600 suns peak flux on receiver
(July 20, 2015)
On-Sun Tower Testing

Particle Flow Through Mesh Structures
(June 25, 2015)
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Summary

- Renewables require energy storage for increased penetration
- Concentrating solar power provides utility-scale electricity AND energy storage
- Thermal energy storage options
  - Sensible heat storage (molten salt, particles)
  - Latent heat storage
  - Thermochemical storage
- Cost of CSP with storage is currently cheaper than photovoltaics with large-scale battery storage
Questions?

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Backup Slides
## Comparison of Energy Storage Options

<table>
<thead>
<tr>
<th>Energy Storage Technology</th>
<th>Solid Particles</th>
<th>Molten Nitrate Salt</th>
<th>Batteries</th>
<th>Pumped Hydro</th>
<th>Compressed Air</th>
<th>Flywheels</th>
</tr>
</thead>
</table>
| **Levelized Cost**
1 ($/MWh<sub>e</sub>) | 10 – 13 | 11 – 17 | 100 – 1,000 | 150 – 220 | 120 – 210 | 350 - 400 |
| **Round-trip efficiency**
2 | >98% thermal storage ~40% thermal-to-electric | >98% thermal storage ~40% thermal-to-electric | 60 – 90% | 65 – 80% | 40 – 70% | 80 – 90% |
| **Cycle life**
3 | >10,000 | >10,000 | 1000 – 5000 | >10,000 | >10,000 | >10,000 |
| **Toxicity/environmental impacts** | N/A | Reactive with piping materials | Heavy metals pose environmental and health concerns | Water evaporation/consumption | N/A | N/A |
| **Restrictions/limitations** | Particle/fluid heat transfer can be challenging | < 600 °C (decomposes above ~600 °C) | Very expensive for utility-scale storage | Large amounts of water required | Unique geography required | Only provides seconds to minutes of storage |
Thermal Energy Storage Goals

- Capable of achieving high temperatures (> 700°C)
- High energy and exergetic efficiency (>95%)
- Large energy density (MJ/m³)
- Low cost (<$15/kWh; <$0.06/kWh for entire CSP system)
- Durable (30 year lifetime)
- Ease of heat exchange with working fluid (h > 100 W/m²-K)
<table>
<thead>
<tr>
<th>Storage Medium</th>
<th>Specific Heat (kJ/kg K)</th>
<th>Latent Heat Reaction (kJ/kg)</th>
<th>Density (g/cm³)</th>
<th>Temperature Range (°C)</th>
<th>Volumetric Storage Density (kJ/m³)</th>
<th>References</th>
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<td>Concrete</td>
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<td>2000</td>
<td>400</td>
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<td>4000</td>
<td>1000</td>
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<td>770</td>
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<tr>
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<td>794</td>
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| Sensible Energy Storage—Liquids   |                         |                             |                 |                        |                                   |            |
| Nitrate salts (ex. KNO$_3$:0.46NaNO$_3$) | 1.6                   | 1815                        | 300             | 600                    | 560                               | 1016       |
| Therminol VP-1®                    | 2.5                     | 750                         | 300             | 400                    | 875                               | 656        |
| Silicone oil                       | 2.1                     | 900                         | 300             | 400                    | 735                               | 662        |
| Carbonate salts                    | 1.8                     | 2100                        | 450             | 850                    | 630                               | 1323       |
| Coltrix HT-47®                     | 2.8                     | 690                         | 150             | 316                    | 900                               | 676        |
| Sodium liquid metal                | 1.3                     | 960                         | 316             | 700                    | 455                               | 427        |
| Na$_2$O/79K metal eutectic         | 1.1                     | 900                         | 300             | 700                    | 385                               | 347        |
| Hydride salts (ex. NaOH)           | 2.1                     | 1700                        | 350             | 1100                   | 735                               | 1250       |

| Latent Energy Storage              |                         |                             |                 |                        |                                   |            |
| Aluminum                           | 1.2                     | 397                         | 2380            | -                      | 660                               | 946        |
| Aluminum alloys (ex. Al$_2$O$_3$)  | 1.5                     | 515                         | 2250            | -                      | 579                               | 1159       |
| Copper alloys (ex. Cu-0.25S)       | -                       | 196                         | 7090            | -                      | 803                               | 1390       |
| Carbonate salts (ex. U$_3$O$_5$)   | -                       | 607                         | 2200            | -                      | 726                               | 1335       |
| Nitrate salts (ex. KNO$_3$:0.46NaNO$_3$) | 1.5                   | 100                         | 1950            | -                      | 222                               | 195        |
| Bromide salts (ex. KBr)            | 0.53                    | 215                         | 2400            | -                      | 730                               | 516        |
| Chloride salts (ex. NaCl)          | 1.1                     | 481                         | 2170            | -                      | 801                               | 1644       |
| Fluoride salts (ex. LiF)           | 2.4                     | 1044                        | 2200            | -                      | 842                               | 1229       |
| Lithium hydride                    | 8.04                    | 2582                        | 790             | -                      | 683                               | 2040       |
| Hydride salts (ex. NaOH)           | 1.47                    | 160                         | 2070            | -                      | 329                               | 331        |

| Thermochemical Energy Storage      |                         |                             |                 |                        |                                   |            |
| SO$_2$(g) $\rightarrow$ SO$_2$(g) + 1/2O$_2$(g) | -                   | 1225                        | -              | -                      | 650                               | 1225       |
| CaCO$_3$(s) + CO$_2$(g) $\rightarrow$ CaO(s) + CO$_2$(g) | 1.75 | 1757                  | -              | -                      | 527                               | 1757       |
| CH$_4$(g) + CO$_2$(g) $\rightarrow$ 2CO(g) + H$_2$(g) | 4100 | -                     | 538             | 4100                   | - 35                              |           |
| CH$_3$(g) + H$_2$O(g) $\rightarrow$ 3H$_2$(g) + CO(g) | -   | 6064                  | -              | 538                    | 6064                              | - 35       |
| Ca(OH)$_2$(s) $\rightarrow$ CaO(s) + H$_2$O(g) | 1351 | -                     | 521             | 1351                   | - 35                              |           |
| NH$_3$(g) $\rightarrow$ 1/2N$_2$(g) + 3/2H$_2$(g) | 3900 | -                     | 195             | 3900                   | - 36                              |           |

Siegel (2012)