Techno-economic Analysis of a High-Temperature Concentrated Solar Power Plant with a Multi-Level Storage System for a Year-Round Guaranteed Dispatchability

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Introduction

Although there are many technologies that cover short-term (daily) energy storage to stabilize the grid, only a few covers medium-term (weekly) and long-term (seasonal) energy storage and are not yet sufficiently developed.

Weekly and seasonal storage provides a year-round guaranteed dispatchability.
CSP with multi-level storage system

This system offers a unique flexibility, where we can buy and sell electricity when it is most convenient and is allowed to sell Hydrogen as a commodity to offset the operational and capital costs.

Level 1 (Daily): Sensible heat
Level 2 (Weekly): Thermochemical heat
Level 3 (Seasonal): Hydrogen
System design: Next-generation CSP

Gen3 plant based: combines a free-falling particle receiver and a supercritical CO₂ power block
System design: Thermochemical energy storage

L2 storage is based on a two-step redox-active metal oxide (MO\textsubscript{x}) thermochemical cycle

The TCES subsystem performs the thermal reduction of the MO\textsubscript{x} in a low oxidation environment

The ER subsystem performs the re-oxidation of the MO\textsubscript{x} with air, dispatching sensible and chemical energy to the sCO\textsubscript{2} power block
**System design: Thermochemical energy storage**

**L3 storage** produces and stores hydrogen with off-peak electricity.

It is based on a two-step redox-active MOₓ thermochemical cycle whose reactor is designed to work counter-current in both reactions at have an internal solid-solid heat recovery.

Note that the **L3 storage** is not directly connected to the power cycle and uses the L2 as an intermediary.
Both, L2 and L3 storage systems, require inert gas for its operation.

The O₂ removal subsystem purified this inert gas based on a two-step adsorption/desorption cycle.

System design: Thermochemical energy storage

Next-generation CSP

Level 1
- Heliostat field
- Free-falling particle receiver
- sCO₂ Power Block
- Daily Storage
- High-T heat
- Electricity

Level 2
- Thermochemical (Reduction & Storage)
- Energy Recovery
- High-T heat
- MO₃-₅
- MOₓ
- High-T heat
- Electricity

Level 3
- Oxygen Removal (&N₂ Storage)
- Off-peak grid power
- Low-T heat
- N₂ + O₂
- N₂
- O₂ market
- O₂ depleted air
- Environment
- Low-T heat
- Water return
- Electricity

Weekly and Seasonal Thermochemical and Chemical Energy Storage

- Hydrogen (Production & Storage)
- H₂
- H₂ market
- H₂
System design: Full plant diagram

Next-generation CSP

Collection System
- Sun
- Concentrated solar heat flow
- Collection area

Daily Storage
- Hot tank
- Heat exchanger
- Cold tank
- sCO₂ recompression Brayton cycle compressor

Power Cycle
- sCO₂
- Turbine
- Power to grid

Weekly and Seasonal Thermochemical and Chemical Energy Storage

Thermochemical (Reduction & Storage)
- N₂ + O₂
- Reduction
- MO₃ storage
- Low-T heat
- Off-peak grid power

Oxygen Removal (& N₂ Storage)
- N₂ storage
- sorption desorption
- TDSO₅
- O₂ market

Energy Recovery
- sCO₂
- Re-compression
- Final air

Hydrogen (Production & Storage)
- Steam + H₂
- H₂ reactor
- H₂ storage
- Water return
- H₂ market

Environment (Water & Air)
System modeling: next generation CSP

The simulation platform provides a method of quickly and accurately evaluating solar tower systems.
Results: next generation CSP

**Design parameters**
- Receiver configuration
- Receiver width (5-30 m step 1 m)
- Tower height (100-400 m step 5 m)

**Optimization**
- Optimization algorithm: *surrogateopt*
- Objective function: cost-heat flow ratio

R3\(_{90}\) exhibits the lowest LCOH for all the SMs assessed, LCOH \(\sim\)$11/MWh between SM: 1-3

Best solution for each receiver configuration as function of solar multiple: LCOH and annual efficiency (Daggett CA)
System modeling: multi-level energy storage

- User friendly simulation platform to simulate multi-level energy storage systems
- It is constructed using mixed-integer linear programming (MILP) formulation
- Includes constraints and objective functions
- Uses reduced order models and cost model of each of the subsystems

This tool can calculate the optimal system operation given a scenario to achieve the minimum levelized cost of energy
## Results: multi-level energy storage

LCOE ($/MWh) for 100 MWe Nameplate

<table>
<thead>
<tr>
<th>Level 1 Storage (MWh)</th>
<th>Solar Multiples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
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<tr>
<td>1500 (7.5 hrs)</td>
<td>189.8</td>
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<tr>
<td>1800 ( 9 hrs)</td>
<td>193.9</td>
</tr>
<tr>
<td>2000 (10 hrs)</td>
<td>190.8</td>
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<tr>
<td>2400 (12 hrs)</td>
<td>196.1</td>
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<tr>
<td>2800 (14 hrs)</td>
<td>201.3</td>
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<tr>
<td>3200 (16 hrs)</td>
<td>206.6</td>
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<tr>
<td>3600 (18 hrs)</td>
<td>211.9</td>
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<tr>
<td>4000 (20 hrs)</td>
<td>217.2</td>
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<tr>
<td>4400 (22 hrs)</td>
<td>222.5</td>
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<tr>
<td>4800 (24 hrs)</td>
<td>227.8</td>
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</tbody>
</table>

Baseline selected from lowest LCOE at minimum CapEx
Results: multi-level energy storage

Problem: Develop a system design that generates more than the baseline with guaranteed dispatch

• Dynamic electricity pricing model: every day prices can be modified by solar availability, **365 separate cases** possible
• Assumption: At least **6 hours of off-peak** (low-cost) electricity is available every day (likely nights) irrespective of weather
• **10 hours of “guaranteed” generation** under all conditions every day, targeting the highest price hours
• Assumes a **continuous demand for H_2** in the market
• H_2 Price: $60/MWh ($2/kg, based on 120 MJ/kg LHV)
• Does not include revenues from sales of O_2 or capacity payments or other
# Results: multi-level energy storage

L1, L2, and L3 systems under study

<table>
<thead>
<tr>
<th>Case No</th>
<th>L1 MWh (Hours)</th>
<th>SM</th>
<th>L2 MWh (Hours)</th>
<th>RR MW</th>
<th>L3 eTCH₂ MWh (Hours)</th>
<th>eTCH₂ MW</th>
<th>Weather</th>
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<td>2000 (10)</td>
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<tr>
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<td>2000 (10)</td>
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<tr>
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<td>2.25</td>
<td>2200 (10)</td>
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Only L1

L1-L2

L1-L2-L3

Data “modified” by adding 1 week of low insolation (avg. 2 hours of sun/per day) to all months

Level 1, 2 and 3 with similar storage capacity

- L1-to-electricity: 50%
- L2-to-electricity: 45.5%
- L3-to-electricity: 41.7%

TMY Daggett CA
Results: multi-level energy storage

L1-L2 system

- Generation went up with addition of Level 2 because generation gaps in low insolation periods are filled.
- The revenue does not compensate the higher investment cost and operating cost of off-peak electricity.

<table>
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<th>Annualized Plant Cost</th>
<th>Off-peak Electricity Cost</th>
<th>Hydrogen Revenue</th>
<th>LCOE</th>
<th>Annual Generation</th>
<th>Electricity Revenue</th>
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<tr>
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<td>$M</td>
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<td>% Capacity</td>
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<td>$M</td>
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<tr>
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LCOE 15% more than baseline
Results: multi-level energy storage

L1-L2 system

Capital expenses distribution

Solar plant and power block make up 80% of the total investment costs
Results: multi-level energy storage  L1-L2-L3 system

- Generation w.r.t. L1-L2 system did not increase significantly because not many additional “profitable” generation hours.
- The revenues from the H₂ sell compensates for the higher CapEx and OpEx.

LCOE 16% less than baseline.

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Results: multi-level energy storage

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LCOE 16% less than baseline

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Results: multi-level energy storage

L1-L2-L3 system

Capital expenses distribution

Solar plant and power block make up 74% of the total investment costs
Summary

• Three receiver configuration with 90-degree difference between each other exhibits the lowest LCOH

• L1-L2 LCOE is 15% above the baseline LCOE, but has a “guaranteed” dispatchable generation

• L1-L2-L3 LCOE is 16% less than baseline LCOE due to H\textsubscript{2} revenue

• To make this system profitable we need low off-peak electricity rates for filling storage or H\textsubscript{2} generation
Thank you for your attention!!

We would like to acknowledge the team and institutions involved in this work:

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- Penn State
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