Design and Analysis of a CaO/Ca(OH)$_2$ Thermochemical Energy Storage & Discharge Plant with Concentrated Solar Power

Session 1a: Thermal, Mechanical and Thermochemical Energy Storage

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Concentrated Solar Power (CSP) and Energy Storage

Fig. 1: Illustration of a heliostat field design for concentrated solar power without heat storage [1]

Table 1: Comparison of heat storage options suitable for CSP [2]

Thermochemical Energy Storage (TCES)

- **CaO**: Non-toxic
- Cheap, abundant
- Industrial familiarity

EU SOCRATCES Pilot (ongoing)

Fig. 2: Mass energy storage density versus system turning temperature (surveyed systems for TCES) [2]

Fig. 3: Illustration of flow of heat in CaO/Ca(OH)$_2$ TCES system

\[
\Delta H = -109 \text{ kJ/mol}
\]

Energy stored CaO (s)

\[
\text{Ca(OH)}_2(\text{s}) \rightarrow \text{CaO(}\text{s}) + \text{H}_2\text{O(g)}
\]

Energy stored CaO (s)

\[
\text{CaO(}\text{s}) + \text{H}_2\text{O(g)} \rightarrow \text{Ca(OH)}_2(\text{s})
\]

Steam cycle H$_2$O (g) ext.
Knowledge/Expertise Gaps

• Rigorous simulation capability for reaction flowsheet under TCES conditions

• Design and analysis of charging+discharging process within single plant

• Dynamic (real-world) simulation of TCES plant performance

• Techno-economic viability assessment of TCES+CSP combined plant
Designed Flowsheets

Key areas:

• Rigorous fluidized bed reactor simulation (AspenPlus V9)

• CaO/\text{Ca(OH)}_2 \Delta \text{density}, T_{\text{rxn}}, \text{and potential parallel operation} \rightarrow \text{separate FBR designs}

• Integrated power cycle

Fig. 4: Schematic of simulated flowsheets for charging (top) and discharging (bottom)
FBR Optimization

Key observations:

• Longer reaction times in simulation
  • Influenced by conservative kinetics data used here, adjusting for sintering and particle size changes

• Smaller solids inventories in simulation
  • Partially due to different final reactor dimensions in each study
  • Also influenced by choice of kinetics

• Overall results roughly comparable; simulation can be relied upon

Fig. 5: Comparison of key FBR and process parameters from literature [3] versus the results of this study

Knowledge/Expertise Gaps (Recap)

- Rigorous simulation capability for reaction flowsheet under TCES conditions
- Design and analysis of charging+discharging process within single plant
  - Dynamic (real-world) simulation of TCES plant performance
  - Techno-economic viability assessment of TCES+CSP combined plant
Plant Case Study Location

- **Seville, Spain**
- Among most highly irradiated sites globally (annual basis)
- Home to biggest CSP installations → incentive for implementation
- Ample historical solar data available for analysis

Fig. 6: Historical solar irradiance data for Seville, Spain [4]
Dynamic Simulation Scenarios

- Charging: not 24/7, only during daytime
- Discharging: 24/7? Only at night? What % of max load?
- 3 scenarios considered:
  - S1: nighttime batchwise discharge
  - S2: continuous discharge, 50%
  - S3: continuous discharge, 75%

![Dynamic Simulation Scenarios Diagram](image)

Fig. 7: Charging and discharging loads of the CSP-TCES plant, operating in scenarios S1 (red), S2 (black), S3 (green) in a dynamic simulation.
### Process Economics of Scenarios S1-S3

Economic costing methodology adapted from Sieder et al [5]

- Electricity production directly dependent on discharge schedule
- Little influence of operating cost on LCOE or LCOS
- LCOE heavily influenced by discharge schedule
- In reality, plant will use a mix of S1-S3 over time

<table>
<thead>
<tr>
<th>Operating Scenario</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
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<tbody>
<tr>
<td>Electricity Produced (GWh/y)</td>
<td>174</td>
<td>190</td>
<td>286</td>
</tr>
<tr>
<td>Operating Cost ($M/y)</td>
<td>15.9</td>
<td>16.5</td>
<td>16.8</td>
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<tr>
<td>LCOE ($/kWh)</td>
<td>0.091</td>
<td>0.087</td>
<td>0.059</td>
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<tr>
<td>Annual Energy Stored (GWh)</td>
<td>371</td>
<td>371</td>
<td>371</td>
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<tr>
<td>Plant efficiency (%)</td>
<td>47.0</td>
<td>51.3</td>
<td>76.9</td>
</tr>
<tr>
<td>LCOS ($/kWh)</td>
<td>0.043</td>
<td>0.044</td>
<td>0.045</td>
</tr>
</tbody>
</table>

Table 1: Key techno-economic metrics for the CSP-TCES Plant across three operating scenarios

CSP-TCES Levelized Cost of Electricity (LCOE)

- 3rd in terms of LCOE among both renewable and fossil fuel generation
- Current TRL is low → may become even cheaper (better power cycles, more reactive/stable synthetic materials)
- Standalone solar costs also likely to drop with CSP tech. advancements

![Graph showing comparison of LCOE for different power generation technologies including solar with CSP-TCES](image)

**Fig. 8: Comparison of expected LCOE of power generation technologies including solar with CSP-TCES [6]**

CSP-TCES Levelized Cost of Storage (LCOS)

- 2nd in terms of LCOS across heat and electricity storage means
- Competitive with battery storage (Li-ion, Vanadium) which is also developing fast
- More volume-efficient and transportable at large scales

![Comparison of expected LCOS of energy storage technologies including solar with CSP-TCES](image)

**LCOS (¢/kWh)**

- Solar (with CSP-TCES): 4.5 (3.8 - 5.2)
- Molten salt: 11.1
- Vanadium redox: 5.2
- Li-ion: 5.9
- Flywheel: 7.7
- Pumped hydro: 2.8

Fig. 9: Comparison of expected LCOS of energy storage technologies including solar with CSP-TCES [7]

Next Steps Needed

- Pilot scale testing of reactor configurations (biggest obstacle)
- Development of more robust CaO-based material (synthetic, supported, composites, etc.) (major influence on economics as well as technical performance)
- Assessment of suitable power cycles and working fluids
- Tailoring operation schemes to suit sunlight-poor regions (UK) → energy trading
Personal Current and Future Work

- Impact of plant location on techno-economic performance of process (next slide) [8]
- Discharge schedule matching to demand trends
- Exploration of analogous system involving higher T reactions (e.g. mixed metal oxides): suitable for other types of CSP systems

Acknowledgements

- Prof. Paul S. Fennell
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Reactor Choice

- Fluidized bed reactor (FBR) vs packed bed reactor (PBR) both used for fluid-solid reactions
- PBR:
  + simpler, cheaper operation
  + more complete reactions
- FBR:
  + greater thermal efficiency
  + thorough particle mixing
  + continuous operation possible
  + possibly better for scale-up
- FBRs not well-described in software packages, so only approximate studies in literature… until recently

Fig. 10: Illustration of packed bed (left) and fluidized bed (right) reactors [9]

FBR Optimization (ext.)

- Multi-variable optimization for bed masses, reactor dimensions, conversions done separately for charging and discharging

- Boundary conditions for residence times, reaction T, steady-state conversions established from literature and 1st year PhD work

- Results compared with analytical literature study

Fig. 11: Simulated trends in reaction system behavior within FBR for the discharging process, varying bed mass and reactor dimensions