Peak-Load High-Temperature Carbonate Storage

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1. Motivation

2. Concept

3. Charging Concept
   a) Fluidized Bed
   b) Steam Generator

4. Discharge

5. Summary
Electricity Generation and Prices at Energy Exchange Market in Germany

- Solar
- Wind
- Conventional

Electricity Generation and Prices at Energy Exchange Market in Germany

4 €/MWh /hour
10 GW
2 hours
35 GW conv.
Why Peak-Load High-Temperature Storage?

Power demand peaks
- high load gradients in morning and evening hours
- additional load fluctuation through renewables (> 35% in Germany 2017)
- conventional power plants not flexible enough to compensate
- → need to enhance ability of steam power plants for load flexibility

High temperature storage → solution
- load shift: dynamic (high power density) and flexible (quick start up)
- high storage capacity (cheap material)
- but: short operating times:
  - high electricity prices available to make it feasible
  - lower investment costs through integration with existing infrastructure
Why Peak-Load High-Temperature Storage?

Motivation

Electricity Generation:
- negative prices (min: -7.7 €/MWh)
- average below 10 €/MWh
Concept: High Temperature Carbonate Storage

- calcination heated through **surplus electricity**
- carbonation for discharge/heat output to steam generator

$$CaCO_3(s) \leftrightarrow CaO(s) + CO_2(g)$$

$$\Delta h^0_R = 182 \text{ kJ/mol}$$

→ high energy/power density (630 kWh/m³//65 kW/m³ reactor volume)

- sodium heat pipes: ideal heat transfer and isothermal temperature profile
  - increased reaction zone, high power output possible
  - Pressure variation for fast change variation of equilibrium at 850 °C
    → no need for heating up or cooling down
    - even if storage cools down a little, carbonation works even better
Function of heat pipe

- isothermal temperature over whole length
- evaporation/condensation heat transfer >> latent/convection heat transfer

Equilibrium

- carbonation with high $p_{CO_2}$ and "low" temperatures
- calcination with low $p_{CO_2}$ ($< \frac{1}{2} p_{eq}$) and "high" temperatures
- TGA result: at 850 °C similar reaction times carbonation/calcination in TGA

1 Kubato et al. 2000 – Study of decarbonation of CaCO3 for high temperature thermal energy storage
Project goals

- proof-of-concept in pilot plant: 250 kWh, 20 kW_{th}
  - isothermal temperature profile in carbonate bed through heat pipes
  - isothermal operation: carbonation and calcination at same temperature level
- experimental investigations:
  - fluidisation with varying CO₂ partial pressure
  - heat transfer measurements in fixed/fluidised bed
  - optimisation of process conditions
    - dynamic power output
    - cyclic stability and cycle number of CaO/CaCO₃
- feasibility analysis:
  - technical and economical investigation
  - steam injection to different pressure levels in power plants
Charging/Heating

**design challenges**
- 20 kW electrical heating
- 2 kW/heat pipe at 1000 °C
- heat transfer in & out with heat pipes
- minimisation of losses during storage

**idea**
- integration of heating elements in heat pipe bottom

<table>
<thead>
<tr>
<th></th>
<th>heating wire Kanthal</th>
<th>SiC heating element</th>
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</thead>
<tbody>
<tr>
<td>surface load density</td>
<td>up to 2 W/cm²</td>
<td>up to 16.5 W/cm²</td>
</tr>
<tr>
<td>stability up to</td>
<td>1300 °C</td>
<td>1600 °C</td>
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<tr>
<td>required heated length</td>
<td>2 m</td>
<td>0,25 m</td>
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</table>
Charging/Heating

challenges
- electrical insulation, fragility, thermal expansion
- temperature control essential
- HP dry-out: inner mesh & sodium filling ratio

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature</th>
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<tbody>
<tr>
<td>CaCO₃</td>
<td>ca. 850°C</td>
</tr>
<tr>
<td>heat pipe</td>
<td>ca. 900°C</td>
</tr>
<tr>
<td>inner tube</td>
<td>ca. 930°C</td>
</tr>
<tr>
<td>SiC-element</td>
<td>ca. 1250°C</td>
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</tbody>
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\[ \Delta T \approx 50K \]
\[ \Delta T \approx 300K \]

first results
- 2 kW transferred
- increased heat transfer resistance in heating zone through new HP concept \( \rightarrow \) solve!

Location Temperature

- CaCO₃: ca. 850°C
- Heat pipe: ca. 900°C – 850°C
- Inner tube: ca. 930°C
- SiC-element: ca. 1250°C
Discharge with fluidized bed carbonation

**challenge**
- CO\(_2\) flow/fluidisation diminishes in reactor
- limitation for heat transfer: heat transfer from CaCO\(_3\) to heat pipes

→ sufficient/stable fluidization in whole reactor necessary (u/u\(_0\) > 1.5)!

**options**
1. reactor diameter < 0.4 m. **but**: constant capacity makes it taller
2. higher CO\(_2\) volume flow. **but**: added heat losses/higher power output
3. fine particles < 200 μm for lower u\(_{mf}\), **but**: cohesive
4. dilution with N\(_2\)/steam during carbonation
   - higher fluidisation at bed surface
   - possibly higher cyclic CaO conversion
   - **but**: decreasing operating temperature, added heat losses

→ compromise to be found in pre-tests
Discharge/Steam Generator

challenge
- insulation during storage and charging (calcination)
- dynamic & flexible power generation during carbonation
- → dynamic control and safety

experimental
- 1 HP, pressure up to 5 bar, saturated vapour
- characterisation of operating behaviour depending on power demand
- fluidised bed reactor under construction

results
- first tests with 20 mm microporous insulation
- 350 W loss over steam generator for 850°C heat pipe
Summary

- **isothermal** high temperature carbonate storage can support conventional power plants during **high load gradients**
- multiple applications for integration to power plant
- variation of $p_{\text{CO}_2}$ allows quick switch between charge/discharge mode and variety of temperature levels
- currently test of different components regarding charge/discharge
  → compromise for fluidised bed operation
- construction of pilot plant in 2019 for proof-of-concept
- **optimisation of operating conditions**
  - for dynamic operation
  - for cyclic stability of CaO/CaCO$_3$