Thermal Energy Storage for Concentrated Solarthermal Power Plants

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Why Concentrated Solarthermal Power Plants?
Renewable energies for power production
Integration in the electricity supply system

Adaptation to electricity demand

- Run-of-the-river
- Geo-thermal
- Solarthermal power plants
- Tides
- Waves
- Photovoltaic
- Wind

Supply-oriented

Integration in the energy supply system

Adaptation to electricity demand

- Partly demand-oriented
- Run-of-the-river
- Geo-thermal
- Solarthermal power plants
- Tides
- Waves
- Photovoltaic
- Wind

Supply-oriented
Principle of solarthermal power plants
Thermodynamic cycle (Clausius-Rankine, Joule)

Principle of solarthermal power plants
Replacement of conventional fuels by solar energy
Principle of solar thermal power plants
High temperatures through concentration of solar radiation

Parabolic Reflector

Rinne, Turm, Dish

Parabolic trough (PSA)  Power Tower (SNL)
Linear Fresnel (MAN/SPG)  Dish-Stirling (SBP)

Up to 500 ºC  over 1000 ºC
Integration in the electricity supply system
Adaptation to electricity demand with thermal storage

Thermal Storage => more operating hours => cost reduction

Source: C. Libby, EPRI

Energy storage necessary for successful market implementation of CSP technology

- Higher solar annual contribution
- Reduction of part-load operation
- Power output management
- Dispatchable power
Parabolic Trough Power Plant

Collector field  Molten salt storage  Conventional steam power plant

Syn. Oil  NaNO₂-KNO₃  H₂O

Highly specific design specifications regarding:
- primary HTF - pressure - temperature - power level - capacity

Storage system

ONE single storage technology will not meet the unique requirements of different solar power plants
Storage Concepts

**Sensible Heat**
- Storage capacity: 20 – 100 kWh/m³ (dependent on temperature difference)

**Latent Heat**
- Storage capacity: 50 – 150 kWh/m³ (for minimal temperature difference)

**Heat of Reaction**
- Storage capacity: 100 – 400 kWh/m³ (dependend on driving gradient (temperature or pressure))
Commercially available storage systems
- Steam Accumulator
- 2-Tank sensible molten salt storage based on nitrate salts

Alternative materials and concepts tested in lab and pilot scale
- Improved molten salt storage concepts
- Solid medium sensible heat storage, e.g. concrete storage
- Solid media storage for Solar Tower with Air
- Latent heat - PCM storage
- Thermo-chemical storage

Future focus for CSP
- Higher plant efficiency => Increase process temperature
- New fluids: steam, molten salt, gas/air
State-of-the-Art - Steam Accumulators
PS10

- Saturated steam at 250 °C
- 50 min storage operation at 50% load
State-of-the-art - Molten salt storage
Indirect 2-Tank Storage

Andasol

- Storage capacity 1010 MWh (7.7h)
- Nitrate salts
  (60% NaNO3 + 40% KNO3)

Salt inventory 28.500 t
Tank volume 14.000 m³
6 HTF/salt heat exchangers


Parabolic trough power plants with thermal oil
ANDASOL 1: 50 MWe, 7.7 hours storage capacity
State-of-the-art - Molten salt storage
Direct 2-Tank Storage

- Heat transfer fluid and storage medium are the same

- 1st system: Solar Two Project by Sandia

- 2nd commercial system at Gemasolar plant: *Solar Tower plant with 15 h storage*

Thermal Energy Storage for CSP Plants
Status und Development

**Commercially available storage systems**
- Steam Accumulator
- 2-Tank sensible molten salt storage based on nitrate salts

**Alternative materials and concepts tested in lab and pilot scale**
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**Future focus for CSP**
- Higher plant efficiency => Increase process temperature
- New fluids: steam, molten salt, gas/air
Storage Concepts – Sensible Heat Storage

**Sensible Heat**
- solid
- liquid
- solid/liquid

**Latent Heat**
- Salts solid-solid
- Salts solid-liquid

**Heat of Reaction**
- Sorption
- Gas-solid reaction

Molten Salt Storage
Current Developments – Thermocline concept

- Most of the salt volume is replaced by a low cost solid filler material
- Molten Salt is stored in one tank ➔ Cost Reduction
Molten Salt Storage
Current Developments – Thermocline concept

Status:
- Most solids react with molten salt
- Thermal ratcheting can occur
- No long term experience have been published so far
- Cost reduction potential: approx. 33%
- Lots of simulation research has been done
- Test loop with test module is in the design stage at DLR

Molten Salt Storage
Current Developments – New Salt Mixtures

- Demand for…
  - …higher thermal stabilities of molten salts $\rightarrow$ 700 °C
  - …lower melting points $\rightarrow$ < 140 °C
  - …improved thermo-physical properties

- Research on new salt mixtures:

<table>
<thead>
<tr>
<th>Ternary system</th>
<th>Ca(NO$_3$)$_2$-KNO$_3$-NaNO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary system</td>
<td>Li, Na, K // NO$_2$,NO$_3$</td>
</tr>
</tbody>
</table>

Source: DLR
Alternative Storage Technology for Trough Plants with Oil HTF – Concrete Storage

- Heat transfer fluid and storage medium are different
- Low cost storage material with integrated heat exchanger
- No risk of solidification
- Modular and scalable design
- Economic and reliable TES (< 35 € / kWh TES capacity)
- Flexible to large no. of sites and construction materials

Concrete Storage
Set-up
Concrete Storage
Status

- 400 kWh pilot storage in operation since May 2008
- Storage capacity: 0.65 kWh/(m³·K)
- Over 10,000 operation hours
- No indication of any degradation effects

Concrete Storage
Strategy for commercialization

- Definition a standardized 5 MWh basic module design
- Detailed design according to specifications (ΔT, MW, MWh)
- Up-scaling to desired capacity by adding modules
Concrete Storage
Layout for trough plant of Andasol type

1100 MWh Capacity
Configuration of 4 x 63 = 252 modules
Storage Concepts – Latent Heat Storage

Sensible Heat
- solid
- liquid
- solid/liquid

Latent Heat
- Salts solid-solid
- Salts solid-liquid

Heat of Reaction
- Sorption
- Gas-solid reaction

Storage Systems for DSG Plants
Latent Heat Storage

Solar Receiver
- Parabolic solar field
- Fresnel solar field
- Solar tower

Temperature
- Preheating
- Evaporation
- Superheating

Entropy

260 °C – 400 °C
107 bar

Preheating 16%
Superheating 19%
Evaporation 65%
Latent Heat Storage

Features of PCM (phase change material) Storage

- Nitrate salt represent possible PCMs for applications beyond 100 ºC
- Important PCM criteria: thermal conductivity, heat capacity, thermal stability, material cost, corrosion, hygroscopy

Heat transfer coefficient is dominated by the thermal conductivity of the solid PCM → Low thermal conductivity is bottleneck for PCM
Latent heat storage
Approaches for heat transfer enhancement

- Composite material
  - PCM/graphite composite

- Macro encapsulation
  - Pressure vessel

- Extended heat exchanger structure
  - Phase Change Material (PCM)
  - Tubes
  - Fins
    - Heat carrier: water/steam
Status of Latent Heat Storage

Phase change material
Demonstrated at DLR:
- $\text{NaNO}_3 - \text{KNO}_3 - \text{NaNO}_2$ 142 °C
- $\text{LiNO}_3 - \text{NaNO}_3$ 194 °C
- $\text{NaNO}_3 - \text{KNO}_3$ 222 °C
- $\text{NaNO}_3$ 306 °C

Storage concepts
- Graphite fins / horizontal tubes < 250 °C
- Aluminum fins / vertical tubes < 350 °C

Experimental validation
- 6 test modules with 140 – 14,000 kg PCM

Storage System for DSG
Latent heat storage for evaporation

PCM-Evaporator module:
- PCM: NaNO3
- Melting point: 306 °C
- Salt volume: 8.4 m³
- Total height 7.5 m
- Inventory ~ 14 t
- Capacity ~ 700 kWh

⇒ Worlds largest high temperature latent heat storage with 14 tons of NaNO3 (700 kWh) tested in 2010 / 2011 with 2949 h, 95 cycles
Storage Concepts – Thermo-chemical Heat Storage

Sensible Heat
- solid
- liquid
- solid/liquid

Latent Heat
- Salts solid-solid
- Salts solid-liquid

Heat of Reaction
- Sorption
- Gas-solid reaction

Thermo-chemical Heat Storage
Gas-Solid Reactions – Principle and Potential

A+B ↔ AB + Heat
Thermo-chemical heat storage
Thermo-chemical Heat Storage
Gas-Solid Reactions – Principle and Potential

\[ A + B \rightleftharpoons AB + \text{Heat} \]

Thermo-chemical heat storage
- Reversible gas-solid reactions
- Utilization of enthalpy of reaction

\[ AB_{(s)} + \Delta H \rightleftharpoons A_{(s)} + B_{(g)} \]

Potential:
- High storage densities
- Loss-free and long-term storage
- Detachment of storage capacity and thermal power
- Possibility for heat transformation
- Application in a wide temperature range (below ambient up to 1000°C)
Thermo-chemical Heat Storage
Calcium Hydroxide as Storage Material

- Known reaction system
- Gaseous reactant: steam
- Low cost basic material (limestone)
- High reaction enthalpy ~ 100 kJ/mol

- Cycle stability needs to be proven
- Process engineering needs to be simplified

- Theoretical storage densities:

<table>
<thead>
<tr>
<th>$T_{eq}$ [1 bar]</th>
<th>$\Delta H$ [1 bar]</th>
<th>Storage Density$^*$</th>
<th>Porosity of 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>kJ/mol</td>
<td>Solid only kWh/m$^3$</td>
<td>Solid + H$_2$O kWh/m$^2$</td>
</tr>
<tr>
<td>507</td>
<td>100</td>
<td>410</td>
<td>323</td>
</tr>
</tbody>
</table>

$^*$ Porosity of 0.5

Thermo-chemical Heat Storage
Test facility - 10 kW, $T_{max} = 1000$ °C

Quelle: DLR
Electrically heated latent heat storage

Problem: Increasing amount of renewable energy are challenging the grid
Idea: store „surplus” electricity from renewable energies as high
temperature heat
⇒ Use for process heat applications in industry (e.g. bakeries)
(„inversing the concept of the night storage heaters“)

Storage concept:
- Latent heat storage with sodium nitrate (T_melt = 305 °C)
- Apply new design with plate heat exchanger
- Directly charge PCM with special resistance heater
- Discharge of PCM through plate heat exchanger with air or thermal oil
Thermal Energy Storage for Concentrated Solar Power

Summary and Conclusions

- Energy storage is a key issue for CSP → dispatchability & efficiency
- Steam accumulators: Commercial, only economic as buffer storage
- Molten salt technology: Commercial concepts for indirect/direct 2-tank storages are available → Further research aims at cost reduction (new materials & concepts)
- Concrete storage technology is attractive alternative → demonstration in pilot scale needed
- PCM storage technology is the most promising technology for DSG plants → demonstrated in 1 MW scale
- Thermo-chemical storage development is in a basic research stage
- Continuous research and development effort is needed especially for higher process temperatures (> 400°C) and for further cost reduction
- High temperature storage also needed for energy efficiency in industrial processes and grid stability with increasing share of renewables

Thank you for your attention!

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