Overview of SCCER Heat-Storage Research and Development Efforts

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8/12/2014
WP2 Collaborators and Partners

Prof. Beat Ribi
FHNW

Prof. Stefan Roth
FHNW

Prof. Sophia Haussener
EPFL

WP Deputy Leader

Dr. Andreas Haselbacher
ETH

WP Leader

Prof. Matthias Rommel
SPF-HSR

Prof. Maurizio Barbato
SUPSI
## Background and Motivation

<table>
<thead>
<tr>
<th></th>
<th>Space heat</th>
<th>Warm water</th>
<th>Process heat</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td><strong>Households</strong></td>
<td>0.697</td>
<td>0.129</td>
<td>0.023</td>
<td>0.312</td>
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<tr>
<td><strong>Services</strong></td>
<td>0.499</td>
<td>0.08</td>
<td>0.017</td>
<td>0.174</td>
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<tr>
<td><strong>Industry</strong></td>
<td>0.123</td>
<td>0.02</td>
<td>0.531</td>
<td>0.21</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>Fuels</th>
<th>Total</th>
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<tbody>
<tr>
<td>Space heat in households</td>
<td>0.082</td>
<td>0.83</td>
<td>0.218</td>
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<tr>
<td>Process heat in industry</td>
<td>0.252</td>
<td>0.748</td>
<td>0.112</td>
</tr>
</tbody>
</table>

Background and Motivation

Background and Motivation

- **Material systems for process heat (EPFL/SUPSI)**
- **TES for AA-CAES (ETH/SUPSI/FHNW)**
- **PHES (FHNW)**
- **Aqueous salt lye (HSR-SPF)**
- **Space heat for buildings**

**Industrial/power-generation applications**

**temperature (°C)**

- 1000
- 500
- 100
- 50

**Time**

- hours
- weeks
- months
High-Temperature Combined Sensible/Latent Thermal Energy Storage

Lukas Geissbühler,¹ Michael Kolman,¹ Andreas Haselbacher,¹ Giw Zanganeh,³ Aldo Steinfeld¹,²

¹Professorship of Renewable Energy Carriers, Swiss Federal Institute of Technology Zurich
²Solar Technology Laboratory, PSI
³Airlight Energy SA
Background

• Outflow temperature of sensible TES drops during discharging
• Could have unfavorable (power cycles) or unacceptable consequences (chemical reactions)

• Phase-change materials (PCMs) can deliver heat at constant temperature
• PCMs have advantage of higher energy density
• However, PCMs are expensive and not advantageous for large temperature ranges

Combined Sensible/Latent TES Concept

- Basic idea: Add layers of encapsulated PCM on top of packed bed of rocks

- Rocks from Rafzerfeld area and AlSi\textsubscript{12} encapsulated in steel tubes
- Labscale storage with $E_{\text{tot}} = 42.4$ kWh\textsubscript{th}

G. Zanganeh et al., *Stabilization of the outflow temperature of a packed-bed thermal energy storage by combining rocks with phase change materials*, Applied Thermal Engineering, 70:31-320, 2014
Labscale Experiments and Simulations

Temperature [°C]

Time [h]

\( \dot{m}_d / \dot{m}_c = 1 \)

\( \dot{m}_d / \dot{m}_c = 1/2 \)

\( \dot{m}_d / \dot{m}_c = 1 \)

\( \dot{m}_d / \dot{m}_c = 1/2 \)

Time [h]
Large-Scale Storage Simulations

- \( N_{\text{cycles}} \): 20
- \( r_{\text{tank}} \): 8 m
- \( m_{\text{max}} \): 30 kg/s
- \( t_c (= t_d) \): 5 h
- \( T_c \): 595 °C
- \( T_d \): 220 °C
- \( T_{c,\text{out,max}} \): 231 °C
- \( T_{d,\text{out,min}} \): 575/565/555/550 °C

\( \Delta T_{\text{max,discharge}} = 20 \degree C \)
Outlook

• Determine physical properties for more accurate simulations

• Upcoming experiments:
  - Parametric studies
  - Alternative PCM
  - Different storage configurations

• Optimization of tank properties considering efficiency and costs

• Detailed simulations of combined TES (in collaboration with SUPSI)

• Simulation of TES for AA-CAES in tunnel

• Experiments with TES in tunnel
AA-CAES Based on Sensible and Latent Heat Storage/Thermal Energy Storage for the Process Industry

Maurizio Barbato, Alberto Ortona, Marco Fossati, Simone Zavattoni, Ehsan Rezaei, Antonio Gaetano, Jonathan Roncolato

Department of Innovative Technologies
University of Applied Sciences and Arts of Southern Switzerland
Objectives

- Task A: AA-CAES based on sensible and latent heat storage
  - Modeling and simulation of TES
  - Assessment of new configurations and HTFs

- Task B: TES for the process industry
  - Design, rapid prototyping, and optimisation of lattices and random structures for high-temperature TES
Approach

• Task A: CFD-based approach
  - Porous media
  - Effective thermal conductivity\(^1\)
  - PCM modeling:\(^2\)
    › Effective heat-capacity method
    › Enthalpy method
    › Enthalpy-porosity technique

• Task B:

Direct FEM

- Accurate results
- Computationally expensive

FEM-based homogenisation\(^3,4\)

- Reduced computational cost
- Local properties such as failure and stress concentration

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\(^1\) S. Yagi and D. Kunii. *Studies on effective thermal conductivities in packed beds*, AIChE J., 3:373-381, 1957


\(^4\) G. Dai and Z. Weihong *Cell size effect analysis of the effective Young’s modulus of sandwich core*, Computational Materials Science, 46:744-748, 2009
Results

• Low-temperature latent TES with encapsulated PCM:¹


• High-temperature sensible TES based on packed bed of pebbles:²

• Thermomechanical analysis (Direct FEM):
Outlook

• Task A:
  - Review of approaches to simulate phase change of PCM
  - Explore effect of changing HTF
  - Explore different concepts for TES (collaboration with ETH and Airlight)
    › Combined sensible/latent TES
    › Cascaded arrangement of PCMs with different melting temperatures

• Task B:
  - Thermo-mechanical study of foam couples thermal physics and structural mechanics of ceramics for cellular structures
  - Computational expense motivates alternative approaches based on homogenisation
Phase-change material systems for high-temperature heat storage in the process industry

David Perraudin, Sophia Haussener

Laboratory of Renewable Energy Science and Engineering
École Polytechnique Fédérale de Lausanne
• Advanced heat storage technologies required to ensure availability of thermal energy from waste heat and renewable resources

• Heat storage in latent heat:
  - Applicable to high temperatures (> 400°C)
  - Discharged heat at constant temperature
  - High energy density
  - Enhanced heat-transfer characteristics

• Design material systems for efficient and stable high-temperature TES
• Design multi-layered reticulate metal-ceramic porous structures as PCM
  - Porous structures for enhanced performance
  - Multi-layered to ensure stability and long-term performance
• Basics: Heat and mass transfer of multiphase flow in complex PCM structures
  - Development of advanced numerical modelling framework
• Classical Stefan problem\(^1\) in one dimension coupled to heat and mass transport

\[
\begin{align*}
 c_S \rho_S \frac{\partial T_S}{\partial t} &= \kappa_S \frac{\partial^2 T_S}{\partial^2 x^2} & 0 < x < S(t) \\
 c_L \rho_L \frac{\partial T_L}{\partial t} &= \kappa_L \frac{\partial^2 T_L}{\partial^2 x^2} & S(t) < x < \infty \\
 \kappa_S \frac{\partial T_S}{\partial x} - \kappa_L \frac{\partial T_L}{\partial x} &= \rho_s l_h \frac{dS}{dt} & x = S(t)
\end{align*}
\]

• Optimization: Structure-engineering of solid/PCM phase, materials choice, and operational conditions
• Prototype: Performance measurements and long-term stability testing

Results

- Copper encapsulated in silicon carbide, constant rate of heat removal and addition (50 kW)

- Observations:
  - Encapsulation limiting for heat transfer
  - During cycling development of multiple melting/solidification fronts, leading to reduced charging and discharging efficiency
Outlook

• Model enhancement to include other relevant physical phenomena (convection and radiation), extend to 3D and complex material structure

• Apply model to variety of material combinations to scout interesting temperature levels, charging/discharging requirements, and corresponding industrial use (in collaboration with industrial partners)

• Specifically focus on long-term stability (>10’000 cycles) and contained PCM interaction (chemical and mechanical integrity)

• Building prototype for model validation and testing
Aqueous salt lye seasonal thermal-energy storage: development and measurements on the heat and mass exchangers

Xavier Daguenet-Frick, Paul Gantenbein, Mercedes Hannelore Rittmann-Frank, Matthias Rommel

Institute for Solar Technologies SPF
University of Applied Sciences Rapperswil
• Liquid sorption energy storage concept:
  - Seasonal storage with low thermal losses and high volumetric energy density
  - Thermochemical storage based on water absorption/desorption in an aqueous salt lye (NaOH-H₂O, LiBr-H₂O, LiCl-H₂O, etc.)
  - High fraction of renewable energy by using solar collectors and environment heat
• Liquid sorption energy storage concept:
  - Seasonal storage with low thermal losses and high volumetric energy density
  - Thermochemical storage based on water absorption/desorption in an aqueous salt lye (NaOH-H₂O, LiBr-H₂O, LiCl-H₂O, etc.)
  - High fraction of renewable energy by using solar collectors and environment heat
Modeling of Heat and Mass Exchanger

- Choice of tube bundle heat and mass exchanger technology:
  - Large vapour to liquid contact area
  - High heat and mass transfer (compact design)
- Design of the heat and mass exchangers (desorber):
Surface Wetting Improvement

• Manifold optimisation (view under nozzles):

• Measurements of the wet surface fraction development:
Outlook

- Heat and mass transfer prediction (modeling)
  - For tube bundles, approximate models coded
  - Validation remains to be done

- Optimization of the heat and mass exchanger function (fluid distribution, surface wetting)
  - Design of a functional manifold achieved
  - Influence of surface texturing and of surfactant use will be studied

- Research on the absorption process kinetics; validation of the models
  - Construction of a small-scale non-isothermal experiment planned (focus on heat and mass exchangers)
New Projects
High-temperature combined sensible/latent-heat storage based on novel materials for electricity storage using advanced adiabatic compressed air energy storage

Project partners:
- ETH (A. Steinfeld, A. Haselbacher)
- EPFL (S. Haussener, A. Mortensen, L. Weber)
- SUPSI (M. Barbato)
- PSI (P. Burgherr, W. Schenler, C. Mutel)
- Airlight Energy

Funding: CHF 1.24M

Duration: 48 months

Starting date: December 1, 2014
Backup Slides
FHNW
Decentralized Heat Supply and Electricity Storage using a Combined Heat Pump/Power Cycle Process

Beat Ribi,¹ Frank Tillenkamp,² Gianfranco Guidati³

¹Fachhochschule Nordwestschweiz, Brugg
²Zürcher Fachhochschule der Angewandten Wissenschaften, Winterthur
³Alstom
• **Background:**
  - Change of centralised power generation (e.g., by nuclear power plants) to decentralised PVs calls for a local smart energy management

• **Envisaged solution:**
  - Project focuses on development of electricity storage based on well-established heat-pump technology and the addition of a hot-water storage and an expander → Pumped Heat Electricity Storage (PHES)

• **Result of project:**
  - Experimental demonstration of the concept in a 5-10 kW plant is planned
Boundary Conditions

• Requirements:
  - Decentralized storage of electricity is subject to several constraints:
    › Electric power range rather moderate (100 kW to 10 MW)
    › Storage media and working fluids should not pose safety hazard, environmental or health risk
    › Location independent of specific geographical properties such as reservoirs at higher elevation (pumped hydro storage) or geological properties (CAES)
    › Reasonable price

• Potential:
  - Decentralized storage of electricity offers on the other hand additional possibilities such as direct integration with supply of low-temperature heat for heating or cooling
• Charging: System works as heat pump
• Discharging: Power cycle process for electricity generation plus heat supply for domestic heating and hot water
• Simulation for block with 30 units
• Based on meteorological conditions: 7 days in February
PHES System: Simulation

- Simulation for block with 30 units
- Based on meteorological conditions: 7 days in May

Temperature in:
- cold storage tank
- hot storage tank

Consumption of:
- electrical power
- heat

Electricity:
- PV usage
- power cycle
- from grid

Operation of:
- heat pump
- cut-off of PV
With use of temperature storage tanks and power cycle, amount of electrical power consumption covered by own production can be increased by approx. 20%
• Use of water as working fluid:
  - Within certain temperature and pressure rise uncritical
  - State-of-the-art technology for heating hot water supply already based on water
    → use of existing technologies/equipment
Requirements for Working Fluid

- Use of non-critical working fluids
  - Non-toxic
  - Inflammable
  - Low ODP, low GWP

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>R12</th>
<th>R22</th>
<th>R134a</th>
<th>R290</th>
<th>NH₃</th>
<th>CO₂</th>
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<tbody>
<tr>
<td>Natural fluid</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ODP</td>
<td>0.82</td>
<td>0.055</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GWP (100yr) IPCC</td>
<td>8100</td>
<td>1500</td>
<td>1300</td>
<td>20</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>112</td>
<td>96.2</td>
<td>101.2</td>
<td>96.7</td>
<td>132.3</td>
<td>31.1</td>
</tr>
<tr>
<td>Critical pressure</td>
<td>4.14</td>
<td>4.99</td>
<td>4.06</td>
<td>4.25</td>
<td>11.27</td>
<td>7.38</td>
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<tr>
<td>Flammable</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Toxic</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>Relative price</td>
<td>n/a</td>
<td>1</td>
<td>4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
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<td>Volumetric capacity</td>
<td>1</td>
<td>1.6</td>
<td>1</td>
<td>1.4</td>
<td>1.6</td>
<td>8.4</td>
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</table>
Combination of storage medium and working fluid:
- For low temperatures: evaporation as well as condensation within two-phase zone

- Use of water with latent heat and of working fluid with sensible heat provokes large temperature differences
• Variable pressure level for:
  - Evaporation
  - Condensation
Consequences

• Variable pressure level calls for highly adaptive turbomachinery
  - Variation of mass flow: Factor of 1-5
  - Variation of pressure: Factor of 3-10
  - Independent variation required, widely changing flow field (compressibility effects)

Influence of temperature and pressure on speed of sound (for R134a)
Consequences

- Evaporation and condensation
  - Heat pump cycle: compressor
  - Power cycle: turbine

\[
\begin{align*}
\text{operation close to saturation line} & \quad \rightarrow \quad \text{correlation between steepness and polytropic efficiency}
\end{align*}
\]

Maximum polytropic efficiency to allow expansion/compression in gas phase
Consequences

- Evaporation and condensation
  - Heat pump cycle: compressor
  - Power cycle: turbine

\[ \text{operation close to saturation line} \rightarrow \text{correlation between steepness and polytropic efficiency} \]
Backup Slides
CAES & AA-CAES
ETH-Airlight Sensible-Heat TES

- Use rocks as storage material
  - Abundant and low-cost material
  - Stable over wide temperature range
  - Direct contact between HTF and storage material
- Use truncated concrete cone as storage vessel
  - Simple construction
  - Mechanical stability
  - Improved efficiency compared to cylindrical tank
- Results of collaboration:
  - 6.5 MWh$_{th}$ storage prototype in Biasca
  - 7.2 GWh$_{th}$ storage in Ait Baha, Morocco

ETH-Airlight Sensible-Heat TES

Depth: 4 m
ETH-Airlight Sensible-Heat TES
ETH-Airlight Sensible-Heat TES

Helvetic Siliceous Limestone
Limestone
Quartzite
Calcarenous Sandstone
Gabbro
Comparison: Experiments/Simulations
Labscale Combined TES

- **Double Cone**
- **Microtherm**
- **Perforated Plate**
- **PCM**
- **Rocks**
- **Rockwool**
- **Felt**
- **Perforated Plate**

Dimensions:
- 394 mm
- 100 mm
- 90 mm
- 1270 mm
- 1680 mm
- 550 mm

Masses:
- $m_{PCM} = 9.6 \text{ kg}$
- $m_{enc} = 13 \text{ kg}$
- $m_s = 245 \text{ kg}$
PCM Selection

<table>
<thead>
<tr>
<th>Property</th>
<th>Molten Salts</th>
<th>Metal Alloys</th>
<th>AlSi$_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (C)</td>
<td>100 – 900</td>
<td>&gt; 250</td>
<td>576</td>
</tr>
<tr>
<td>Heat of fusion (KJ/Kg)</td>
<td>high</td>
<td>high</td>
<td>560</td>
</tr>
<tr>
<td>Congruent melting</td>
<td>x</td>
<td>✓</td>
<td>574-577 °C</td>
</tr>
<tr>
<td>Volume expansion</td>
<td>high</td>
<td>low</td>
<td>5 %</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>very low</td>
<td>high</td>
<td>160 W/mK</td>
</tr>
<tr>
<td>Chemical stability</td>
<td>x</td>
<td>✓</td>
<td>under Argon atmosphere</td>
</tr>
<tr>
<td>Compatibility</td>
<td>x</td>
<td>✓</td>
<td>with stainless steel</td>
</tr>
<tr>
<td>Toxicity</td>
<td>high</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>low</td>
<td>inert atmosphere</td>
<td>dry atmosphere</td>
</tr>
</tbody>
</table>
# PCM Selection

<table>
<thead>
<tr>
<th>Material</th>
<th>CHF/kg</th>
<th>Ratio</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocks</td>
<td>0.017</td>
<td>-</td>
<td>Kieswerk Gränichen</td>
</tr>
<tr>
<td>AlSi</td>
<td>20</td>
<td>1176</td>
<td>Weldability-SIF</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>MJ/kg</th>
<th>Ratio</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocks</td>
<td>0.53</td>
<td>-</td>
<td>Zanganeh (2014)</td>
</tr>
<tr>
<td>AlSi</td>
<td>1.26</td>
<td>2.4</td>
<td>Kenisarin (2010)</td>
</tr>
</tbody>
</table>

1 Assuming heating from 25 to 650°C
PHS in Switzerland

- Energy strategy 2050:
  - Increases reliance on intermittent renewable energy sources
  - Calls for 5.5 GW installed power from pumped hydro storage (PHS):

<table>
<thead>
<tr>
<th>Status</th>
<th>Year</th>
<th>Facility</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>2014</td>
<td></td>
<td>1839</td>
</tr>
<tr>
<td>Under construction</td>
<td>2014</td>
<td>FMHL+</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>Linth-Limmern</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>Nant de Drance</td>
<td>900</td>
</tr>
<tr>
<td>Permit granted, but</td>
<td>?</td>
<td>Lago Bianco</td>
<td>1000</td>
</tr>
<tr>
<td>construction delayed</td>
<td>?</td>
<td>Grimsel 3</td>
<td>600</td>
</tr>
<tr>
<td>Total</td>
<td>2050</td>
<td></td>
<td>5579</td>
</tr>
</tbody>
</table>

Source: Swiss Energy Strategy 2050

- Obstacles to construction of PHS power plants:
  - Specific site requirements, environmental considerations
  - Very high and site-dependent capital costs, uncertain profitability
### Alternatives to PHS

<table>
<thead>
<tr>
<th></th>
<th>Mikrospeicher</th>
<th>Kleintechnische Speicher</th>
<th>Mitteltechnische Speicher</th>
<th>Grosstechnische Speicher</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Monate</strong></td>
<td></td>
<td></td>
<td></td>
<td>Power-to-Gas</td>
</tr>
<tr>
<td><strong>Tag / Wochen</strong></td>
<td></td>
<td></td>
<td></td>
<td>Pumpspeicher</td>
</tr>
<tr>
<td><strong>Stunden / Tage</strong></td>
<td>Batterien</td>
<td>Batterien</td>
<td>Elektrothermische Speicher</td>
<td>Batterien</td>
</tr>
<tr>
<td><strong>Minuten / Stunden</strong></td>
<td>Batterien</td>
<td>Batterien</td>
<td>Elektrothermische Speicher</td>
<td>Batterien</td>
</tr>
<tr>
<td><strong>Sekunden / Minuten</strong></td>
<td>Superkondensatoren, Spulen</td>
<td>Schwungräder Batterien</td>
<td>Batterien (Pumpspeicher) (Druckluftspeicher)</td>
<td>(Pumpspeicher) (Druckluftspeicher)</td>
</tr>
</tbody>
</table>

Source: SFOE, *Energiespeicher in der Schweiz*, 2013
Alternatives to PHS

Figure 4: Current global installed grid-connected electricity storage capacity (MW)


Source: IEA, Technology Roadmap Energy Storage, 2014
• Alternative to PHS: Compressed Air Energy Storage (CAES)
• Diabatic CAES:
  - Heat from compression is wasted, fossil fuels required
  - Cycle efficiencies of about 40-55%\(^1\)
• Diabatic CAES proven in practice:

• Advanced **Adiabatic** CAES (AA-CAES):
  - Heat from compression stored and reused during expansion
  - Projected cycle efficiencies of about 70-75%
  - Compares favorably with PHES efficiencies of about 75-80%
• Construction and operating costs estimated to be lower than or comparable to PHS\(^1\)\(^-\)\(^4\)
• AA-CAES could be well-suited to Switzerland:
  - Existing caverns could be reused at low cost
  - Cavern/tunnel expertise available

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1 Chen et al., *Progress in Electrical Energy Storage Systems*, Progress in Natural Science, 2009
3 SFOE, *Energiespeicher in der Schweiz*, 2013
4 Deutsche Bank, *Moderne Stromspeicher*, 2012
Alternatives to PHS: Cost Comparison

Source: van der Linden, Bulk energy storage potential in the USA, current developments and future prospects. Energy, 2006

Source: SFOE, Energiespeicher in der Schweiz, 2013
Figure 8: LCOE in the "breakthrough" scenario in 2013 and 2050

Source: IEA, Technology Roadmap Energy Storage, 2014
Figure 10: Land and water footprint for electricity storage and generation technologies


Source: IEA, Technology Roadmap Energy Storage, 2014
Maturity of PHS, CAES, and AA-CAES

Figure 3: Maturity of energy storage technologies


Source: IEA, Technology Roadmap Energy Storage, 2014
## Existing CAES Systems

<table>
<thead>
<tr>
<th></th>
<th>Huntorf</th>
<th>McIntosh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commissioned</td>
<td>-</td>
<td>1978</td>
</tr>
<tr>
<td>Maximum output power</td>
<td>MW 321</td>
<td>110</td>
</tr>
<tr>
<td>Cycle efficiency</td>
<td>42%</td>
<td>54%</td>
</tr>
<tr>
<td>Cavern type</td>
<td>Salt dome</td>
<td>Salt dome</td>
</tr>
<tr>
<td>Cavern volume</td>
<td>m 310'000</td>
<td>538'000</td>
</tr>
<tr>
<td>Cavern pressure</td>
<td>bar 46-72</td>
<td>46-75</td>
</tr>
<tr>
<td>Charge mass flow</td>
<td>kg/s 108</td>
<td>90</td>
</tr>
<tr>
<td>Discharge time</td>
<td>h 2</td>
<td>26</td>
</tr>
<tr>
<td>Discharge start-up time</td>
<td>min 14</td>
<td>12</td>
</tr>
<tr>
<td>Discharge mass flow</td>
<td>kg/s 455</td>
<td>154</td>
</tr>
</tbody>
</table>

Comparison of CAES and AA-CAES

- Time-decoupled Brayton cycle
- Compression heat discarded
- Fuel needed to heat compressed air before entering the turbine
- Electric-to-electric efficiency $\geq 40\%$
- Power of up to 1GW

- Time-decoupled Brayton concept
- Compression heat stored
- No fuel needed thanks to TES
- Electric-to-electric efficiency up to 70-75%
- Power of up to 1GW
<table>
<thead>
<tr>
<th>Year</th>
<th>Type</th>
<th>Power</th>
<th>Duration</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tennessee Colony, TX</td>
<td>2017</td>
<td>CAES</td>
<td>317 MW</td>
<td>105 h Construction permit issued</td>
</tr>
<tr>
<td>San Joaquin County, CA</td>
<td>?</td>
<td>AA-CAES</td>
<td>300 MW</td>
<td>10 h Compression testing of cavern</td>
</tr>
<tr>
<td>Stassfurt, Germany</td>
<td>2019</td>
<td>AA-CAES</td>
<td>260 MW</td>
<td>5 h Construction to start in 2016</td>
</tr>
</tbody>
</table>

Source: DOE Energy Storage Database, Presentations on ADELE project
Market Potential of CAES/AA-CAES

- Navigant Research:\(^1\)
  - Installed CAES power by 2023: 11.2 GW (2013: 440 MW)
  - New system installed revenue by 2023: $4.8b/year

- AA-CAES in Germany:
  - Fifteen salt dome locations suitable for AA-CAES identified\(^2\)
  - Natural-gas caverns with 150M m\(^3\) in use or in construction, additional potential of 200M m\(^3\)\(^3\)

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\(^1\) Navigant Research, *Compressed Air Energy Storage*, October 2013
\(^2\) Calaminus, *Innovatives Druckluftspeicherkraftwerk der EnBW*, October 2007
\(^3\) Deutsche Bank, *Moderne Stromspeicher*, January 2012
AA-CAES in Swiss Caverns: Estimate

- Armasuisse data: Currently at least 108 unused military caverns with total area $A=350'000 \text{ m}^2$
- Assuming $h_{\text{mean}} = 4 \text{ m}$ gives $V=1.4M \text{ m}^3$
- Assuming compression to 60 bar and 655 °C
- Assuming cavern to be free of heat losses and air leakage
- Assuming cavern to be filled to 80% with rocks, solid fraction of 50%, and capacity factor of 50%, get $E=170 \text{ GWh}_{\text{th}}$
- Assuming 10% of energy to be discharged at flow rate of 500 kg/s, get energy flow rate of 440 MW and duration of 39 days
- For largest cavern of $A=19'925 \text{ m}^2$, get duration of 2 h