Implications of subsurface heat or gas energy storage

Numerical modelling studies of design and induced effects

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Motivation

• The transition from fossil energy production to renewable energy production requires a strong increase of energy from renewable sources like wind power, solar power, biomass, solar heat and geothermal energy.

• However, power generation from wind or solar power plants fluctuates on a daily to seasonal time scale due to climatic and weather reasons.

• Large storage capacities (up to 50 TWh in e.g. Germany in 2050) are required to compensate for short-term (seconds to hours), mid-term (hours to days) and long-term (seasonal, months) fluctuations in electric power production.

• Storage scenarios could be:
  - storage of surplus renewable energy -> averaging power supply
  - conversion to gas (Power2Gas) or fuel for re-electrification or other uses like mobility (i.e. H₂, CH₄)
  - Compressed Air energy Storage (CAES)
  - Conversion to heat for later heating purposes (Power2Heat)

• The geologic subsurface offers large potential storage capacities for mid-term to long-term geotechnical energy storage, e.g. natural gas storage or heat storage.
Hydrogen or methane gas storage

Porous formation storage requirements
• Tight cap rock, permeable storage formation in adequate depth
• Cushion gas, accessibility by multiple wells
• Very large capacities and rates possible
• Rates limited by geological setting
• Pressure losses and induced reactions possible
• Proof of tightness required

Cavern storage requirements
• Existence of tight rock salt deposits in adequate depth
• Solution mining of cavern, brine disposal
• Cushion gas, accessibility by one well
• Large capacities and rates possible
• No pressure losses or induced reactions possible
• Tightness basically given
Compressed Air Energy storage (CAES)

Storage times: half-hours to daily
100s of MW possible as combined gas power station

Suitable geological formations
- Caverns in salt deposits (existing plant: Huntorf, Germany; 320 MW for 2 h)
- Porous reservoirs (research stage)

Off-peak Energy for Compression
Generation during peak hours

Compressor Generator & Gas Tubine

Energy production rate vs time

Air in & out Subsurface Storage Porous aquifer or salt cavern

The Hydrodynamics Group, LLC (2011) and Bauer et al.(2013)
Geological heat and energy storage

Borehole thermal heat storage (BTES)
- using borehole heat exchangers (BHE) for heat injection / extraction
- work in low permeable geologic settings
- only choice when water cycling is not feasible
- scalable by increasing the number of BHEs

Aquifer thermal heat storage (ATES)
- using injection and extraction wells for circulating the water
- work in high permeable geologic formations (aquifers)
- high energy rates can be achieved
- scalable by increasing the number of wells

Scalable to GWh capacity and kW extraction rates
Geological storage options cover a wide range of time scales as well as capacities. Many options exist in Germany, especially the North, so storage sites can be flexibly placed.
Use of the geological subsurface

- ground water
- humans
- soil / vegetation
- fauna

Type of use:
- near surface geothermal systems
- heat storage
- natural gas and hydrogen storage
- compressed air storage
- conventional / unconventional hydrocarbon production
- mining
- deep geothermal energy
- CO₂ or nuclear waste disposal

Protected entities:
- ground water abstraction
- mining
Planning of the geological subsurface

**Conflicts of use** in the subsurface can be due to:
- multiple uses of one storage formation / site or
- induced effects of other types of use already present or intended in future
- monitoring requirements of other types of use.

Therefore, planning and weighting of the individual types of use for possible storage locations is required, i.e. a subsurface **use planning**, as e.g. definition of regions reserved for a specific storage option.

Only this will yield an economical and ecological optimized use of subsurface resources. Planning has to include the surface infrastructure and conditions.

For this, not only the **storage locations** but also the **effects** of an individual **storage / usage operation** have to be considered, as well as **monitoring** requirements.

Conflicts of use occur both in the **deep** (mass energy storage) as well as the **shallow subsurface** (i.e. heat storage – drinking water supply).
Use of urban subsurface with potential heat influences

- **Warm water production**
  - ground heat collector
  - ground heat exchangers
  - open well doublet

- **Climatization of buildings**
  - Energy piles
  - technical storages

- **Process heat storage / retrieval**
  - BHE-fields

- **Heat and energy supply**
  - Solar heat
  - Power-To-Heat

Depth [m]

- 10
- 100

Urban settings

EERA Conference 2016
24.11.2016, Birmingham
Urban ground and heat

Menberg et al., 2013
ANGUS+ project objectives and methods

Development of concepts for planning the use of the subsurface
Analysis and dimensioning of storage capacities for mass and heat storage, considering the mutual effects of the individual storage options, the effects on protected resources (e.g. drinking water) as well as the surface conditions

Scenario analysis
Realistic numerical scenario analysis of impacts and of monitoring for storage of mass and heat storage in porous formations and caverns

Parameterization
Development of type scenarios
Parameterization of the deep and shallow subsurface
Experimental determination of
- geomechanical parameters
- geochemical effects induced
- microbial populations

Model development
Development and implementation of numerical process models for the simulation of coupled thermal, hydraulic, geomechanical and geochemical (THMC) processes
- quantification of effects
- development and verification of monitoring methods
Spatial planning approach

Assignment of 3D subsurface spaces to each type of use, either directly, by induced effects, or required by monitoring.
**Scenario:**
Securing electric energy supply during a period of one week with no electricity production from renewable sources in Schleswig-Holstein

- 821205 GJ = 234 GWh
- Required $\text{H}_2$ volume: 129.12 mio. sm$^3$ at 60% re-electrification efficiency and 0.0106 GJ/m$^3$ energy density

**Geological storage site:**
- Porous sandstone in anticlinal structure
- 500 m depth
- 5 operation wells
- Pressure ranges from geological setting
H₂ Storage scenario: Simulation results

**Gas phase saturations**
- Gas phase accumulates in the top of the structure (cap rock required)
- No net gas movement, compressibility used

**Gas component distribution**
- Concentric spreading of H₂ around the wells (blue = cushion gas, red = H₂)
- Distribution reflects state of storage cycle

**Storage Performance**

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>mean</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas extraction rate [Mio. sm³/d]</td>
<td>3.54</td>
<td>4.42</td>
<td>5.0</td>
</tr>
<tr>
<td>Energy retrieved [GWh]</td>
<td>39</td>
<td>49</td>
<td>56</td>
</tr>
<tr>
<td>Extraction rate [MW]</td>
<td>235</td>
<td>294</td>
<td>335</td>
</tr>
</tbody>
</table>

Provides 21 ±4 % of required storage  => increase well number to cover 100%
**H₂ Storage scenario: Induced effects**

### Pressure changes
- Large pressure changes of 20 bar at the wells, >1 bar at 8 km from wells
- Small effect of geological variety
- 88 km² affected area

### Gas phase distribution
- Represents area of chemical reactions
- Extends ~3 km from wells
- Affected by reservoir heterogeneity
- 4 km² affected area
Geophysical monitoring

- Potential Methods: *Seismic*, geoelectric, gravity
- Thin gas phase body makes detection difficult

Gas phase detection possible with geophysical methods
- High spatial density of measuring points required
Comparison of storage options

Comparison of a CAES, CH₄ and H₂ gas storage at one possible site

- Different typical storage operation profiles for CAES and H₂- or CH₄ storage assumed
- “Complete” use of a “small” anticline structure
- Increased well number to 9 and 13 wells

**Storage performance**

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>Energy (GWh)</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAES</td>
<td>10</td>
<td>320</td>
</tr>
<tr>
<td>H₂ storage</td>
<td>102</td>
<td>600</td>
</tr>
<tr>
<td>CH₄ storage</td>
<td>365</td>
<td>2175</td>
</tr>
</tbody>
</table>

Reflects the different energy densities of used storage gases
Boundary conditions:

- Temperature at pipe inlet (during injection): 90 °C
- Temperature at pipe inlet (during injection): 1 °C
- Fluid flow rate: 1 L/s
BTES Scenario simulations

Storage scenario with 19 BHEs

Temperature profile

Heat injection

Heat extraction

Temperature profile

1st injection
1st extraction
4th injection
4th extraction
10th injection
10th extraction

Distance [m]

T [°C]

x [m]

y [m]
Comparison of multi-BHE systems

- Strongly variable heat storage rates, decreasing with time by more than factor of 10
- Heat recovery increases with number of BHEs

<table>
<thead>
<tr>
<th></th>
<th>1 BHE</th>
<th>7 BHE</th>
<th>19 BHE</th>
<th>37 BHE</th>
<th>61 BHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat extracted [MWh]</td>
<td>25</td>
<td>510</td>
<td>940</td>
<td>1890</td>
<td>3260</td>
</tr>
<tr>
<td>Minimum heat extraction rate [kW]</td>
<td>4</td>
<td>51</td>
<td>49</td>
<td>68</td>
<td>116</td>
</tr>
<tr>
<td>Average heat extraction rate [kW]</td>
<td>6</td>
<td>117</td>
<td>218</td>
<td>437</td>
<td>755</td>
</tr>
<tr>
<td>Heat Recovery [%]</td>
<td>29</td>
<td>60</td>
<td>74</td>
<td>81</td>
<td>85</td>
</tr>
<tr>
<td>Heat extraction rate per BHE [kW]</td>
<td>6.0</td>
<td>16.8</td>
<td>11.5</td>
<td>11.8</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Spatial extension: 50 m * 50 m * 100 m; area influenced: 0.01 km², but close to surface
Spatial Information System

Subsurface Geology

Energy consumption

Energy-Infrastructure

Spatial Planning

Identify and visualize spaces suited for potential storage sites
• Geological storage can provide large capacities and a range of withdrawal rates. Storage choice and dimensioning depends not only on geology but on power grid requirements, power plant configurations, and economics as well.

• Subsurface space used by the storage site and the induced effects can be assessed by the newly developed methodology.

• Conflicts of use can be addressed by comparison of different usage options and a benefit analysis.

• The analysis of storage demand ("usage scenario") requires a full quantification and simulation of the power grid and of the technical installations (power stations). For geothermal energy, this is the quantification of the heat flows. This requires inclusion of other disciplines and experts from a variety of backgrounds.

• Hydrogen gas storage can reach 10 GWh capacity and 60 MW per well, but strongly depends on suitable geology.

• For the scenarios simulated, the BTES (and also ATES) systems can each store up to a few GWh of heat and accommodate extraction rates of some 100s kW using 50+ BHEs / one well doublet. Heat recovery is from about 65% (ATES) to about 80% (BTES).
Follow up Information

- www.angusplus.de
- Bauer et al (2013), Environmental Earth Sciences 70(8)
- Topical Issue “Subsurface Energy Storage” Environmental Earth Sciences 75
Thank you very much for your attention!