Combining CCS with CO$_2$-Plume Geothermal (CPG) power generation in Switzerland

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Mahmoud Hefny, Geothermal Energy and Geofluids, Dept. of Earth Science, ETH Zürich

And also: Andrea Moscariello, Luca Guglielmetti, Ovie Eruteya, Jonathan Ogland-Hand, .....
Direct CPG generates 2-3 times net electric power of brine + ORC (base case)

Adams et al., Applied Energy 2015
Approx. upscale by multiplying 5-spot well pattern footprint area of 1 km$^2$
# Levelized Cost of Electricity (LCOE)

Measured as $/MWh

<table>
<thead>
<tr>
<th>Technology</th>
<th>LCOE 2017</th>
<th>LCOE 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV Utility Scale</td>
<td>$46</td>
<td>$53</td>
</tr>
<tr>
<td>Solar PV Thermal &amp; Storage</td>
<td>$98</td>
<td>$181</td>
</tr>
<tr>
<td>Geothermal H₂O</td>
<td>$77</td>
<td>$117</td>
</tr>
<tr>
<td>Geothermal CO₂ (CPG)</td>
<td>$50</td>
<td>$120</td>
</tr>
<tr>
<td>Biomass Direct</td>
<td>$55</td>
<td>$114</td>
</tr>
<tr>
<td>Wind</td>
<td>$30</td>
<td>$60</td>
</tr>
<tr>
<td>Gas Peaking</td>
<td>$156</td>
<td>$210</td>
</tr>
<tr>
<td>Nuclear</td>
<td>$112</td>
<td>$183</td>
</tr>
<tr>
<td>Coal</td>
<td>$60</td>
<td>$143</td>
</tr>
<tr>
<td>Gas Combined Cycle</td>
<td>$42</td>
<td>$78</td>
</tr>
</tbody>
</table>

Expansion of geothermal resource base (e.g. USA)

Example USA

LCOE (S/MWh):
- 20 - 50
- 50 - 100
- 100 - 200
- 200 - 500

Greenfield

Cost-ordered available capacity

For Comparison
US: 1200 GWe Capacity

Adams and Saar (in prep. 2020)
Estimate of power generation at (depleted) Swiss hydrocarbon reservoir at 4.3 km depth

- Malm karst reservoir thickness: 20 m thick
- Dual permeability system (matrix + fracture)
- Permeability (with karst, fractures): 10 - 1'000 mD
- Effective Transmissivity: 20 - 20'000 mD-m
- Power generation: up to 10'000 kW\textsubscript{e} = 10 MW\textsubscript{e} per 5-spot well pattern (similar for doublet) of 1 km\textsuperscript{2}

Approx. upscale by multiplying footprint area of 1 km\textsuperscript{2}.
Where (else) to do CCS with CPG in Switzerland?

<table>
<thead>
<tr>
<th>No</th>
<th>Criterion</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Reference / remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Storage capacity</td>
<td>Injection rate</td>
<td>&lt; 30 km</td>
<td>&lt; 5 km</td>
<td>&lt; 20 km</td>
</tr>
<tr>
<td>2</td>
<td>Proximity to CO₂ source</td>
<td>Close to site</td>
<td>&lt; 30 km</td>
<td>&lt; 5 km</td>
<td>&lt; 20 km</td>
</tr>
<tr>
<td>3</td>
<td>Depth to reservoir/aquifer</td>
<td>4300 m</td>
<td>2042 m</td>
<td>2681 m</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Porosity</td>
<td>&gt; 800</td>
<td>4300 m</td>
<td>2042 m</td>
<td>2681 m</td>
</tr>
<tr>
<td>5</td>
<td>Permeability</td>
<td>&gt; 10%</td>
<td>No data</td>
<td>1-7.5%</td>
<td>2-6%</td>
</tr>
<tr>
<td>6</td>
<td>Reservoir thickness</td>
<td>&gt; 20 m</td>
<td>20 m</td>
<td>62.5 m</td>
<td>62 m</td>
</tr>
<tr>
<td>7</td>
<td>Caprock thickness</td>
<td>&gt; 10 m</td>
<td>&gt; 10 m</td>
<td>&gt; 10 m</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Faulting and Fracturing</td>
<td>Limited to moderate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Seismicity</td>
<td>Limited-moderate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Hydrocarbon resource</td>
<td>Absent or small</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Site accessibility</td>
<td>Road, well head</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Socio-environ. concerns</td>
<td>Protected areas</td>
<td>UNESCO</td>
<td>NPA</td>
<td></td>
</tr>
</tbody>
</table>

**CO₂ storage in the Swiss Molasse Basin**

**Preliminary deductions?**

**Structure/Trap**  **Porosity**  **Permeability**  **Thickness**

**The way forward?**

Further understanding of **fracture and karst porosity and permeability** in key reservoir and aquifers – core study & outcrop analogues

from Elegancy presentation by Ovie Emmanuel Eruteya and Andrea Moscariello, 2020
Where (else) to do CCS with CPG in Switzerland?

GIS overlay for CO₂ emitters, geo-energy developments, deep geological repositories, population centres, surface infrastructure, ..... and sectors for CCS in Switzerland

from Elegancy presentation by Ovie Emmanuel Eruteya and Andrea Moscariello, 2020
Where (else) to do CCS with CPG in Switzerland?

To answer, need to do much more geoscience and other research in Switzerland on site-specific factors, including:

- **Reservoir characterization**, particularly regarding:
  - dual/multiple porosity/permeability systems (with fractures, karst, etc.)
  - transmissivity
  - relative permeability, capillary pressure
  - pore-fluid pressure
  - formation temperature
  - usefulness for CPG Energy Storage
  - Geometry (3D seismic, MT, active EM, etc.)

- **CO2 source and sink as well as transport (SimCCS?)**:
  - expected CO2 capture rate
  - CO2 source location in relationship to reservoir → CO2 transport (CO2 pipeline, train/truck)
  - CO2 sink locations (including Northern Lights)
  - Intermittent storage of CO2 in CH

- **Power grid**
  - Amount and type (dispatchable, etc.) power needed
  - Power grid proximity to potential CPG site
  - Proximity of intermittent power sources (wind/solar) for CPGES (Earth Battery)

- **Economics factors**:
  - taxes
  - Feed-in tariffs

Hefny et al., *International J. of Greenhouse Gas Control* 2020
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! An example (1/6)

Fig. 1: Schematic diagram of key processes of CO2 sequestration in a saline aquifer.

Fig. 15: [A] Depth to the top of the Nubian Sandstone sequence in the Gulf of Suez (Egypt). The map is constructed based on the interpretation of aeromagnetic and geological data by Mesheref et al. (1976) for basement rocks and modified after Farhoud (2009). [B] The distribution of in-situ CO2 densities across the Gulf of Suez.

Hefny et al., *International J. of Greenhouse Gas Control* 2020
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! Examples.

Fig. 3: Pore throat diameters in Nubian Sandstone

Fig. 4: Pore size distribution in Nubian Sandstone

Fig. 5: 3D view of the pore-network in Nubian Sandstone

Fig. 6: Quantification of the porosity in Nubian Sandstone

Hefny et al., *International J. of Greenhouse Gas Control* 2020
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! Examples.

Fig. 7: Wetting-phase (water in gray) distribution in a pore element

Table 3: Average values of hydraulic and capillary properties for Nubian Sandstone, determined by lab experiments and pore-network simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nubian Sandstone</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porosity; $\phi_{in}$</td>
<td>Laboratory</td>
<td>0.269</td>
</tr>
<tr>
<td></td>
<td>SRXFM</td>
<td>0.254</td>
</tr>
<tr>
<td>Permeability; $k_{eff}$</td>
<td>Laboratory</td>
<td>$1.70 \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>PNM</td>
<td>$2.00 \times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>LBM</td>
<td>$2.57 \times 10^{-12}$</td>
</tr>
<tr>
<td>Capillarity properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entry Pressure; $P_e$</td>
<td>MIP (Hg - air)</td>
<td>2534.76</td>
</tr>
<tr>
<td></td>
<td>MIP (Levett-Jkol)</td>
<td>$3.91 \times 10^{-8}$</td>
</tr>
<tr>
<td></td>
<td>PNM</td>
<td>$3.59 \times 10^{-8}$</td>
</tr>
<tr>
<td>Irreducible Saturation; $S_{irr}$</td>
<td>MIP (Levett-Jkol)</td>
<td>0.089</td>
</tr>
<tr>
<td></td>
<td>PNM</td>
<td>0.099</td>
</tr>
<tr>
<td>van Genuchten parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_1$</td>
<td>0.466</td>
<td></td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>$3.72 \times 10^{-3}$</td>
<td>[MPa$^{-1}$]</td>
</tr>
<tr>
<td>$m_2$</td>
<td>0.580</td>
<td></td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>$1.85 \times 10^{-3}$</td>
<td>[MPa$^{-1}$]</td>
</tr>
</tbody>
</table>

Fig. 8: PN model network calibration

Fig. 9: Simulations of CO2 (red) and brine (blue) saturation distributions
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! Examples.

**Fig. 11:** Comparison between the predicted and the experiment-based relative permeability curves for brine vs. CO2

![Fig. 11](image)

**Table 4:** Sensitivity analysis statistics of the impact of the wettability changes on the fluid displacement and trapping mechanisms after a complete cycle of primary drainage, main imbibition quasi-static pore-network modeling for Nubian Sandstone.

<table>
<thead>
<tr>
<th>Fluid displacement &amp; trapping</th>
<th>Advancing contact angle ($\theta_a$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta_a = 0^\circ$</td>
</tr>
<tr>
<td>Drainage</td>
<td>2626</td>
</tr>
<tr>
<td>Piston-like advance in pore body</td>
<td>(53%)</td>
</tr>
<tr>
<td>Piston-like advance in pore throat</td>
<td>7519</td>
</tr>
<tr>
<td>Imbibition</td>
<td>3522</td>
</tr>
<tr>
<td>Cooperative</td>
<td>1386</td>
</tr>
<tr>
<td>Co-operative pore-body filling</td>
<td>(28%)</td>
</tr>
<tr>
<td>Snap-off event</td>
<td>39</td>
</tr>
</tbody>
</table>

**Fig. 12:** Predicted residual trapping of CO2 in Nubian Sandstone, compared to Berea Sandstone.

![Fig. 12](image)

**Fig. 13:** Comparison between the uid-displacement mechanisms in the pore-network model of the Nubian Sandstone as a function of wettability and minimum aspect ratio.

![Fig. 13](image)
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! Examples.

Selected Conclusions

- This investigation included (1) constructing a realistic 3D pore network model that represents the characteristic features of Nubian Sandstone, (2) developing a quasi-static pore-network numerical simulator that mimics in-situ conditions that are similar to those prevailing at a CO2-storage site, at the trailing edge of the CO2 plume, and (3) predicting the two-phase flow characteristics.

- Two-phase constitutive relationships, including the capillary pressure and relative permeability curves, were computed for water-wet rocks at a low capillary number. We determine a Land trapping coefficient of $C = 1.2$ for the Nubian sandstone sample. These relationships can be employed in field-scale numerical models to estimate the extent of CO2-plume migration, at a representative geological scale.

- The estimated capillary-trapping curves for Nubian Sandstone are in good agreement with those observed experimentally for similar rocks. This confirms, that residual trapping due to hysteresis can be a key mechanism for long-term CO2 storage in Nubian Sandstone.

- The pore-network model developed in this work improves our understanding of the different trapping mechanisms in Nubian Sandstone, as they pertain to CCS- and CPG-related applications.

Table 5: The physical parameters used to calculate the storage capacity of Nubian Sandstone in Gulf of Suez basin (Egypt).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>0.4</td>
<td>current study</td>
</tr>
<tr>
<td>$z_f$</td>
<td>1 - 5</td>
<td>Gupta et al. (2006)</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>647.7</td>
<td>Span and Wagner (1996)</td>
</tr>
<tr>
<td>$\rho_o$</td>
<td>999.4</td>
<td>Driessen (2007)</td>
</tr>
<tr>
<td>$C_o$</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>$k_o$</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>$C_w$</td>
<td>0.45</td>
<td>Kapp et al. (2009)</td>
</tr>
<tr>
<td>$C_i$</td>
<td>0.19 - 0.63</td>
<td>van der Meer (1995)</td>
</tr>
<tr>
<td>$C_{i-I}$</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$S_{sat}$</td>
<td>0.5 - 1.7</td>
<td></td>
</tr>
<tr>
<td>Surface area [m²]</td>
<td>9,990</td>
<td></td>
</tr>
<tr>
<td>$V_{sat}$ [m³]</td>
<td>4,477.5</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 14: Volume fraction (saturation) of the trapped nonwetting phase (CO2) in the pore network

Fig. 15: [A] Depth to the top of the Nubian Sandstone sequence in the Gulf of Suez (Egypt). The map is constructed based on the interpretation of aeromagnetic and geological data by Mesheref et al. (1976) for basement rocks and modified after Farhoud (2009). [B] The distribution of in-situ CO2 densities across the Gulf of Suez.
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! Examples.

![Image](image.png)

**Figure 3.3:** [A] Interpreted geo-seismic faults of NE on seismic crossline (No. 328) from the Ras Budran PSDM 3D survey and borehole data. The seismic profile was selected to demonstrate the structural framework of the study area. [B] Three-dimensional visualization of 72 fault planes which are robustly extracted, separated, and labeled using the integration of seismic data and well logging. [C] 3D view of the final structural and geological model for Paleozoic-Mesozoic formations. [D] Spyder map showing the trajectory of the boreholes that reaching the top of Nubian III blocks. The reddish dash lines represent the lease concession boundary. Its location is referred to Figure 3.1B.
Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples

**Aquistore in Canada**

320 ktons CO₂ present in the subsurface

- densely monitored
- open-minded management

- **Part 1:** Theoretical Approach
- **Part 2:** CO₂ Injection Model
- **Part 3:** CO₂ Circulation Model

- For two sets of \(k_{rel}\) and four different \(k_{abs}\)

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**Figure 8:** Flowchart of the workflow used in the MSc thesis of Kevin Hau (2020).
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! Examples

Aquistore in Canada

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model size</td>
<td>156 m x 96 m x 12 m</td>
</tr>
<tr>
<td>Porosity</td>
<td>7.3 %</td>
</tr>
<tr>
<td>Eff. permeability:</td>
<td></td>
</tr>
<tr>
<td>- IJ-direction</td>
<td>23.8 mD</td>
</tr>
<tr>
<td>- K-direction</td>
<td>2.38 mD</td>
</tr>
<tr>
<td>Components</td>
<td>Brine, CO₂ and CH₄ (trace comp.)</td>
</tr>
<tr>
<td>Salinity</td>
<td>300 000 ppm</td>
</tr>
<tr>
<td>Reservoir Temperature</td>
<td>120°C</td>
</tr>
<tr>
<td>Reservoir Pressure</td>
<td>32.5 MPa</td>
</tr>
<tr>
<td>Equation of state</td>
<td>Peng-Robinson</td>
</tr>
<tr>
<td>Injection well (Max. BHP)</td>
<td>42.5 MPa</td>
</tr>
<tr>
<td>Initial conditions</td>
<td>Hydrostatic equilibrium, no heat flow, fully saturated reservoir</td>
</tr>
</tbody>
</table>

Overview over some of the model array parameters.

Comparison of field data with obtained simulation data (gas volume at surface conditions).
Geothermal energy extraction by circulation of supercritical CO\(_2\)

Geothermal power:

\[
W_{\text{geoth}} = \frac{c_p \rho_{\text{fluid}}}{\mu} \frac{r^4 \Delta T \Delta P}{8\pi l}
\]

<table>
<thead>
<tr>
<th></th>
<th>sCO(_2)</th>
<th>H(_2)O</th>
<th>brine</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_p)</td>
<td>[J/K]</td>
<td>1920</td>
<td>4170</td>
</tr>
<tr>
<td>(\rho)</td>
<td>[kg/m(^3)]</td>
<td>620</td>
<td>960</td>
</tr>
<tr>
<td>(\mu)</td>
<td>[Pa s]</td>
<td>(5 \cdot 10^{-5})</td>
<td>(2.4 \cdot 10^{-4})</td>
</tr>
<tr>
<td>(\frac{c_p \rho_{\text{fluid}}}{\mu})</td>
<td>[kJ/kg]</td>
<td>(2.4 \cdot 10^7)</td>
<td>(1.7 \cdot 10^7)</td>
</tr>
</tbody>
</table>

\(T = 120^\circ \text{C} \text{ and } P = 32.5 \text{ MPa}\)

Phase properties of supercritical CO\(_2\), brine (sal = 300 000 ppm) and pure water (Bell et al. 2014, Ezekiel et al. 2020).

Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples

Aquistore in Canada

Simplified phase diagram of CO\(_2\) (modified from Pruess, 2006).

Concept of a direct CO\(_2\) Plume geothermal system (Adams et al., 2015).
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! Examples

Aquistore in Canada

Based on Buckley and Leverett (1942):

- **Relative Permeability**: 
  \[ k_r = \frac{k_{eff}}{k_{abs}} \]
- **Mobility of a phase \( \alpha \)**: 
  \[ \lambda_\alpha = \frac{k_{r\alpha}}{\mu_\alpha} \]
- **Fractional flow of a phase \( \alpha \)**: 
  \[ f_\alpha(S_\alpha) = \frac{\lambda_\alpha}{\lambda_\alpha + \lambda_\beta} \]

![Conceptual diagram showing the effects of CO₂ saturation and mass flow rate on the production stream.](image)

Both relative permeability data sets used in this study.
Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples

Aquistore in Canada

**Figure 12a:** Model gas distribution around the breakthrough time ($k_{rel} = \text{Bennion et al. 2005}$).

**Figure 12b:** Model gas distribution around the breakthrough time ($k_{rel} = \text{Guyant et al. 2015}$).

**Figure 13:** Model gas saturation over time for both relative permeability data sets.
Where (else) to do CCS with CPG in Switzerland?
What needs to be done! Examples

Aquistore in Canada

**Figure 16:** Production stream flow behaviour, simulated for different absolute permeabilities, based on the relative permeability data from Guyant et al. 2015.
Conclusions

To evaluate Switzerland's CCS and CPG potential properly, a lot more needs to be done, including:

- Reservoir characterization, particularly regarding:
  - dual/multiple porosity/permeability systems (with fractures, karst, etc.)
  - transmissivity
  - relative permeability, capillary pressure
  - pore-fluid pressure
  - formation temperature
  - usefulness for CPG Energy Storage
  - Geometry (3D seismic, MT, active EM, etc.)

- CO2 source and sink as well as transport (SimCCS)?:
  - expected CO2 capture rate
  - CO2 source location in relationship to reservoir \( \rightarrow \) CO2 transport (CO2 pipeline, train/truck)
  - CO2 sink locations (including Northern Lights)
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  - Amount and type (dispatchable, etc.) power needed
  - Power grid proximity to potential CPG site
  - Proximity of intermittent power sources (wind/solar) for CPGES (Earth Battery)

- Economics factors:
  - taxes
  - Feed-in tariffs

“We barely scratched the surface regarding CCS+CPG in Switzerland…”
(approx. Andrea Moscariello in a recent Elegancy meeting)

But some of this “surface scratching” was presented here and is presented next…

Selected Saar publications and patents on CPG and CPG Energy Storage (CPGES or Earth Battery):

Saar et al., *Patents* 2012
Adams et al., *Energy* 2014
Adams et al., *Applied Energy* 2014
Garapati et al., *Geothermics* 2015
Fleming et al., *Stanford Geothermal Workshop* 2018
Saar and Adams, *Patent Pending* 2018
Ezekiel et al., *Applied Energy* 2020
Fleming et al., *Geothermics* 2020
Garapati et al., *J. of CO₂ Utilization* 2020
Hefny et al., *International J. of Greenhouse Gas Control* 2020
The Geothermal Energy and Geofluids (GEG) Group
More than just CPG

Current GEG Projects

Reactive transport
Analyzing spatial scaling effects in mineral reaction rates in porous media with a hybrid numerical model
Simultaneous visualization of fluid flow and mineral precipitation in fractured porous media
A new paradigm in imaging and characterizing flow structures and solute transport in three dimensions
Evolution of permeability and porosity due to mineral precipitation in natural and/or artificial granite fractures
Software Development: Reactoro, a unified framework for modeling chemically reactive systems

Solute transport in 3D fractured reservoirs
Evaluation of DNA-labeled silica nanoparticles for use as hydrogeologic tracers: field study and column experiments
Tracer-based characterization of stimulation enhanced pore volume and application of novel DNA nanotracers in fractured rock
Chemical stimulation of geothermal reservoirs using reactive flow-through system

MT and Heatflow
Magnetotelluric investigation of active rifting and the formation of geothermal energy resources in Ethiopia (MIRIGE)
Development of a geoscientific framework for geothermal exploration and energy utilization in Mongolia
Magnetotelluric Investigation of the Northern Swiss Heat Flow Anomaly
Pilot Study Geothermal Energy Aargau
Unmanned Aerial Vehicle (UAV) based geomagnetic mapping and thermal imaging

Poroelasticity
Hydro-mechanical processes in natural and 3D printed fractures
Thermo-Hydro-Mechanical (THM) Processes in Aquifer Thermal Energy Storage (ATES)

Drilling
Modeling thermal spallation drilling
Modeling the Hydraulic Fracture Stimulation performed for Reservoir Permeability Enhancement at the Grimsel Test Site, Switzerland
Plasma Pulse Geo-Drilling (PPGD)
Combined Thermo-Mechanical Drilling (CTMD) technology to facilitate deep geo-resource utilization

CPG & Earth Battery
Assessment and optimization of carbon storage and combined EGR-CPG development from high-temperature natural gas reservoirs
Numerical Modeling of CO2-Plume Geothermal (CPG) Systems
Auxiliary heating of low- to moderate-temperature geothermal resources to boost electricity production
2020 Publications with GEG authors (underlined)


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  - Geometry (3D seismic, MT, active EM, etc.)

- CO2 source and sink as well as transport (SimCCS?):
  - expected CO2 capture rate
  - CO2 source location in relationship to reservoir → CO2 transport (CO2 pipeline, train/truck)
  - CO2 sink locations (including Northern Lights)
  - Intermittent storage of CO2 in CH

- Power grid
  - Amount and type (dispatchable, etc.) power needed
  - Power grid proximity to potential CPG site
  - Proximity of intermittent power sources (wind/solar) for CPGES (Earth Battery)

- Economics factors:
  - taxes
  - Feed-in tariffs

“We barely scratched the surface regarding CCS+CPG in Switzerland…”
(approx. Andrea Moscariello in a recent Elegancy meeting)

But some of this “surface scratching” was presented here and is presented next…

Selected Saar publications and patents on CPG and CPG Energy Storage (CPGES or Earth Battery):

- Randolph & Saar, Geophysical Research Letters 2011
- Saar et al., Patents 2012
- Adams et al., Energy 2014
- Adams et al., Applied Energy 2015
- Garapati et al., Geothermics 2015
- Fleming et al., Stanford Geothermal Workshop 2018
- Saar and Adams, Patent Pending 2018
- Ezekiel et al., Applied Energy 2020
- Fleming et al., Geothermics 2020
- Garapati et al., J. of CO2 Utilization 2020
- Hefny et al., International J. of Greenhouse Gas Control 2020