
*Karsten Pruess*

Earth Sciences Division
Lawrence Berkeley National Laboratory

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U.S. Geothermal Resources are Huge

Heat content in subsurface rocks to 6 km depth, relative to ambient temperature (Dave Blackwell, SMU)

- \( T > 200 \, ^\circ C \): 296,000 EJ*
- \( T > 125 \, ^\circ C \): 2,410,000 EJ

(* EJ = ExaJoule; 1 EJ = 10^{18} J)

(Map c/o INL Geothermal Program)


- total primary energy consumption: \( \approx 100 \) EJ
- total U.S. geothermal energy use: 0.31 EJ (\( \approx 0.3 \, \% \) of primary)
Why is Geothermal Energy Contribution so Small?

- Geothermal energy extraction is currently limited to hydrothermal systems (the “low-hanging fruit”).
- There is a vast store of geothermal heat that is difficult to recover (hot rocks lacking fluid and permeability).
- How can the essentially inexhaustible heat in deep geologic formations be tapped and transferred to the land surface for human use?

Source: Geothermal Education Office (GEO)
http://www.geothermal.marin.org/
Enhanced Geothermal Systems (EGS)

- Artificially create permeability through hydraulic and chemical stimulation.
- Transfer heat to the land surface by circulating water through a system of injection and production boreholes.
- Experimental projects in U.S., U.K., France, Japan, Australia, Sweden, Switzerland, Germany.
- EGS is currently not economically viable; the chief obstacles are:
  - dissolution and precipitation of rock minerals, that may cause anything from short-circuiting flows to formation plugging
  - large “parasitic” power requirements for keeping water circulating
  - water losses from the circulation system
  - inadequate reservoir size - heat transfer limitations
  - high cost of deep boreholes (≈ 5 km)
How about using \( \text{CO}_2 \) as Heat Transmission Fluid?

<table>
<thead>
<tr>
<th>property</th>
<th>( \text{CO}_2 )</th>
<th>water</th>
</tr>
</thead>
<tbody>
<tr>
<td>chemistry</td>
<td><strong>poor solvent for rock minerals</strong></td>
<td>powerful solvent for rock minerals: lots of potential for dissolution and precipitation</td>
</tr>
<tr>
<td>fluid circulation in wellbores</td>
<td><strong>highly compressible and larger expansivity</strong></td>
<td>low compressibility, modest expansivity</td>
</tr>
<tr>
<td></td>
<td>( \implies \text{more buoyancy, lower parasitic power consumption} )</td>
<td>( \implies \text{less buoyancy} )</td>
</tr>
<tr>
<td>ease of flow in reservoir</td>
<td><strong>lower viscosity, lower density</strong></td>
<td>higher viscosity, <strong>higher density</strong></td>
</tr>
<tr>
<td>heat transmission</td>
<td>smaller specific heat</td>
<td>larger specific heat</td>
</tr>
<tr>
<td>fluid losses</td>
<td><strong>earn credits for storing greenhouse gases</strong></td>
<td>costly</td>
</tr>
</tbody>
</table>

Favorable properties are shown **bold-faced**.
EGS-CO$_2$ Issues

- Effectiveness of CO$_2$ as a heat transfer medium.
- Other processes induced by CO$_2$, that may affect feasibility and sustainability of EGS with CO$_2$ (chemical reactions, corrosion).
- Can we make an EGS-CO$_2$ reservoir? (Circulate CO$_2$ to remove the water.)
- Energy conversion system (binary plant w/ heat exchanger; directly using CO$_2$ on the turbines)
- Economics.
- Fluid lost = fluid stored?
General Makeup of a CO₂-Based EGS Reservoir

Zone 1
Central zone and core of EGS system, where most of the fluid circulation and heat extraction is taking place. This zone contains supercritical CO₂; all water has been removed by dissolution into the flowing CO₂.

Zone 2
An intermediate region with weaker fluid circulation and heat extraction, which contains a two-phase mixture of CO₂ and water.

Zone 3
The outer region affected by EGS activities. The fluid is a single aqueous phase with dissolved CO₂.
Comparing Operating Fluids for EGS: CO$_2$ vs. Water

- monitor mass flow, heat extraction rates

- fractured reservoir
  - $T_{\text{res}} = 200$ °C
  - $P_{\text{res}} = 100 - 500$ bar

- pore fluid
  - all CO$_2$
  - all water

- injection
  - $P_{\text{res}+10 \text{ bar}}$

- production
  - $P_{\text{res}-10 \text{ bar}}$
Reference Case

\[ T_{res} = 200 \, ^\circ C, \quad P_{res} = 500 \, \text{bar}, \quad T_{inj} = 20 \, ^\circ C \]

Heat extraction

Mass flow
Simulation Results for Different Reservoir Pressures at $T = 200 \, ^\circ\text{C}$

- Heat extraction rate (MW) vs. time (years)
- Mass flow rate (Kg/s) vs. time (years)
Fluid Mobility
(density:viscosity; units of $10^6$ s/m²)

CO₂

water
Injecting CO$_2$ into an Aqueous System

- At early time ($\leq 0.1$ year), produce single-phase water
- This is followed by a two-phase water-CO$_2$ mixture (0.1 - 2.5 yr)
- Total production rate during two-phase period is low due to phase interference
- Subsequently produce a single supercritical CO$_2$-rich phase with dissolved water
Rate and Composition of Produced CO₂

- Water is removed from fracture network fairly rapidly (about 4.4 % remaining after 5 years)
- The low-permeability rock matrix provides a long-term source of water, with almost half of initial inventory remaining after 36.5 years
Wellbore Flow: CO$_2$ vs. Water

Pressure difference between production and injection well

CO$_2$: $288.1 - 57.4 = 230.7$ bar

Water: $118.6 - 57.4 = 61.2$ bar

CO$_2$ generates much larger pressures in production well, facilitating fluid circulation.
CO₂ Storage Capacity

- Need a mass flow of approximately 20 tons of CO₂ per second, per GW electric power capacity.
- Expect a fluid loss rate of order 5%, or 1 ton per second of CO₂ per GW of installed EGS capacity.
- This is equivalent to CO₂ emissions from 3 GW of coal-fired power generation.
- The MIT report (2006) projects 100 GW of EGS electric power by 2050.
- 100 GW of EGS with CO₂ would store 3.2 Gt/yr of CO₂, approximately 40% of total current U.S. emissions.

➢ CO₂ lost = CO₂ stored?
Power Generation from CO$_2$-Based EGS

- One option is **binary conversion** technology, using similar equipment as water-based systems.
- Alternatively, it may be possible to **directly feed the produced CO$_2$** to the turbines. This may be possible because supercritical CO$_2$ without admixed liquid water is not corrosive to metals.
- Direct expansion of CO$_2$ in the turbines would avoid otherwise inevitable and irreversible heat losses in a heat exchanger.
- However, the produced **CO$_2$ stream** will need to be **dried** before entering the turbines, to avoid condensation of liquid water during decompression and cooling.
- Clarify the relative merits and thermodynamic efficiencies of different options for power generation.
- Need to **balance and optimize tradeoffs** between power generation and CO$_2$ storage.
Path Forward*

- Fluid-rock reaction experiments with supercritical CO$_2$
- Laboratory flow experiments for water-CO$_2$ mixtures and pure anhydrous CO$_2$
- Modeling of fluid flow, heat transfer and rock-fluid interactions (chemical/mechanical)
- Design studies for a field pilot test of EGS with CO$_2$

*cooperation with BRGM - French geological survey
Concluding Remarks

• Water-based enhanced geothermal systems (EGS) face difficult hurdles to (1) achieve adequate heat extraction rates, and (2) maintain injectivity and heat extraction performance in the face of strong rock-fluid interactions.

• CO₂ has attractive properties as a heat transmission fluid for EGS.
  - **Heat extraction** rates when using CO₂ are estimated to be approximately 50% larger than for water.
  - CO₂ is very favorable in terms of wellbore hydraulics.
  - Unavoidable **fluid losses** are costly for water, but could earn greenhouse gas storage credits when using CO₂.

• The fluid produced from an EGS operated with CO₂ will change from initially water (≈ 1 month), to a two-phase aqueous-CO₂ mixture (a few years), to scCO₂ with dissolved water of order 0.1 wt.-%.

• Use of CO₂ as heat transmission fluid for EGS looks promising and deserves more study (geochemistry/geomechanics!).

• We are aiming to develop the scientific basis for a field demonstration.

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# Reactivity of Rocks for scCO₂

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Characteristics</th>
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<tbody>
<tr>
<td>granite</td>
<td>- generally high in SiO₂, low in carbonates</td>
</tr>
<tr>
<td></td>
<td>- limited surface area and reactivity of mineral grains</td>
</tr>
<tr>
<td>sandstone</td>
<td>- may have carbonate cements</td>
</tr>
<tr>
<td>graywacke</td>
<td>- relatively low in carbonates</td>
</tr>
<tr>
<td>ignimbrite</td>
<td>- welded tuffs, lithophysal cavities</td>
</tr>
<tr>
<td>felsite</td>
<td></td>
</tr>
<tr>
<td>non-welded tuff</td>
<td>- more reactive</td>
</tr>
<tr>
<td></td>
<td>- zeolitized by water</td>
</tr>
<tr>
<td>marine sediments</td>
<td>- can be high in carbonates</td>
</tr>
<tr>
<td>basalt</td>
<td>- amorphous, highly reactive</td>
</tr>
</tbody>
</table>