Grid Scale Energy Storage using CO_2 in Sedimentary Basins: The Cost of Power Flexibility

Benjamin M. Adams[1,2], Mark R. Fleming[3], Jeffrey M. Bielicki[4,5], Jil Hansper[6], Stefan Glos[6], Marcel Langer[6], Michael Wechsung[6], and Martin O. Saar*[1,2]

[1] Geothermal Energy and Geofluids Group, Dept of Earth Sciences, ETH Zürich, Switzerland

[2] CO_2 POWER, Zürich, Switzerland

[3] Dept. of Mechanical Engineering, University of Minnesota, U.S.A.

[4] Dept. of Civil, Environmental, and Geodetic Engineering, The Ohio State University, U.S.A.

[5] John Glenn College of Public Affairs, The Ohio State University, U.S.A.

[6] Siemens AG, Power and Gas Division, Germany

*saarm@ethz.ch

Keywords: CO_2 Plume Geothermal, CPG, Sedimentary Geothermal, Grid-scale Energy Storage, CO_2 Plume Geothermal Energy Storage, CPGES, Flexible Generation

ABSTRACT

CO_2 Plume Geothermal (CPG) is a CO_2-based geothermal energy technology that generates electricity typically using a sedimentary reservoir. We have expanded this technology into a CO_2 Plume Geothermal Energy Storage (CPGES) system by adding a second, shallow reservoir. The CPGES system can separate and time-shift its generation and parasitic powers, allowing for energy storage. Energy storage may be done for periods ranging from hours to months.

We simulate here several permutations of CPGES systems for a single day, modifying the generating period and mass flow rate. We find a trade-off between energy generation and power—CPGES tends to provide higher power, but less energy than CPG.

Additionally, we find that large CO_2 injection flow rates into the deep reservoir cause large inefficiencies. Thus, we have devised a combined CPG and CPGES system, CPG+CPGES, which offers flexibility in operation—it can operate either as a continuous power generator (100% CPG) or completely as energy storage (100% CPGES). We find that CPG+CPGES can generate more power and energy than a 100% CPGES system for some configurations.

1. INTRODUCTION

CO_2 Plume Geothermal (CPG) is a CO_2-based geothermal energy utilization system which extracts heat from a deep, naturally permeable, sedimentary reservoir. CO_2 has been shown to be a preferred geothermal working fluid due to its low viscosity, which greatly reduces reservoir pressure losses, and due to its compressibility, which creates natural circulation currents, reducing the need for pumps (Brown, 2000; Pruess, 2008; Randolph and Saar, 2011; Adams et al., 2014; Adams et al., 2015). Additionally, CPG has been shown to generate more power than Organic Rankine Cycles (ORCs) for moderate temperatures (i.e. a 35 °C/km geothermal temperature gradient) and permeabilities ($10 \leq mD \leq 100$) (Adams et al., 2015).

To meet the emission targets to mitigate climate change, there will be an increase in low-carbon electric generation, such as wind and solar. Wind and solar generation is inherently variable—power is only generated when the wind blows or the sun shines. As wind and solar grid penetration increases, conventional baseload power generation will be supplanted with new variable generators. This will cause grid instability and, thus, a premium will be placed on on-demand (dispatchable), fast-acting generators that can come online the moment wind and solar generation declines (Bird et al., 2013; Koohi-Kamali et al, 2013).

In contrast to most renewables, geothermal energy can be operated as both a baseload power supply and as dispatchable power. The geothermal resource is always available and thus geothermal power may be brought online to make up gaps between power generation and demand. Few other renewable generators are dispatchable, one example being hydro-electric generation; however, hydro-electricity has resource constraints which limit its generation flexibility and environmental concerns limit future hydro-electric development.

Energy storage is an alternative to dispatchable power generation. With energy storage, excess power can be removed from the grid and re-dispatched later when there is power demand. Thus, energy storage, as a technology, complements variable renewable generation because energy storage can time-shift such intermittent power generation to meet demand.

Here, we combine energy storage with geothermal power generation into a CO_2 Plume Geothermal Energy Storage (CPGES) system. CPGES has the benefit of being a dispatchable renewable generator that can additionally store electricity from other renewable, but intermittent power generators (e.g. wind and solar) and sell it back to the power grid later when required. CPGES can store electricity for periods of hours to months (Fleming et al., 2018)

CPGES is created by adding a second, shallow reservoir to a CPG system (Figure 1). This allows produced CO_2 to be temporarily stored before returning it to the subsurface. Thus the components which generate electricity (i.e. the red components in Figure 1) can be time-separated from those which consume electricity (i.e. the blue components in Figure 1), providing energy storage.

Other geology-based energy storage systems exist, in different configurations, but few directly use CO_2 to store energy in a deep reservoir. The earth battery of Buscheck et al. (2016) uses CO_2 in a deep reservoir, but primarily as a cushion gas to stabilize reservoir brine pressures between intermittent brine injection and production phases. Alternatively, the design by Liu et al. (2016) requires fossil-generation. In our case, CPGES stores energy by way of a direct CO_2 power cycle that is carbon neutral.

This paper summarizes the current state of progress in the simulation of CPGES operation. We test the CPGES system operation for four different generation periods and different system flow rates to determine the change in power generation, storage power, and daily energy generation. Lastly, we combine CPG and CPGES systems to create a flexible system which both can generate baseload electricity and provide energy storage, depending on power grid demands.

2. METHODOLOGY

The CO_2 Plume Geothermal (CPG) system is shown on the left in Figure 1. The modelling assumptions and methods are detailed in our publications (Adams et al., 2015; Fleming et al., 2018, Fleming et al., in preparation). The system parameters for this test case are shown in Table 1.

Table 1: System Parameters.

Parameter	Value
Deep Reservoir Depth	2500 m
Deep Reservoir Temperature	102.5 °C
Deep Reservoir Pressure	25 MPa
Shallow Reservoir Depth	1500 m
Shallow Reservoir Pressure	15 MPa
Geologic Temperature Gradient	35 °C/km
Reservoir Permeability	50 mD
Reservoir Thickness	300 m
Surface Temperature	15 °C
Well Diameter	0.41 m
Turbine Isentropic Efficiency	78%
Pump Isentropic Efficiency	90%

CO_2 is stored beneath an impermeable caprock in a sedimentary reservoir (State 1). Hot CO_2 is produced up the production well to the surface (State 2). CO_2 is expanded in a turbine, producing electricity (State 3). The turbine back pressure is the saturation pressure of CO_2 at 22 °C (sub-critical). The CO_2 is condensed in a closed cooling tower to liquid (State 4). Often, the net power output of the CPG system may be increased through additional surface pumping (State 5); however, this is not necessary. CO_2 is reinjected at the wellhead and finally into the reservoir (State 6).

The density of CO_2 is very sensitive to the temperature change. For instance, the injection well density can be a factor of two greater than the production well density. As the wellbore pressure change is linearly dependent on fluid density, the production wellhead pressure would be a factor of two greater than the injection wellhead pressure, without considering pumping. This density change drives the thermosiphon and provides a pressure difference to operate a turbine, which is a fundamental advantage of CO_2-based over water-based geothermal systems (Adams et al., 2014).

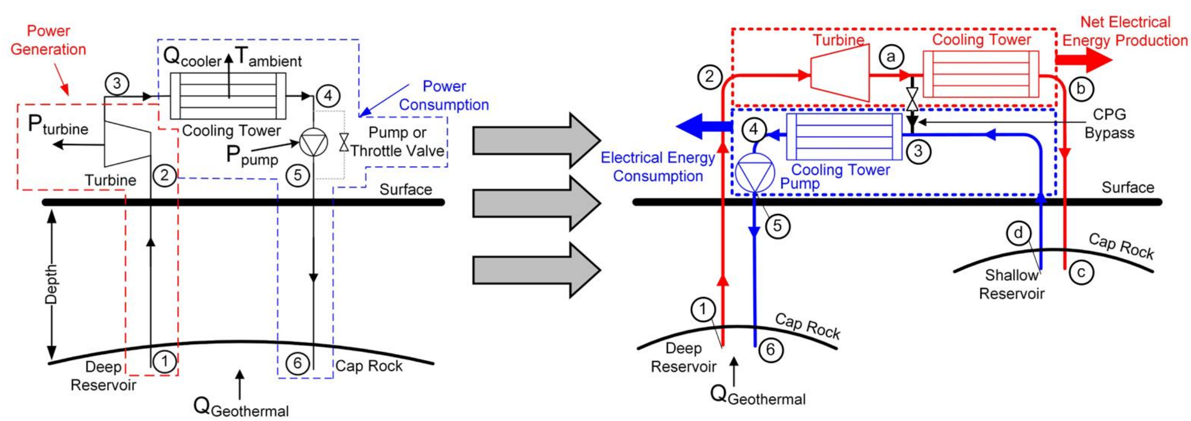

Figure 1: A CO_2 Plume Geothermal (CPG) system (left) converted into a CO_2 Plume Geothermal Energy Storage (CPGES) system (right) by adding a second, shallow reservoir.

The addition of the second reservoir is shown on the right in Figure 1. The pressure at State (a) is fixed at 7.5 MPa, which is supercritical to avoid the dynamics of two-phase flow within the injection wellbore. The critical pressure of CO_2 is 7.4 MPa.

In order to obtain the necessary downhole pressure at State (c) to inject into the shallow reservoir, the CO_2 density is increased through a cooling tower (State b). Cooling CO_2 to increase the downhole pressure has been found to be a more efficient method than pumping (Adams et al., 2013). Thus, much of the cooling load is time-shifted from the power generation to the energy storage operation, but not all.

When the energy storage period begins, CO_2 is produced from the shallow reservoir (State d) at the same temperature, but decreased pressure, of State (c). CO_2 arrives at the surface (State 3). It is then condensed (State 3 to 4), pumped (State 4 to 5), and injected identically to the CPG system.

2.1 Reservoir and Power Plant Models

The reservoirs are modelled using TOUGH2/ECO2N (Pruess, 2005). The reservoirs are 2D axisymmetric, initially filled with 20% NaCl, and are not compartmentalized, extending horizontally to a distance of 100 km. There is no fluid flow through the boundaries. Heat flow is conducted across the horizontal boundaries from the surrounding rock using a semi-analytical heat transfer solution (Pruess, 2005).

The reservoirs are primed with CO_2 until the production fluid is greater than 94% CO_2. The deep reservoir has a horizontal, circular production well just below the caprock at a radius of 707 m and a horizontal, circular injection well at the base of the reservoir at a radius of 200 m. The shallow reservoir has a single horizontal "huff and puff" well, used for both injection and production, at a radius of 400 m.

The vertical well segments and surface equipment are modelled using Engineering Equation Solver (EES) (Klein & Alvarado, 2002). Four vertical production wells connect the horizontal production well in the deep reservoir with the surface and one vertical injection well connects the horizontal injection well in the deep reservoir with the surface. The shallow reservoir has two vertical injection and production wells which connect the horizontal well with the surface.

2.2 Simulation Metrics

Four different operational cycles, each 24 hours in duration, were used, described in Table 2.

Table 2: Operational Cycles

Name	Generation Period	Storage Period
16h-8h	16 hours	8 hours
12h-12h	12 hours	12 hours
8h-16h	8 hours	16 hours
4h-20h	4 hours	20 hours

Daily CO_2 circulation is the total CO_2 mass produced from the deep reservoir in a 24-hour period. The generation and storage mass flow rates are the total mass of circulated CO_2 divided by their respective operation durations.

The power generated by the CPGES system is the turbine power less parasitic cooling loads during the generation period. The power stored is the sum of the parasitic pumping and cooling loads during the storage period. The CPG power is the turbine power less the pumping and parasitic cooling power. The net daily energy is the time integral of the generation power during the generation period less the time integral of the storage power during the storage period.

3. PRELIMINARY RESULTS

The power generated and stored by the CPGES system is shown in Figure 2. The generation power increases at low generation mass flow rates as the turbine mass flow rate increases. However, at higher mass flow rates, the pressure losses in the production well decrease the pressure difference across the turbine and eventually the generation power reaches a maximum. The generation powers for shorter generation periods (e.g. 4h-20h) tend to be greater as they have higher generation mass flow rates.

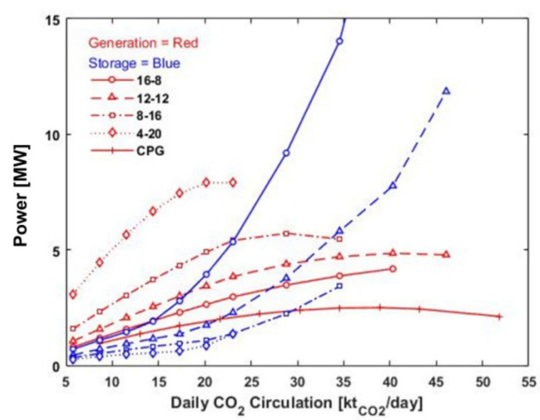

Figure 2: The power generated for varying daily CO_2 circulation rates.

The storage power increases quadratically with daily CO_2 circulation rate. Sharp increases in storage power are required at higher CO_2 injection mass flow rates to operate surface injection pumps to overcome large downhole reservoir injection pressures.

Figure 3 shows the net energy delivered to (or required from, if negative) the power grid per day. At their respective flow rates with maximum energy, the CPG system generates more power than the CPGES systems by approximately a factor of three.

The smaller net energy generated from the CPGES system is due to two reasons: 1) the decreased operation time and 2) the decreased efficiency due to a second reservoir. By alternately operating the generation and storage equipment, the generation time is reduced from 24 hours by the storage time. In many cases, this roughly halves the energy generated. Also, the turbine outlet pressure of the CPGES system is necessarily higher to inject the fluid into the second reservoir. Thus, CPGES net energy will be reduced from CPG.

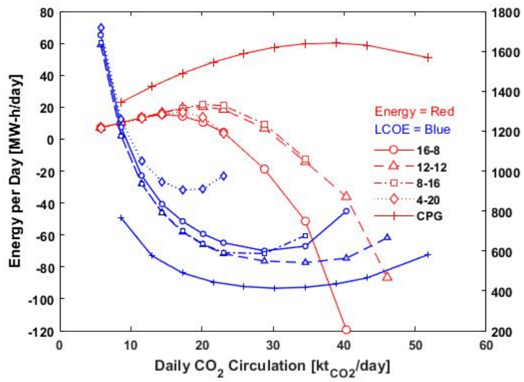

Figure 3: The energy generated per day and Levelized Cost of Electricity (LCOE) for varying daily CO_2 circulation rates.

Thus, a trade-off occurs: CPGES systems will have higher power generated than CPG for a fraction of the day, but lower energy generated.

Figure 4 shows the capital cost of the CPGES system for all four generation periods tested. Usually, more than half the cost of the system is due to well and wellfield development costs, which are fixed costs. The well and wellfield cost fraction is larger for shorter generation periods because the cost of the surface plant is reduced.

The cooling tower tends to be the most expensive piece of surface equipment. By extending the storage period (i.e. shortening the generation period), the storage flow rate is decreased, reducing the cooling tower size, thus reducing its cost.

In general, we find that longer storage periods tend to decrease capital costs. Also, longer storage periods resulted in lower storage power (Figure 2) and higher net daily energy (Figure 3). So, increasing storage periods, or decreasing injection rates, decrease cost and increase storage efficiency. Therefore, lastly, we combined and operated in parallel CPG and CPGES systems. The combined system should operate more efficiently and reduce cost through the continuous, lower injection rate of CO_2.

3.1 CPG+CPGES

Figure 5 shows the generation power and net energy of the CPG+CPGES system. More power generation was possible operating at a “75% CPG + 25% CPGES” configuration than by operating at “100% CPGES.” This is due, in part, to the simultaneous injection into both the deep and shallow reservoirs. The combination of CPG and CPGES lowers the injection mass flow rate into both reservoirs, reducing downhole pressures, reducing losses, and increasing efficiency.

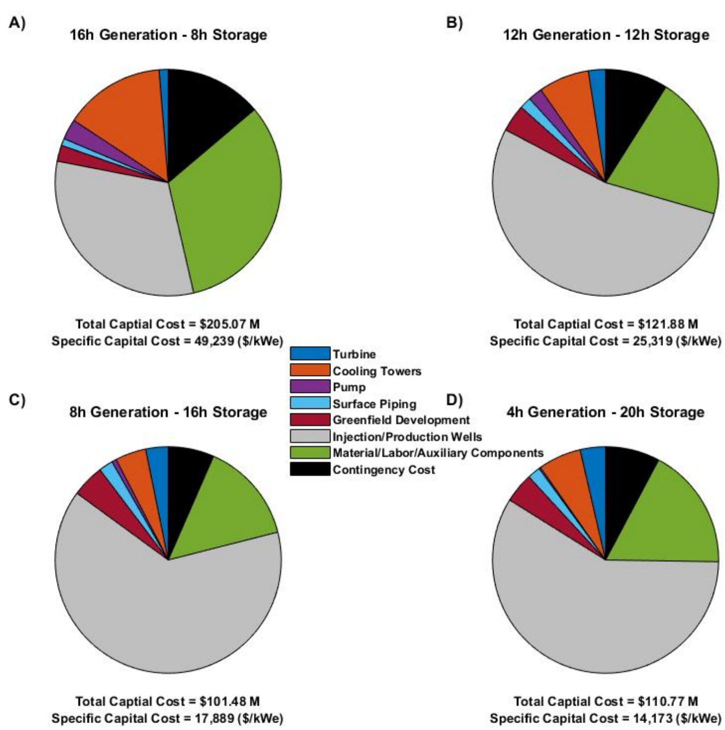

Figure 4: The total capital cost for the four different operational cycles.

The net energy generated increased in Figure 5 from approximately 20 MW-h/day with "100% CPGES" to 40 MW-h/day with "75% CPG + 25% CPGES." This is due to the increased operational efficiency, described previously, and the increase in the utilization of the turbine. When CPG and CPGES systems are combined, the turbine operates continuously, albeit at sometimes low power output, thus generating more energy than the CPGES system.

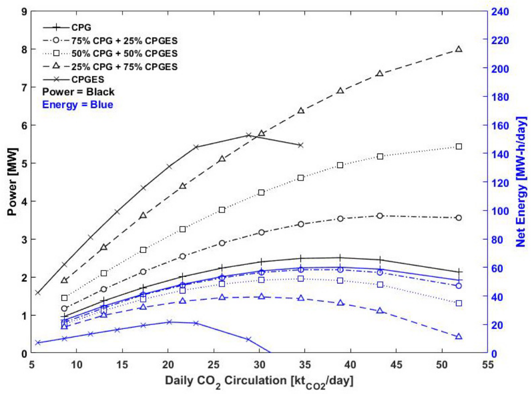

Figure 5: The power generated and net energy per day for the CPG+CPGES system. The CPG+CPGES system is operated between fully CPG (100% CPG + 0% CPGES) and fully CPGES (0% CPG + 100% CPGES).

3. CONCLUSIONS

We show here preliminary CPGES and CPG+CPGES results. We have identified the following trends:

- A CPGES system may be operated at higher CO_2 mass flow rates than CPG, generating more power, but only for portions of the day. Our shortest generation period (i.e. 4h-20h) generated approximately four times the power output but approximately one-third of the energy.

- Injection pumping power into the deep reservoir is often the largest source of parasitic power loss. Large injection powers are due to large downhole pressures in the deep reservoir caused by large injection flow rates. Thus, increases in the duration of the storage period reduce injection flow rate and often result in increases in net energy generated.

- Well and wellfield costs are generally more than half the total capital cost. Furthermore, the cooling towers constitute the greatest cost of the surface equipment. Thus, longer storage periods tend to decrease the cost of the surface equipment.

- Combining CPG and CPGES and operating them in parallel decreases inefficiency and operates the turbine more, increasing net energy generated. This combination allows flexible operation of the system, ranging from 100% CPGES to 100% CPG, depending on the power grid demands.

REFERENCES

Adams, B.M., Kuehn, T.H., Randolph, J.B., & Saar, M.O. (2013). The reduced pumping power requirements from increasing the injection well fluid density. GRC *Transactions*, 37, 667-672.

Adams, B.M., Kuehn, T.H., Bielicki, J.M., Randolph, J.B., & Saar, M.O. (2014). On the importance of the thermosiphon effect in CPG (CO_2 plume geothermal) power systems. *Energy*, 69, 409-418. http://dx.doi.org/10.1016/j.energy.2014.03.032

Adams, B.M., Kuehn, T.H., Bielicki, J.M., Randolph, J.B., & Saar, M.O. (2015). A comparison of electric power output of CO_2 Plume Geothermal (CPG) and brine geothermal systems for varying reservoir conditions. *Applied Energy*, 140, 365-377.

Bird, L., Milligan, M., & Lew, D. (2013). Integrating variable renewable energy: Challenges and solutions. National Renewable Energy Laboratory Technical Report, NREL/TP-6A20-60451.

Brown, D. (2009). Hot dry rock geothermal energy: Important lessons from fenton hill. *Proceedings of the thirty-fourth workshop on geothermal reservoir engineering*, Stanford University, Stanford, California, February 9-11, 2009.

Buscheck, T.A., Bielicki, J.M., Edmunds, T.A., Hao, Y., Sun, Y., Randolph, J.B., et al. (2016). Multifluid geo-energy systems: Using geologic CO2 storage for geothermal energy production and grid-scale energy storage in sedimentary basins. *Geosphere*, 12, 678-696.

Fleming, M.R., Adams, B.M., Randolph, J.B., Ogland-Hand, J.D., Kuehn, T.H., Buscheck, T.A., Bielicki, J.M., and Saar, M.O. (2018). High efficiency and large-scale subsurface energy storage with CO2. Proceedings, 43rd workshop on geothermal reservoir engineering, Stanford University, Stanford, California, February 12-14, 2018.

Fleming, M.R., Adams, B.M., Kuehn, T.H., Bielicki, J.M., & Saar, M.O. (In preparation). The Generation, Storage, and Operation of CO2-Plume Geothermal Energy Storage (CPGES) in a Low-Temperature Sedimentary Reservoir. *Applied Energy*.

Klein, S.A. & Alvarado, F. (2002). Engineering Equation Solver. F-chart Software.

Koohi-Kamali, S., Tyagi, V.V., Rahim, N.A., Panwar, N.L., Mokhlis, H. (2013). Emergence of energy storage technologies as the solution for reliable operation of smart power systems: a review. Renewable and Sustainable Energy Reviews, 25, 135-165.

Lui, H., He, Q., Borgia, A., Pan, L., & Oldenburg, C.M. (2016). Thermodynamic analysis of a compressed carbon dioxide energy storage system using two saline aquifers at different depths as storage reservoirs. *Energy Conversion and Management*, 127, 149-159.

Pruess, K. (2005). ECO2N: A TOUGH2 fluid property module for mixtures of water, NaCl, and CO_2. Lawrence Berkeley National Laboratory Technical Report LBNL-57952.

Pruess, K. (2006). Enhanced geothermal systems (EGS) using CO_2 as working fluid—A novel approach for generating renewable energy with simultaneous sequestration of carbon. *Geothermics*, 35, 351-67.

Randolph, J.B. & Saar, M.O. (2011). Combining geothermal energy capture with geologic carbon dioxide sequestration. *Geophysical Research Letters*, 38, L10401. http://dx.doi.org/10.1029/2011GL047265

Acknowledgements

The authors thank the Werner Siemens Foundation (Werner Siemens-Stiftung) for its support of the Geothermal Energy and Geofluids (GEG) Group at ETH Zürich, Switzerland. We also thank the colleagues in the Geothermal Energy and Geofluids Group at ETH Zürich, in particular, Dr. Samrock, Dr. Kyas, Dr. Birdsell, Dr. Vogler, Dr. Ebigbo, Dr. Niederau, and Philipp Schädle, for their thoughtful feedback and constructive criticism.