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Geospatial Estimation of the Electric Power Potential in Sedimentary Basin Geothermal Resources Using Geologically Stored Carbon Dioxide

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ABSTRACT

Sedimentary basins have emerged as potential candidates for geothermal development, in part because the aquifers within them are also the targets for the emplacement of carbon dioxide (CO_2) to isolate it from the atmosphere. This geologically stored CO_2 could be used as a geothermal heat extraction fluid and circulated between the CO_2 storage reservoir and a surface power plant where it could be expanded in a turbine to produce electricity, and thus be a CO_2 capture, utilization, and storage approach. The use of CO_2 for geothermal heat mining has a number of thermophysical advantages over the use of native brine. Here, we used an integrated power cycle-well-reservoir modeling approach from our prior work to estimate the capacity of a CPG power plant as a function of important parameters of the aquifers into which CO_2 would be emplaced. We then produced a reduced-form equation that predicts these estimated power generation capacities. In a case study of the continental United States, we applied this reduced-form equation to the relevant geospatial data for sedimentary basins and the aquifers and heat fluxes within them. While the availability of relevant data with high fidelity is limited, the results of this geospatial assessment suggest that there are large areas within the continental United States in which CPG power plants could be constructed and have power generation capacities on the order of those of other components of the electricity system. In particular, if other siting issues could be addressed, CPG developments in portions of Central Utah, Northwest and Southwest/South Central Colorado, Southwest and Central New Mexico, Eastern and Southern Arkansas, Northern Louisiana, West-Central Wyoming/Eastern Idaho, the central valley in California, Western Texas, and the Texas gulf coast may be able to have power generation capacities on the order of 100s of megawatts or more.

1. INTRODUCTION

Sedimentary basin geothermal resources have emerged as a potential resource for geothermal energy production (SedHeat, 2013). Despite typically having lower temperatures than conventional hydrothermal resources in faulted and fractured systems or having hot, dry rock resources with very low permeabilities such as those resources targeted for so-called enhanced or engineered geothermal systems (EGS) (MIT, 2006; SedHeat, 2013), the aquifers within sedimentary basins are often naturally porous and permeable. As such, the existing permeability can result in improved flow of fluids through the sedimentary basin geothermal resource and may not require hydraulic stimulation to enhance permeability. . Sedimentary basins typically have large areal extents; they are ubiquitous worldwide, underlie approximately half of North America, and contain the aquifers that are typically targeted for geologic carbon dioxide (CO_2) storage during the CO_2 capture and storage (CCS) operations to mitigate climate change (Bachu, 2015; IPCC, 2005; NETL, 2015).

Recent work has investigated how geologically stored CO_2 could be used to extract geothermal heat, either as the pressure drive for producing geothermally heated brine (Buscheck et al., 2017, 2015, 2013), or by directly using of CO_2 as the subsurface heat extraction fluid (Adams et al., 2014, 2015; Buscheck et al., 2015, 2016, 2017; Garapati et al., 2015; Levy et al., 2018; Ogland-Hand et al., 2019; Pan et al., 2016, 2018; Randolph and Saar, 2011a, 2011b)— which is often referred to as CO_2 Plume Geothermal (CPG) technology (Randolph and Saar, 2011b). Thermophysically, the injected CO_2 will be a supercritical fluid below depths of about 800 m, where it will have a higher mobility than brine, increased heat advection, and a highly temperature-dependent density (Brown, 2000; Pruess, 2008, 2006). The subsequent large density differences between injection and production wells can result in a self-convecting thermosiphon that can reduce or eliminate the need for pumps and their parasitic pumping power requirements to drive fluid circulation (Adams et al., 2014; Atrens et al., 2010; Haghshenas Fard et al., 2010). Research on CPG has yielded a number of published studies that show promise for the potential of sedimentary basin, CO_2-based, geothermal energy extraction. For example, some of this work has investigated how much CO_2 is necessary to prime the system for CPG electricity production (Garapati et al., 2015), and other work has estimated the potential power output of a CPG facility (Adams et al., 2015). With the theoretical potential of CPG in mind, which has been developed based on individual, hypothetical, but realistic, combinations of subsurface parameters (e.g., geothermal temperature gradient; reservoir permeability, fluid pressure, depth, and thickness), this work investigated the geospatial potential of CPG in the continental United States (CONUS).

2. APPROACH

2.1 CO_2 Plume Geothermal Power Capacity Estimation

We used a model from our prior work to estimate the power generation capacity of a CPG power plant (Adams et al., 2015). In this model, cold CO_2 is injected into the porous and permeable aquifer. The CO_2 extracts heat as it flows through the reservoir to the production well, where the heated CO_2 is produced through a well and flows through a surface power plant. The hot CO_2 is expanded through a turbine to generate electricity. The cooled CO_2 is then re-injected into subsurface. We ran this model, which included a direct CO_2 power cycle, a well model, and a reservoir model for a variety of operational decisions, subsurface parameters, and design choices. The direct CO_2 power cycle included a turbine, a cooling tower, a condensing tower and an optional pump. The turbine and pump were assumed to be non-isentropic and the appropriate efficiencies were applied. As in that prior work, the analyses considered systems that use a pump and those that rely only on the thermosiphon to power fluid circulation.

For the reservoir simulations, we assumed a fully developed CO_2 plume so that production wells contain almost pure CO_2, and that all resident brine has been displaced so that CO_2 is the only working fluid in the system (Garapati et al., 2015). In the reservoir model, we implemented a 1/8-symmetric model to represent an inverted 5-spot injection pattern, which is common in the CO_2-enhanced oil recovery (CO_2-EOR) industry and in prior research on using CO_2 as a geothermal heat extraction fluid (Adams et al., 2015; Levy et al., 2018; Jimmy B. Randolph and Saar, 2011b). In an inverted 5-spot, cold CO_2 is injected into a well at the center of a square, where wells that would produce geothermally heated CO_2 are located on each corner of that square. In these simulations, the square was 1 km on a side, so that the distance between the CO_2 injection well and each CO_2 production well was ½ $[(1\ km)^2 + (1\ km)^2]^{0.5}$ = 0.707 km. We used TOUGH2 with the ECON2N module to estimate the flow and heat extraction of the CO_2 in the sedimentary geothermal reservoir (Pruess, 2005, 2004). The reservoir modeling was conducted for a range of depths (1.5 – 5.0 km), geothermal temperature gradients (20 – 50°C/km), and permeabilities ($1\text{x}10^{-15}$ – $1\text{x}10^{-11}$ m^2). The reservoir was assumed to be 305 m thick, and the surface temperature was assumed to be 15°C.

The well model applied conservation of energy, conservation of momentum, and patched Bernoulli equations at the end of each 100 m element, which were numerically integrated over the vertical depth of the well (Adams et al., 2015, 2014). Since the diameter of the well affects the pressure drop and heat loss of the fluid flowing through the well, we allowed the well diameters to vary between 0.15 m and 0.41 m in stepwise increments that were extracted from GETEM (U.S. DOE EERE, 2012) in order to maximize the net amount of power output from the CPG facility. We also modeled the power cycle with various approach temperatures, from 7°C to 28°C. The approach temperature is a design decision that indicates how close to ambient temperature the CO_2 is cooled.

As in prior work (Adams et al., 2015), the power production was estimated for each injection-production well pair, and scaled to the inverted 5-spot well pattern. Since multiple inverted-5 spots can be created by adding extra wells (e.g., two inverted five-spots can be created by doubling the production mass flowrate in two neighboring existing production wells and adding an injection well and two production wells), we considered the expansion of the well pattern to keep an overall square footprint that is comprised of multiple inverted five-spot patterns, where the flow through a production well could be due to the injection of CO_2 through multiple wells. For example, a 4x4 pattern would have sixteen inverted 5-spots (four on each side), cover sixteen km^2, contain sixteen injection wells, and 25 production wells—all but four of which would receive CO_2 from more than one injection well. Coupling the inverted 5-spot well patterns in this manner results in an assumption of lateral symmetry in the reservoir, regardless of the compartment size.

2.2 Capacity Regression

We represented the power capacity of a CPG facility as a function of the relevant characteristics of the subsurface, using a few forms (power, exponential) for the independent variables in a power equation. We then linearized this function by taking the natural log of both sides, to produce a reduced-form equation that could be fit to the estimated capacities using a linear regression. The following functional form was used in the regression,

$$\ln(MW) = \alpha + \beta_1 \kappa^N + \beta_2 D^N + \beta_3 G^N + \beta_4 \cdot \ln(\kappa^N) + \beta_5 \cdot \ln(D^N) + \beta_6 \cdot \ln(G^N) \quad (1)$$

where *MW* is the estimated power capacity of the CPG facility, κ is the homogeneous reservoir permeability (m^2), *D* is the depth of the aquifer (km), and G is the geothermal temperature gradient (°C/km). Each of these regressors were also normalized by "base" conditions: $\kappa^N = \frac{\log(\kappa)}{\log(5x10^{-14}\ m^2)}$, $D^N = \frac{D}{2.5\ km}$, and $G^N = \frac{G}{35\frac{°C}{km}}$.

2.3 Geospatial Data

We compiled a database of geospatial data for relevant subsurface parameters in the CONUS by integrating data from the United States Geologic Survey, the National Carbon Sequestration Atlas, and the National Geothermal Data System, among others (Frezon et al., 1983; Fuis et al., 2001; Jachens et al., 1995; Jachens and Moring, 1990; Langenheim and Jachens, 1996; Mooney and Kaban, 2010; NETL, 2015; SMU, 2015; U.S. Geological Survey, 2013). These data include the thickness of onshore sedimentary basins and their geothermal heat fluxes, depth, permeability, thickness, and estimated CO_2 storage capacity. Where reservoir permeability data were missing, we gap-filled that missing data with three potential values: $1\text{x}10^{-14}$ m^{-2}, $1\text{x}10^{-13}$ m^{-2}, and $5\text{x}10^{-13}$ m^{-2}.

3. RESULTS

3.1 Capacity Regressions

Our other work suggests that well patterns of 7x7 inverted 5-spots (49 km^2) typically make the best use of the economies of scale for a CPG facility (Bielicki et al., 2019). We thus limited our analyses to those estimated capacities. Table 1 shows the estimated coefficients for the reduced-form representation of the estimated power capacity of a CPG power plant in Equation 1.

Table 1: Estimated Coefficients for the Reduced Form Representation the Capacity of a CO_2 Plume Geothermal Power Plant (Equation 1).

	System	
	Pumped	Thermosiphon
α	139.3	139.3
β_1	-130.1	-131.6
β_2	-1.6	-1.3
β_3	-2.3	-1.6
β_4	118.1	118.1
β_5	5.3	4.9
β_6	5.8	4.7
R^2	0.93	0.93

The results of estimating the coefficients of the reduced-form equation suggest that there is little, if any, difference in the dependence on permeability between the pumped systems and the thermosiphon systems: β_1 = -130.1 and -131.6 for the pumped and thermosiphon systems, respectively, and β_4 is 118.1 for both systems. The reduced-form representation suggests that estimated power capacities increase with depth (coefficients β_2 and β_5) and with geothermal temperature gradient (coefficients β_3 and β_6). These results are consistent with the results of the modeling in our prior work (Adams et al., 2015). When combinations of the reservoir parameters that we used in the modeling of CPG power capacity were inserted into Equation 1 with the estimated coefficients in Table 1, pumped systems generally had higher predicted power capacities than thermosiphon systems. This result is also generally consistent with the findings in our prior work.

Figure 1 shows a comparison of the CPG power plant capacity that was predicted by the regression results with the data from the integrated power cycle-well-reservoir model results. The spread in the data increases at higher capacities, with a tighter distribution of data at smaller estimated capacities—which are more likely to be the capacities for actual CPG developments—than at the larger estimated capacities.

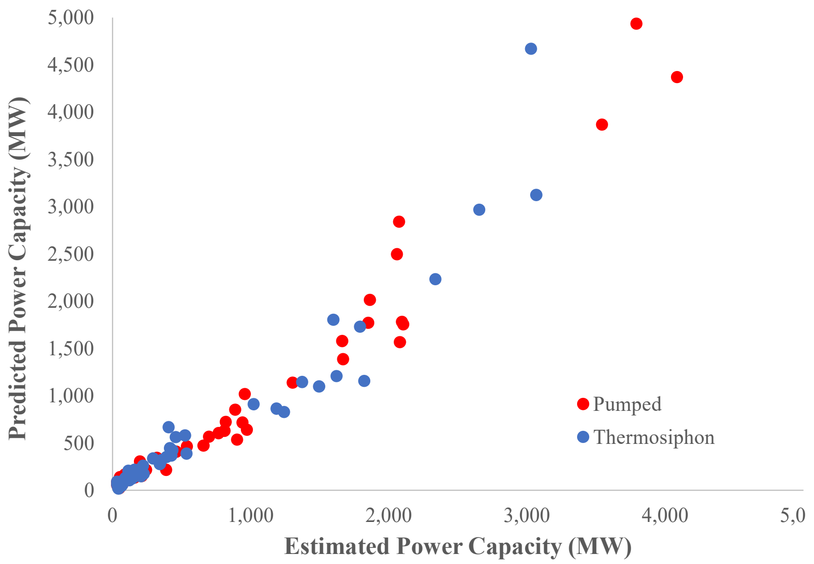

Figure 1: Scatter Plot of CO_2 Plume Power Plant Capacity that is Predicted from the Regressions and Estimated from the Modeling

The trends in the scatterplot in Figure 1 are relatively linear throughout the scale of the data as shown, but there appears to be a kink in the data around 1,500 MW. We performed a simple linear regression of the predicted capacity on the estimated capacity for the full set of data and for two linear segments (< 1,500 MW; >1,500 MW). For the regressions of the full data and of those limited to be below 1,500 MW, we set the intercept to be zero so to force the regression line to go through (0,0) so that it properly conveys that the fit should predict a capacity of 0 MW when the estimated capacity is 0 MW. The results of these regressions are shown in Table 1.

Table 2: Fit of Predicted CO_2 Plume Geothermal Capacity to Estimated CO_2 Plume Geothermal Capacity in Sedimentary Basin Geothermal Resources in the United States.

	Pumped		Thermosiphon	
	Regression*	R^2	Regression*	R^2
All Data	1.16x	0.90	1.04x	0.90
<1,500 MW	0.76x	0.92	0.80x	0.95
>1,500 MW	1.15x – 63	0.82	1.52x – 922	0.73
*the “x” in the regression equation refers to “Estimated Capacity”				

The regression of the full set of data slightly overpredicts the estimated capacity when all of the data are used (i.e., the slopes are greater than one), because the sparser and more variable data at high estimated capacities is influencing the regression fit. When the data are parsed into two linear segments above and below 1,500 MW, the results indicate that the fits are better and the estimated capacities tend to be underpredicted for the data below 1,500 MW. That is, the slope decreases from 1.16 to 0.76, and the R^2 increases from 0.90 to 0.92, for the pumped systems. For the thermosiphon systems, the slope decreases from 1.04 to 0.80 and the R^2 increases from 0.90 to 0.95. For the estimated capacities that are above 1,500 MW, the higher variability in the data results in lower values for R^2, with slopes that are the same (pumped system) or greater (thermosiphon system) than when all of the data are used in the regression.

3.2 Geospatial Assessment

We applied the reduced-form representation (Equation 1) with the estimated coefficients (Table 1) to the geospatial data that we acquired. Since only one thickness was used in the modeling of the CPG system, we multiplied the permeability (κ) in the reduced-form Equation (1) by the ratio of the thickness in the geospatial data (τ) over 305 m. The transmissivity of an aquifer is inversely proportional to its thickness, so that when the reduced form equation was applied, the κ term in the mapping used an input of $\kappa\frac{\tau}{305}$. Some of the data lacked information on the depth and thickness of aquifers within the sedimentary basin. Given the prospects of these regions, we only considered depths of the basins in these areas down to 5 km.

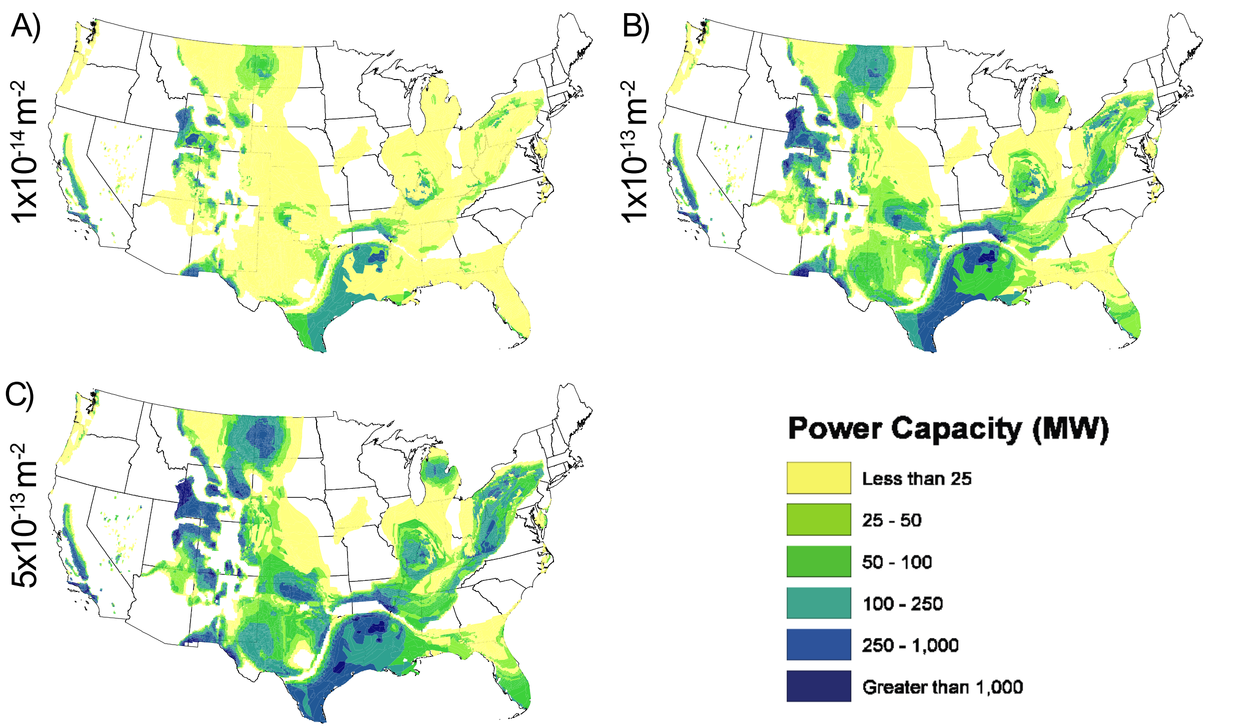

Figure 2: Predicted Potential Capacities of CO_2 Plume Geothermal Power Plants in the Continental United States. The power capacities are shown for individual CPG power plants with well patterns that cover 49 km^2. Gap-filled permeabilities are indicated to the left of each panel.

Figure 2 shows the geospatial mapping of potential CPG power capacity with the results for either the pumped system or the thermosiphon system shown, whichever is greater. Areas of Central Utah, Northwest and Southwest/South Central Colorado, Southwest and Central New Mexico, Eastern and Southern Arkansas, Northern Louisiana, West-Central Wyoming/Eastern Idaho, the central valley in California, Western Texas, and the Texas gulf coast appear to have the potential for large capacity CPG facilities. These areas are more broadly distributed than the locations of existing geothermal power plants in the naturally faulted and fractured geologic systems in California and Nevada. The deployment of CPG in some of these areas may be attractive because of their vicinity to growing metropolitan population centers, and thus areas of high electricity demand. In particular, Northern Louisiana and Eastern and Southern Arkansas are in the Eastern Interconnection grid and within the jurisdiction of the Southeastern Electric Reliability Council, which is an entity that seeks to balance electricity generation and demand in the region. Development of a CPG system in this area could thus facilitate satisfying electricity demand sourced from the New Orleans, Atlanta, and Memphis Metropolitan Statistical Areas, among others.

4. DISCUSSION AND CONCLUSIONS

This work provided an initial assessment of the geospatial potential for sedimentary basin geothermal energy production using geologically stored CO_2 as the heat extraction fluid. The predicted capacity of these CO_2 plume geothermal (CPG) power plants was based on modeling that couples a direct CO_2 power cycle model, a well model, and reservoir modeling to collectively estimate power generation potential. The results of this modeling were regressed to predict how the power capacity of a CPG power plant varies by the parameters of the aquifer into which CO_2 would be emplaced (e.g., depth, geothermal temperature gradient) and engineering design decisions (e.g., size of the well pattern, approach temperature). The resulting reduced-form equation was applied to geospatial data for sedimentary basins and their geothermal heat fluxes. While the predicted CPG capacity contains important assumptions, including lateral symmetry in scaling the reservoir modeling to coupled inverted 5-spots, and the geospatial mapping is only as good as the quality and completeness of the datasets that we could acquire, the results of this initial assessment suggest that there are large regions of the United States where CPG power plants could have attractive power capacities.

In order to determine the degree to which realistic CPG facilities could realize the power production potential, additional work will be necessary to consider reservoir compartment size and to improve the fidelity of datasets—especially for the aquifers in sedimentary basins. We used geospatial data from the geothermal community and from the CO_2 capture and storage (CCS) community, but compiled and publicly available data on the permeability, thickness, and variations of these important parameters in three dimensions is lacking. Ideally, well logs and cores at prospective sites would need to be assessed and, ideally, included in easily accessible databases. With these caveats, there are a number of other considerations and areas of inquiry to determine the potential for CPG and the degree to which that potential could be realized.

While the work in this paper implicitly illustrates the potential of using CPG to provide baseload power, because it is driven by stored pressure, CPG can also be operated to provide dispatchable, responsive, load-following power and thereby assist in the integration of variable renewable energy (e.g., wind and solar), with much less CO_2 emissions intensity, on electricity grids. Further, the use of CO_2 to generate electricity from sedimentary basin geothermal resources is considered to be a CO_2 capture, utilization, and storage (CCUS) approach. Since it is possible that the sources of CO_2 would not be co-located with the locations of geology that is amenable for CPG, CO_2 supply chain logistics would need to be assessed to determine the viability of CPG and how it may scale to make meaningful contributions to regional electricity systems and the mitigation of climate change. Such research on source-sink matching has been applied for integrated CCS systems in various ways, including capturing CO_2 from fossil-fueled power plants and a variety of industrial sources (Bielicki et al., 2018, 2014; Dai et al., 2014; Kuby et al., 2011; Middleton et al., 2012b, 2012a; Middleton and Bielicki, 2009). Such work would likely require detailed assessment of the levelized cost of electricity and the capital cost of CPG power plants (Bielicki et al., 2019), which could then be collated to produce supply curves that could be integrated into assessment models that are used to determine the optimal mix of energy technologies to meet economic and climate goals. These source-sink matching and integrated assessment efforts would be useful in understanding the degree to which policy and economic incentives, such as the 45Q federal tax credit in the United States, could stimulate the deployment of CPG.

In addition to the availability of CO_2, the deployment of energy infrastructure such as a CPG power plant has many other siting issues, such as the proximity to adequate transmission infrastructure, the public acceptance and social license of developing such projects, and the proximity of a development to population centers. Without simultaneous consideration of the physical, social, and economic concerns for the deployment of new energy technology and infrastructure, CPG may not be able to scale and contribute much to the overhaul of electricity systems to those that are more environmentally benign.

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DISCLAIMER

One author declares the following competing financial interest: M.O. Saar declares financial interest in the form of technology commercialization through CO_2 POWER GmbH, of which he is a shareholder.

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