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CO2 Plume Geothermal (CPG) and the Earth Battery – Innovative, Dispatchable Geothermal Power Production and Geologic Energy Storage Using Non-Water Working Fluids

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ABSTRACT

CO2 Plume Geothermal (CPG) and Earth Battery technologies constitute a continuum of renewable power and geologic energy storage systems that are innovative in their use of non-water, and combinations of water and non-water, fluids as the working media to harness geothermal heat and store energy in permeable subsurface formations. These non-water fluids – primarily CO2, but also nitrogen and air – are expected to allow a dramatic expansion of the areas worldwide where geothermal power and bulk aquifer energy storage can be technically and economically deployed (e.g., Randolph and Saar (2011); Buscheck et al. (2016)). Ultimately, our approach will use CO2 as a below-ground working fluid, with each system using MMtonnes of CO2, helping to turn CO2 from a liability into a renewable power resource.

Here, we discuss non-water geo-energy technologies in the context of existing power generation and energy storage systems. We discuss the current state of academic research and make note of next steps in the planned commercial deployment of these new geo-energy technologies.

1. Introduction

Meeting the Paris Climate Agreement goal of limiting the increase in the global average temperature to below 1.5 °C, compared to pre-industrial levels, requires aggressive, large-scale implementation of a range of measures, including increased use of renewable and low-carbon energy and reducing the CO2 intensity of fossil energy use. Unfortunately, each of these measures faces major technical and economic deployment barriers. Variability of the predominant renewables (wind, solar) requires transformative advances in utility-scale energy storage and baseload power-capable renewables, such as geothermal. Renewable energy resources and low-carbon nonrenewable energy resources, such as fossil-energy plants integrated with CO2 capture utilization and storage (CCUS), will have very high up-front capital cost and low operating cost, which economically favors high capacity factors. Fossil-energy power plants integrated with CCUS will have difficulty co-existing on electric grids and maintaining high capacity factors with an ever-increasing presence of variable renewables. No existing energy-storage technology can address the need to balance the seasonal mismatches between renewable energy supply and energy demand, which is a large potential market.

TerraCOH's technical approach addresses the major deployment barriers to geothermal power, CCUS, and utility-scale energy storage. It uses the huge fluid and thermal storage capacity of the earth's subsurface, together with overpressure driven by CO2 storage, to harvest, store, and dispatch energy from subsurface (geothermal) and surface (solar, fossil) thermal resources, as well as excess energy from electric grids. In our approach, the permanent storage of CO2 enables the earth to function as a low-carbon energy-system hub.

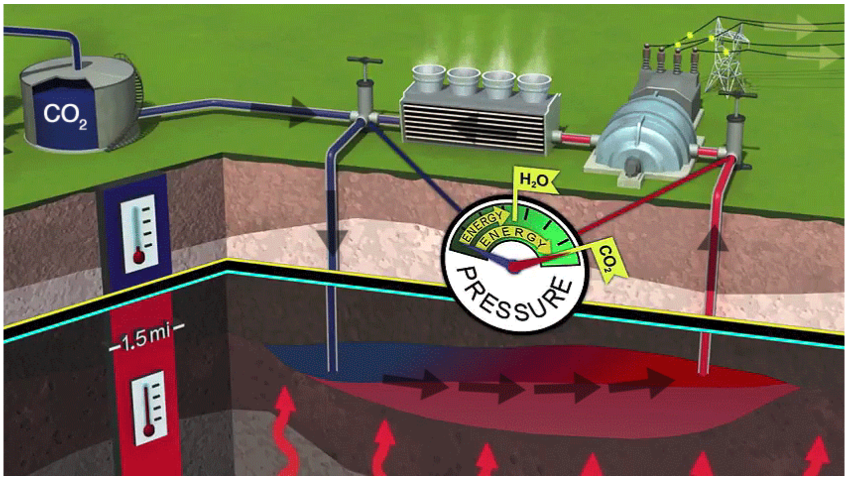

Figure 1 – Simple CPG Schematic, in which CO2 from a conventional emitter is injected into a deep saline aquifer, which is at a moderate temperature (90-150 ^{o}C) and allowed to form a plume. Once the CO2 becomes hot, it is produced to the surface, sent through a power system to spin a turbine and generate electricity, then reinjected into the subsurface.

2. Potential and Opportunities for Non-Water Geo-Energy Technologies in the Current Power Sytem

Energy systems, and the key market players such as electrical utilities, face a number of environmental and systems-dispatch challenges. From the environmental perspective, energy systems are under pressure to reduce atmospheric greenhouse gases (GHG) emissions, as well as the amount of water that is required throughout the energy supply chain. As concerns emissions, the challenge seeks to avoid substantially altering the present climatic envelop by limiting the increase in the global average temperature to below 1.5 °C, compared to pre-industrial levels, while the water challenge seeks to reduce water stress caused by development patterns and changing environmental conditions. CO_2 has been clearly implicated as a problematic GHG due to its 100-yr av. atmospheric residence time and position as by far the most widely-emitted GHG. In 2016, fossil-fueled power plants accounted for about 65% of the 4.08 million GWh of electricity that was generated in the United States and emitted about 35% of the total energy-related CO_2 emissions (1,821 $MtCO_2$), EIA (2017). These power plants also require water for cooling and were responsible for withdrawals of over 58 trillion gallons in 2010 - more than 40% of total freshwater withdrawals that year (Maupin et al. (2014)). The demand for water exceeds supply in nearly 10% of the watersheds in the United States, and water stress such as this is expected to worsen (Averyt et al. (2013); Blanc et al. (2014)).

Conventional renewable energy technologies – wind and solar – can help to address these challenges because they generate electricity with few, if any, operational CO_2 emissions or water requirements -- NREL (2013); Meldrum et al. (2013); Chandel et al. (2011); Fricko et al. (2016). They also have low operational costs, and with increased development and economies of scale, can provide electricity that has or is becoming cost competitive with fossil fuel-based power, though such cost competitiveness may rely on government subsidies (Lazard (2017)). With such low levelized cost of electricity (LCOE), wind and solar electricity is often dispatched before other sources (e.g., coal-fired power plants). Such a rank-ordering of dispatch by operating costs seeks to ensure that the cost of electricity is kept as low as possible. But wind and solar are variable over time and space, limiting the degree to which these relatively environmentally-benign technologies can be relied upon to meet electricity demand. Grid-scale energy storage can help increase market penetration of variable renewable power technologies. Except for compressed air energy storage (CAES), all current utility-scale, energy storage technologies are deployed above ground, involving expensive fabrication while being limited in capacity to diurnal storage. To date, the energy storage technology with the greatest capacity is pumped hydroelectric energy storage (PHES). However, PHES has topographic requirements that greatly limit its geographic deployment. No existing energy-storage technology can address the need to balance the seasonal mismatches between renewable energy supply and energy demand, which is a large potential market.

Fossil energy plants – integrated with carbon capture, utilization and storage (CCUS) in saline aquifers – can ensure stable power supplies while helping address the emissions challenge and easing the transition to a predominantly renewable power-based system. However, they face several barriers to deployment, including: (1) CO_2 capture and storage costs; (2) water intensity of CO_2 capture, and (3) overpressure, which is fluid pressure that exceeds the original reservoir pressure due to CO_2 injection, because it drives key storage risks of induced seismicity, caprock fracture, and CO_2 leakage. Moreover, fossil-energy power plants, including those integrated with CCUS, have difficulty co-existing on electric grids and maintaining high capacity factors with an ever-increasing presence of variable renewables.

Society demands 24x7 power. The deployment and growth of wind and solar puts pressure on the existing grid system to meet both the baseload need and environmental goals. TerraCOH technology delivers a path to meet these conflicting objectives.

Geothermal Energy:

The installed electrical capacity of the US exceeds 1.19 TW (Zummo (2017)), of which wind power exceeds 81.7 GW and solar power exceeds 23.6 GW of nameplate capacity. Like the US, globally from 2000 to 2016, there has been significant growth in renewable technologies: 28-fold to for solar and 107.2-fold for wind (GWEC (2013)). While this growth is substantial, utilization capacity has been limited due to variability. In the US, the capacity factors (electricity dispatched per year / capacity for dispatch each year) from 2014-2016 for wind and solar energy facilities was only 33.6% and 26.3%, respectively -- EPIA (2014); U.S. EIA (2017). As such, wind and solar facilities cannot generate electricity when desired.

Geothermal energy facilities, in contrast, can generate electricity when desired, permitting them to have high capacity factors (up to 92% in the US) (U.S. EIA (2017)). Moreover, geothermal power has amongst the lowest LCOE of any power technology, at $0.047 per kWh unsubsidized in the US (Lazard 2017). Despite these advantages, there was only 3.9 GW of installed geothermal capacity in the US as of 2017 (U.S. EIA (2017)). Present geothermal electricity facilities are geographically-limited to places, such as California and Nevada, with high temperature gradients and relatively shallow fracture networks that allow heated geofluids to migrate fairly close to the surface. Moreover, conventional geothermal facilities have generally been limited to continuous operation to maximize electricity generation and returns, and avoid issues such as pump degradation and scaling. The lack of a widespread resource base for conventional geothermal technologies has impeded development.

Sedimentary basins, in contrast, are more ubiquitous than exploitable faulted and fractured systems, and they provide a potential solution for energy storage. The geothermal resource potential of conventional hydrothermal, brine-based systems in major sedimentary basins of the United States (Porro and Augustine (2012)) is a market opportunity in itself of tens of thousands of MW's of electrical power. But the properties of supercritical CO2, at the temperatures and pressures common to saline aquifers in sedimentary basins, increase heat advection and making CO2 more mobile than brine in the subsurface. As a consequence, CO2 that is deliberately emplaced into sedimentary basins could be circulated to extract geothermal heat (Randolph and Saar (2011)) and, consequently, offers a larger market opportunity than conventional hydrothermal in sedimentary basins. This CO2 could be from a CO2 capture and storage (CCS) process (IPCC (2005); Holloway (2007); GCCSI (2014)), the conventional model of which involves separating CO2 from the exhaust gasses of large point sources (e.g., coal-fired power plants), compressing and transporting that CO2 by pipeline, and injecting it into sedimentary basins. These basins are targets for CO2 storage in part because they contain deep saline formations with permeabilities and volumes high enough to enable storage of large amounts of CO2. These relatively shallow (1-5 km) sedimentary reservoirs are ubiquitous throughout the world (IPCC (2005)), and underlay approximately half of North America (NETL (2015); Coleman (2012)).

Energy Storage:

Energy storage technologies could enable increased use of variable electricity generation by time-shifting excess electricity production from when it is generated to when it is demanded (Denholm and Hand (2011)). In this type of operation, the excess electricity would be stored when it is generated—often as another form of energy (e.g., potential energy, chemical energy)—and later dispatched when the electricity is needed.

For example, batteries store electricity as chemical energy, flywheels store kinetic energy by spinning wheels with little resistance, and capacitors store energy in a magnetic field between two poles -- Ibrahim et al. (2008); Awadallah et al. (2015). But these types of energy storage technologies cannot be used for large, grid-scale, applications like firming variable renewable electricity generation capacity because they have relatively small power capacities (typically ranging from ~1kW to ~10 MW) and can only discharge electricity at capacity for time lengths ranging from seconds to minutes -- Dunn et al. (2011).

Bulk energy storage (BES) technologies, however, have capacities of ~100 MW or more and discharge times on the order of hours, and can thus be used for large scale applications -- Dunn et al. (2011). Pumped Hydroelectric Energy Storage (PHES) is a BES approach that stores electricity as potential energy by pumping water to a reservoir at a higher elevation and generates electricity by letting that stored water flow through a turbine to a lower reservoir -- Deane et al. (2010); Ardizzon et al. (2014); Yang and Jackson (2011). Newer PHES technology can generate electricity when pumping and generating -- Paine et. al. (2014). As of 2014, there were over 129 GW of installed PHES capacity, which accounts for 99% of the energy storage capacity worldwide, Deane et al. (2010). Another BES technology, Compressed Air Energy Storage (CAES), uses electricity to compress air into a salt cavern. Electricity is later dispatched by injecting a fuel (natural gas) into a portion of the stored air, burning that fuel, and expanding the combustion products through a turbine.

Given the advantages of geothermal energy (dispatchability), and of sedimentary basins (ubiquity), the need to reduce the environmental consequences of electricity generation (CO2 emissions, water requirements) in regional energy systems, and the fact that sedimentary basins could be used for geothermal development and as geologic CO2 storage repositories, there is an opportunity to use these technologies (geothermal, CCS) and resources (sedimentary basins) in conjunction with wind and solar energy to increase the generation of electricity that has fewer environmental consequences. In addition to PHES and CAES—the only two industrial scale BES technologies at present— CO2 Bulk Energy Storage (CO2 -BES), i.e., the Earth Battery™, is another potential BES approach. CO2 -BES offers several advantages over PHES and CAES: neither CAES nor PHES can provide seasonal energy storage (Blanco (2018)), and both of these BES technologies have siting challenges with respect to the availability of relevant topography in the subsurface (CAES) or the on the surface (PHES), whereas CO2 -BES does not have those siting challenges due to the ubiquity of sedimentary basins in North America.

With CO2 -BES via the Earth Battery, energy could be stored by pressurizing and injecting CO2 into deep (>800 m) porous and permeable aquifers, and electricity would be generated later by producing the pressurized CO2 and in situ brine to the surface and flowing the fluids through a power plant, Buscheck et al. (2016). An alternative operational strategy for CO2 -BES would be to pre-heat the injected CO2 to store energy as heat instead of as pressure. Thermal energy – such as from solar thermal or off-peak conventional sources -- storage can introduce flexibility into the system on a diurnal basis, to accommodate the variable output of wind- and solar-energy technologies, or it can provide capacity on the seasonal timeframe where the renewable resources are not as robust year-round. Regardless of the type of energy storage, the CO2 would be permanently isolated from the atmosphere.

The subsurface is a highly insulated container that can store large amounts of energy for long periods of time, which can be used to support the electricity grid in various ways. In regions (e.g., California), solar power installations will be the primary source of growth in renewable energy capacity, according to Williams et al (2012). Such growth will produce large diurnal and seasonal mismatches between energy supply and demand. In other regions, electricity transmission constraints must also be addressed: (a) in Texas overinvestment in the deployment of wind turbines led to negative electricity prices; (b) in the Midwest, wind turbine deployment has been insufficient relative to the wind resources. Unlike other approaches, CO2 -BES could provide diurnal and seasonal energy storage, relieve transmission constraints, enable new variable renewable energy capacity, and do so in a manner that also addresses the needs of the fleet of inflexible, baseload generating facilities as increasing amounts of variable electricity from wind and solar facilities come on line. Overall, implementing CO2 -BES in regional energy systems could result in reductions in CO2 emissions and water requirements while assuring the overall system operates as efficiently as possible.

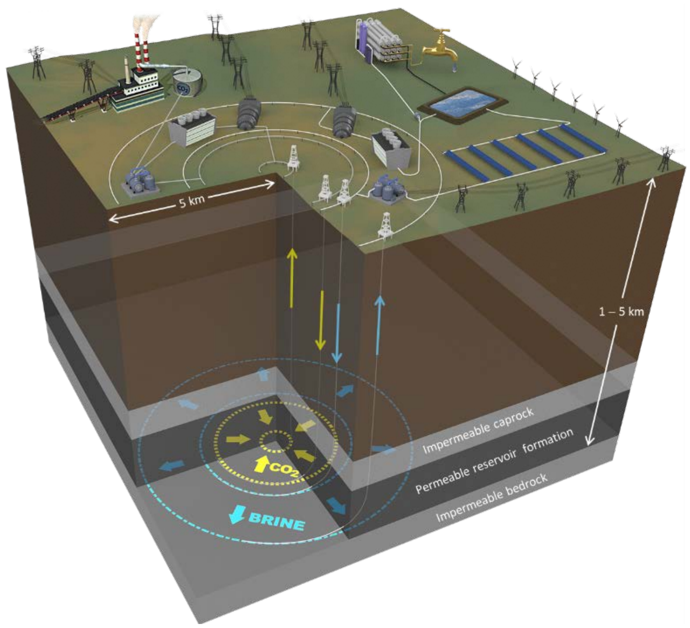

Figure: The Earth Battery schematic, from Buscheck et al. (2016).

Technical Approach:

The Innovation:

Our approach (Randolph and Saar (2011); Buscheck et al. (2014, 2016)) takes CO2 that has been captured from a fossil-energy power plant and injects it into a saline reservoir to store pressure, generate artesian flow of brine, and provide a supplemental working fluid to efficiently extract heat from the earth for power generation.

For energy storage, concentric rings of horizontal injection and production wells create a hydraulic curtain to confine the stored pressure, CO2, and thermal energy (in the form of heated brine) below the caprock that overlies the CO2 storage reservoir. Our approach is equivalent to underground PHES; but, because pressurized brine is heated, it is much more energy intensive. For example, water pressurized to 100 bars (1000 meters of head) and heated to 250 °C, contains 100 times more energy per unit volume than water in an above-ground PHES application. Pressurized CO2 and naturally-occurring brine is allowed to flow up production wells to generate electricity when it is demanded. Revenues generated by geothermal power and utility-scale energy storage can cause CO2 to become a valuable commodity, thereby creating a business case for CO2 capture and storage. Because CO2 can be readily transported 1000 miles or more by pipeline, and because saline reservoirs occur over at least half of the continental United States, our approach is capable of utilizing CO2 from nearly all large stationary emitters of CO2 in the United States. The products of our approach are: (1) generation of electricity from renewable sources, (2) utility-scale energy storage, and (3) industrial-scale sequestration of CO2.

CPG and Earth Battery systems have the potential to change the economic viability of geo-energy technologies. By using a more efficient, less expensive power cycle, and minimizing well drilling, total installed system costs and risks will be reduced. We estimate that the first commercial systems will have an LCOE below $0.05 per kWh ($3500 per kW installed), falling to below $0.03 per kWh ($2000 per kW installed) with scale.

Opportunities for Non-Water Geothermal in Hydrocarbon Fields:

Geothermal power generation in existing hydrocarbon fields offers substantial opportunity to harness underutilized resources and provide additional revenue streams for oilfield operators, e.g., Gosnold (2013). However, geothermal temperatures in such fields rarely approach the values required for economical energy conversion using conventional geothermal power technologies. Generally, with the exception of high temperature fields in the Gulf Coast region, North American hydrocarbon fields can deploy only binary cycle geothermal plants, which have payback periods that are far longer than the returns on investment (ROI's) that oilfield operators are used to. Non-water geothermal operations can help improve ROI's in hydrocarbon fields while providing numerous other advantages compared to other geothermal options.

CO2-based geothermal power systems, when deployed using CO2 as the underground working fluid, are particularly efficient compared to water-based systems when geothermal resource temperatures are in the range of 90-120 ^{o}C, Randolph and Saar (2011), which corresponds to the resource temperatures of numerous North American hydrocarbon fields, including but not limited to the Williston Basin, Alberta Basin, and portions of California, Wyoming, Colorado and the Gulf Coast. Naturally, such non-water geothermal deployments require CO2 to be circulated belowground, thus those regions with a long history of CO2-based enhanced oil recovery (EOR) are natural targets for deployment. Challenges of such deployments will include achieving sufficiently pure CO2 plumes belowground to achieve affective heat mining and will likely require additional, new CO2 injection.

Even when CO2 cannot immediately be deploy as a belowground working fluid, non-water geothermal deployed using only a CO2-based power system at the surface can be beneficial in hydrocarbon fields. In particular, such systems can be used as hybrid power facilities, Garapati et al. (2017). Hybrid geothermal facilities make use of all low-value energy resources available in hydrocarbon fields, including geothermal heat, industrial waste heat, and natural gas. Non-water, CO_2-based power systems provide an advantage over conventional binary geothermal technologies in that they can operate efficiently using high-grade energy source such as natural gas – for example, CO_2 power systems can use heat resources exceeding 600 ^oC, whereas most binary-cycle fluids operate below 165 ^oC. With the ongoing excess of natural gas in many hydrocarbon fields and its associated low value, providing an onsite, revenue-generating use for this resource may be of value to oilfield operators.

Finally, hybrid non-water geothermal facilities in hydrocarbon fields offer the opportunity to prevent CO_2 emissions from gas combusting without the need to transport that CO_2 and simultaneously incrementally develop underground CO_2 plumes for expanded non-water geothermal deployment. In a hybrid geothermal/natural gas facility, the CO_2 from gas combustion can be captured onsite and injected back into the hydrocarbon field, forming a CO_2 plume that can eventually be used for a CO_2 geothermal operation. We are working with a US company called Enviro Ambient, which holds CO_2 capture technology, to design and deploy such a facility in North America.

Scientific Background:

Our approach leverages the vast experience gained from CO_2 capture, utilization, and storage (CCUS) research community. The TerraCOH team and partners have advanced the pressure management strategy of producing brine to make room for safe CO_2 storage in saline reservoirs (Buscheck et al. (2016b; 2016c)). Our CO_2 Earth Battery approach manages pressure in the storage reservoir by diverting a portion of the produced brine once a target overpressure is reached at the injection wells. The target overpressure is that determined to efficiently drive working fluid circulation, while being low enough to reduce the risk of induced seismicity, caprock fracture, and CO_2 leakage. Diverted brine is available for beneficial consumptive use, such as for power-plant cooling, or for generating fresh water using desalination technologies.

CCUS in sedimentary basins is a promising approach that can reduce CO_2 intensity of fossil energy use, but the high cost of capturing CO_2 requires valuable uses for CO_2 to justify those costs. Our approach of using CCUS to generate geothermal energy and store energy is designed for locations where a permeable sedimentary formation is overlain by a caprock that is impermeable enough to constrain the vertical migration of buoyant, pressurized CO_2. In our approach, the initial "charging" of the system requires permanently isolating large volumes of captured CO_2 and thus creates a market for its disposal. Once charged, our system can take power from, and deliver power to, electricity grids in a way that mitigates issues with high penetration of variable wind and solar energy sources (e.g., reduce curtailments of wind power deliveries during periods of high winds and low loads). Our approach also constrains the potential migration of CO_2 while the well field is being operated, and reduces the potential for CO_2 leakage long after well-field operations have ceased.

As a heat extraction fluid, CO_2 has multiple thermophysical advantages (Adams et al. (2015)), including:

- low kinematic viscosity, compared to brine, allowing for effective heat advection despite its relatively low heat capacity.

- high thermal expansibility, compared to brine, generating a much stronger thermosiphon effect through the injection well, the reservoir, and the production well.

Compared to steam-cycle based power systems, when CO_2 is the working fluid, it reduces water intensity of power generation. Because our approach also generates water from diverted brine, our approach can be a water-neutral or even a water-negative electricity power-generation process.

Recently our CCUS-enabled geothermal energy approach has evolved to include storing thermal energy. Virtually all baseload power plants use heat to generate electricity. However, with the rapidly expanding use of variable renewable energy, it is becoming increasingly difficult for baseload power plants to operate at economically viable capacity factors. This is particularly problematic for deploying low-carbon fossil-energy power plants, due to the high up-front capital cost of the CO_2 capture infrastructure. Our approach provides an alternative pathway for utilizing low-carbon thermal energy at high capacity factors. During periods of over-generation, the thermal output from a low-carbon fossil-energy plant can be used to heat brine, which is pressurized and injected into our CO_2 Earth Battery™, using excess power from the grid. When demand exceeds supply, stored pressurized hot brine and stored pressurized CO_2 are produced. Heat from the hot brine is transferred to the produced CO_2 prior to sending the CO_2 through a Brayton Cycle turbine. An advantage of using CO_2, N_2, or flue gas in a Brayton Cycle turbine is that the exit temperature on a multi-stage process can be stepped down to close to ambient temperature, which allows for more efficient compression and storage. The heat of compression can also be recuperated to boost power.

Our approach has operational advantages over hydrostatic or under-pressured geothermal systems that require submersible pumps. Large centralized pumps located on the surface should be more efficient than submersible pumps. Moreover, surface-based pumps would not be exposed to the harsh conditions in production wells and would not require frequent maintenance that could disrupt production. When surface-based pumps require servicing, access is much easier than for submersible pumps. The multi-fluid geo-energy system would be particularly valuable in hydrostatic reservoirs where temperatures are too hot (> 200 °C) for submersible pumps, and it could also produce flow rates that are greater than the capacity of submersible pumps. Because bulk energy storage (BES) capacity increases with the ability to store pressure and because pressure-storage capacity increases with cushion gas volume, BES capacity increases with stored CO_2, N_2, or air mass.

Our team and academic partners have analyzed energy storage scenarios that store 90% of the CO_2 generated by 550 and 1100 MW coal-fired power plants. We have compared the levelized cost of storage (LCOS) for our energy technology with a range of existing energy-storage technology. We applied the same reservoir-simulation and techno-economic analysis methodologies used in Buscheck et al (2016), assuming a reservoir at a 1.5 km depth. Note that a depth of 1.5 km is quite shallow, compared with many geothermal reservoirs. Because drilling costs in relatively soft sedimentary rock will be less than in igneous and metamorphic rock associated with typical geothermal reservoirs, well-development costs for the Earth Battery compare favorably with geothermal power systems. Consequently, the estimated LCOS for the Earth Battery is similar to the LCOE associated with high-grade geothermal reservoirs. We compared the estimated energy storage capacity on a per cycle basis for the Earth Battery™, with current energy- storage technologies. We have conducted initial estimates of the per unit value of stored CO2, based on the assumption of selling energy storage for $100/MWh. For a storage temperature of 275 °C, we estimated energy-storage sales of about $200 per tonne of stored CO2.

Additionally, current models or storage efficiency show very promising results, including that the CPG system, operated in a diurnal cycle as an energy storage type system, can generate up to 2.93 times as much power as it consumes from the grid (including the geothermal energy generated by the system), Fleming et al. (2018). See Figures below. In an example analysis for the Midwest Independent System Operator, with such operation, the CPG system can generate equal returns to continuous CPG operation if the diurnal fluctuation in energy prices equals approx. a factor of 1.5 (i.e., the average maximum daily electricity price per kWh is 1.5 times the average low price), Fleming et al. (2017). This result is from pure electricity sales and does not yet include any values from ancillary services, which could be layered on top of the cyclical values.

Conclusion: Next Steps in Commercial Deployment of Non-Water Geo-Energy Systems

Power System Technology:

The extensive numerical modeling, completed over the previous nine years by the team of geoscientists, mechanical engineers, and economists that originally conceived of and investigated CP, has indicated that CPG, with appropriate power cycle technology, should be able generate electricity from low (<90 °C) or moderate (90 – 150 °C) temperature geologic energy resources, which are largely unused at present (Randolph and Saar (2011); Adams et al. (2015)). Geothermal resources with such lower temperatures, which generally occur in sedimentary basins, are far more ubiquitous in the US and worldwide than higher temperature resources (Gosnold et al. (2013)). Thus, deployment potential for CPG and the Earth Battery is broad.

Few components of a CPG power system have been tested in an integrated way, but the technology is based on existing understanding of geothermal technology, CO2 capture and storage, and decades of experience with CO2-EOR. Presently, we are in discussions with suppliers of novel power systems that can work with our technology, as we need to identify systems with rapid response times yet are still cost competitive. We are also in the early stages of designing a CO2-based power system for our applications with a large, multinational engineering/turbine company, and we will integrate on-demand operational considerations into these discussions.

Economic Modeling:

Current models developed by our team and academic partners have shown how our system can be operated dispatchably to capture diurnal and seasonal cyclical system behavior, and that the system can be cost-competitive with system operating continuously if there is sufficient difference between local minimum and maximum electricity sales rates. These models have accounted only for pure electricity sales and not for ancillary grid services, but they have begun to show that CPG operated as an energy storage/geothermal system can help balance cyclical behavior on the grid, providing a framework for true dispatchable analyses. Similar results are seen with seasonal energy storage – the CPG energy storage system appears able to effectively store energy for several months, which is completely unique for large-scale energy storage systems.

Finally, compared to other geothermal and renewable energy alternatives, our approach is uniquely able to capture value from direct CO2 credits associated with CO2 sequestration and utilization. This additional revenue stream, which may not be available everywhere, can substantially improve the LCOE of our system. One element of upcoming analyses will consider how the revenue stream associated with carbon credits might be affected by dispatchable operation.

Although our approach is not yet field tested, the required technology to test and deploy is readily available from the CCUS, geothermal, oil, and power industries. Consequently, we are in discussions with site owners in the US, Canada and Europe to develop pilot field projects of non-water geo-energy systems.

Disclaimer

Dr. Randolph has a significant financial and business interests in TerraCOH Inc., a company that may commercially benefit from the results of this research. The University of Minnesota has the right to receive royalty income under the terms of a license agreement with TerraCOH Inc. This relationship has been reviewed and managed by the University of Minnesota in accordance with its conflict of interest policies.

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