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Using Sequestered CO_2 as Geothermal Working Fluid to Generate Electricity and Store Energy

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ABSTRACT

The CO_2-Plume Geothermal (CPG) power system can operate either as a baseload power source or as a dispatchable generator, making power when it is needed on the electric grid. Unlike wind and solar, which are intermittent power sources that operate only when the wind blows or the sun shines, geothermal heat is always available and can be extracted as needed to generate electricity. As wind and solar begin to constitute a larger portion of the electricity provided to the grid, there is an increased need to provide flexible power generation that makes up the difference between demand and this varying renewable supply. Thus, CPG is a carbon-neutral, renewable, flexible power generator that can fulfill this need.

Unlike most geothermal technologies, CPG can be extended to be an energy storage system, termed CO_2 Plume Geothermal Energy Storage (CPGES). To create one version of a CPGES system, a second shallow reservoir is added to the CPG system. CO_2 is stored in this shallow reservoir in an intermediate state after power is generated but before the energy-intensive parasitic loads, which reduce the power plant's overall output. When the generation and parasitic stages are separated by time, nearly the full gross turbine electric generation can be sent to the grid when power is needed. Later, when electricity is cheap, power is taken from the grid and used to cool (and sometimes pump or compress) the CO_2. Thus, CPG is expanded into CPGES, adding energy storage to the electric grid.

In this work, we describe a new type of CPGES, termed Earth Battery Extension II (EBE II), which uses a large surface storage tank, or gasometer, to store the CO_2 at near-atmospheric pressure. This permits up 260 MW_e of electricity to be generated during the battery discharge phase compared to 2.5 MW_e for CPG alone. Additionally, the new CPGES system can be configured to produce solid CO_2 (dry ice) that can be sublimated at near atmospheric pressure, providing a -78 °C heat sink that can be used for cooling purposes in general and, specifically, to cryogenically capture CO_2 from the air. This CO_2 can, in turn, be used to develop more such CPGES systems. If no heat sink is desired, the turbine can be optimized by including (additional) stages that result in increased electric power output without dry ice formation.

1. INTRODUCTION

Global climate change, driven by the emission of CO_2 into the atmosphere, is changing the way humanity generates power. To meet projected climate goals, set by the Intergovernmental Panel on Climate Change (IPCC), the electricity generation sector is increasing the deployment of clean renewable energy systems, such as geothermal energy, while decreasing CO_2 emissions from existing power plants, using carbon capture and storage (CCS) (IPCC, 2005, 2014). Both geothermal energy and CCS can be combined into a CO_2-based geothermal system, where captured CO_2 is used to extract geothermal energy.

CO_2 can replace brine as the geologic heat extraction fluid in geothermal systems (Brown W., 2000; Randolph and Saar, 2010, 2011a). CO_2 is a better geothermal heat extraction fluid than brine, as CO_2 has a lower kinematic viscosity, which reduces the reservoir pressure loss in enhanced/engineered geothermal reservoirs (Brown W., 2000; Pruess, 2007; Pruess and Spycher, 2010) and in sedimentary-basin reservoirs (Randolph and Saar, 2011a, 2011b). Additionally, CO_2 has the advantage of generating a thermosiphon, which uses the density difference in the production and injection well to reduce the need for circulation pumps (Brown W., 2000; Atrens et al., 2009, 2010; Adams et al., 2014). These advantages allow CO_2-based geothermal systems to generate more power than brine-based geothermal systems at low to moderate geothermal reservoir temperatures and permeabilities (Adams et al., 2015).

CO_2-Plume Geothermal (CPG) is a technology that uses CO_2 as a geologic working fluid to extract heat from deep, naturally permeable sedimentary reservoirs (Randolph and Saar, 2011a, 2011b; Saar et al., (2012-2015); Adams et al., 2014, 2015). CPG systems are different from CO_2-based enhanced/engineered geothermal systems (CO_2-EGS), as EGS in general, by definition, requires artificial stimulation via hydraulic fracturing to increase the reservoir's permeability. Additionally, naturally permeable sedimentary reservoirs are typically considered for CCS sites due to their large CO_2 storage capacities. This allows CPG systems to store significantly more CO_2 than CO_2-EGS systems and operate at previously developed CCS sites. Additionally, CPG can operate at enhanced gas recovery (EGR) and enhanced oil recovery (EOR) sites, as long as CPG-specific conditions, particularly regarding reservoir temperature and pressure (Adams et al., 2015) as well as CO_2 saturation in the pore space (Garapati et al., 2015), are fulfilled. In fact, due to their closed-loop nature, CPG systems constitute permanent CO_2 storage (Randolph and Saar, 2011b).

The increased grid penetration of renewable energy will increase the need for both dispatchable power systems and for energy storage. Wind and solar are currently the fastest growing renewable energy systems, however, both of these technologies are inherently variable—generating power only when the wind blows or the sun shines. When these systems are integrated into the electricity grid, particularly at large capacities, dispatchable power generators or energy storage systems will be required to ensure that sufficient electricity generation (supply) is available to meet the grid load (demand). Energy storage systems are ideal for this role of supplementing variable renewable systems, as they can store energy when the renewable systems over-generate electricity and then dispatch the energy back to the grid later when the renewables under-generate.

Traditional energy storage systems include pumped hydroelectric, compressed air, and chemical batteries. However, each of these systems has significant drawbacks when supporting variable renewable power generation systems, such as solar and wind power, at large scales. Pumped hydroelectric systems are limited by the environmental impacts, long construction times, and high capital costs of new system creation, limiting additional development (Azzuni and Breyer, 2018). Compressed air systems are limited by the use of fossil fuels that are typically used during the power generation phase to heat air and therefore emit CO_2 into the atmosphere. In addition, geologic locations (caverns), suitable for compressed-air energy storage, are globally limited. Chemical batteries are limited by required rare earth element availability, their short service life, and the generation of hazardous pollutants over their complete life cycles (Dehghani-Sanij et al., 2019) including significant CO_2 emissions. Thus, alternative, large-scale, and environmentally more-sustainable energy storage systems are needed to supplement variable renewable energy systems.

CO_2-Plume Geothermal (CPG) systems can supplement variable renewable energy (solar/wind), either by operating as a dispatchable power generation system (basic CPG) or as a CPG Energy Storage (CPGES) system. A basic CPG system does not provide storage, but can vary its output as needed, as geothermal energy is always available for power generation unlike solar and wind, which are variable. A CPGES system supplements variable renewables by storing surplus (solar/wind) energy from the electricity grid and dispatching it back to the grid when the energy demand is high. The CO_2-Plume Geothermal Energy Storage (CPGES) system was first introduced in 2018 (Fleming et al., 2018). A modification of that CPGES system into the Earth Battery Extension II (EBE II) is the focus of this paper.

In this paper, we document a new CPGES system, specifically EBE II. The EBE II system, defined here, uses a surface storage tank or gasometer to store the CO_2 on the land surface (Saar and Adams, 2018). The storage of CO_2 at near-atmospheric pressure in a gasometer on the land surface between the power generation and storage modes differentiates this new system from the previous CPGES system, EBE I (Fleming et al., 2018; Adams et al., 2019; Fleming et al., in prep.). The EBE I uses a second, relatively shallow reservoir to intermittently store the CO_2 between the two modes at significantly above-atmospheric pressure. The reduced geologic constraints of the EBE II (with the gasometer) also increase the regional applicability of this new CPGES system. To distinguish between these two systems in this paper, we refer to the previous multi-reservoir CPGES system as the CPGES Earth Battery Extension I (EBE I) and the surface storage CPGES systems as the Earth Battery Extension II (EBE II) system (Saar and Adams, 2018), summarized in Table 1.

Table 1: CO_2-Plume Geothermal Systems

Term	*Acronym*	*Definition*
CO_2-Plume Geothermal	**CPG**	A geothermal system that uses CO_2 as the geologic working fluid in sedimentary reservoirs.
CO_2-Plume Geothermal Energy Storage	**CPGES**	A CPG system that is configured to operate as an energy storage system.
Earth Battery Extension I	**EBE I**	A CPGES configuration that uses multiple reservoirs to provide energy storage capabilities.
Earth Battery Extension II	**EBE II**	A CPGES configuration that uses a near-atmospheric pressure surface storage tank (gasometer) to provide energy storage capabilities. This system uses a multi-stage turbine with atmospheric reheating to increase power generation.
Earth Battery Extension II – Cooling	**EBE II-COOL**	A CPGES configuration that uses a near-atmospheric pressure surface storage tank (gasometer) to provide energy storage capabilities and to provide cooling, for example, for a cryogenic direct air CO_2 capture (DAC) system (not discussed in detail here).

2. METHODOLOGY

We numerically simulate the CO_2-Plume Geothermal (CPG) system and the CO_2-Plume Geothermal Energy Storage (CPGES) Earth Battery Extension II (EBE II) configuration. Both the CPG and the EBE II systems are shown in Figure 1. We simulate both systems as individual plants operating using the same geothermal reservoir and not as part of a larger CPG/CPGES field—such as the 25-system field, which was determined to reduce the Levelized Cost of Electricity/Energy (LCOE) and provide ~25 times more power generation than a single system in isolation (Bielicki et al., 2016).

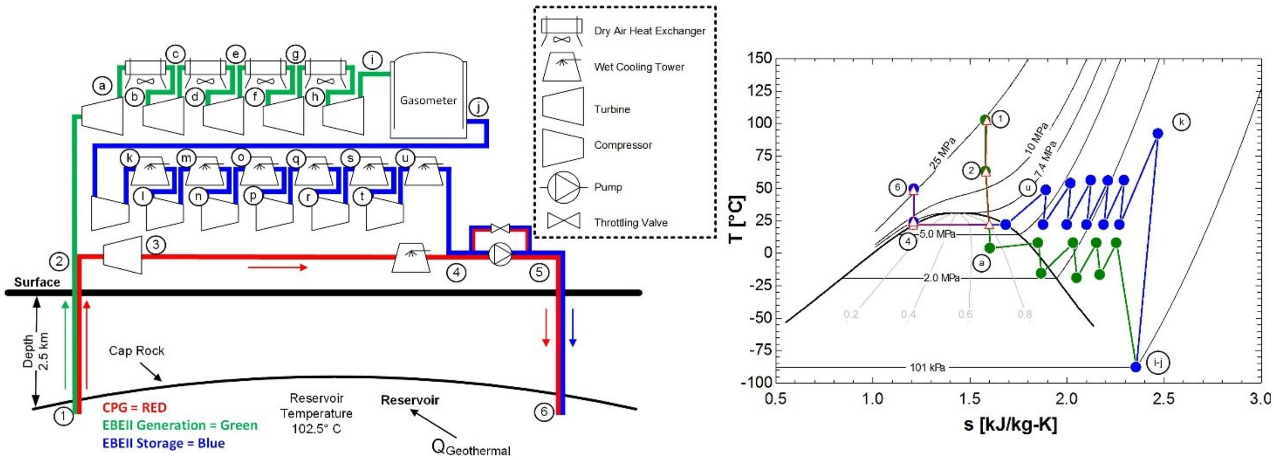

Figure 1: The system diagram (left) and temperature-entropy (T-s) diagram (right) for the CPG power cycle (red) and the CPGES-EBE II generation mode (green) and storage mode (blue). The CPG system is converted to the CPGES-EBE II system by adding a surface gasometer to store the CO_2 between modes and adding low-temperature turbines with atmospheric reheat elements to increase power generation (and to avoid solid CO_2 (dry ice) formation – thus no cooling is included in this particular implementation).

2.1 The CPG System

The CO_2-Plume Geothermal (CPG) system is shown by the red lines in Figure 1. A detailed description of the CPG model and assumptions is provided in our previous publications (Adams et al., 2015, 2019) and is thus only summarized here.

The CPG system continuously circulates CO_2 between the reservoir and the surface plant to generate electricity. Hot CO_2 is extracted from the reservoir at the production well at State 1 and is produced to the surface (State 2) in an adiabatic production well. At the surface, the CO_2 is expanded in a turbine to generate power (State 2 to 3). The turbine back pressure is set at 6.0 MPa—the saturation pressure at a 22°C CO_2 condensing temperature (i.e. sum of the 15°C ambient and 7°C approach temperature). After the turbine, the CO_2 is isobarically cooled and condensed to achieve a saturated liquid state using wet cooling towers (State 3-4). The cold dense CO_2 is compressed and injected back into the reservoir through the adiabatic vertical injection wells. A circulation pump is used prior to the injection well to augment the thermosiphon and increase the power generation of the system.

2.2 The CPGES-EBE II System

The CPGES-EBE II system (EBE II hereafter) operates as an energy storage system by separating the components that generate and consume power by using a gasometer storage tank to store the CO_2 at near-atmospheric pressure at the land surface. The use of the surface storage tank differentiates this system from the previous CPGES-EBE I configuration (EBE I hereafter), which instead uses a second, relatively shallow reservoir to store the CO_2 (Fleming et al., 2018; Fleming et al., in prep.).

The EBE II power generation mode process (green line) including the addition of the gasometer is shown in Figure 1. At the land surface, the EBE II system replaces the single-stage turbine of the CPG system with a five-stage turbine with atmospheric re-heating between each stage (States 2 to i). The pressure drop across each turbine stage (i.e. turbine expansion) is selected to optimize the overall power generation of the system, with turbine back pressures of: 3.85 MPa, 2.26 MPa, 1.41 MPa, and 0.89 MPa. The gasometer storage pressure, and thus the final stage turbine backpressure, is assumed to be at atmospheric pressure—as the gasometer storage is a constant-pressure process. Each turbine stage is modeled using a 78% isentropic efficiency (Adams et al., 2014, 2015, 2019; Fleming et al., 2018), and each reheating process is assumed to reheat the CO_2 to 8°C (i.e. a 7°C approach temperature). The parasitic power consumption by the atmospheric re-heaters is modeled using the parasitic power loss fraction of dry cooling towers from the supplemental information of Adams et al. (2015). Thus, the net power that is generated during the generation mode is the sum of the turbine power generation and the power consumed (negative) by the inter-stage re-heating fans.

The EBE II power storage process is shown by the blue line in Figure 1. The CO_2 is retrieved from the isobaric and isothermal gasometer and is compressed and cooled in a six-stage compressor with atmospheric inter- cooling and condensing via wet cooling towers (State j to 4). Each compression process is modeled, using a 78% isentropic efficiency and each cooling tower operates with a minimum temperature of 22°C (i.e. 7°C approach temperature). The parasitic power consumption of each wet cooling tower is determined from the relations in the supplemental information of Adams et al. (2015). Finally, a pump is used at the land surface to augment the gravitational compression in the vertical well, similar to the CPG system.

Additionally, it is worth noting that the EBE II system will always have net energy consumption over a complete cycle, despite the atmospheric and geothermal heat addition, as the compression and cooling processes occur at higher temperatures and pressures than the turbine expansion process, as shown in the T-s diagram in Figure 1.

The EBE II system can be modified to an EBE II-COOL system, which provides a cold sink from sublimating solid CO_2 (dry ice) to CO_2 gas during the power generation mode (Saar and Adams, 2018). As the CO_2-sublimation-based heat sink temperature is -78°C, it can be used for cryogenic direct air CO_2 capture (CO_2-DAC). The EBE II-COOL implementation removes the additional turbine stages (State b to i) from the EBE II and adds an isobaric heat exchanger before the gasometer. We do not further discuss this modified EBE II-COOL system here, as the system generates less power (but adds a -78°C heat sink that can be of interest for certain applications, such as district cooling or the aforementioned CO_2-DAC).

2.3 Numerical Models

The subsurface reservoir is modeled using TOUGH2 (Pruess et al., 1999), using the ECO2N equation of state module (Pruess, 2005). The reservoir is modeled using a radial 2D axisymmetric grid. The grid extends horizontally to 100km to reduce boundary effects. The circular, horizontal injection well is located at the bottom of the reservoir at a radius of 200m. The circular horizontal production well is located beneath the caprock at a radius of 707m, consistent with previous simulations (Garapati et al., 2014, 2015; Adams et al., 2015; Fleming et al., 2018). The reservoir is initially filled with a 20% NaCl brine. The CO_2 plume is developed by injecting 15.8 Mt of CO_2 over 2.5 years prior to the system onset. The CPG and EBE II systems both use the same 2.5 km deep reservoir configuration. All reservoir parameters are given in Table 2.

The vertical wells and the surface power plant are simulated using Engineering Equation Solver (EES) (Klein and Alvarado, 2002). The surface power plant parameters are given in Table 2, and the surface power plant model is consistent with previous studies (Garapati et al., 2014; Adams et al., 2014, 2015, 2019; Fleming et al., 2018; Fleming et al., in prep.).

We demonstrate the performance of the EBE II system, operating on a diurnal (i.e. 24-hour) cycle. We use four duty cycles to simulate the different operations of the system, listed in Table 2.

Table 2: Simulation Parameters.

Parameter	*Value*		
Vertical Injection Wells	1		
Vertical Production Wells	4		
Reservoir Depth	2.5 km		
Reservoir Temperature	102.5 °C		
Reservoir Pressure	25 MPa		
Geologic Temperature Gradient	35 °C/km		
Reservoir Thickness	300 m		
Surface Temperature	15 °C		
Vertical Well Diameter	0.41 m		
Turbine Isentropic Efficiency	78%		
Compressor Isentropic Efficiency	78%		
Pump Isentropic Efficiency	90%		
Reservoir Permeability	50 mD		
Cycle Period	24 hours		
Duty 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 Circulation Rates/ Storage Tank Characteristic Length*	Rate	Cube Length	
	5.8 kt/day	124.7 m	
	8.6 kt/day	142.8 m	
	11.5 kt/day	157.1 m	
	14.4 kt/day	169.3 m	
	17.3 kt/day	179.9 m	
	20.2 kt/day	189.3 m	
	23.0 kt/day	198.0 m	
	28.8 kt/day	213.2 m	
	34.6 kt/day	226.6 m	

* The characteristic dimension for a cube storage tank, the cube root of the storage volume

3. RESULTS

We characterize the performance of the EBE II system in terms of power generation, power consumption, energy generation capacity, and the energy storage capacity. The presented results reflect the performance in the 10th year of the system operation.

The operation of each of the four diurnal duty cycles for the EBE II system is shown in Figure 2. These duty cycles demonstrate the flexibility of the EBE II system, ranging from sustained power generation (16h-8h cycle in Figure 2A) to short peaking power (4h-20h cycle in Figure 2D). The flexibility of this system indicates that this system is ideal for supporting the highly variable wind and solar power systems. For example, when supporting a solar energy farm, the EBE II system can provide short-term power when clouds pass over the solar collectors (i.e. the 4h-20h duty cycle), as well as longer sustained generation to time-shift the dispatch of solar energy to night periods or prolonged cloud cover, when solar is not available (i.e. the 16h-8h duty cycle).

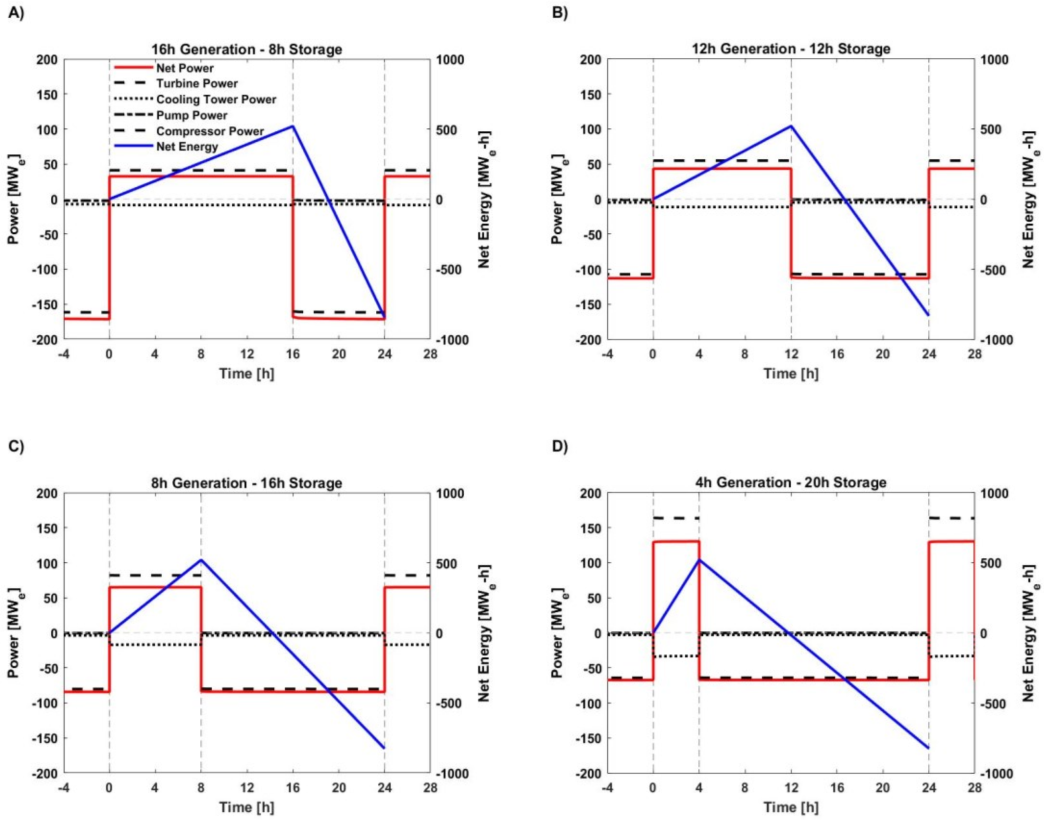

Figure 2: The power and energy generated and consumed over the complete 24-hour cycle for each duty cycle at a daily CO_2 circulation rate of 17.3 kt/day.

The power generated and stored by the CPGES system is shown in Figures 3A and 3B, with the CPG net power generation included for reference. The powers generated and consumed by the EBE II system are not impacted by the reservoir pressure loss (i.e. the reservoir pressure drawdown at the production well and the reservoir over-pressurization at the injection well), indicated by the linear relation with the mass flow rate. This differs from the performance of the CPG and EBE I systems that are impacted by the same reservoir pressure loss and have concave down power generation and concave up power consumption profiles, resulting in a daily circulation rate that maximized the power/energy generation (Adams et al., 2015, 2019; Fleming et al., in prep.).

The EBE II system limits the impact of the varying reservoir pressure on power generation by storing the CO_2 at a lower pressure at the surface, increasing the pressure differentials across the turbine. The turbine stage shared by both the EBE I and EBE II systems generates less than 16% of the total turbine power generation in the EBE II system. Thus, while the EBE II system has the same varying reservoir production pressure as the EBE I system, it has a minimal impact on the total power generated by the EBE II system.

Similarly, unlike in the EBE I system, the power consumption of the EBE II system is not impacted by the overpressure at the injection well downhole. In the EBE II system, the low storage pressure requires the addition of several compression and cooling stages which are not present in the EBE I system, significantly increasing the total power consumption. Thus, while both the EBE I and EBE II systems have similar circulation pump powers to overcome the high reservoir injection pressure, it accounts for less than 5% of the total power consumed in the EBE II system. Thus, unlike the EBE I system, the power performance of the EBE II system is not substantially affected by high and varying reservoir pressures.

The reservoir pressure variations do not constrain the maximum power generated by the EBE II system. Thus, the volume of the gasometer for CO_2 storage is the factor that limits the energy storage. The gasometer stores the CO_2 in a low-density state, requiring large storage volumes, unlike the relatively high-density storage within the shallow subsurface reservoir of EBE I. For example, at the highest daily CO_2 circulation rate considered, 34.56 kt/day, the EBE II system requires a CO_2 storage volume of 1.16×10^7 m^3, or a cube with length of 227 m. Thus, the size of the EBE II system will be limited by the size constraints of the surface storage volume, i.e. the gasometer(s).

The total energy discharge and storage capacities of the EBE II system are shown in Figures 3C and 3D. The generation and storage energies of the system are linear and do not vary significantly with the duty cycle, as the power generation and storage are both linear functions and do not vary with the reservoir pressure loss. The only exception is, that, at high circulation rates, the 16h-8h duty cycle has a slightly higher storage energy than the other duty cycles because pump power is greater at shorter energy storage periods.

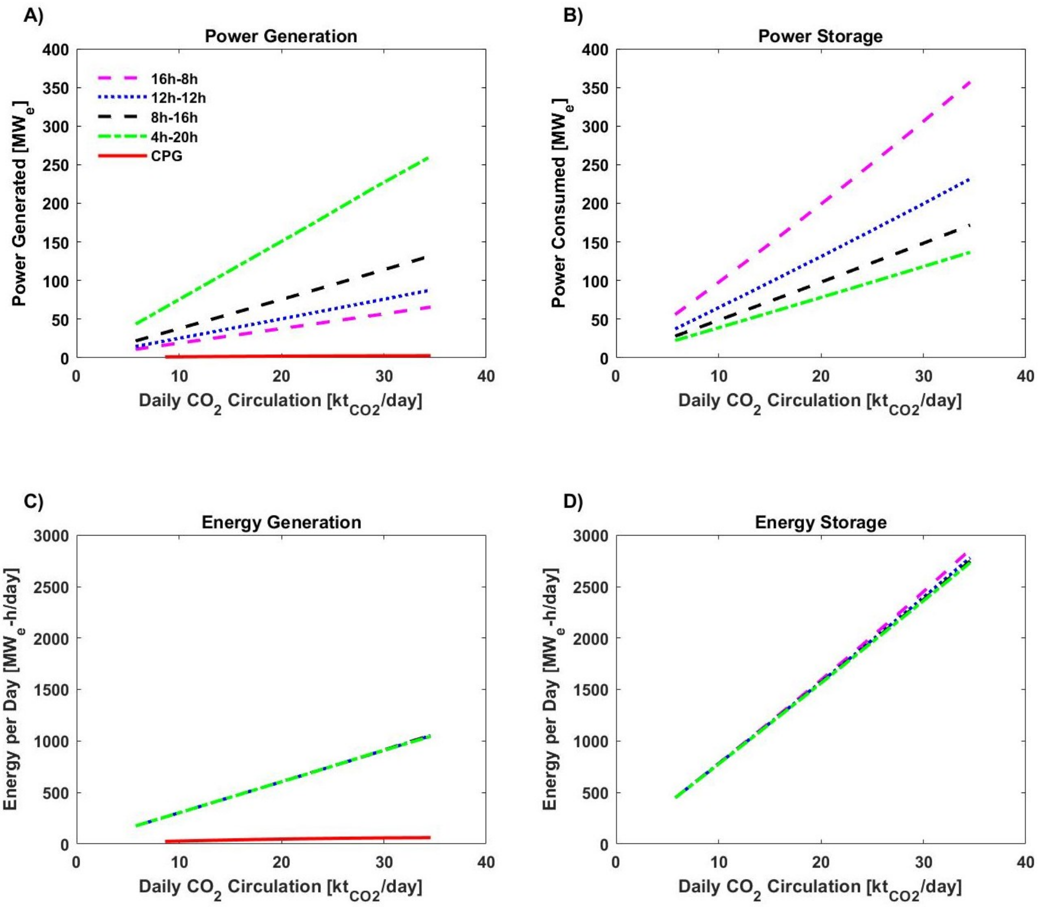

Figure 3: The performance of the CPGES-EBE II system, relative to the CPG power system, demonstrated in terms of (A) the dispatchable power, (B) the stored power, (C) the generation capacity, and (D) the storage capacity. Note: The CPG power system generates power continuously and thus does not have a storage power or energy storage capacity.

4. CONCLUSION

We demonstrate the performance of a new type of CO_2-Plume Geothermal Energy Storage System (CPGES), termed EBE II, that operates using a surface gasometer to store the CO_2 near atmospheric pressure. The results allow us to draw the following conclusions.

- The CPGES-EBE II system (or EBE II for short) can provide flexible power dispatch that can support variable renewable energy systems such as solar or wind power. Operating on a diurnal (i.e. 24-hour) cycle, the EBE II system can generate short peaking power for several hours or for sustained power generation for extended periods of time.

- The power and energy generation and storage capacities are not impacted by the pressure loss in the reservoir, with power generation always increasing with the daily circulation rate. This differs from the CPG and the previous EBE I systems, which have reduced generation capacities at larger mass flow rates. As a result, the EBE II system is not constrained by reservoir performance, but is instead limited by the surface storage volume of the gasometer(s).

- At a daily CO_2 circulation rate of 34.6 kt/day, the EBE II generates approximately 1050 MW_e-h of energy, varying power generation between approximately 65 and 260 MW_e, depending on the duty cycle. For comparison, at the same circulation rate, CPG alone generates 2.5 MW_e.

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DISCLAIMER

The authors declare the following competing financial interests: M.O. Saar declares financial interest in the form of technology commercialization through CO2 POWER GmbH, of which he is a shareholder, and B.M. Adams declares financial interest in the form of royalties from technology commercialization on a related patent.

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