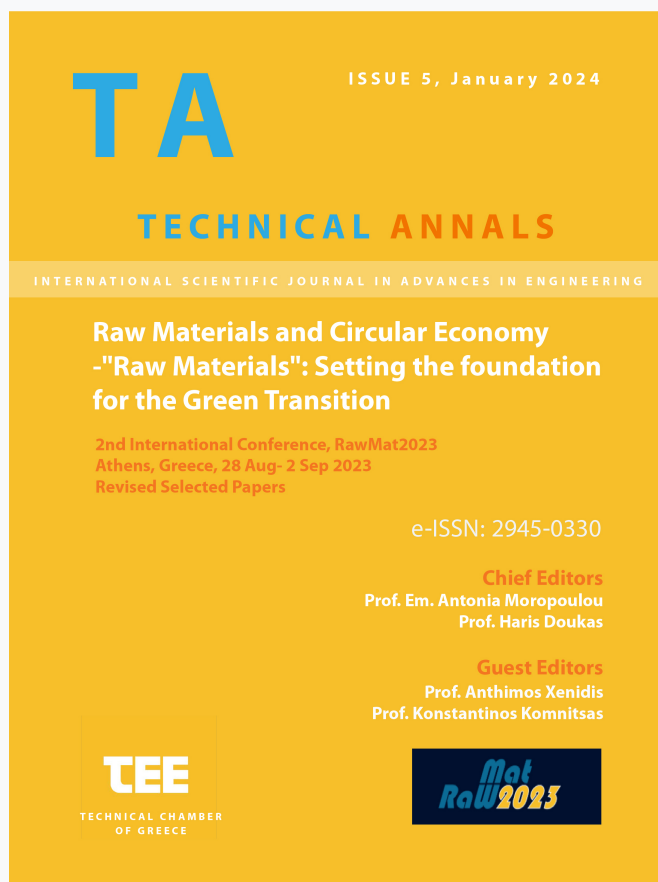


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Integrated Raw Material Approach to Sustainable Geothermal Energy Production: Harnessing CO₂ for Enhanced Resource Utilization

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Abstract. CPG (CO₂ Plume Geothermal) has recently emerged as a promising technology that combines the extraction of geothermal energy with underground CO₂ storage, thus aligning with the energy objectives of Greece according to the National Energy and Climate Plan. The concept of CPG revolves around treating CO₂ as a raw material, recycling it through continuous injection and production to and from a subsurface reservoir, taking advantage of the discrete plume that forms on top of the subsurface formation. As CO₂ is injected, it contacts the hot formation and captures thermal energy which is eventually transferred from the reservoir to the surface facilities where it gets exploited in thermal plants. The CO₂ flow system is closed thus offering the permanent storage option. Despite the favorable aspects of this technology, such as reduced energy requirements for fluid recycling, improved mobility and a smaller environmental footprint, there are also challenges that require careful consideration. CO₂ is less viscous and lighter than resident brine, thus fingering effects are more prominent than sweeping displacement. As a result, CO₂ breakthrough appears soon, even at wells designed for pressure maintenance through brine extraction. This highlights the need for a thorough study of the geological field and reservoir, along with the optimization of the production system's design. This study presents a comprehensive analysis of a geothermal reservoir and covers an optimized dynamic simulation for a combined geothermal, CO₂ storage and CPG system. Results demonstrate that a sustainable carbon-negative energy-producing power plant is possible. Such systems can also be implemented in already existing industries, providing a source of energy for secondary operations while also positioning the operators more strongly in the carbon tax market.

Keywords: CO₂ Plume Geothermal, Reservoir simulator, CO₂ injection

1 Introduction

The incessant rise in carbon dioxide (CO₂) emissions, particularly at the industrial level, has become a pressing global concern, propelling the exploration of innovative

strategies for mitigation. Industries, traditionally significant contributors to greenhouse gas emissions, are now compelled to reassess their environmental impact. Carbon Capture and Utilization (CCU) [1] has emerged as a beacon in this pursuit, providing a dual-pronged solution. The capture element involves deploying advanced technologies to intercept CO₂ emissions at their source, curbing their release into the atmosphere and thereby mitigating climate change. This approach not only aligns with environmental goals but also positions industries as proactive participants in the global transition toward sustainable practices.

As the emphasis on reducing carbon footprints intensifies, the concept of CCU extends beyond emission handling, delving into the realm of CO₂ utilization as a raw material [2]. Captured CO₂ is transformed from a perceived environmental liability into a valuable resource. Chemical utilization techniques offer a diverse array of possibilities, ranging from the production of synthetic fuels and chemicals to carbonating concrete. By integrating CO₂ into various industrial processes, CCU not only minimizes environmental impact but also drives innovation, paving the way for a more sustainable and circular economy. This chemical utilization aspect of CCU represents a transformative step toward turning emissions into assets, fostering economic growth while simultaneously mitigating climate change [3]. As a result capture and utilization (Figure 1) allow CO₂ to be considered as a raw material rather than as an environmentally detrimental waste product.



Figure 1 Classification of CO₂ utilisation options (Provided by the US Department of Energy's National Energy Technology Laboratory)

Fig. 1. CO₂ utilization.

[<https://www.linkedin.com/pulse/carbon-capture-utilization-conference-con4-final-bookings-lavery/>]

In the context of sustainable energy practices, CO₂ Plume Geothermal (CPG) emerges as a pioneering method that seamlessly intertwines carbon capture with the

efficient utilization of Earth's geothermal resources by utilizing CO₂ as the processing material. Resources are defined as naturally occurring substances or phenomena that can be used for economic gain. When it comes to geothermal energy, resources refer to the geothermal heat available in the Earth's crust that can be harnessed for power generation.

Usually as we move from the earth's surface towards the core, temperature increases as a result of heat transfer from the much hotter interior of it to the outer layers, a parameter named geothermal gradient. While the average values of it are around 3 degrees per km, at specific areas, the geothermal gradient is much higher, enabling for utilization of it as geothermal energy in relatively medium to deep depths. Geothermal power plants, in their classic framework, harness the temperature gradient between the Earth's heated subsurface rock and the cooler surface to generate electricity. These systems transfer thermal energy from below the ground to the surface using a working fluid, which then undergoes a partial conversion of its thermal energy to electricity in a power plant. The cooled working fluid is usually reinjected into a subsurface reservoir to maintain hydraulic sustainability. Conventional geothermal energy technologies use hot brine as the working fluid. Subsequently, geothermal power plants are usually constructed in regions with active tectonic or volcanic activity, where the temperature gradient is exceptionally high [4]. These areas are referred to as high enthalpy fields and are exploited for power generation. In Greece, for instance, most of them are directly linked to the well-known subduction of the African lithospheric plate beneath the Aegean microplate and the subsequent formation of the South Aegean Active Volcanic Arc (SAAVA). Geothermal fields associated with the volcanic activity are found in the Cyclades group of Islands (such as the established Milos and Nisyros fields) and in the broader vicinity of Lesbos Island (the former location of the arc that has now shifted southwards) [5]. Additionally, within the same region, shallow-depth, low-temperature geothermal fields also exist, as seen in the case of Santorini Island, classified as "probable". In the context of geothermal energy, "probable" refers to areas where geothermal activity is suspected but not yet fully confirmed or exploited. Additionally, in northern continental Greece, particularly within the sedimentary basins of Strymon in the Deltas of Evros and Nestos Rivers and in the Island of Samothrace, low, medium and high enthalpy resources, exploitable down to depths of 2 to 3km have been reported [6]. The latter potential fields located in the wider area of Alexandroupolis city, may very well be suitable for the dual-purpose of CPG, since they are deep geothermal energy carriers near highly populated cities that need this kind of green-generated power. Nevertheless, these unique thermal resources are limited in terms of both size and location, necessitating the development of innovative technologies to tap into the abundant thermal energy within the Earth's crust.

Enhanced Geothermal Systems (EGS) have been proposed as a way to extend the reach of geothermal resources by artificially creating reservoirs in regions lacking suitable conditions [7]. These systems typically entail injecting cold pressurized water to hydraulically fracture a subsurface formation. The injected water absorbs heat and is then brought back to the surface.

As opposed to conventional geothermal energy extraction, which relies on water as a heat transfer medium, CPG leverages captured CO₂ as the working fluid. This not only

addresses the need for emission reduction but also enhances the efficiency of geothermal energy extraction. By utilizing CO₂ in this geothermal context, the technology demonstrates its versatility in contributing to both environmental stewardship and sustainable energy generation. The integration of CPG represents a noteworthy stride toward achieving a balance between carbon capture and geothermal energy utilization. Apart from its environmental footprint, CO₂ has been suggested as an alternative working fluid thanks to it being abundant and possessing non-flammable properties [8]. CPG systems utilize CO₂ as the primary subsurface working fluid in naturally permeable sedimentary basins or EGS, creating a large-scale CO₂ plume. Additionally, a buoyancy-driven thermosiphon can be established by exploiting variations in CO₂ density between injection and production wells. This approach eliminates the need for costly pumping, which is commonly associated with conventional hydrothermal setups.

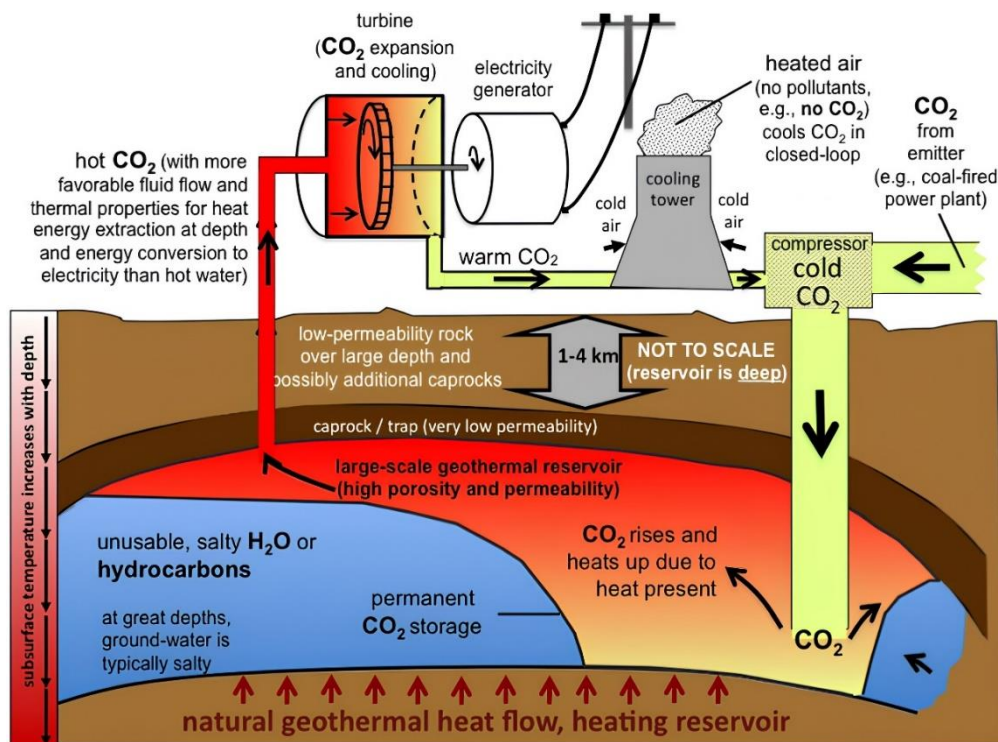


Fig. 2. CPG system.

[<https://www.thinkgeoenergy.com/cpg-systems-storing-co2-for-geothermal-energy-production/>]

Sedimentary basins suitable for CPG systems are found worldwide [9]. These basins often consist of aquifers with excessive salinity, making them unsuitable for drinking or industrial purposes. They may also include partially depleted oil and gas fields utilized for Enhanced Oil Recovery (EOR) operations [10]. In a CPG system, the buoyant CO₂ needs to be confined by very low-permeability or fully impervious caprock beds covering the permeable reservoirs. CPG systems can be seamlessly integrated with CO₂

Capture and Storage (CCS) sites [11], [12], [13], enabling the simultaneous generation of electricity and heat while securely sequestering CO₂. This integration ensures reservoir stability by mitigating overpressurization concerns associated with standalone CCS operations, which could trigger human-induced seismicity and CO₂ leakage. Furthermore, a combined CPG-CCS system can enhance the economic viability of CCS, thereby supporting global initiatives to address climate change. However, challenges associated with using CO₂, such as its reduced density at reservoir conditions and potential environmental impact in case of leakage, require further research and development. To address the risks linked with employing CO₂, CPG (Figure 2) energy systems have been recently introduced and developed [14], [15], [16].

A meticulously designed CPG development plan is required for industries characterized by substantial CO₂ emissions, reminiscent of operational dynamics found in cement plants, refineries, or offshore oil rigs. At the heart of the plan lies the integration of a carbon-negative energy-producing subsystem, leveraging advanced carbon capture technologies to convert emissions into valuable resources while simultaneously generating clean energy. For example, within the cement industry, captured CO₂ [17] is harnessed in chemical processes like synthetic fuel production or concrete carbonation, not only minimizing the industry's environmental footprint but also fostering a circular economy. Offshore oil rigs, benefit from reduced carbon tax liabilities by securely storing captured emissions underground. The stored CO₂ is repurposed for Enhanced Oil Recovery (EOR) or other industrial processes, creating an additional revenue stream and contributing to a more sustainable energy landscape. This strategic approach seamlessly applies to energy-intensive manufacturing sectors such as steel production [18], where advanced carbon capture technology enables the creation of valuable chemicals or the generation of green hydrogen. This contributes significantly to the broader shift towards sustainable energy sources. Moreover, the integration of a carbon-negative subsystem not only tackles environmental issues but also boosts the economic feasibility of these operations. Through the active production of clean energy, this approach not only reduces emissions but also diminishes dependence on conventional energy sources, thereby establishing a more robust and eco-friendly energy provision for these industries. Crucially, the carbon-negative subsystem positions these industries strategically within the carbon tax market. By proactively managing emissions, generating clean energy, and offering storage services to other sectors, these industries not only reduce their carbon tax liabilities but also capitalize on the burgeoning carbon market, creating new revenue streams. This cross-industry utilization of captured CO₂ exemplifies a holistic strategy, transforming emissions into valuable resources, producing clean energy, and positioning industries as active contributors to global climate change mitigation. By embracing environmental responsibility and strategically placing themselves in the carbon tax market, these industries not only ensure regulatory compliance but also foster sustainable and circular industrial practices for a greener and more resilient future.

In this work, a joint CPG-CCS plan is designed, in continuation to our previous work [19], to showcase its operational stability as an energy producing subsystem of a greater industrial plant. The basis of the operation is a deep anisotropic saline aquifer that is expansive, closed and inclined while being fully saturated with brine. The elevated

temperature of the aquifer exceeds typical thermal gradient expectations, attributable to underlying magmatic activity. Additionally, the aquifer exhibits slight underpressurization, suggesting that the total stored CO₂ mass may surpass initial estimates before reaching the fracturing pressure. The high and isotropic permeability of the aquifer results in a nearly uniform pressure distribution across all its cells. Monitoring the pressure within the aquifer becomes crucial to ensure that the fracturing limit, which could lead to undesired rock fractures, is not exceeded. Numerical solutions are employed to solve the mass, momentum, and energy differential equations governing fluid flow in the porous medium. Nevertheless, various analytical solutions, corroborated by numerical simulations, have been proposed to address related issues such as cap rock uplift [20], plume pressure buildup [21], and the analysis of flow regimes [22].

The rest of the paper is organized as follows. In Section 2, the most important aspects of Carbon Capture Utilization and Storage (CCUS) processes are explored. The subsurface system along with the injection/production schedules followed will be presented in detail in Section 3. Results and discussion are facilitated in Section 4. Finally conclusions are drawn in Section 5.

The units used throughout the text and their conversion factors are shown in Table 1.

Table 1: Unit conversion

Property	Name	Symbol	SI conversion
Pressure	pounds per square inch	<i>psi</i>	6,894.76 <i>Pa</i>
Temperature	Fahrenheit	<i>F</i>	$(K - 273.15) \cdot 9/5$
Depth	feet	<i>ft</i>	0.3048 <i>m</i>
Permeability	milliDarcy	<i>mD</i>	10^{-15} m^2
Gas volume	cubic feet	<i>cf</i>	0.028 <i>m</i> ³
Liquid volume	stock tank barrel	<i>STB</i>	0.16 <i>m</i> ³
Mass	pounds	<i>lbm</i>	0.45 <i>kg</i>

2 CCUS

2.1 Carbon capture

Carbon capture is the first in a series of steps contributing to the global effort to mitigate climate change, as it plays a pivotal role in reducing greenhouse gas emissions. The process involves capturing CO₂ emissions from various sources, preventing their release into the atmosphere and contributing to the accumulation of greenhouse gases. According to the Global Carbon Project, in 2022, human activities released approximately 37 billion metric tons of CO₂ into the atmosphere [23]. These emissions originated from industrial facilities, power plants, cement factories, as well as natural sources like wildfires and volcanic activity. Given their contribution to the greenhouse effect, the significant scale of these emissions underscores the urgent need for effective carbon capture strategies to address the escalating levels of greenhouse gases and mitigate their

impact on climate change. A major issue arises from the fact that CO₂ typically occupies a small fraction of the emitted streams typically of the order of 10%. Therefore, developing economically viable methods to capture a nearly pure stream of CO₂ from emissions remains an ongoing area of research.

One of the most widely studied and implemented methods for CO₂ capture is post-combustion capture (PCC) shown in Figure 3. In the context of power plants, PCC involves capturing CO₂ emissions after the combustion of fossil fuels, mainly aiming to remove the CO₂ along with other combustion byproducts such as nitrogen oxides (NO_x) and sulfur oxides (SO_x). Amine-based solvents, such as monoethanolamine (MEA), are frequently employed in PCC systems due to their high affinity for CO₂ [24]. These solvents absorb CO₂ from flue gas streams, facilitating its separation. Another technique in PCC involves the utilization of advanced sorbents, such as supported amine sorbents. These solid sorbents, with amine groups immobilized on a solid substrate, offer advantages such as reduced energy requirements and potentially lower operating costs compared to liquid solvents. Supported amine sorbents exhibit high CO₂ capture capacity and can be regenerated for multiple cycles, making them an attractive option for PCC applications [25].

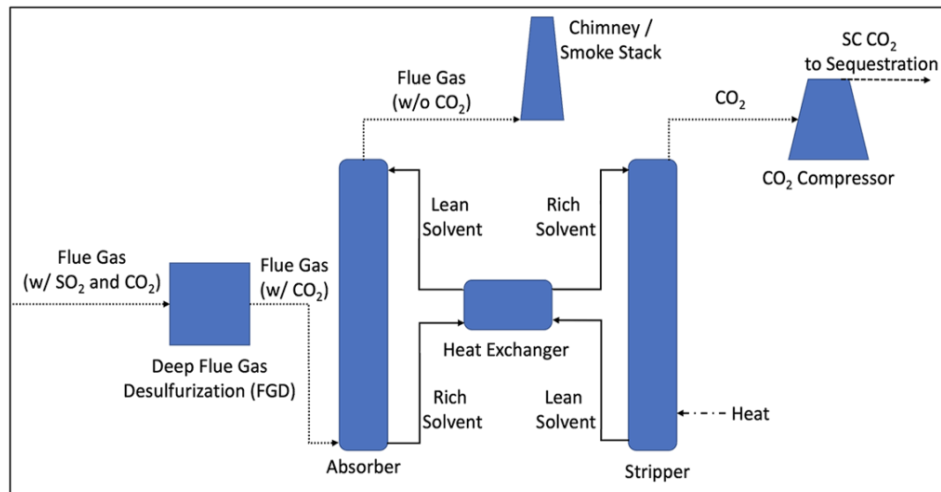


Fig. 3. Post combustion capture.

[<https://www.long-intl.com/blog/post-combustion-capture/>]

On the other hand, pre-combustion capture seen in Figure 4, involves the removal of CO₂ before the combustion of fossil fuels, commonly associated with Integrated Gasification Combined Cycle (IGCC) power plants [26]. In IGCC, fossil fuels are gasified to produce a syngas, from which CO₂ can be captured before combustion, allowing for the more efficient capture as the fuel gas contains a higher concentration of CO₂ compared to the overall combustion products.

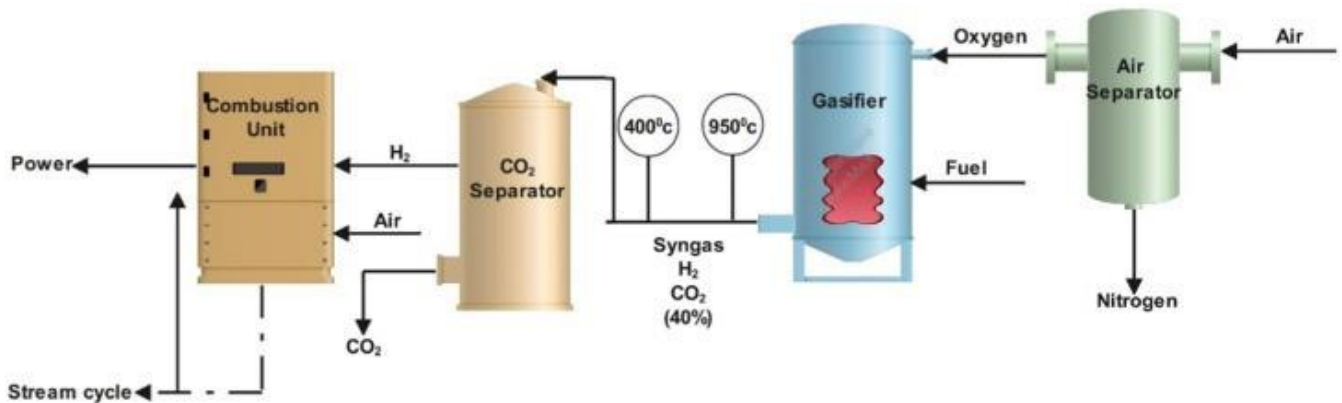


Fig. 4. Pre combustion capture [27].

[<https://www.sciencedirect.com/topics/earth-and-planetary-sciences/pre-combustion-capture>]

Finally, oxyfuel combustion involves burning fossil fuels in an oxygen-rich environment, resulting in a flue gas predominantly composed of CO₂ and water vapor rather than N₂ (see Figure 5). Thanks to its rich concentration, the CO₂ stream can be easily captured. This method is often considered for its compatibility with existing combustion technologies [28].

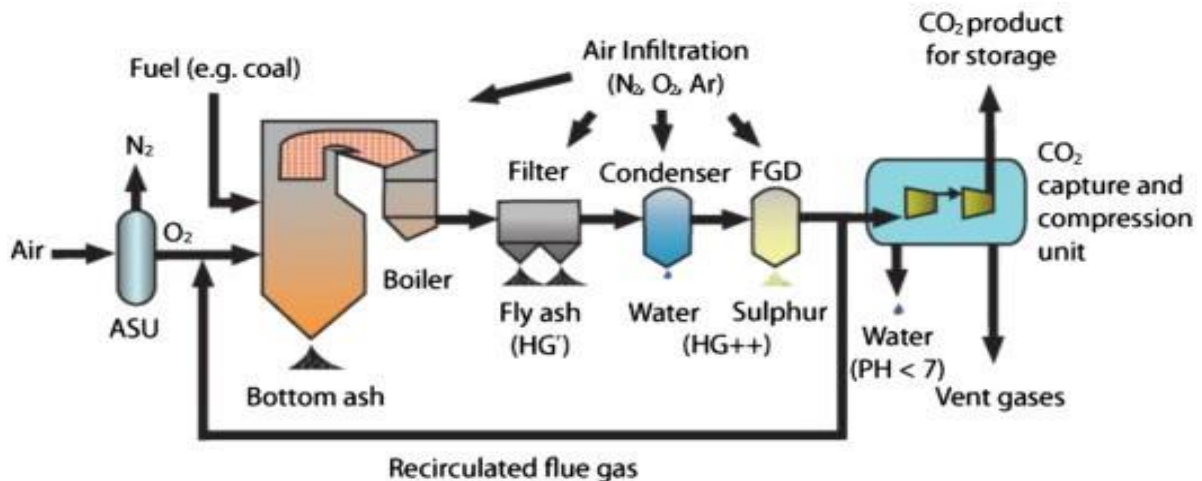


Fig. 5. Oxyfuel combustion capture [27].

[<https://www.sciencedirect.com/topics/engineering/oxyfuel-combustion>]

2.2 Carbon Utilization

Carbon utilization, or carbon capture and utilization (CCU), stands as a pivotal approach in the global initiative to combat climate change by considering CO₂ as a raw material which can be converted into valuable products. This strategy offers an alternative to traditional emission reduction methods and contributes to the establishment of a circular carbon economy. Diverse pathways within carbon utilization have been explored, each offering distinctive opportunities for sustainable carbon management.

One significant avenue in carbon utilization involves incorporating CO₂ into chemical synthesis processes to produce valuable compounds, such as chemicals, polymers, and fuels. Catalytic processes, for instance, can convert CO₂ into methane or ethylene, showcasing the potential for reducing emissions while generating useful materials [29]. Biological carbon utilization represents a sustainable avenue, where microorganisms can be engineered to utilize CO₂ for the production of biofuels, chemicals, and other bioproducts, offering a nature-inspired solution to carbon management challenges [30]. In the realm of electrochemical conversion, technologies such as electrochemical reduction enable the conversion of CO₂ into valuable products using renewable energy sources. This approach presents a promising tool for synthesizing fuels like methane or ethylene [31]. Additionally, while the production of certain products from CO₂ may result in emissions of other greenhouse gases or pollutants, comprehensive lifecycle analyses and strict environmental regulations can help minimize these unintended consequences and ensure that the net impact on the environment remains positive. In summary, carbon utilization strategies offer promising pathways to transform CO₂ from a pollutant into a valuable resource. Continued research and innovation are essential for developing efficient processes, optimizing economic viability, and promoting widespread adoption of carbon utilization technologies across various industries.

2.3 Carbon storage

Carbon storage is a critical component of global efforts to mitigate climate change by preventing CO₂ emissions from entering the atmosphere. CCS involves the capture of CO₂ emissions from industrial processes and power generation, followed by liquefaction transportation and secure storage underground. This technology plays a crucial role in achieving carbon neutrality and addressing the challenges of reducing greenhouse gas emissions. The most significant approach within carbon storage is probably the geological option, where captured CO₂ is injected into geological formations such as depleted oil and gas reservoirs, deep saline aquifers, or unmineable coal seams. These subsurface formations, are usually high pressure environments where CO₂ can be injected and stay as a supercritical fluid. In such conditions, CO₂'s density is much higher than its gaseous phase and it is comparable to that of oil, taking up much less volume than it would at surface. These formations provide a secure and stable environment for long-term carbon storage, preventing CO₂ from contributing to the greenhouse effect [32]. Eventually, mineralization of CO₂ into stable carbonates takes place. CO₂ is transformed into a geologically stable form so as its release into the atmosphere under seismic or other geological events is prevented, mitigating the potential for environmental harm and contributing to long-term carbon sequestration efforts. The storage of CO₂ in geological

formations, such as depleted oil and gas reservoirs or deep saline aquifers, is a well-established technique [33]. Ongoing research and interdisciplinary collaboration are essential for refining existing methods, exploring new approaches, and optimizing the overall efficiency of carbon capture processes.

Another avenue is ocean storage, which involves injecting liquid CO_2 into the deep ocean since it can dissolve and disperse gases. When liquid CO_2 is released into the deep ocean, it encounters high pressures and low temperatures. At these conditions, supercritical CO_2 is heavier than seawater and will sink to the bottom of the ocean [34]. In the long term, CO_2 will be dissolved into the surrounding seawater. The dissolution process involves the physical interaction between CO_2 molecules and water molecules, forming carbonic acid (H_2CO_3). The carbonic acid can then further dissociate into bicarbonate ions (HCO^-) and hydrogen ions (H^+). This dissolution mechanism allows the CO_2 to be stored in the ocean in a dissolved form rather than as a separate gas phase. While this approach can be effective in removing CO_2 from the atmosphere, it raises environmental and ecological concerns, necessitating careful consideration of potential impacts on marine ecosystems [35].

In summary, carbon storage technologies are diverse and multifaceted, offering solutions to capture and sequester CO_2 emissions. Each one presents unique opportunities and challenges. Continued research, innovation, and international collaboration are essential to advancing these technologies and integrating them into comprehensive climate change mitigation strategies.

3 CPG plan

To demonstrate the potential of utilizing captured CO_2 as the working fluid in geothermal applications, a thorough CPG plan is studied by conducting simulations that integrate plans for concurrent CO_2 storage and geothermal energy production. The simulations involve modeling of the dynamic interactions between the injected CO_2 plume and geothermal fluids within a subsurface, deep aquifer. The aquifer is highly permeable and slightly heterogeneous with an abnormally high temperature justifying the CPG application. Through careful optimization, best injection strategies were devised, aimed at maximizing the benefits of both CO_2 storage and enhanced geothermal energy extraction. The coupling of CO_2 storage with geothermal operations demonstrated promising results, showcasing improved heat transfer efficiency and increased geothermal energy production. The integration not only provided a sustainable means of reducing CO_2 emissions but also offered a dual-purpose solution by harnessing renewable geothermal energy.

3.1 The aquifer

The characteristics of the subsurface system are presented in Table 2.

Table 2: Aquifer characteristics

Parameter	Value	Units
Average pressure (P)	3, 800	Psi
Temperature (T)	360	$^{\circ} F$
Porosity (ϕ)	0.25	
Average depth (D)	10, 180	ft
Average xy permeability (k)	300	mD
Bulk volume (V)	$2.5 \cdot 10^{11}$	cf
Water in place	$1.1 \cdot 10^{10}$	STB

3.2 Aquifer flow simulation

The primary objective of the schedule optimization is to address a hydraulic problem within the aquifer by fine-tuning the well placements and flow rates. A reasonable key assumption is made regarding a uniformly distributed specific heat capacity throughout the aquifer. This assumption simplifies the consideration of thermal dynamics, implying consistent heat absorption or release capabilities across the entire system. Moreover, there are no designated zones or boundaries within the aquifer serving as thermal sources. Therefore, the adjustment of well placements is influenced solely by inclination and not by specific thermal considerations.

To properly solve the fluid flow problem, reservoir simulation is utilized through the commercial software Reveal [36] by Petroleum Experts. Simulation is a crucial tool in the field of reservoir engineering that aids in modeling and predicting fluid flow behavior within subsurface reservoirs. The primary objective is to simulate the complex interactions among various components, such as rock, fluids, and wells. One of the fundamental principles underlying reservoir simulation is Darcy's law, which describes the flow of fluids through porous media, relating fluid velocity to the pressure gradient, permeability, and fluid viscosity [37].

Combined to mass conservation, the Darcy equation is a second-order partial differential equation (PDE), derived from homogenization of the Navier-Stokes equations and can be analytically solved only under severe assumptions. However, when modelling realistic subsurface formations, these assumptions do not hold. In this case, the discretization of the equation through linearization is essential. This process involves dividing the reservoir into a grid to represent the spatial distribution of rock properties and fluid flow. Common methods for discretization include finite differences, finite volumes, and finite elements. Finite volumes [38], in particular, are widely used in reservoir simulation due to their simplicity and efficiency. Gridding (Figure 6) plays a vital role in the discretization process, involving defining the size and shape of the cells within the reservoir grid. Various types of grids, such as Cartesian, corner-point, and unstructured grids, may be used based on the geological complexity of the reservoir, whereas the choice of grid impacts the accuracy and computational efficiency of the simulation.

Petrophysical fluid properties, including porosity, permeability, fluid saturations, compressibility and relative permeability are crucial inputs for reservoir simulation.

Accurate characterization of these properties is essential for realistic simulation results. Furthermore, the incorporation of phase behavior models is required to capture the complex interactions between brine and CO₂ including phase expansion and solubility. Expanding beyond this scope, thermodynamic properties of the fluids were derived using the CoolProps software [39], to estimate the specific enthalpy of both CO₂ and brine

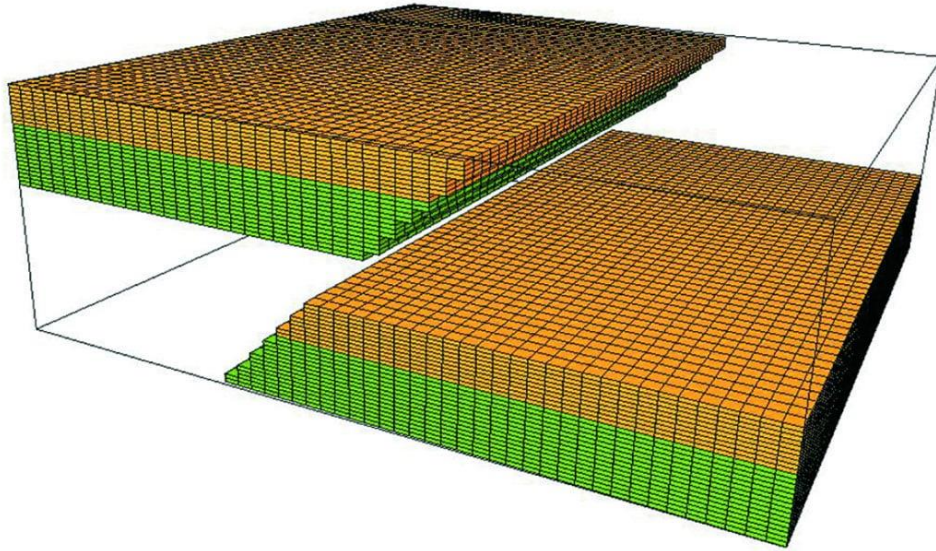


Fig. 6. Discretization of anticline reservoir

[<https://csegrecorder.com/articles/view/improving-the-reservoir-modeling-of-compressional-structures>]

3.3 Schedule

The schedule for achieving carbon sequestration and energy generation relies heavily on strategic well placement and precise control of injection and production rates. Placing injection wells close to emission sources like industrial facilities reduces transportation costs and logistic challenges. Furthermore, well placement and rate control directly influence pressure buildup within reservoirs and the delay of breakthrough events. Managing injection rates ensures optimal CO₂ storage while balancing pressure dynamics. Similarly, controlling production rates maximizes energy extraction without compromising storage integrity. Continuous monitoring and advanced modeling inform rate adjustments, minimizing breakthrough risks and optimizing operational efficiency. CCS operations optimization has been extensively explored in the literature [40]. However, in this study, a more conventional fine-tuning approach was employed by utilizing engineering intuition to space the wells along the aquifer and manually changing flow rates when deemed necessary.

After taking into account all of those parameters, the resulting schedule is delineated into three distinct phases, as illustrated in Figure 7, which align with the project's goals. Each phase represents a specific stage in the system's implementation, with tailored actions and parameters designed to simultaneously achieve carbon sequestration and geothermal energy generation.

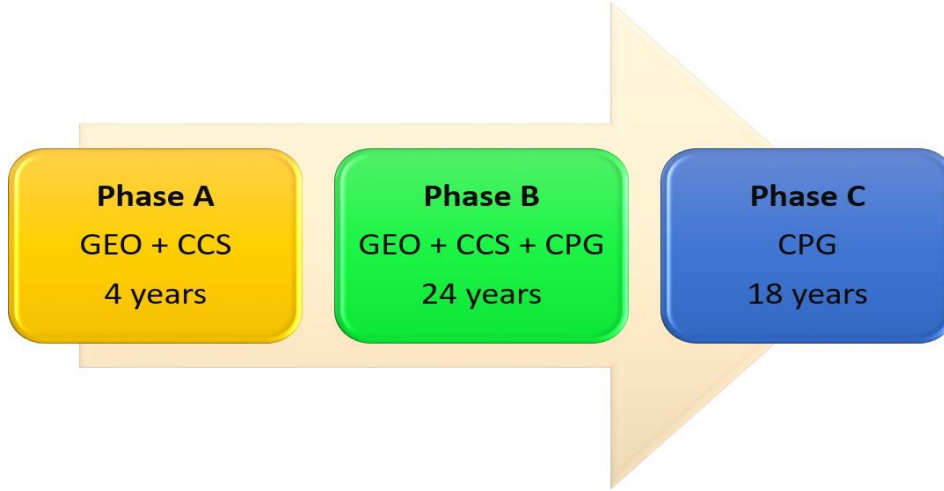


Fig. 7. Schedule phases. GEO stands for geothermal production with brine.

As the system is closed, pressure buildup while injecting CO₂ for CCS must be managed by simultaneous brine production (phase A). Note that, an open system with stratigraphic traps would maintain pressure through brine migration to adjacent formations. Since CO₂ is lighter than brine, even when in supercritical phase, the configuration depicted in Figure 8 can be effectively harnessed. Therefore, the brine producers need to be drilled at the reservoir's bottom and perforated solely in the lowest layers, while CO₂ be injected at the crest, to achieve maximum breakthrough delay. The density difference between the two fluids results in an expanding CO₂ plume within the upper layers, enabling it to reach the deeper production well's upper layers. However, due to the limited vertical permeability (compared to the horizontal one $k_z \approx 0.1 \cdot k_x$), the migration of the CO₂ plume to the brine producers' perforations is slowed down. This phase involves controlling brine extraction rates in each well to maintain the overall constant brine production for as long as possible, thus ensuring stable power output. Subsequently, brine is utilized for energy production and treated for safe disposal.

The Voidage Replacement Ratio (VRR), defined as the ratio between the downhole volume of the injected and the produced fluid, exhibits variations during the process due to reservoir temperature and pressure changes, drastically influencing the injected fluid's density as well as the occurrence of CO₂ breakthrough in the latter stages. On average, the VRR in the optimized schedule maintains a value of 267%, resulting in a steady but controlled increase in reservoir pressure of about 800 psi/year. This phase is designed to last for four years.

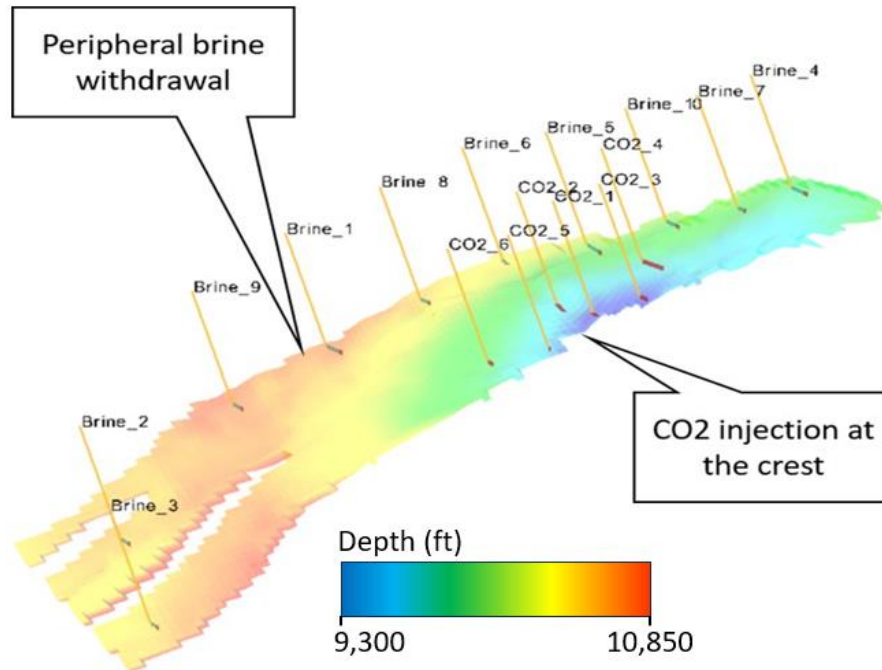


Fig. 8. Aquifer inclination and wells placement

Once brine can no longer be produced at the selected constant rate due to the risk of breakthrough, its production is slowed down and phase B is initiated. However, reduced brine production leads to a decline in the power output of the geothermal system. This situation is unfavorable and to counterbalance the system's power output loss, some CO₂ injectors are converted into producers to initiate CPG. This phase is characterized by controlling both brine and CO₂ production rates to level the system's power output to phase A. Furthermore, system pressure buildup is more easily controlled in this phase due to the increase in controllable parameters. This transitional phase where brine production is steadily decreased and CO₂ saturation is increased may last up to 24 years.

Finally, once breakthrough has reached all brine producers, the system transitions to phase C. The power output of the geothermal plant depends solely on CPG, while CCS and brine production are minimized. This phase was simulated [36] for 18 years, although the steady state flow conditions achieved can be extended arbitrarily long.

4 Discussion and Results

Selecting an appropriate CO₂ storage schedule is a nontrivial task. Unlike primary or secondary oil production, where the objective is to maximize the hydrocarbons recovery factor "as much and as fast as possible", this development plan involves various targets and limitations. It is crucial for power output to remain constant throughout the

resource utilization, as a power plant, whether autonomous or a subsystem of a larger facility, must consistently meet specific energy demands over time. Several trade-offs have to be considered for the case study in this work. Firstly, higher production rates are inversely correlated with breakthrough time. Secondly, the minimum CO₂ storage mass rate needs to remain higher than the mass rate produced from the carbon storage facilities, allowing space for excess CO₂ needs to be met through the market. The trade-off here is that an increased mass rate leads to sooner pressure buildup and faster breakthrough.

CCS takes place during in phases A and B, spanning a 28-year timeframe in this aquifer. Therefore, operators must identify and develop plans for more subsurface formations or target other storage operators to store emissions after this period. Development plans, especially in the case of CPG, needed to be engineered to suitably space CO₂ injectors, as once transformed into producers, CO₂ must be reheated sufficiently to serve as a geothermal fluid. In the plan presented in this work, the schedule was developed based on the expertise of the research team, and results may not be globally optimized.

The most important results obtained are the total mass of CO₂ sequestered, as depicted in Figure 9, and the geothermal power output that can be extracted from the produced CO₂ before it is recycled as shown in eq. (1)

$$E = (h_{prod}^{wh} - h_{inj}^{wh}) \cdot \dot{m} \quad (1)$$

where h_{prod}^{wh} , h_{inj}^{wh} is the specific enthalpy of CO₂ at the wellhead conditions in the production and injection wells respectively and \dot{m} is the mass flow rate. Clearly, the enthalpy difference corresponds to the heat load utilized by the steam turbine, taking off system losses that occur due to the selection of the thermodynamic cycle, as well as the cooling and pressurization of the CO₂ effluent from the turbine and prior to the injection well.

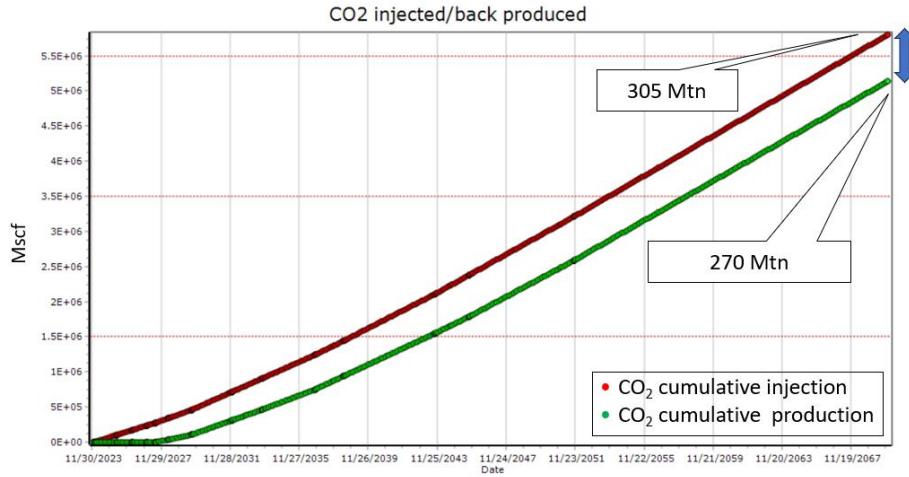


Fig. 9. Cumulative CO₂ injection/production rates.

After phase B is completed, the total mass of CO₂ that has been sequestered within the reservoir is estimated at 35 Mtn (Figure 9). To calculate the power output, the produced CO₂ and brine mass rate are directly obtained from the simulation for each phase (Figures 10, 11).

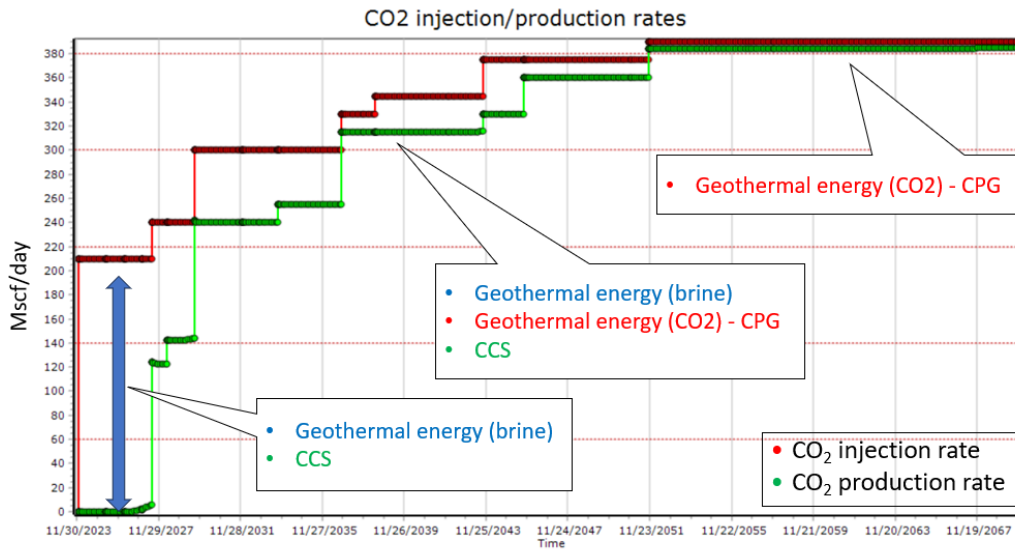


Fig. 10. CO₂ injection/production mass rates

High enthalpy wells, can be considered near isenthalpic, implying that fluid enthalpy remains almost constant along the well as long as the CO₂ remains in a supercritical state. The power output can be calculated straightforwardly as the sum of the enthalpy differences of the two produced fluids at each phase and is determined to vary between 41 – 46 MW. The variability in power output, is attributed to fluctuations in the project's schedule and the need for long-term integrity.

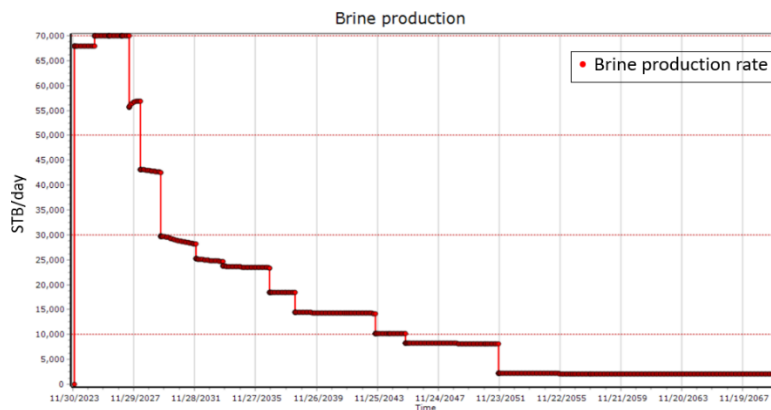


Fig. 11. Brine production mass rates

To further boost power output in phase C, injection and production rates can be increased as needed and additional CO₂ wells may be drilled. There is no need for global concern regarding average pressure increase, as the fluid is injected and produced simultaneously at similar bottomhole rates thus creating a closed loop system. Additionally, there is low only concern regarding pressure buildup due to the high and isotropic permeability of the reservoir. When considering increasing the recycling rates, the primary consideration is the time it takes for the returned fluid to reach the reservoir's temperature. Ideally, it would be preferable for the fluid to reach the aquifer's temperature before being produced, as the density of supercritical CO₂ decreases with an increase in temperature, maximizing geothermal energy retrieval.

With the flow rates simulated in this study, the temperature of the produced fluid converges to a value close to the temperature of the aquifer. Nevertheless, there are many control options to be exploited to optimize production temperature, such as horizontally perforating existing wells, drilling new ones as mentioned earlier, or even temporarily halting CPG for a few hours every day to allow the fluid to reach the aquifer's temperature. This may be a common practice in industrial cases, as power plant needs vary throughout the day.

5 Conclusions

In the broader landscape of carbon management, the utilization of CO₂ as a raw material in industry holds considerable significance. CO₂, often considered a byproduct of various industrial processes, can be repurposed for various applications. Industries can capture and utilize it as a feedstock in the production of chemicals, fuels and materials, contributing to a more circular and sustainable approach. This not only mitigates emissions by preventing the release of CO₂ into the atmosphere but also transforms it into a valuable resource for industrial processes, aligning with the principles of a circular carbon economy.

In conclusion, the CPG-CCS joint system emerges as a highly promising approach, seamlessly integrating energy generation with carbon-negative emissions. This study concentrated on a deep saline aquifer situated within a basin characterized by substantial subsurface magmatic activity. Over the course of 28 years, our results showcase the successful sequestration of over 35 million tonnes of CO₂. Concurrently, a geothermal system was established, harnessing the sequestered CO₂ and produced brine to yield noteworthy energy outputs. The implementation of this innovative system offers quantifiable benefits. Firstly, it contributes significantly to carbon negativity, securely storing a substantial amount of CO₂ and thereby mitigating environmental impact. Secondly, it facilitates energy extraction through the geothermal system, resulting in a notable increase in overall energy production. By combining carbon sequestration and geothermal energy, our findings underscore the potential for a system that not only achieves carbon negativity but also contributes positively to overall energy production. To enhance practical implications, our study prompts consideration of real-world applications. Addressing potential challenges, exploring economic feasibility, and evaluating scalability

are crucial steps toward understanding the practicality and applicability of the CPG-CCS joint system. While acknowledging the limitations inherent in our study, such as uncertainties in modeling approaches and site-specific factors, we envision a roadmap for future research and development. Our primary emphasis centered on optimizing the fluid flow problem. Further research is warranted to conduct a comprehensive technical and economic analysis, considering factors such as the efficiency of the thermodynamic cycle employed, the increased cost associated with CO₂ wells necessitating non-corrosive materials, and the incorporation of a heat exchanger to mitigate energy loss in turbine working fluids. Addressing these challenges can pave the way for widespread adoption and further refinement of the CPG-CCS joint system. In a broader context, the CPG-CCS joint system aligns with global efforts to combat climate change. Its potential role in achieving carbon neutrality should be seen as part of a larger strategy, contributing not only to local sustainability but also to international climate goals and agreements. Emphasizing long-term sustainability, we highlight the resilience of the CPG-CCS joint system to changing environmental conditions and its ongoing effectiveness in carbon storage and energy production. This reinforces the system's viability as a sustainable solution over the long run.

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