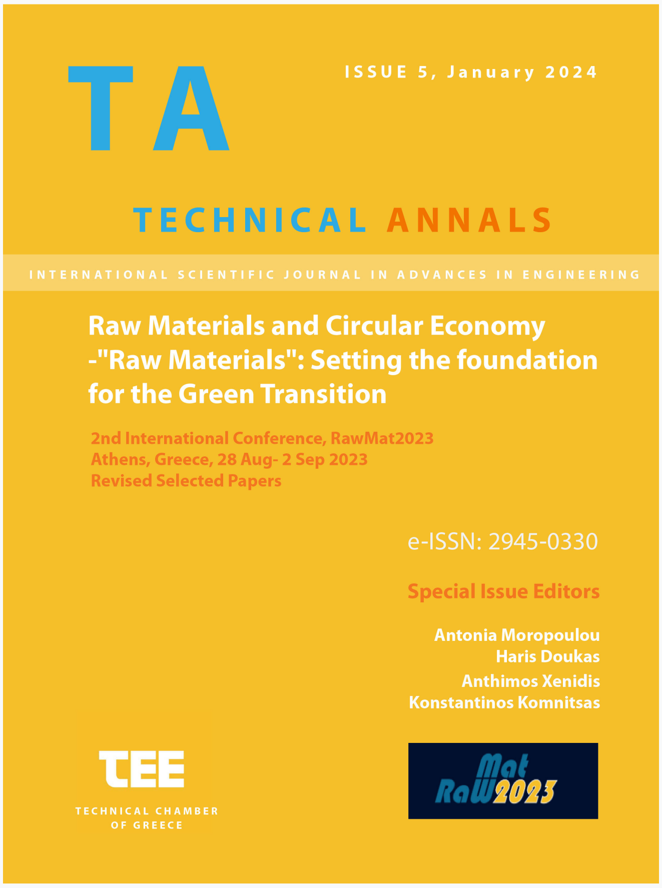
Technical Annals

Vol 1, No 5 (2024)

Technical Annals



TA

ISSUE 5, January 2024

TECHNICAL ANNALS

INTERNATIONAL SCIENTIFIC JOURNAL IN ADVANCES IN ENGINEERING

Raw Materials and Circular Economy -"Raw Materials": Setting the foundation for the Green Transition

2nd International Conference, RawMat2023
Athens, Greece, 28 Aug- 2 Sep 2023
Revised Selected Papers

e-ISSN: 2945-0330

Special Issue Editors

Antonia Moropoulou
Haris Doukas
Anthimos Xenidis
Konstantinos Komnitsas

TEE
TECHNICAL CHAMBER OF GREECE

MatRaW2023

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

Sofianos Panagiotis Fotias, Vassilis Gaganis, Spyros Bellas

doi: [10.12681/ta.37117](https://doi.org/10.12681/ta.37117)

To cite this article:

Fotias, S. P., Gaganis, V., & Bellas, S. (2024). Integrated Raw Material Approach to Sustainable Geothermal Energy Production: Harnessing CO2 for Enhanced Resource Utilization. *Technical Annals*, *1*(5). https://doi.org/10.12681/ta.37117

Integrated Raw Material Approach to Sustainable Geothermal Energy Production: Harnessing CO_2 for Enhanced Resource Utilization

Sofianos Panagiotis Fotias[1,*], Spyros Bellas[2] and Vassilis Gaganis[1,2]

[1]School of Mining and Metallurgical Engineering, National Technical University of Athens,
Athens 157 73, Greece
[2]Institute of Geoenergy, Foundation for Research and Technology (IG/FORTH),
Chania, 73100, Greece
`sfotias@metal.ntua.gr`

Abstract. CPG (CO_2 Plume Geothermal) has recently emerged as a promising technology that combines the extraction of geothermal energy with underground CO_2 storage, thus aligning with the energy objectives of Greece according to the National Energy and Climate Plan. The concept of CPG revolves around treating CO_2 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 CO_2 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 CO_2 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. CO_2 is less viscous and lighter than resident brine, thus fingering effects are more prominent than sweeping displacement. As a result, CO_2 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, CO_2 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: CO_2 Plume Geothermal, Reservoir simulator, CO_2 injection

1 Introduction

The incessant rise in carbon dioxide (CO_2) 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 CO_2 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 CO_2 utilization as a raw material [2]. Captured CO_2 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 CO_2 to be considered as a raw material rather than as an environmentally detrimental waste product.

Figure 1 Classification of CO_2 utilisation options (Provided by the US Department of Energy's National Energy Technology Laboratory)

Fig. 1. CO_2 utilization.
[https://www.linkedin.com/pulse/carbon-capture-utilization-conference-ccon4-final-bookings-laverty/]

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 Lesvos 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 CO_2 as the working fluid. This not only addresses the need for emission reduction but also enhances the efficiency of geothermal energy extraction. By utilizing CO_2 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, CO_2 has been suggested as an alternative working fluid thanks to it being abundant and possessing non-flammable properties [8]. CPG systems utilize CO_2 as the primary subsurface working fluid in naturally permeable sedimentary basins or EGS, creating a large-scale CO_2 plume. Additionally, a buoyancy-driven thermosiphon can be established by exploiting variations in CO_2 density between injection and production wells. This approach eliminates the need for costly pumping, which is commonly associated with conventional hydrothermal setups.

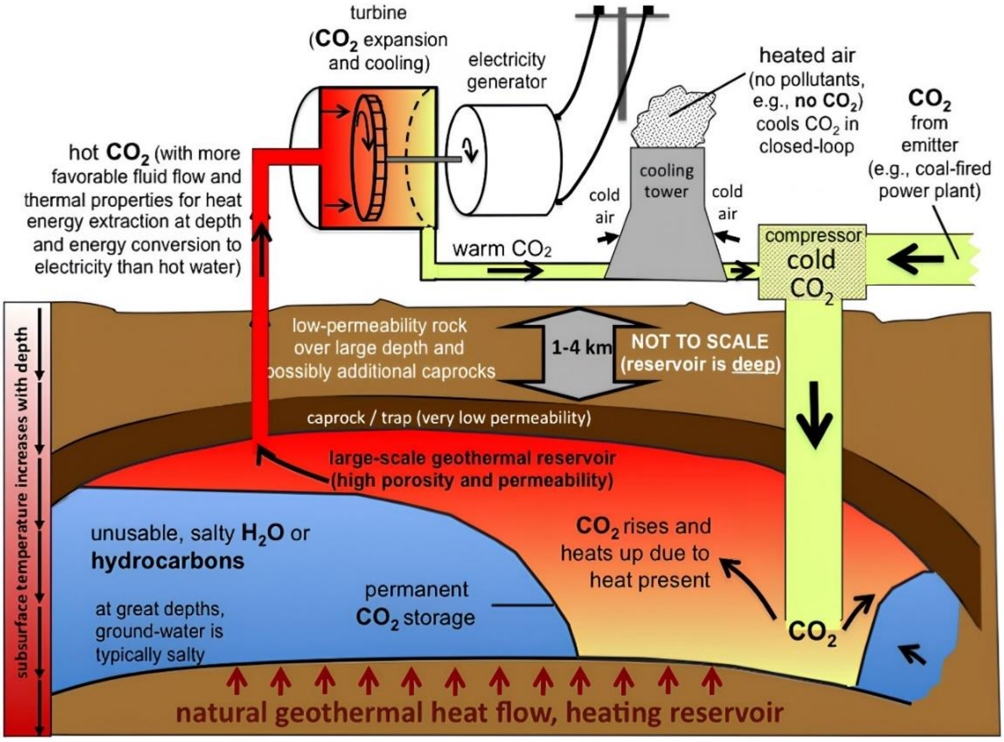


Fig. 2. CPG system.
[https://www.thinkgeoenergy.com/cpg-systems-storing-co2-for-geothermal-energy-production/]

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 CO_2 needs to be confined by very low-permeability or fully impervious caprock beds covering the permeable reservoirs. CPG systems can be seamlessly integrated with CO_2

Capture and Storage (CCS) sites [11], [12], [13], enabling the simultaneous generation of electricity and heat while securely sequestering CO_2. This integration ensures reservoir stability by mitigating overpressurization concerns associated with standalone CCS operations, which could trigger human-induced seismicity and CO_2 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 CO_2, 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 CO_2, 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 CO_2 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 CO_2 [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 CO_2 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 CO_2 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 CO_2 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	psi	$6,894.76\,Pa$
Temperature	Fahrenheit	F	$(K-273.15)\cdot 9/5$
Depth	feet	ft	$0.348\ m$
Permeability	milliDarcy	mD	$10^{-15}\ \ m^2$
Gas volume	cubic feet	cf	$0.028\,m^3$
Liquid volume	stock tank barrel	STB	$0.16\,m^3$
Mass	pounds	lbm	$0.45\,kg$

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 CO_2 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 CO_2 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 CO_2 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 CO_2 from emissions remains an ongoing area of research.

One of the most widely studied and implemented methods for CO_2 capture is post-combustion capture (PCC) shown in Figure 3. In the context of power plants, PCC involves capturing CO_2 emissions after the combustion of fossil fuels, mainly aiming to remove the CO_2 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 CO_2 [24]. These solvents absorb CO_2 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 CO_2 capture capacity and can be regenerated for multiple cycles, making them an attractive option for PCC applications [25].

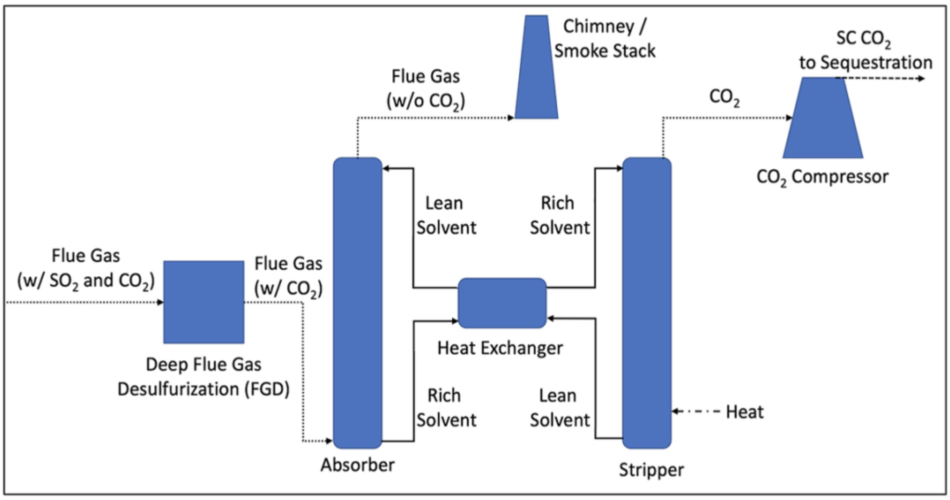


Fig. 3. Post combustion capture.
[https://www.long-intl.com/blog/post-combustion-capture/]

On the other hand, pre-combustion capture seen in Figure 4, involves the removal of CO_2 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 CO_2 can be captured before combustion, allowing for the more efficient capture as the fuel gas contains a higher concentration of CO_2 compared to the overall combustion products.

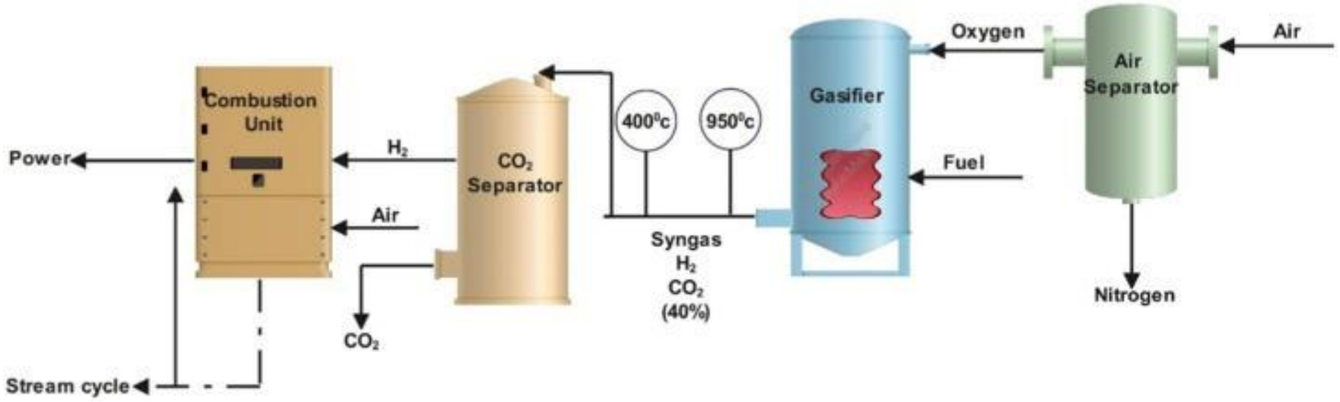


Fig. 4. Pre combustion capture [27].
[https://www.sciencedirect.com/topics/earth-and-planetary-sciences/pre-combustion-capture]

Finally, oxyfuel combustion involves burning fossil fuels in an oxygen-rich environment, resulting in a flue gas predominantly composed of CO_2 and water vapor rather than N_2 (see Figure 5). Thanks to its rich concentration, the CO_2 stream can be easily captured. This method is often considered for its compatibility with existing combustion technologies [28].

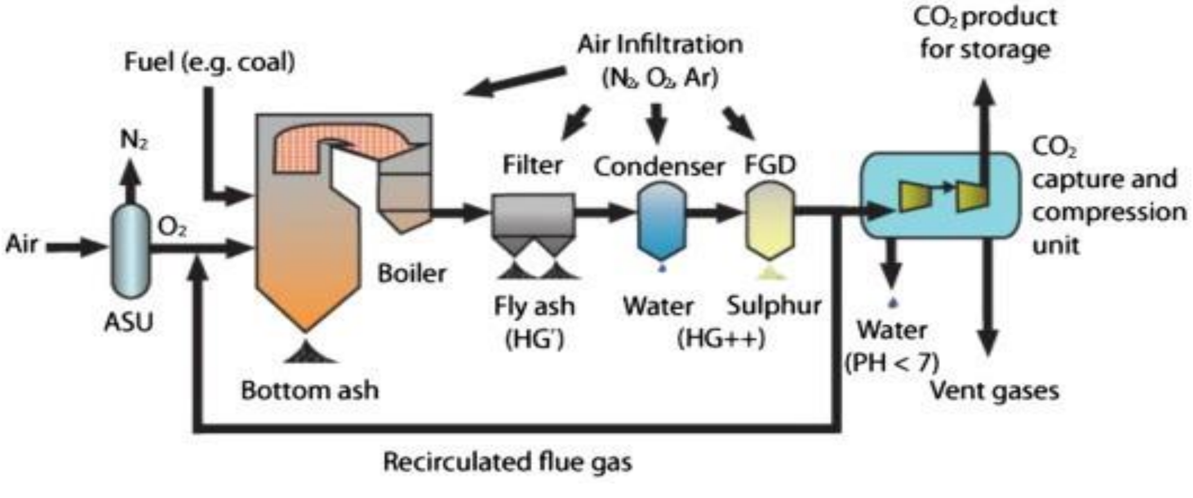


Fig. 5. Oxyfuel combustion capture [27].
[https://www.sciencedirect.com/topics/engineering/oxyfuel-combustion]

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 CO_2 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 CO_2 into chemical synthesis processes to produce valuable compounds, such as chemicals, polymers, and fuels. Catalytic processes, for instance, can convert CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 emissions from entering the atmosphere. CCS involves the capture of CO_2 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 CO_2 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 CO_2 can be injected and stay as a supercritical fluid. In such conditions, CO_2'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 CO_2 from contributing to the greenhouse effect [32]. Eventually, mineralization of CO_2 into stable carbonates takes place. CO_2 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 CO_2 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_3^-) 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 CO_2 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 CO_2 and brine

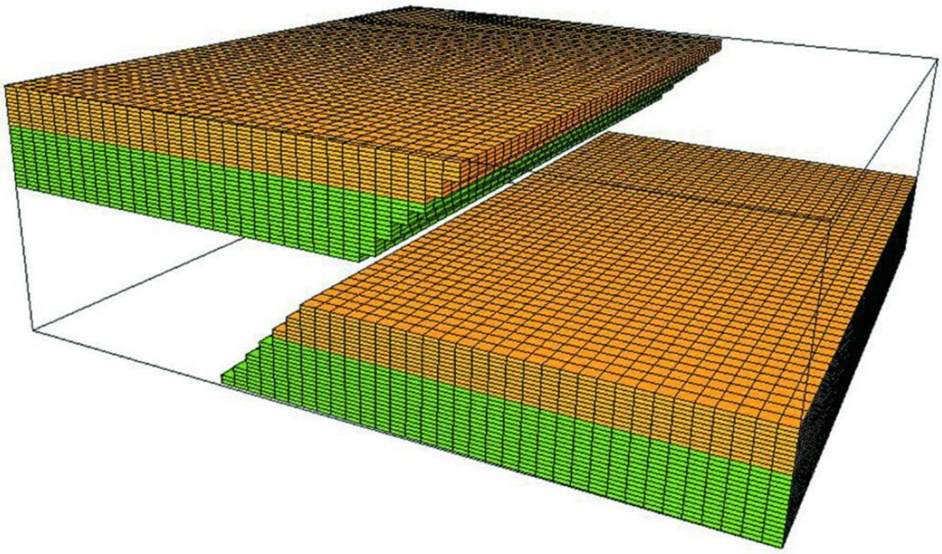


Fig. 6. Discretization of anticline reservoir [https://csegrecorder.com/articles/view/improving-the-reservoir-modeling-of-compressional-structures]

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 CO_2 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 CO_2 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 CO_2 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.

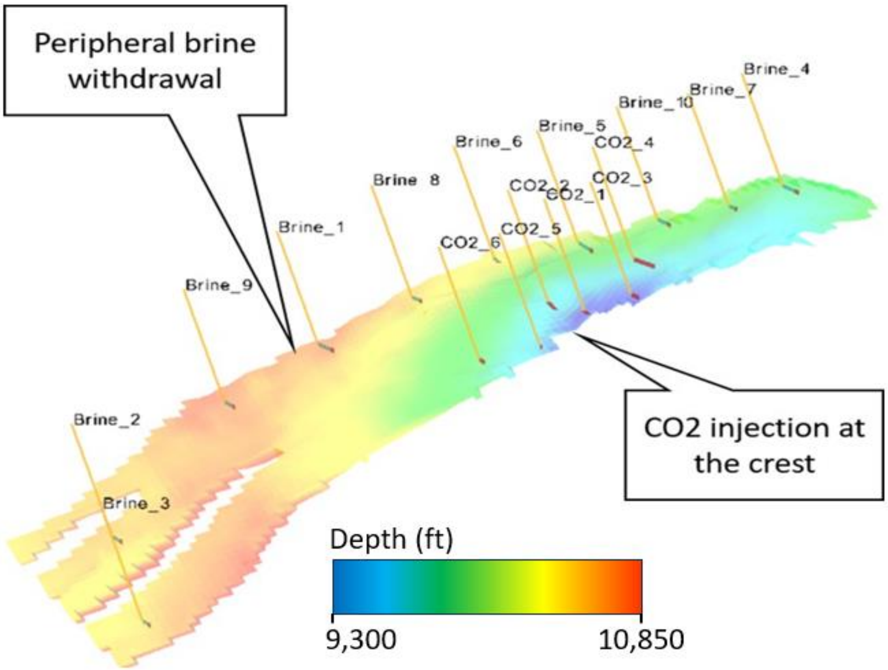


Fig. 8. Aquifer inclination and wells placement

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 CO_2 injectors are converted into producers to initiate CPG. This phase is characterized by controlling both brine and CO_2 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 CO_2 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 CO_2 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 CO_2 storage mass rate needs to remain higher than the mass rate produced from the carbon storage facilities, allowing space for excess CO_2 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 CO_2 injectors, as once transformed into producers, CO_2 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 CO_2 sequestered, as depicted in Figure 9, and the geothermal power output that can be extracted from the produced CO_2 before it is recycled as shown in eq. (1)

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

where $h_{prod}^{wh}, h_{inj}^{wh}$ is the specific enthalpy of CO_2 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 CO_2 effluent from the turbine and prior to the injection well.

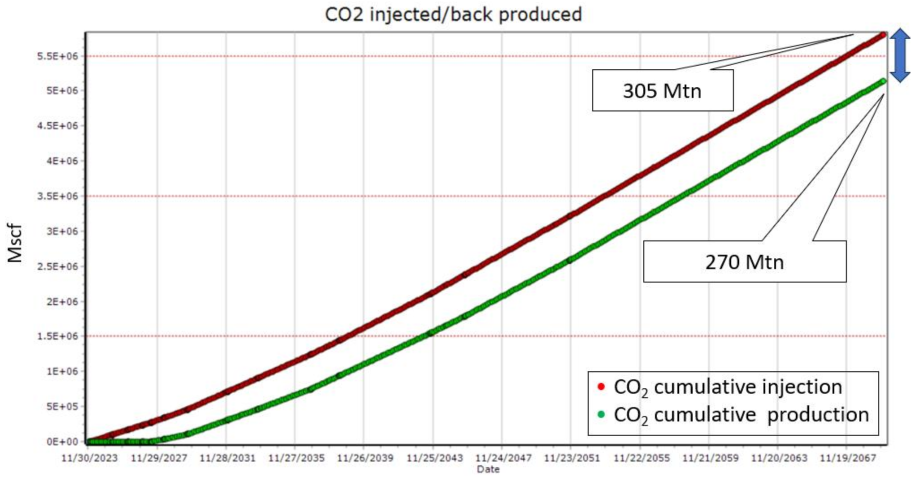


Fig. 9. Cumulative CO_2 injection/production rates.

After phase B is completed, the total mass of CO_2 that has been sequestered within the reservoir is estimated at 35 Mtn (Figure 9). To calculate the power output, the produced CO_2 and brine mass rate are directly obtained from the simulation for each phase (Figures 10, 11).

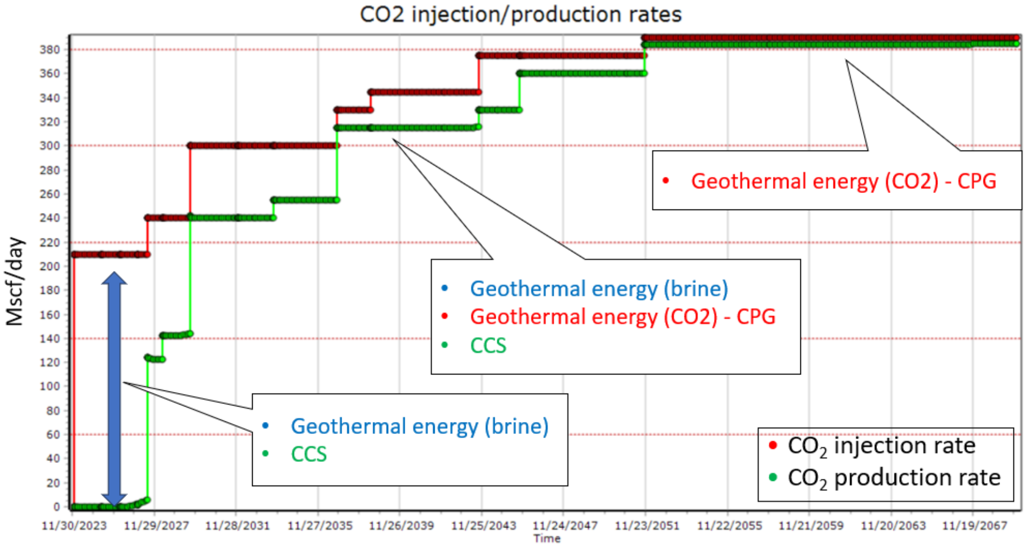


Fig. 10. CO2 injection/production mass rates

High enthalpy wells, can be considered near isenthalpic, implying that fluid enthalpy remains almost constant along the well as long as the CO_2 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.

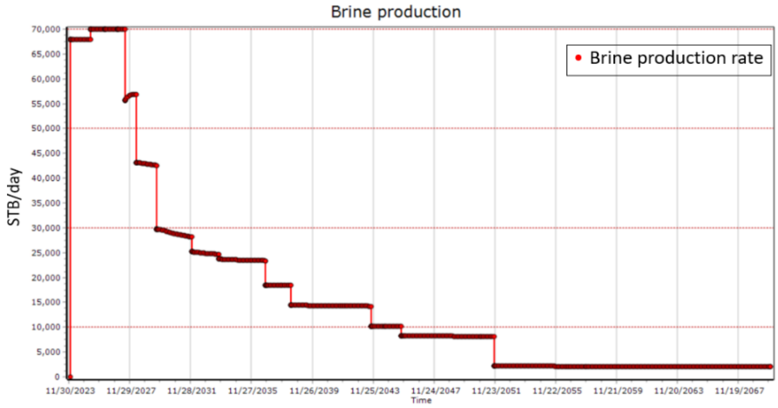


Fig. 11. Brine production mass rates

To further boost power output in phase C, injection and production rates can be increased as needed and additional CO_2 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 CO_2 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 CO_2 as a raw material in industry holds considerable significance. CO_2, 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 CO_2 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 CO_2. Concurrently, a geothermal system was established, harnessing the sequestered CO_2 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 CO_2 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 CO_2 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.

Credit author statement. Conceptualization, S.F., S.B and V.G.; methodology, S.F.; software, S.F.; validation, S.F. and V.G.; resources, S.F.; writing—original draft preparation, S.F.; writing—review and editing, S.F., S.B. and V.G.; visualization, S.F. All authors have read and agreed to the final version of the manuscript.

References

1. Turgut M Gu¨r. Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. Progress in Energy and Combustion Science, 89:100965, 2022.
2. Chih-Hung Huang, Chung-Sung Tan, et al. A review: Co2 utilization. Aerosol and Air Quality Research, 14(2):480–499, 2014.
3. Cameron Hepburn, Ella Adlen, John Beddington, Emily A Carter, Sabine Fuss, Niall Mac Dowell, Jan C Minx, Pete Smith, and Charlotte K Williams. The technological and economic prospects for co2 utilization and removal. Nature, 575(7781):87–97, 2019.
4. Ronald DiPippo. Geothermal power plants: principles, applications, case studies and environmental impact. Butterworth-Heinemann, 2012.
5. M Fytikas. Updating of the geological and geothermal research on milos island. Geothermics, 18(4):485–496, 1989.
6. Dimitrios Mendrinos, Ioannis Choropanitis, Olympia Polyzou, and Constantine Karytsas. Exploring for geothermal resources in Greece. Geothermics, 39(1):124–137, 2010.
7. Katrin Breede, Khatia Dzebisashvili, Xiaolei Liu, and Gioia Falcone. A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geothermal Energy, 1:1–27, 2013.
8. Donald W Brown. A hot dry rock geothermal energy concept utilizing supercritical co2 instead of water. In Proceedings of the twenty-fifth workshop on geothermal reservoir engineering, Stanford University, pages 233–238, 2000.

9. Julie K Langenfeld and Jeffrey M Bielicki. Assessment of sites for co2 storage and co2 capture, utilization, and storage systems in geothermal reservoirs. Energy Procedia, 114:7009–7017, 2017.
10. Barry Freifeld, Steven Zakim, Lehua Pan, Bruce Cutright, Ming Sheu, Christine Doughty, and Timothy Held. Geothermal energy production coupled with ccs: a field demonstration at the secarb cranfield site, cranfield, mississippi, usa. Energy Procedia, 37:6595–6603, 2013.
11. Edesio Miranda-Barbosa, Bergur Sigfu´sson, Johan Carlsson, and Evangelos Tzimas. Advantages from combining ccs with geothermal energy. Energy Procedia, 114:6666–6676, 2017.
12. Global CCS Institute. Global ccs institute 2022 status report. https://status22. globalccsinstitute.com/2022-status-report/introduction/, 2022.
13. Hon Chung Lau, Seeram Ramakrishna, Kai Zhang, and Adiyodi Veettil Radhamani. The role of carbon capture and storage in the energy transition. Energy & Fuels, 35(9):7364–7386, 2021.
14. Jimmy B Randolph and Martin O Saar. Combining geothermal energy capture with geologic carbon dioxide sequestration. Geophysical Research Letters, 38(10), 2011.
15. Jimmy B Randolph and Martin O Saar. Coupling carbon dioxide sequestration with geothermal energy capture in naturally permeable, porous geologic formations: Implications for co2 sequestration. Energy Procedia, 4:2206–2213, 2011.
16. Benjamin M Adams, Thomas H Kuehn, Jeffrey M Bielicki, Jimmy B Randolph, and Martin O Saar. A comparison of electric power output of co2 plume geothermal (cpg) and brine geothermal systems for varying reservoir conditions. Applied Energy, 140:365–377, 2015.
17. Adina Bosoaga, Ondrej Masek, and John E Oakey. Co2 capture technologies for cement industry.
18. Energy procedia, 1(1):133–140, 2009.
19. Mar P´erez-Fortes, Jos´e Antonio Moya, Konstantinos Vatopoulos, and Evangelos Tzimas. Co2 capture and utilization in cement and iron and steel industries. Energy Procedia, 63:6534–6543, 2014.
20. Sofianos Panagiotis Fotias, Spyridon Bellas, and Vassilis Gaganis. Optimizing geothermal energy extraction in co2 plume geothermal systems. Materials Proceedings, 15(1):52, 2023.
21. Elias Gravanis and Ernestos Sarris. A working model for estimating co2-induced uplift of cap rocks under different flow regimes in co2 sequestration. Geomechanics for Energy and the Environment, 33:100433, 2023.
22. Ernestos Sarris and Elias Gravanis. Flow regime analysis of the pressure build-up during co2 injection in saturated porous rock formations. Energies, 12(15):2972, 2019.
23. Sarris Ernestos, Gravanis Elias, and Papanastasiou Panos. Investigation of self-similar interface evolution in carbon dioxide sequestration in saline aquifers. Transport in porous media, 103(3):341– 359, 2014.
24. Pierre Friedlingstein, Michael O'sullivan, Matthew W Jones, Robbie M Andrew, Luke Gregor, Judith Hauck, Corinne Le Qu´er´e, Ingrid T Luijkx, Are Olsen, Glen P Peters, et al. Global carbon budget 2022. Earth System Science Data Discussions, 2022:1–159, 2022.
25. Zhiwu Liang, Kaiyun Fu, Raphael Idem, and Paitoon Tontiwachwuthikul. Review on current advances, future challenges and consideration issues for post-combustion co2 capture using amine- based absorbents. Chinese journal of chemical engineering, 24(2):278–288, 2016.

26. Arunkumar Samanta, An Zhao, George KH Shimizu, Partha Sarkar, and Rajender Gupta. Post- combustion co2 capture using solid sorbents: a review. Industrial & Engineering Chemistry Re- search, 51(4):1438–1463, 2012.
27. Anamaria Padurean, Calin-Cristian Cormos, and Paul-Serban Agachi. Pre-combustion carbon dioxide capture by gas–liquid absorption for integrated gasification combined cycle power plants. International Journal of Greenhouse Gas Control, 7:1–11, 2012.
28. Toheeb A Jimoh, Fredrick O Omoarukhe, Emmanuel I Epelle, Patrick U Okoye, Emmanuel Oke Olusola, Alivia Mukherjee, and Jude A Okolie. Introduction to carbon capture by solvent-based technologies. In Elsevier Reference Collection in Earth Systems and Environmental Sciences. Elsevier, 2023.
29. Rohan Stanger, Terry Wall, Reinhold Sp¨orl, Manoj Paneru, Simon Grathwohl, Max Weidmann, Gu¨nter Scheffknecht, Denny McDonald, Kari My¨oh¨anen, Jouni Ritvanen, et al. Oxyfuel combustion for co2 capture in power plants. International journal of greenhouse gas control, 40:55–125, 2015.
30. Abass A Olajire. Valorization of greenhouse carbon dioxide emissions into value-added products by catalytic processes. Journal of CO2 Utilization, 3:74–92, 2013.
31. Frederic D Meylan, Vincent Moreau, and Suren Erkman. Co2 utilization in the perspective of industrial ecology, an overview. Journal of CO2 Utilization, 12:101–108, 2015.
32. Sichao Ma, Paul JA Kenis, et al. Electrochemical conversion of co2 to useful chemicals: current status, remaining challenges, and future opportunities. Current Opinion in Chemical Engineering, 2(2):191–199, 2013.
33. Franklin M Orr Jr. Storage of carbon dioxide in geologic formations. Journal of Petroleum Technology, 56(09):90–97, 2004.
34. Vyacheslav Romanov, Yee Soong, Casey Carney, Gilbert E Rush, Benjamin Nielsen, and William O'Connor. Mineralization of carbon dioxide: a literature review. ChemBioEng Reviews, 2(4):231– 256, 2015.
35. Kurt Zenz House, Daniel P Schrag, Charles F Harvey, and Klaus S Lackner. Permanent car- bon dioxide storage in deep-sea sediments. Proceedings of the National Academy of Sciences, 103(33):12291–12295, 2006.
36. Nianzhi Jiao, Gerhard J Herndl, Dennis A Hansell, Ronald Benner, Gerhard Kattner, Steven W Wilhelm, David L Kirchman, Markus G Weinbauer, Tingwei Luo, Feng Chen, et al. Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. Nature Reviews Microbiology, 8(8):593–599, 2010.
37. Petroleum Experts. Ipm suite.
38. Stephen Whitaker. Flow in porous media i: A theoretical derivation of darcy's law. Transport in porous media, 1:3–25, 1986.
39. Robert Eymard, Thierry Gallou¨et, and Rapha`ele Herbin. Finite volume methods. Handbook of numerical analysis, 7:713–1018, 2000.
40. Ian H. Bell, Jorrit Wronski, Sylvain Quoilin, and Vincent Lemort. Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library coolprop. Industrial & Engineering Chemistry Research,53(6):2498–2508,20
41. Ismail Ismail., Gaganis Vassilis. Carbon Capture, Utilization, and Storage in Saline Aquifers: Subsurface Policies, Development Plans, Well Control Strategies and Optimization Approaches—A Review. Clean Technol. 2023, 5, 609-637.https://doi.org/10.3390/cleantechnol5020031