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To Extract the Geothermal Energy using Supercritical Carbon Dioxide for Saskatchewan Province's Reservoirs

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Summary (All headings should be Arial 12pt bold, DELETE SECTIONS THAT ARE NOT USED)

Article text should be Arial 11pt, left and right justified. 2 pages including at least one graphic is suggested. Please use the headings that are appropriate for your work, deleting the ones that are not.

In this study, cyclic $SCCO_2$ injection for geothermal energy recovery has been proposed for the first time. We simulated cyclic and continuous injection by using water or $SCCO_2$ as working fluids. The geothermal energy production performance for different well patterns and various injection strategies were compared in terms of the cumulative energy extracted. The characteristics of cyclic and continuous injection modes for working fluids were presented and analyzed. It was found that the original reservoir fluid initially dominated the energy production before the $SCCO_2$ breakthrough. After the $SCCO_2$ breakthrough, cyclic injection provided higher heat extraction efficiency than continuous injection. This shows that cyclic injection outperforms under relatively poor conditions and overcomes the negative effects of breakthrough to some extent. It also indicates that a proper combination and management of cyclic and continuous injection could synergize the advantages of both strategies, and further optimization of the injection, soaking, and production periods could maximize the net present value (NPV) or cumulative energy production to enhance the $SCCO_2$ process.

Theory / Method / Workflow

Geothermal projects typically use water as the working fluid because of its high heat capacity. Some research has found that CO_2 may outperform water in some scenarios (Luo et al., 2014). Under proper conditions, the implementation of $SCCO_2$ for geothermal energy extraction will not only reduce carbon emissions by capturing and storing carbon dioxide (Chen et al., 2019) but also provide a cleaner and more efficient energy resource.

The use of $SCCO_2$ to extract geothermal energy was first proposed by Dr. David R. Brown (Brown, 2000). To maintain the fluid at the supercritical phase, the system pressure and temperature should be higher than the critical pressure and temperature of CO_2. At a supercritical state, the fluid has intermediate properties between the two phases, enabling it to have a liquid-like density but gas-like viscosity (Morrell, 2012). $SCCO_2$ helps extract heat from the geothermal reservoir more efficiently compared with water and, in the meantime, reduces carbon emissions, making it a potential working fluid for a geothermal project. However, there lacks systematic study of the cyclic pure CO_2 injection and the examination of the effects on the performance by comparing different recovery strategies.

In our previous study (Li, et al, 2022), the heat extraction efficiency using two different types of injection strategies, i.e. cyclic water injection and continuous water injection, were studied and compared. We found that cyclic water injection was more efficient than continuous water injection at the late stage of production. Comparing the performance of cyclic and continuous injections, cyclic injections are superior in energy recovery efficiency at the late stage of production when cumulative injections are equal. For cyclic water injection, the time duration for the three stages (injection, soaking and energy production) should be carefully designed to give the injected fluid enough time to absorb more heat and thus increase the energy recovered amount. However, in our previous study (Li, et al, 2022), the optimization for different cyclic phase's duration hasn't been performed but adopted a typical cycle period from the oil field (Scott, 2002). In this study, we proposed a three-dimensional geothermal reservoir model and compared various geothermal recovery strategies, including multiple cyclic injections, continuous injection, and their combinations by using $SCCO_2$ or water. To begin with, our fluid model was compared with Pruess's work in order to verify the heat capacity of $SCCO_2$ by using a commercial thermal reservoir simulator (i.e. CMG™). Secondly, a geological model to mimic a real geothermal reservoir in the City of Regina, Saskatchewan Province, Canada, was built, and the efficiency of different recovery strategies and the effects of various well patterns were analyzed. Finally, CMG CMOST-AI was used to perform the optimization in order to determine the optimal strategy for the reservoir model in the 15 years of the simulation period. CMG CMOST-AI allows the user to input various factors and then uses an algorithm such as tabu searching to find the possible best strategy. The workflow will be illustrated in Figure 1.

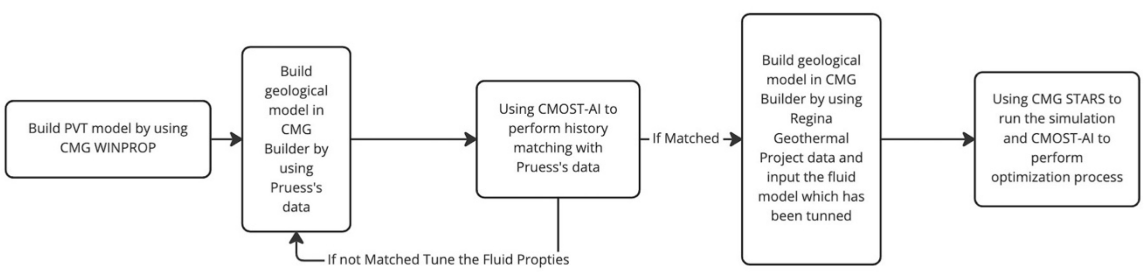

Figure 1 Flow Chart for the Working Process

Results, Observations, Conclusions

Table 1 for a real geothermal reservoir located in the City of Regina, Saskatchewan, Canada. The numerical simulation of the geothermal reservoirs was performed by using CMG-STARS™. The relative permeability for water/ CO_2 system was set to 1.0 at the endpoint to simulate the worst condition since it caused the breakthrough to occur earlier.

Table 1 Geological Parameters of a Typical City of Regina Geothermal Reservoir

Parameters	Value	Reference
Thickness	110 m	(Vigrass et al., 2007)
Horizontal Permeability	350 mD	(Vigrass et al., 2007)
Vertical Permeability	35 mD	
Porosity	0.132	(Vigrass et al., 2007)
Pattern	Invert 5-Spot	
Pattern Area	$1\ km^2$	
Reservoir Fluid	100 % water	
Operation Condition (Injector)	1e6 m^3/day	
Operation Condition (Producer)	7,500 kPa	
Reservoir Pressure	22,000 kPa	(Vigrass et al., 2007)
Reservoir Temperature	60 ℃	(Vigrass et al., 2007)
Injected Fluid Temperature	35 ℃	

To keep CO_2 in the supercritical phase, the minimum bottom hole pressure for the producer has been adjusted to 7,500 kPa, and injected fluid temperature has been changed to 35 ℃. Since there are no publicly available geothermal energy recovery field data from the City of Regina, we used the previously verified fluid property model in a typical City of Regina's geothermal geological model for the case studies (i.e. well pattern, different injection modes) based on the collected literature data and most reasonable justification. Validation and improvement of our simulations could be achieved through future field investigations. Such as using a more realistic geological model and fluid model, or comparing with available field data, or examining the performance of modified cyclic injection in heterogeneous reservoirs.

This study simulates different scenarios for $SCCO_2$ injection for geothermal recovery in terms of continuous injection, cyclic injection, and their combination, at the meantime investigating the effects of the well pattern. The simulation scenarios have been summarized in Table 2.

Table 2 Simulation Scenarios for $SCCO_2$ Injection for Geothermal Energy Extraction

Scenario No.	**Description**	**Well Configuration**
1	Continuous Injection	5-Spot Pattern
2	Continuous Injection (similar injection rate as Scenario 1)	9-Spot Pattern
3	Cyclic Injection (10 days injection, 10 days soaking, 80 days production)	5-Spot Pattern
4	Modified Cyclic Injection (Continuous injection before $SCCO_2$ breakthrough, Cyclic Injection after breakthrough)	5-Spot Pattern

5	Modified Continuous Injection (Similar injection rate as scenario 1,3,4 before $SCCO_2$ breakthrough, lower the injection rate after breakthrough to have similar cumulative $SCCO_2$ injection with scenarios 4,6)	5-Spot Pattern
6	Modified Continuous Injection (Similar cumulative $SCCO_2$ injection as scenarios 4 and 5, Constant injection rate)	5-Spot Pattern

The different well patterns will influence energy recovery performance due to injected fluid's sweep efficiency and energy adsorption capacity. As shown in Figure 2, the cumulative energy and water production for the 5-spot pattern (Scenario 1) is slightly higher than the 9-spot pattern with the same cumulative fluid injection. This indicates that the 5-spot pattern has higher sweep efficiency than the 9-spot case (Scenario 2). The obtained result agrees with previous research on the effect of well patterns on the sweep efficiency in the simulation study of CO_2 EOR for oil reservoirs (Shehata et al., 2012).

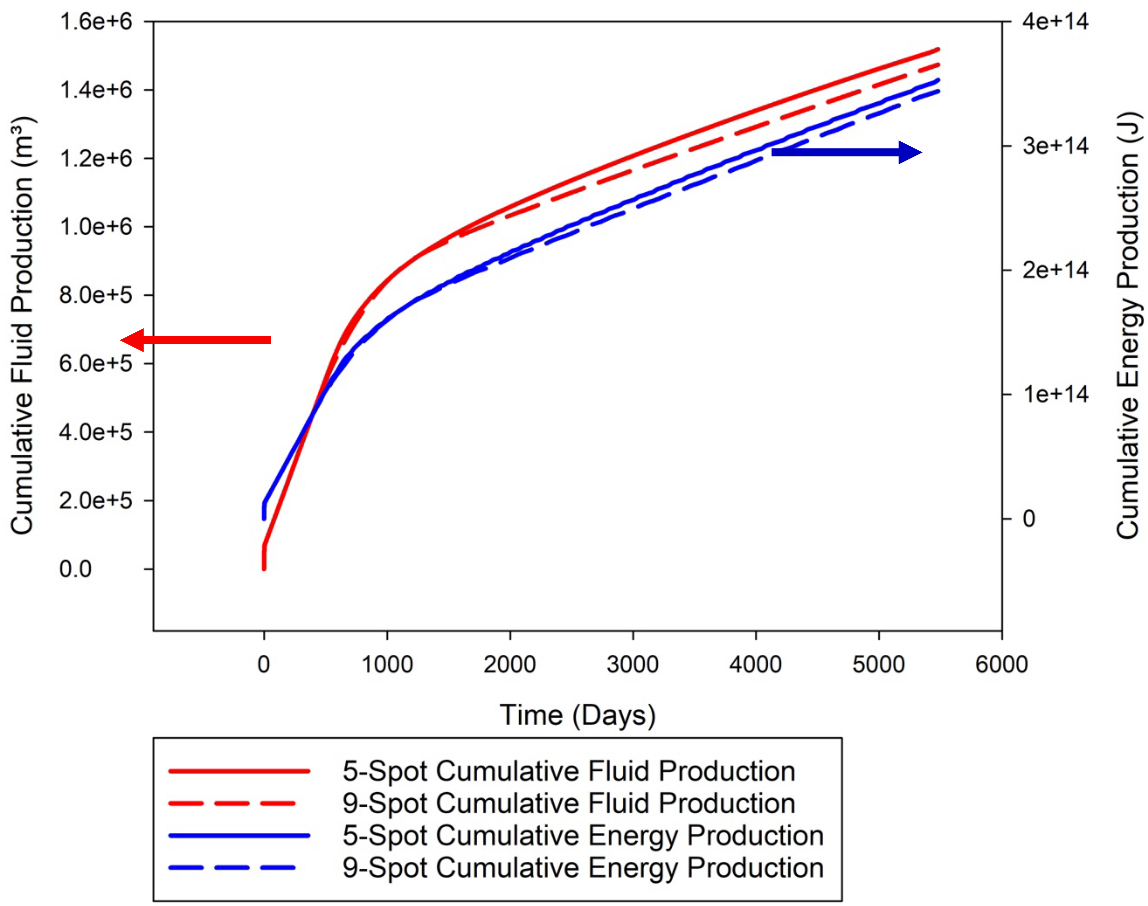

Figure 2 Cumulative Energy and Water Production for 5-spot (Scenario 1) and 9-spot Pattern (Scenario 2)

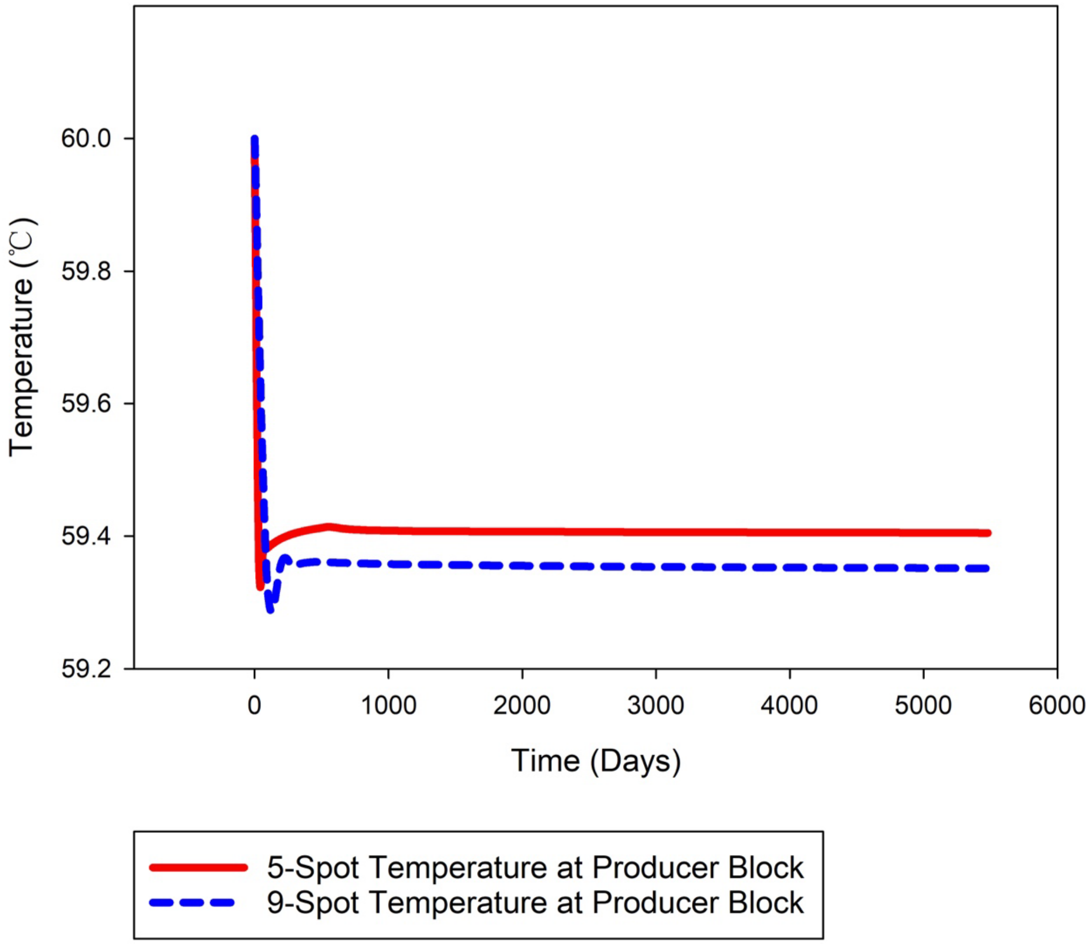

Figure 3 Temperature at Producer Block (Scenario 1 and 2)

Meanwhile, Figure 3 illustrates that the temperature in the 9-spot pattern drops more than that in the 5-spot pattern, indicating that the injected fluid in the 9-spot pattern affects producer block temperature to a greater extent. This manifests that the 5-spot pattern system will have a longer lifetime for geothermal energy recovery from the long-term perspective.

The simulation results shown in Figure 4 are for a comparison of cyclic $SCCO_2$ injection (Scenario 3) and continuous $SCCO_2$ injection (Scenario 1) with 5-spot pattern. For continuous $SCCO_2$

injection mode, four injectors are located at the four corners of the model for continuous supercritical carbon dioxide injection, and the producer is situated in the center. While for cyclic $SCCO_2$ injection, those five wells are injectors at the injection/soaking phase and switch to producers at the production phase. The cyclic process pattern includes 10 days of injection, 10 days of soaking, and 80 days of production (Scott, 2002).

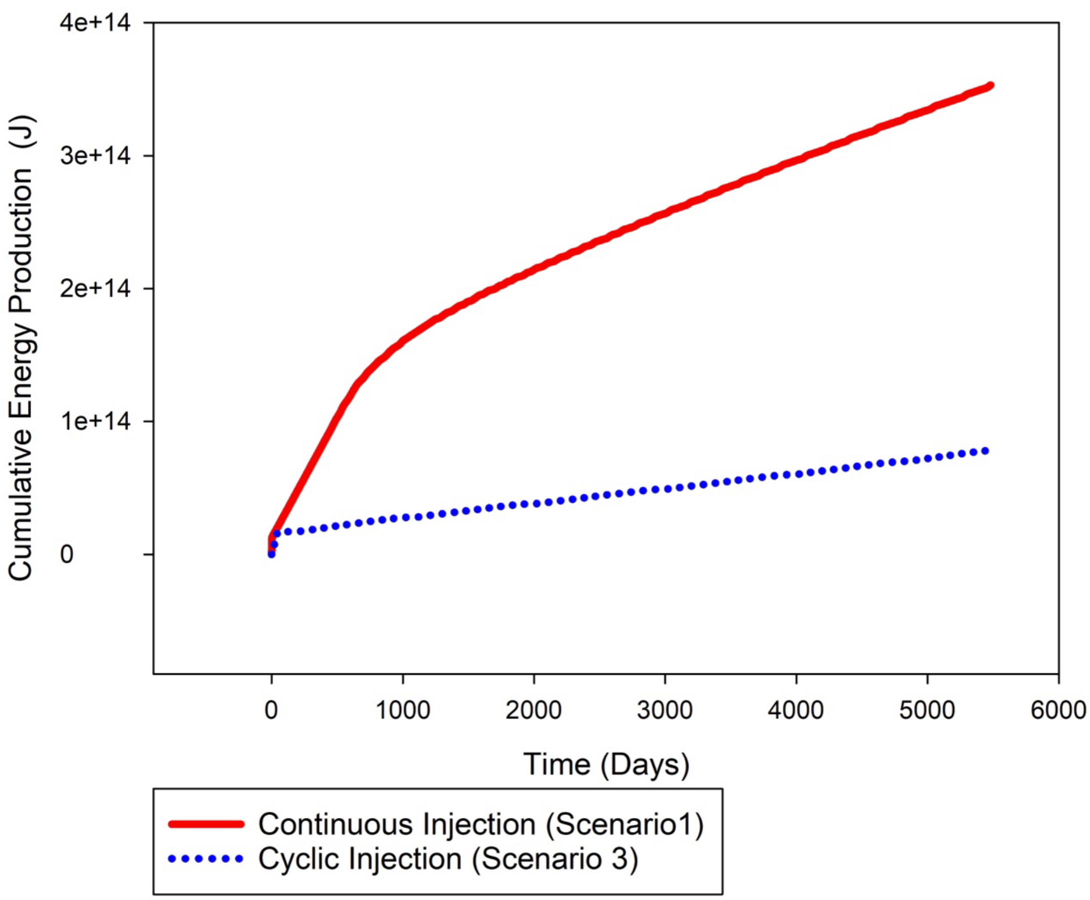

Figure 4 Cumulative Energy Production for Cyclic (Scenario 3) and Continuous Injection (Scenario 1)

Although continuous $SCCO_2$ injection shows an advantage in cumulative energy production, the amount of cumulative gas injected is much higher than cyclic injection. Meanwhile, a phenomenon observed at the continuous $SCCO_2$ injection was that the energy recovery slope changed around day 900. An explanation for this is that the injected $SCCO_2$ will displace the residual water in the geothermal reservoir from the injector to the producer. The injected CO_2 will flow after the formed water bank, and carbon dioxide gas production is found at the producer in day 900, which indicates that the gas bank arrives at the producer at that time. $SCCO_2$ has only one-third of the heat capacity compared with water, resulting in a smaller energy recovery slope after the Year 2025. The results presented in Figure 4 demonstrate that before day 900, residual water recovery would dominate energy production. After day 900, $SCCO_2$ breakthrough will result in the disadvantage of sweep efficiency and lower reservoir fluid production (Hinai et al., 2017; Hatzignatiou & Mohamed, 1994). In the modified model (Scenario 4), the continuous $SCCO_2$ injection starts at the beginning of the process, and cyclic injection will take place following the $SCCO_2$ breakthrough (i.e. day 900); the results are shown in Figure 5.

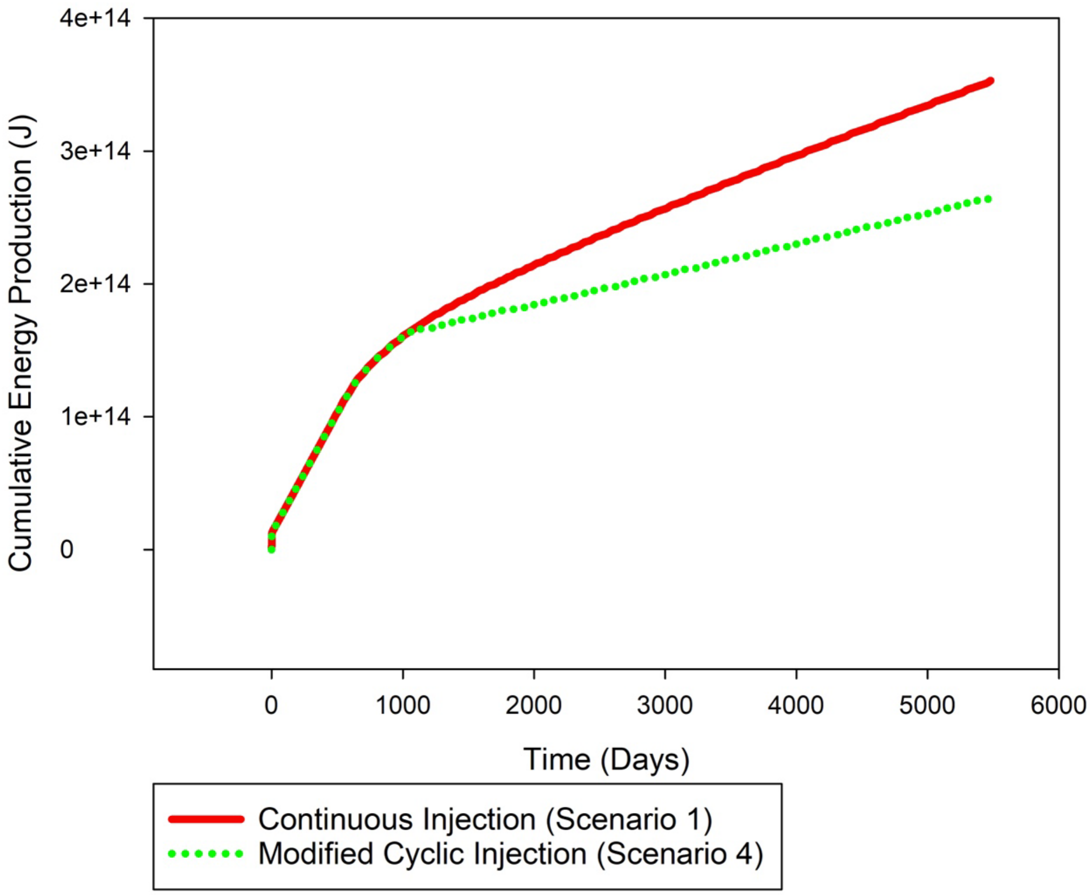

Figure 5 Cumulative Energy Production for Modified Cyclic Injection (Scenario 4) and Continuous Injection (Scenario 1)

Figure 4 and 5 illustrate that the modified cyclic injection started after $SCCO_2$ breakthrough, and the energy production increased significantly, which manifest that the modified cyclic injection takes advantage of continuous injection. In the early stage, the reservoir fluid shows a dominant effect on cumulative energy production. Therefore, continuous injection in the early stage is critical and efficient for energy production. To further investigate the efficiency of those strategies, the gas injection rate will be adjusted, and the cumulative gas injection at the end of the simulation time will equal with each other, the associated results are presented in Figure 6.

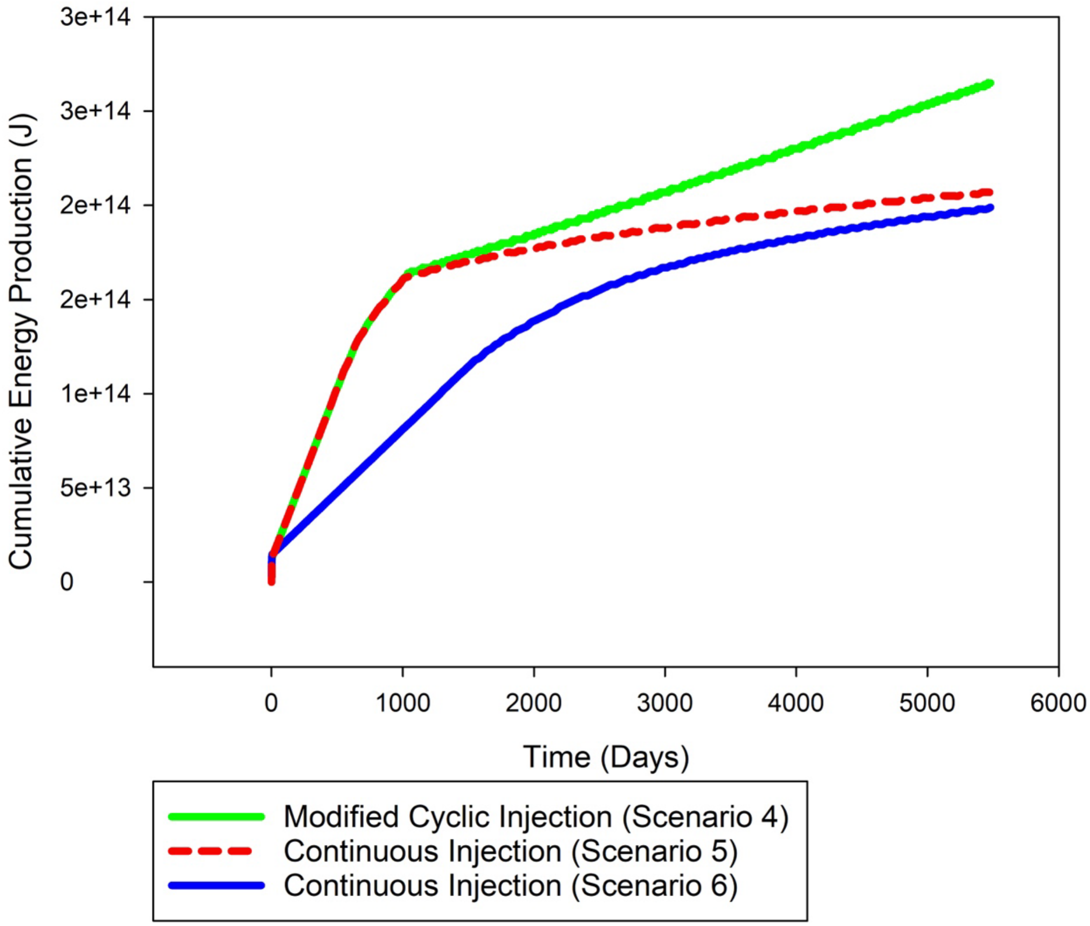

Figure 6 Cumulative Energy Production for Modified Cyclic and Continuous Injection (Scenarios 4,5, and 6)

The red (Scenario 5) and blue (Scenario 6) curves in Figure 6 are the modified continuous $SCCO_2$ injection, and the green curve is the modified cyclic $SCCO_2$ injection (Scenario 4). The initial injection rate for continuous injection (Scenario 5) is equal to the modified cyclic injection scenario before the gas breakthrough. After that, the injection rate for continuous injection (Scenario 5) will be reduced in order to maintain a similar cumulative gas injection amount as the cyclic injection (Scenario 4) at the end of the simulation. For another continuous injection scenario (Scenario 6), the gas injection rate will stay constant, and the cumulative gas injection is similar to Scenarios 4 and 5. In other words, Scenarios 4 and 5 had a high injection rate before the gas breakthrough, and then the Scenario 5 injection rate was reduced. For Scenario 4, the injection rate stays constant for the entire simulation time. Comparing continuous injection (Scenario 5) to cyclic injection (Scenario 4), the continuous injection strategy has an inconspicuous effect on cumulative energy production after the gas breakthrough. This indicates that the cyclic injection process can overcome the negative effects of breakthroughs to a certain extent. Meanwhile, Scenario 6 demonstrates that even though the cumulative gas injection is the same, the different injection rates will result in different breakthrough times and ultimate energy recovery.

Figure 6 manifests that more energy will be extracted by the unit volume of $SCCO_2$ when the cyclic injection strategy has been applied compared with continuous injection. That is caused by the more contact between the injected fluid and hot environment, and more heat transfer occurs due to convection/conduction mechanisms during the soaking period (McSpadden et al., 2022) and four more producers.

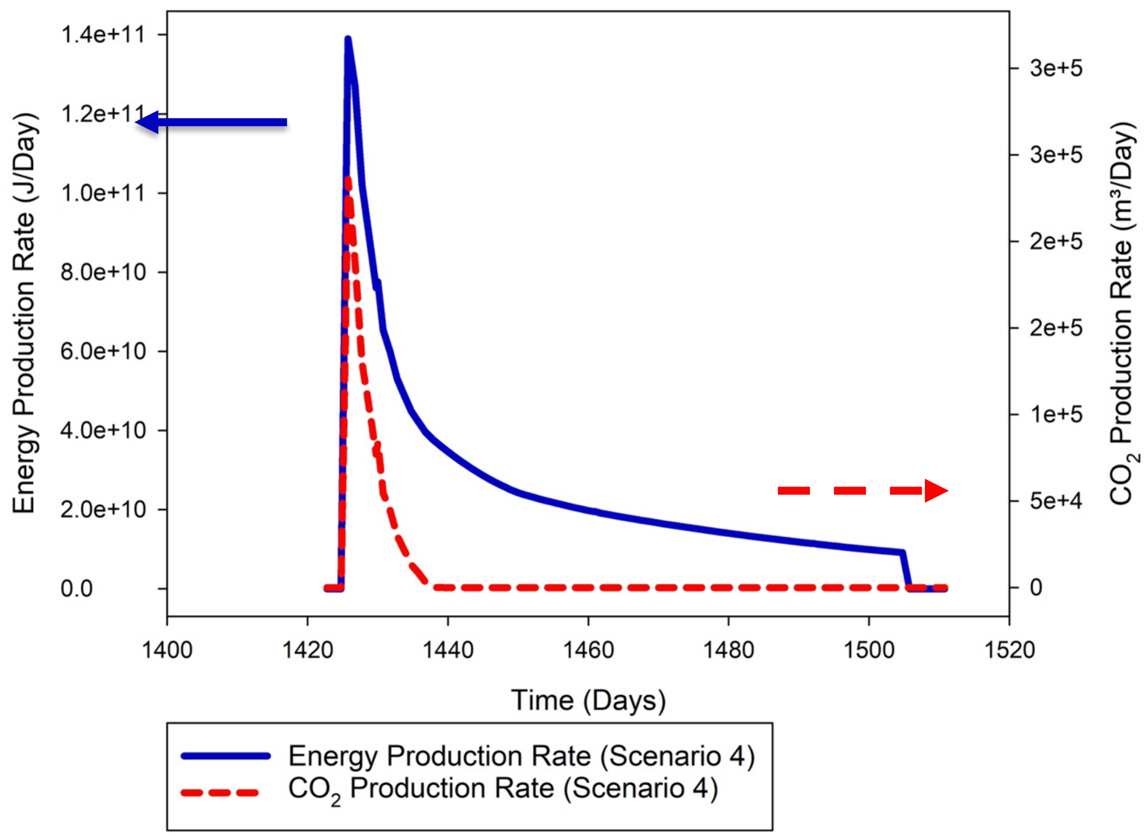

Figure 7 Typical Energy Production Rate and Gas Production Rate for Cyclic Injection (Scenario 4)

Figure 7 shows a typical energy production and gas production for a modified cyclic injection (10 days injection, 10 days soaking, 80 days production). As shown in that figure, the energy production rate reaches a peak two days after production starts, and the energy and gas production rates are close to zero after ten days of production. It means that the effective energy production time is only one-eighth of the designed production period (80 Days). In order to reach the desired outcome, it is essential to reduce the production phase and boost the time of injection or soaking phases.

In our previous study (Li, et al. 2022), cyclic water injection has better performance than the continuous water injection case, and there are similar results shown in Figure 6. In this case, CMG-CMOST-AI is applied in the optimization to further enhance energy recovery. The optimal engine will be CMG DECE, which uses Design of Experiments and Tabu Search to optimize energy production or NPV. In this study, the injection soaking and production duration for the cyclic injection process will be optimized to achieve higher energy production or economic efficiency. The optimization variables and their boundary values have been specified in Table 3.

Table 3 Optimization Variables

Parameters	Initial Value	Upper Boundary	Lower Boundary
Injection Time	10 days	0 day	120 days
Soaking Time	10 days	0 day	90 days
Production Time	80 days	1 day	365 days

500 datasets were selected by CMG CMOST for this process, and the results were organized in Figures 8 and 9. This process helped to identify which dataset or duration set-up has the higher energy recovery. Additionally, it provided insights into how cyclic injection could be implemented in the geothermal project.

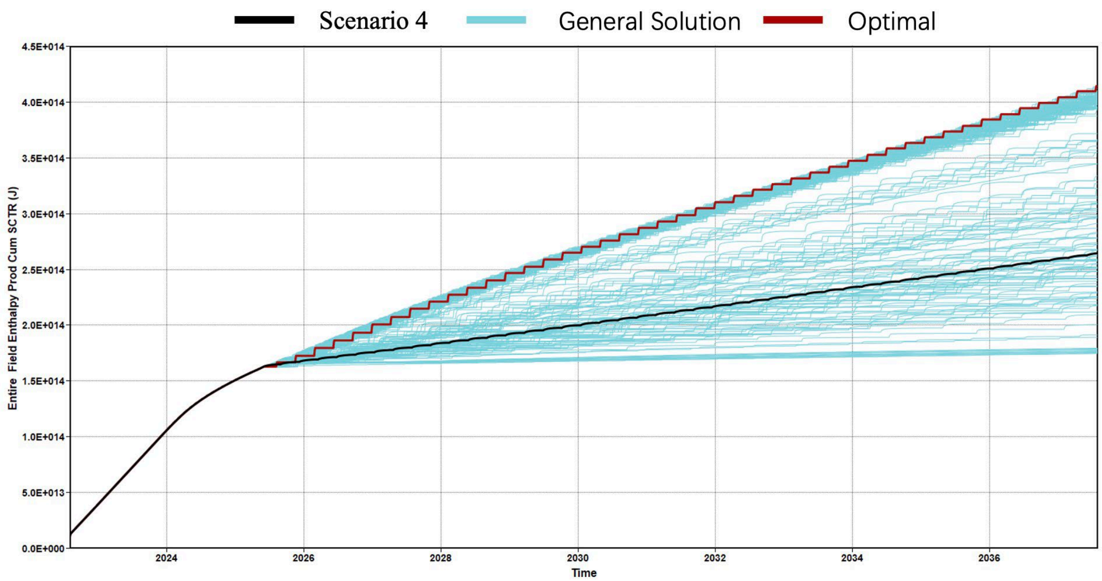

Figure 8 Energy Production Results for Optimization of Cumulative Energy Production

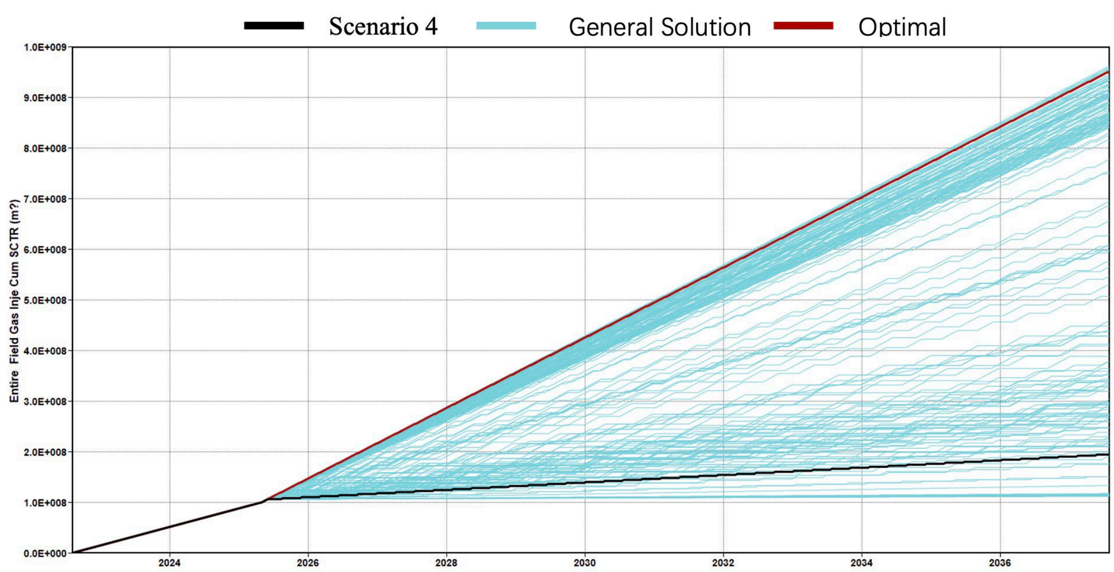

Figure 9 Gas Injection Results for Optimization of Cumulative Energy Production

Based on the cumulative energy production, the optimal case has 96.6 days of injection, one day of soaking, and five days of production. This matches with the hypothesis in Figure 7 that the production time should be reduced—the long injection period results in a relatively higher cumulative gas injection. Figure 8 indicates that after optimization, the cumulative energy production has been enhanced by 59.2 %, and Figure 9 exhibited that the optimal case is not the one with the highest gas injection. The energy production is related to the gas injection and the durations of different cyclic phases (injection, soaking and production), which manifests that the optimization process for cyclic injection is vital. Also, a large amount of gas injection usually affects the project's economic efficiency. Thus, the NPV analysis should be involved for better process optimization.

In this study, the NPV only considers CO_2 cost, energy cost, and associated revenue. The energy revenue and cost value are converted from the natural gas price. Since natural gas sells in energy per dollar, it can be converted to a dollar per Joule to represent the amount of natural gas needed to generate that energy. Also, the energy cost is the required energy for heating the injected CO_2 to 35 degrees Celsius. Those parameters have been organized in Table 4. By using those parameters, the NPV can be calculated by using equation 1.

$$NPV = \sum_{t=N1}^{t=N2} \frac{Energy\ Revenue\ * Q_{EngP}}{\left(e^{\frac{1+interest\ rate}{365}}\right)^{t}} - \frac{CO2\ Cost * Q_{CO2Inj}}{\left(e^{\frac{1+interest\ rate}{365}}\right)^{t}} - \frac{Energy\ Cost * Q_{EngInj}}{\left(e^{\frac{1+interest\ rate}{365}}\right)^{t}} \qquad \text{Eqa (1)}$$

Where Q_{EngP} is energy production rate in J/day, Q_{CO2Inj} is CO_2 injection rate in m3/day, Q_{EngInj} is energy injection rate in J/day, t is time of the cash flow in days, N1 is number of days from NPV present date to the start date time, and N2 is number of days from the NPV present date to the end date time.

Table 4 Parameters for NPV Calculation

Parameters	Value
Energy revenue	\$8.53E-9 /J (Crude Oil Price, 2022)
CO_2 Cost	-\$0.0103 /m³ (Gomes Filho & Sampaio, 2022)
Energy Cost	-\$8.53E-9 /J
Interest rate	9% (Gomes Filho & Sampaio, 2022)

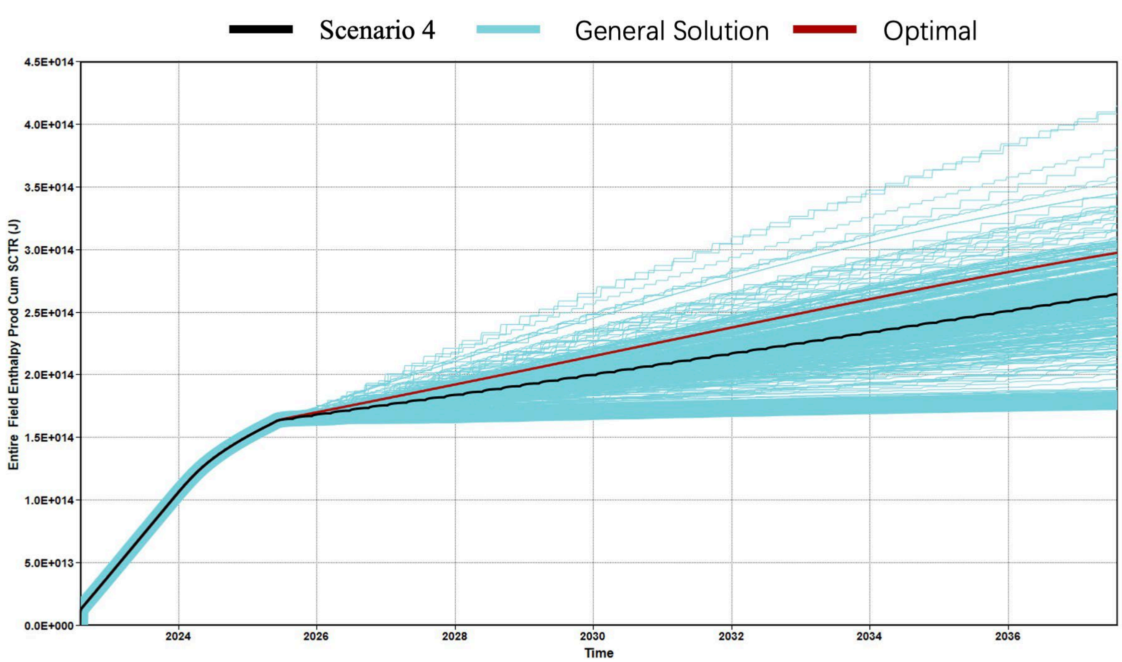

Figure 10 Energy Production Results for Maximization of NPV

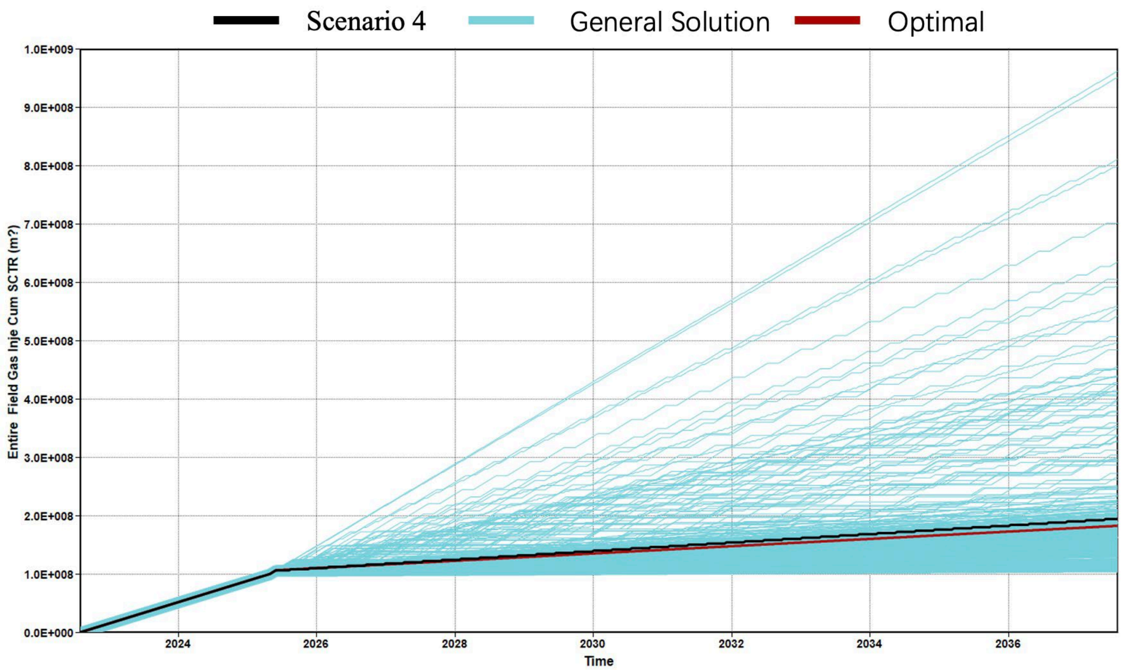

Figure 11 Gas injection Results for Maximization of NPV

Base on the maximization of NPV, the optimal case has three days of injection, 3.15 days of soaking, and 24.8 days of production. And the NPV for the optimal case is $450,212, which is a 109.7% increase compared with the default case, Scenario 4 mentioned in Figure 6. The optimized scenario has 12.5 % higher energy production than the original case by injecting 6.1 % less CO_2. The optimization leads to less injection and higher energy production.

Conclusions

The application of different $SCCO_2$ recovery strategies for energy recovery from geothermal reservoirs was evaluated by constructing and executing a 3D geological model using CMG - STARS. Different recovery approaches (Cyclic Injection, Continuous Injection, and their combination), well patterns, and different injection/soaking/production strategies have been investigated. The conclusions of the simulation can be summarized as follows,

- After 15 years of simulation, the cumulative energy production for the 5-spot pattern is slightly higher than the 9-spot pattern, which indicates the indispensability of the optimization for the well pattern.
- Cyclic injection has less advantage at the beginning of the energy recovery process in terms of cumulative energy production; this is due to dominant energy recovery by the present original reservoir fluid at that period. Also, continuous injection can establish the connection with the reservoir and maintain the reservoir pressure. In order to achieve higher energy recovery, the cyclic injection is suggested to be initiated after the continuous injection, or more specifically, after the gas breakthrough, instead of at the initiation of the project.
- Modified cyclic injection (Continuous injection before gas breakthrough and cyclic injection after gas breakthrough) has an advantage in terms of cumulative energy production compared with an all-time continuous injection when the gas injection is identical. Modified cyclic injection obtains better energy recovery performance from the reservoir fluid, continuous injection, and the cyclic recovery strategy. This process will enhance the energy production performance for the reservoir under premature thermal breakthrough.
- The strategies for the injection/soaking/production period need to be optimized in order to achieve higher energy production or NPV.
- The application of CO_2 in geothermal reservoirs saves water consumption and provides a new field for carbon utilization and storage.

Novel/Additive Information

This work utilized the oil recovery method in geothermal energy production and proposed a new production strategy (modified cyclic injection) for geothermal energy production. And the optimization algorithm has been used in this study. The proposed method would help to reduce the effects of thermal breakthroughs and the optimization algorithm can help to further enhance energy production efficiency. Additionally, the use of carbon dioxide as the working fluid not only sparks interest in carbon capture, utilization, and storage (CCUS) but also aligns with efforts to achieve carbon neutrality.

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