Parametric Analysis of Flow Rate and Fracture Surface Area Effects in an Enhanced Geothermal System

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Abstract

Enhanced Geothermal Systems (EGS) enable sustainable energy extraction from low-permeability crystalline reservoirs through engineered fracture networks and controlled fluid circulation. In this study, a fracture-based EGS model is developed to evaluate the influence of circulation flow rate and effective fracture surface area on thermal performance, net electrical power output, and long-term sustainability. The system is modeled using a deviated well configuration consisting of two injection and two production wells operating in a closed-loop circulation scheme.

A parametric analysis is conducted by varying the flow rate per production well between 20 and 50 kg/s and the effective fracture surface area between 100,000 and 300,000 m^2, while maintaining constant reservoir depth, rock properties, and surface power conversion assumptions. Simulation results indicate that increasing flow rate enhances early-time power output but significantly increases pumping power requirements and accelerates thermal drawdown, thereby shortening the economic lifetime of electricity-only operation. Conversely, larger fracture surface areas improve heat-exchange efficiency, reduce thermal decline, and extend sustainable power generation without increasing pumping demand.

The results highlight the critical trade-off between aggressive energy extraction and reservoir sustainability in EGS design. The study demonstrates that moderate flow rates combined with sufficient fracture surface area provide an optimal balance between net power output and long-term operational viability. This work offers practical insights for preliminary EGS design and screening-level feasibility assessments.

I. INTRODUCTION

The growing global demand for low-carbon and sustainable energy has intensified interest in geothermal resources as a reliable source of baseload power. Unlike solar and wind energy, geothermal energy offers continuous power generation independent of weather conditions. However, conventional geothermal systems are geographically limited to regions with naturally occurring high permeability and fluid-saturated reservoirs. To overcome this limitation, Enhanced Geothermal Systems (EGS) have been developed to enable energy extraction from hot, low-permeability crystalline formations through engineered subsurface stimulation.

Enhanced Geothermal Systems operate by creating artificial fracture networks within deep, hot rock formations and circulating a working fluid, typically water, between injection and production wells. Heat is transferred from the surrounding rock to the circulating fluid, which is then brought to the surface for power generation using thermodynamic cycles such as the Organic Rankine Cycle (ORC). The performance and sustainability of an EGS strongly depend on key design parameters, including circulation flow rate, fracture surface area, well configuration, and pumping requirements. Improper selection of these parameters can lead to excessive pumping losses, rapid thermal drawdown, and reduced economic viability.

Among these parameters, circulation flow rate and effective fracture surface area play a dominant role in controlling heat extraction efficiency and long-term reservoir behavior. Higher flow rates can increase short-term power output by enhancing convective heat transfer, but they also increase pumping power requirements and accelerate thermal depletion of the reservoir. Conversely, larger fracture surface areas improve heat-exchange efficiency and slow thermal drawdown, thereby enhancing system sustainability without significantly increasing hydraulic losses. Understanding the trade-off between these competing effects is essential for designing economically viable and long-lasting EGS projects.

This study presents a parametric analysis of an Enhanced Geothermal System using a simplified fracture-based reservoir model. A deviated well configuration consisting of two injection and two production wells is considered to represent a practical field-scale EGS layout. The investigation focuses on evaluating the impact of varying circulation flow rate and effective fracture surface area on geofluid temperature evolution, net electrical power output, pumping power requirements, and overall system sustainability. The results aim to provide insight into optimal operating conditions for electricity-only EGS applications and to support early-stage feasibility assessments and conceptual system design.

II. MODEL DESCRIPTION

This study employs a simplified, fracture-based Enhanced Geothermal System (EGS) model to evaluate the thermo-hydraulic performance of a stimulated geothermal reservoir under different operating conditions. The model is designed for screening-level analysis and focuses on capturing the dominant physical processes governing heat extraction, fluid circulation, and power generation while avoiding unnecessary numerical complexity.

A. Reservoir and Rock Model

The geothermal reservoir is assumed to be a deep, hot crystalline basement formation representative of granitic rock. The reservoir is located at a depth of approximately 3000 m, where elevated temperatures suitable for electricity generation are present. Rock properties are assumed to be homogeneous and isotropic and remain constant throughout all simulation cases.

The thermal behavior of the reservoir is governed by conductive heat transfer from the surrounding rock matrix to the circulating fluid within the fracture network. Thermal depletion of the reservoir is calculated implicitly based on heat extraction rates, rock thermal properties, and the effective heat-exchange area of the fractures. No natural recharge or external fluid influx is considered, representing a closed-loop EGS configuration.

B. Fracture Network Representation

The stimulated reservoir volume is represented using a multiple parallel fracture model. This approach approximates the hydraulically stimulated fracture network as a set of equivalent planar fractures that provide the primary pathways for fluid flow and heat exchange. Rather than explicitly modeling individual fracture geometries, the model characterizes the fracture system through an effective fracture surface area parameter.

The effective fracture surface area is varied parametrically to investigate its influence on thermal drawdown and system sustainability. Fracture areas of 100,000 m^2, 200,000 m^2, and

300,000 m^2 are considered, representing weak, moderate, and strong stimulation scenarios, respectively. This formulation allows for direct assessment of the role of fracture-mediated heat transfer without introducing additional geometric complexity.

C. Well Configuration and Flow Scheme

A deviated well configuration consisting of two injection wells and two production wells is adopted to represent a practical EGS field layout. Water is injected into the reservoir through the injection wells at a fixed temperature and circulated through the fracture network before being produced at the surface. The circulation scheme is symmetric, and the flow rate specified per well is assumed to be equally distributed among the wells.

The circulation flow rate is varied between 20 and 50 kg/s per production well to examine its effect on pumping power requirements, heat extraction, and net electrical output. Pressure losses associated with fluid circulation are accounted for through an explicit pumping power calculation, ensuring that net power generation reflects both energy production and parasitic losses.

D. Surface Power Conversion Model

Produced geothermal fluid is utilized for electricity generation using a subcritical Organic Rankine Cycle (ORC) power plant. The ORC is selected due to its suitability for moderate-temperature geothermal resources. The power conversion efficiency is determined as a function of geofluid temperature and ambient conditions, while auxiliary power consumption associated with fluid circulation is subtracted to obtain net electrical output.

The system is operated in electricity-only mode over a project lifetime of 30 years. The economic lifetime of the EGS system is defined as the time at which net electrical power output becomes zero, beyond which continued operation for power generation is no longer viable.

E. Governing Equations

The thermo-hydraulic behavior of the Enhanced Geothermal System is described using a set of energy balance and power accounting equations. These equations quantify heat extraction from the fractured reservoir, electrical power generation through the surface power plant, and parasitic losses associated with fluid circulation. The formulation is suitable for screening-level analysis and captures the dominant physical processes governing EGS performance.

The rate of thermal energy extracted from the reservoir is calculated based on the sensible heat carried by the circulating working fluid. It is expressed as a function of the total mass flow rate, fluid heat capacity, and the temperature difference between produced and injected fluid. This formulation assumes single-phase liquid water circulation and neglects phase change within the reservoir.

$$\dot{Q}_{th} = \dot{m} c_p (T_{prod} - T_{inj}) \tag{1}$$

The total initial heat content of the reservoir is estimated from the rock density, heat capacity, effective reservoir volume, and the temperature difference between the reservoir and a reference state. The cumulative fraction of heat mined over time is obtained by comparing the extracted thermal energy to the initial reservoir heat content. This metric provides an indication of long-term reservoir depletion and sustainability.

$$Q_{\text{res}} = \rho_r \, c_r \, V_r \, (T_{\text{res}} - T_{\text{ref}}) \tag{2}$$

Electrical power generation is modeled using a subcritical Organic Rankine Cycle. The gross electrical power output is calculated as a fraction of the extracted thermal power through a temperature-dependent conversion efficiency. As the produced fluid temperature declines due to thermal drawdown, the conversion efficiency and gross electrical output decrease accordingly.

$$P_{\text{gross}} = \eta_{\text{ORC}} \, \dot{Q}_{\text{th}} \tag{3}$$

Fluid circulation between injection and production wells requires pumping power to overcome pressure losses in the wells and fracture network. The pumping power is computed from the pressure drop, mass flow rate, fluid density, and pump efficiency. Pumping requirements increase with circulation rate and represent a major parasitic load in EGS operation.

$$P_{\text{pump}} = \frac{\Delta P\, \dot{m}}{\rho_f\, \eta_p} \tag{4}$$

The net electrical power output of the system is determined by subtracting the pumping power from the gross electrical power generated by the surface plant. Net power is used as the primary performance metric in this study. A positive net power indicates viable electricity generation, whereas a zero or negative net power defines the economic end-of-life for electricity-only operation.

$$P_{\text{net}} = P_{\text{gross}} - P_{\text{pump}} \tag{5}$$

Finally, the first-law efficiency of the system is defined as the ratio of net electrical power output to the extracted thermal power. This efficiency reflects the overall effectiveness of converting geothermal heat into usable electrical energy and provides a consistent basis for comparing different operating scenarios.

$$\eta_{\text{I}} = \frac{P_{\text{net}}}{\dot{Q}_{\text{th}}} \tag{6}$$

where $\dot{m}$ is the total mass flow rate (kg/s), c_p is the specific heat capacity of water (J/kg·K), T_{prod} and T_{inj} are the production and injection temperatures (°C), ρ_r and c_r are the rock density (kg/m^3) and heat capacity (J/kg·K), V_r is the effective reservoir volume (m^3), η_{ORC} is the Organic Rankine Cycle efficiency, ΔP is the circulation pressure drop (Pa), η_p is the pump efficiency, and ρ_f is the fluid density (kg/m^3).

F. Model Assumptions and Limitations

The Enhanced Geothermal System analyzed in this study is evaluated using a screening-level, fracture-based reservoir model. Several assumptions are made to simplify the analysis while retaining the dominant physical processes governing heat extraction and power generation. These assumptions are summarized to ensure transparency and reproducibility of the results.

A deviated well configuration is assumed to represent a practical field-scale EGS layout. The system consists of two injection wells and two production wells operating under symmetric conditions. The mass flow rate specified in the simulations corresponds to the flow rate per production well. Therefore, a circulation rate of 20 kg/s per production well results in a total produced flow rate of 40 kg/s for the system.

For the circulation flow-rate sensitivity study, flow rates of 20, 30, 40, and 50 kg/s per production well are investigated while maintaining a constant effective fracture surface area of 250,000 m^2. This approach isolates the impact of circulation intensity on pumping power, thermal drawdown, and net electrical power output.

For the fracture surface area sensitivity study, the circulation rate is fixed at 20 kg/s per production well, corresponding to a total system flow rate of 40 kg/s. Effective fracture surface areas of 100,000 m^2, 200,000 m^2, and 300,000 m^2 are considered to represent varying levels of reservoir stimulation. All other reservoir, well, and surface plant parameters are kept constant.

Capital and operating costs are estimated using built-in screening-level correlations provided by the modeling framework. These correlations account for well depth, well type, surface plant characteristics, and circulation requirements. The resulting comparative economic indicators are intended for comparative assessment rather than detailed project costing.

III. METHODOLOGY

The methodology adopted in this study follows a structured parametric simulation approach to evaluate the performance of an Enhanced Geothermal System (EGS). A simplified fracture-based reservoir model is used to investigate the influence of circulation flow rate and effective fracture surface area on thermal behavior, net electrical power output, and long-term sustainability. All simulations are carried out by varying one parameter at a time while keeping all other inputs constant to ensure clear interpretation of results.

A. Base Case Definition

A reference base case is established to provide a consistent framework for comparison. The base case represents a fractured granitic reservoir located at a depth of 3000 m and is modeled using a multiple parallel fracture representation. A deviated well configuration consisting of two injection wells and two production wells is considered. Water is circulated in a closed-loop system, and electricity is generated at the surface using a subcritical Organic

Rankine Cycle (ORC).

Rock properties, well geometry, fracture characteristics, surface plant parameters, and economic assumptions are kept constant across all simulation cases. This approach ensures that observed variations in system performance are solely attributed to changes in the selected parametric variables.

B. Flow Rate Sensitivity Analysis

To examine the effect of circulation intensity on EGS performance, a flow rate sensitivity study is conducted. The mass flow rate per production well is varied while maintaining identical reservoir, fracture, and surface plant conditions. Flow rates of 20, 30, 40, and 50 kg/s per production well are analyzed, corresponding to increasing levels of fluid circulation through the fracture network.

Each flow-rate case is simulated over a 30-year operational period. Annual outputs including produced fluid temperature, pumping power, net electrical power, cumulative heat extracted, and percentage of reservoir heat mined are recorded. The economic lifetime of electricity-only operation is defined as the time at which the net electrical power output becomes zero.

C. Fracture Area Sensitivity Analysis

A fracture area sensitivity analysis is performed to evaluate the influence of heat-exchange surface area on reservoir sustainability. In this analysis, the circulation flow rate is fixed at 20 kg/s per production well, while the effective fracture surface area is varied. Fracture areas of 100,000 m^2, 200,000 m^2, and 300,000 m^2 are considered to represent weak, moderate, and strong stimulation scenarios.

The fracture surface area directly controls the rate of heat transfer between the circulating fluid and the surrounding rock matrix. By varying only the fracture area, the impact of thermal drawdown and long-term temperature sustainability can be isolated and quantified.

D. Simulation Execution and Output Evaluation

All simulation cases are executed for a project lifetime of 30 years using annual time steps. The model internally calculates thermal drawdown, pumping power requirements, and ORC conversion efficiency based on the specified input parameters. Output data are extracted in tabular form for post-processing and comparative analysis.

Key performance indicators evaluated in this study include geofluid temperature decline, net electrical power output, first-law efficiency, cumulative thermal energy extracted, and percentage of reservoir heat mined.

E. Performance Criteria and Comparison Strategy

System performance is primarily evaluated based on net electrical power output and operational lifetime. A configuration is considered viable for electricity-only operation as long as the net electrical power remains positive. Cases exhibiting early net power decline are classified as thermally or hydraulically aggressive, whereas cases maintaining positive net power over extended periods are identified as more sustainable.

Comparative analysis of flow rate and fracture area cases is conducted to identify operating conditions that provide an optimal balance between power generation, pumping losses, and reservoir longevity. These comparisons form the basis for the conclusions and recommendations presented in this study.

IV. RESULTS AND DISCUSSION

This section presents the simulation results obtained from the parametric analysis of the Enhanced Geothermal System. The results are organized into two parts: (i) circulation flow rate sensitivity and (ii) fracture surface area sensitivity. All results correspond to a deviated well configuration with two injection and two production wells.

A. Effect of Circulation Flow Rate

(Fracture area fixed at 250000 m^2) Figure 1 illustrates the variation of net electrical power output with time for different circulation flow rates. The results highlight the trade-off between short-term power generation and long-term system sustainability.

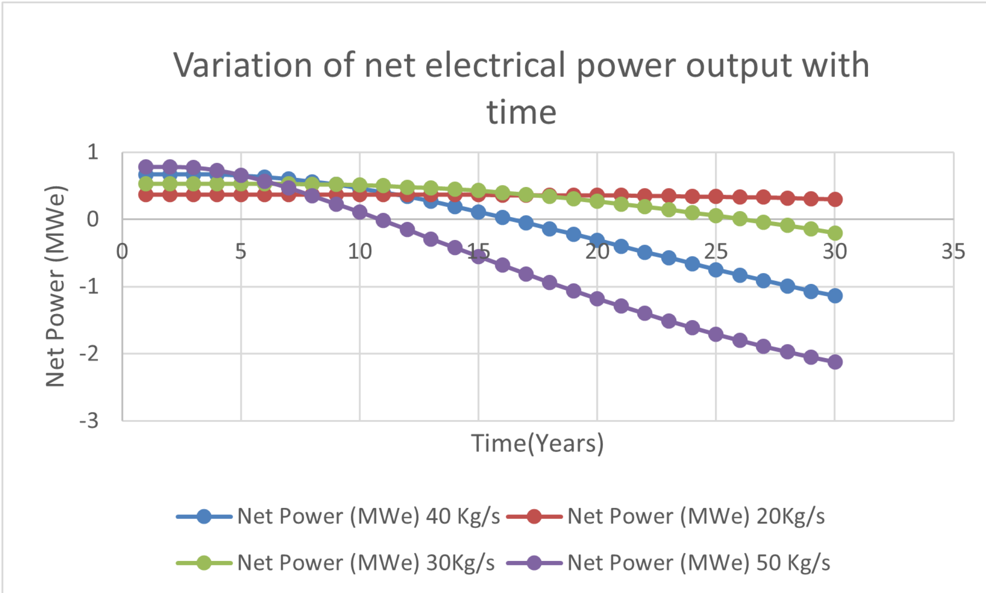

Figure 1: Net power output as a function of time for different circulation flow rates.

At the highest circulation rate of 50 kg/s, net electrical power decreases rapidly and becomes zero after approximately 10–11 years, defining a short economic lifetime for electricity-only operation. Moderate flow rates of 30–40 kg/s provide a balance between power output and sustainability, whereas the lowest flow rate of 20 kg/s maintains positive net power throughout the 30-year simulation period, albeit at lower power levels.

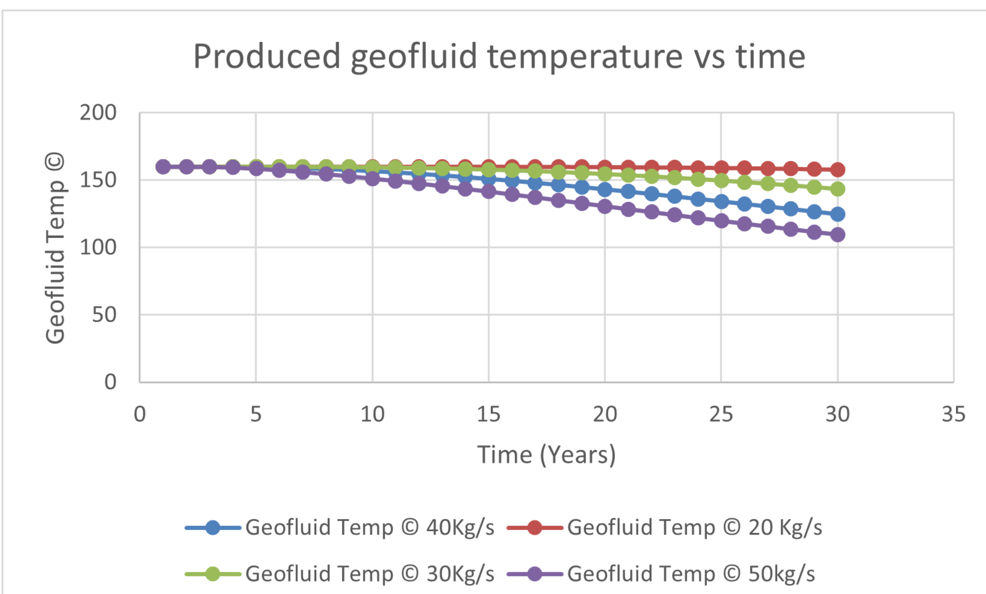

Figure 2: Produced geofluid temperature as a function of time for different flow rates.

The temperature profiles confirm that aggressive circulation accelerates thermal drawdown. Reduced flow rates distribute heat extraction over a larger effective rock volume, thereby enhancing long-term thermal sustainability.

B. Effect of Fracture Surface Area

(Flow rate fixed at 20 kg/s per production well)

Figure 3 presents the impact of effective fracture surface area on net electrical power output at a fixed circulation rate of 20 kg/s per production well.

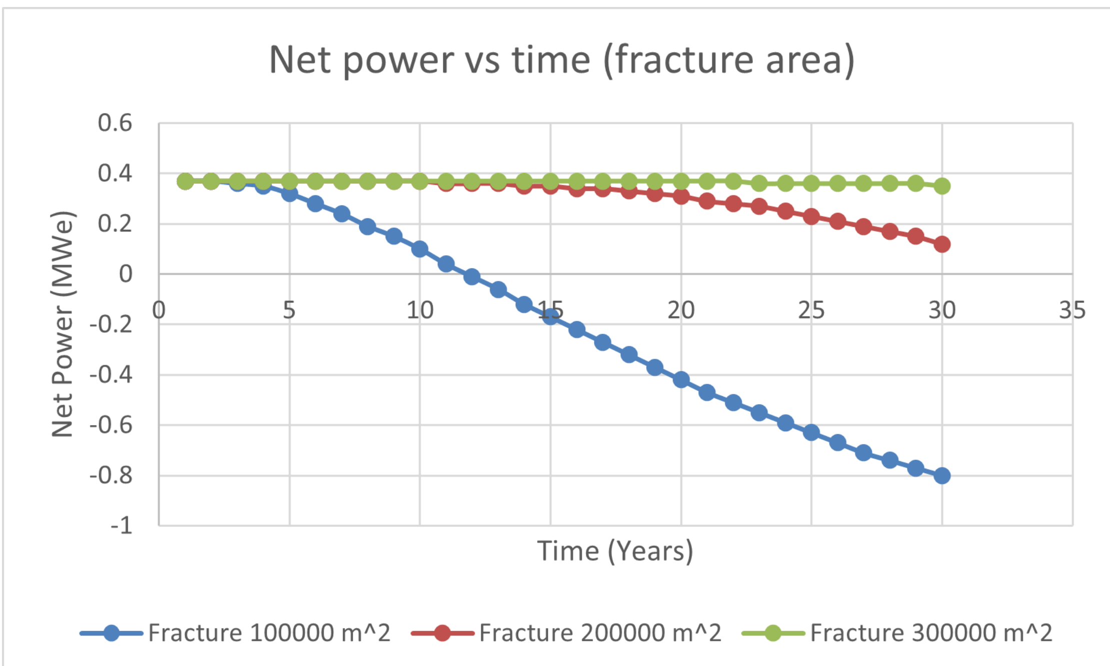

Figure 3: Net power output as a function of time for different effective fracture surface areas.

For a fracture area of 100,000 m^2, net power declines rapidly and becomes negative within the first decade of operation, indicating insufficient heat-exchange capacity. Increasing the fracture area to 200,000 m^2 maintains positive net power throughout the 30-year simulation, representing a balanced and realistic stimulation scenario. The largest fracture area of 300,000 m^2 exhibits minimal power decline and represents an optimistic upper-bound case.

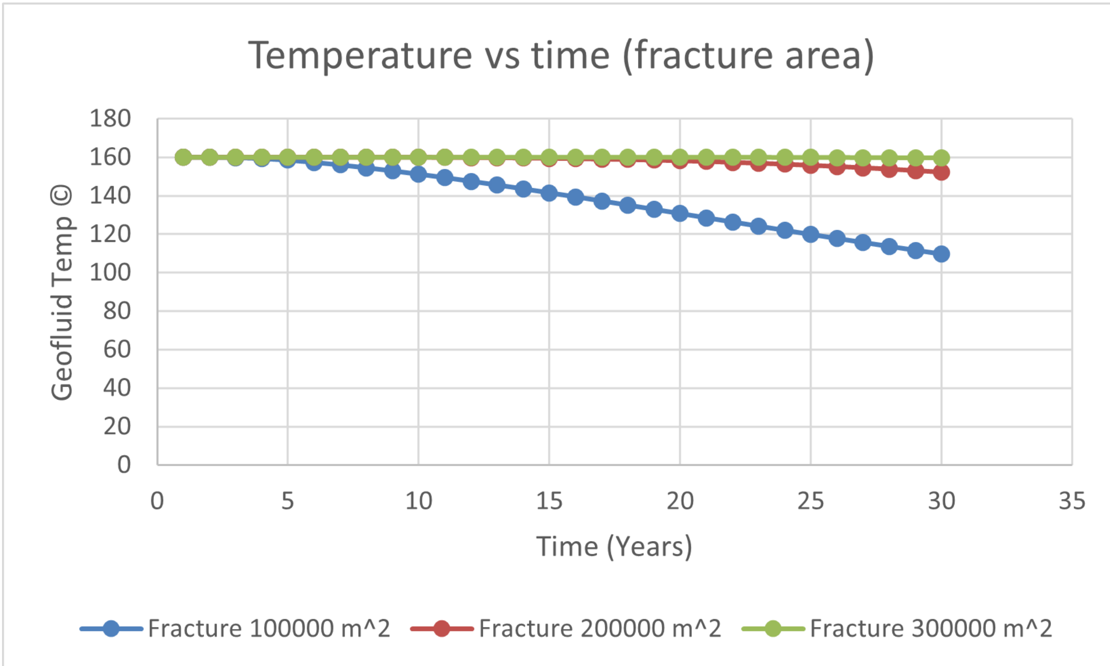

Figure 4: Produced geofluid temperature as a function of time for different effective fracture surface areas.

The fracture area sensitivity results demonstrate that effective fracture surface area is a dominant control on EGS sustainability. Adequate reservoir stimulation is essential to maintain stable production temperatures and extend electricity-generation viability without increasing pumping requirements.

Overall, the results highlight the importance of balancing circulation rate and fracture surface area to achieve sustainable electricity generation in Enhanced Geothermal Systems.

All model inputs and assumptions are explicitly documented to ensure transparency and reproducibility of the simulation results.

Note that the specified circulation rate corresponds to the flow rate per production well; therefore, the total system flow rate is twice the reported value.

C. Discussion

The simulation results demonstrate that the performance of an Enhanced Geothermal System is governed by a strong trade-off between short-term power generation and long-term thermal sustainability. Both circulation flow rate and effective fracture surface area significantly influence net electrical power output, thermal drawdown, and system lifetime.

An increase in circulation flow rate enhances convective heat extraction from the reservoir, resulting in higher initial net electrical power. However, this benefit is offset by a substantial rise in pumping power requirements and accelerated cooling of the fractured rock mass. As observed in the high-flow-rate cases, rapid thermal drawdown leads to a decline in produced fluid temperature, which in turn reduces Organic Rankine Cycle conversion efficiency. Consequently, net electrical power decreases rapidly and becomes negative within a relatively short operational period. These results indicate that aggressive circulation strategies are unsuitable for long-term electricity-only operation.

Lower circulation flow rates exhibit reduced initial power output but significantly improved sustainability. The reduced pumping losses and slower reservoir cooling allow net electrical power to remain positive for extended periods. This behavior highlights the importance of prioritizing long-term energy recovery over short-term power maximization in EGS design, particularly for projects targeting stable electricity generation over multiple decades.

The fracture surface area sensitivity analysis further emphasizes the role of reservoir stimulation in controlling thermal performance. Smaller fracture areas limit the effective heat-exchange surface between the circulating fluid and the surrounding rock, leading to steep thermal gradients and rapid temperature decline. In contrast, larger fracture areas distribute heat extraction over a greater rock volume, thereby reducing thermal drawdown and maintaining higher production temperatures. This results in improved net power stability and extended system lifetime.

The combined results suggest that fracture surface area has a more pronounced impact on sustainability than circulation flow rate alone. While flow rate primarily controls the intensity of heat extraction, fracture area determines the efficiency with which heat is transferred from the rock matrix to the fluid. Adequate reservoir stimulation is therefore essential to avoid premature thermal depletion, especially under continuous electricity-generation scenarios.

Overall, the findings indicate that optimal EGS performance is achieved through a balanced design approach, combining moderate circulation rates with sufficiently large fracture surface areas. Such configurations minimize pumping losses, limit thermal drawdown, and ensure sustained net electrical power generation. These insights are particularly relevant for early stage EGS feasibility assessments and highlight the limitations of purely aggressive operating strategies.

A parametric analysis of an Enhanced Geothermal System was conducted to evaluate the influence of circulation flow rate and effective fracture surface area on thermal performance and net electrical power generation. The study employed a fracture-based reservoir model with a deviated well configuration consisting of two injection and two production wells.

The results indicate that increasing circulation flow rate enhances initial electrical power output but significantly increases pumping power requirements and accelerates thermal drawdown, thereby shortening the economic lifetime of electricity-only operation. High flow rates, such as 50 kg/s per production well, result in rapid loss of net power within the first decade of operation.

Conversely, lower flow rates improve long-term sustainability by reducing pumping losses and slowing reservoir cooling, albeit at the cost of reduced power output. A flow rate of 20 kg/s per production well maintains positive net power throughout the 30-year simulation period.

Fracture surface area is identified as a dominant control on reservoir sustainability. Larger effective fracture areas significantly reduce thermal drawdown and extend the duration of viable power generation. A fracture area of approximately 200,000 m^2 provides a realistic balance between heat-exchange efficiency and long-term performance.

Overall, the study highlights the importance of balancing circulation intensity and fracture stimulation to achieve sustainable electricity generation in Enhanced Geothermal Systems.

V. LIMITATIONS AND FUTURE WORK

The present study is based on a simplified, screening-level fracture-based EGS model. Several physical processes, including coupled thermo-hydro-mechanical behavior, fracture evolution, and geochemical interactions, are not explicitly considered. Rock and fluid properties are assumed constant, and natural reservoir recharge is neglected.

Future work may include detailed numerical modeling with explicit fracture networks, incorporation of mechanical deformation effects, and evaluation of combined heat and power (CHP) operation. Economic optimization and uncertainty analysis could further improve the assessment of EGS feasibility.

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[1] Tester, J. W., et al., *The Future of Geothermal Energy*, MIT Press, 2006.

[2] Grant, M. A., and Bixley, P. F., *Geothermal Reservoir Engineering*, Academic Press, 2011.

[3] IPCC, *Climate Change 2022: Mitigation of Climate Change*, Cambridge University Press, 2022.

VI. APPENDIX

A. Model Input Data

1. Well Configuration

- Well type: Deviated wells
- Number of injection wells: 2
- Number of production wells: 2
- Reservoir depth (true vertical depth): 3000 m
- Measured well depth: 3000 m
- Production well diameter: 7 in
- Injection well diameter: 7 in

2. Operating Conditions

- Injection temperature: 70°C
- Surface temperature: 15°C
- Ambient temperature: 15°C
- Pump efficiency: 0.75
- Project lifetime: 30 years

3. Rock and Reservoir Properties

- Rock type: Granite
- Rock density: 2700 kg/m^3
- Rock heat capacity: 1000 J/kg·K
- Rock thermal conductivity: 2.8 W/m·K
- Effective reservoir volume: 1.25×10^8 m^3
- Maximum reservoir temperature: 400°C

4. Fracture Model Parameters

- Reservoir model: Multiple parallel fractures
- Fracture shape: Circular fracture with known area
- Number of fractures: 10

5. Surface Plant and Economic Assumptions

- End-use option: Electricity-only
- Power plant type: Subcritical Organic Rankine Cycle
- Economic model: Levelised cost approach
- Capital and operating costs: Estimated using built-in screening-level correlations

B. Simulation Case Definitions

1. Flow Rate Sensitivity Cases

In the circulation flow-rate sensitivity analysis, the effective fracture surface area was fixed at 250,000 m^2. The mass flow rate specified corresponds to the flow rate per production well. Since two production wells are present, the total system flow rate is twice the per-well value.

- Case FR-20: 20 kg/s per production well (40 kg/s total)
- Case FR-30: 30 kg/s per production well (60 kg/s total)
- Case FR-40: 40 kg/s per production well (80 kg/s total)
- Case FR-50: 50 kg/s per production well (100 kg/s total)

2. Fracture Surface Area Sensitivity Cases

In the fracture surface area sensitivity analysis, the circulation flow rate was fixed at 20 kg/s per production well (40 kg/s total). The effective fracture surface area was varied to represent different stimulation intensities.

- Case FA-100: 100,000 m^2
- Case FA-200: 200,000 m^2
- Case FA-300: 300,000 m^2

Detailed year wise simulation data are provided in external Excel files for transparency and reproducibility.