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Minimum Propped Fracture Permeability for Economic Multi-stage Enhanced Geothermal Systems

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ABSTRACT

Enhanced Geothermal Systems (EGS) have potential to supply more than 90 GWe of clean and reliable energy to the United States and beyond. One of the keys to commercial success of EGS is that hydraulically stimulated fractures must sustain high conductivity for long durations of 5 years or more. While shear stimulation has been proposed as a solution, the use of solid proppants to sustain fracture permeability holds unique promise in that it is easier to design and to control. Recent field implementation of multi-stage propped hydraulic fracturing for EGS during stimulation has demonstrated energy production from a doublet EGS. However, the minimum proppant pack conductivity (or propped fracture permeability) required for power production, impact of design parameters such as perforation clusters, number of production wells and well spacing on minimum conductivity remains unknown. In addition, it is difficult to control or measure the proppant distribution between fractures in multi-stage stimulations, even though we know that poor distribution will lead to flow heterogeneity and ultimately a risk of thermal short circuiting. To address these unknowns, we seek to identify the minimum propped fracture permeability for hydraulically stimulated fractures that will assure economic energy production from EGS. In this study, we employ models to address the above-mentioned unknowns and thereby provide guidance for designing stimulations for EGS, especially regarding propped fracture permeability (or conductivity). Our analysis is loosely based on the Blue Mountain site by assuming the similar temperatures and depths, 102 perforation clusters, and a two well design. For these conditions, the minimum propped fracture permeability was predicted at 200 D, which equated to individual fracture conductivity ranging from 30 mD-ft to 130 mD-ft depending on the fracture width, to achieve adequate pressures and flow rates for sustained power production. This minimum propped fracture permeability decreased with more perforation clusters. In addition, increasing the number of perforation clusters, production wells, and well spacing increased the power production potential of the system.

1. INTRODUCTION

Geothermal energy has a potential to provide a clean, reliable, and dispatchable energy to meet the base-load demand. Considering technological breakthroughs in Enhanced Geothermal Systems (EGS), Augustine et al., (2023) estimated the U.S.A will have about 38.30 GWe of installed EGS capacity by 2035 and 90.52 GWe by 2050. The technological advancement in drilling and stimulation technique such as multi-stage hydraulic fracturing can help achieve this EGS capacity in the future. Conventionally, an EGS reservoir is stimulated by injecting water through an injection well to create new tensile fractures, or open an existing natural fracture, or both (McClure and Horne, 2014). Then, a production well is drilled intercepting the stimulated fracture network to extract hot fluid from the reservoir for energy generation. The stimulated fracture network must be conductive enough to sustain high flow rate for long duration for economic electricity generation from any EGS. Self-propping of asperities during shear stimulation (hydroshearing) of a fracture has been proposed as a solution to maintain the long-term fracture conductivity in the reservoir (Cladouhos et al., 2016). However, hydroshearing relies on having the goldilocks mix of suitably weak, suitably oriented and sufficiently conductive (but not too conductive) fractures, and adequate in-situ shear stress to mobilize these fractures without inadvertently triggering a seismic event; conditions which are difficult to control in the reservoir. As such, multi-stage hydraulic fracturing with solid proppants holds a unique promise to engineer the reservoir fracture network and sustain fracture conductivity for long-term energy production from EGS.

Proppant has been successfully used in unconventional oil and gas reservoir stimulation to sustain conductivity of the stimulated fractures (Bandara et al., 2020) but the applicability of proppants under high-temperature hard-rock high-stress EGS conditions is limited, unclear and yet to be proven (Huenges et al., 2004; Norbeck et al., 2023). Proppant in EGS reservoir must maintain higher conductivity for longer duration than oil and gas reservoir to be economic (Frash et al, 2023a). Proppant performance under EGS conditions has been investigated through numerical modeling, few laboratory tests, and limited field scale testing (Jones et al., 2014; Norbeck et al., 2023; KC et al., 2024). However, most of these studies focus on proppant-pack conductivity reduction over time due to crushing, or chemical reactivity and do not answer the key question about the minimum proppant pack conductivity that should be targeted during the stimulation to sustain an economic flow rate.

Fervo Energy recently leveraged the multi-stage propped hydraulic fracturing technique used in unconventional oil and gas reservoir to demonstrate the applicability of the technology for EGS stimulation at Blue Mountain geothermal field in Nevada. This project pumped silica sand proppants at concentrations ranging from 0.25 to 1.5 ppg while achieving individual fracture conductivity ranging from 300 to 400 md-ft. The project achieved a flow rate of 63 L/s, which is the maximum reported in any EGS till date (Norbeck et al., 2023). However, the question of whether this conductivity is optimum for achieving the economic flow rate in EGS is still open. Injecting a large quantity of proppants into the fracture increases the pumping cost during the stimulation. Thus, knowing the optimum fracture conductivity will help to reduce the pumping cost during EGS stimulation.

In this study, we use Geothermal Design Tool (GeoDT) to investigate the minimum proppant pack conductivity that should be targeted during EGS stimulation to achieve economic flow rates. Furthermore, we investigated the impact of design parameters such as number of perforation clusters during stimulation, number of production wells, and well spacing on the minimum proppant pack conductivity.

2. MODEL SETUP

We used the Geothermal Design Tool (GeoDT) developed by Frash (2021) to investigate the minimum proppant pack conductivity required to obtain economic flowrate in EGS. GeoDT is a fast simplified numerical model that solves coupled multi-physics problem to support decision making for EGS optimization under uncertain subsurface conditions. GeoDT uses simplified physics to predict the flow and heat transfer through natural or stimulated three-dimensional network of fractures in a EGS reservoir. The flow rate and heat transfer are then used to evaluate the power production and economics of the EGS. GeoDT can simulate thousands of scenarios within a day using desktop computer allowing us to identify the important parameters in EGS optimization in highly uncertain conditions.

We loosely based our model on Fervo Energy's site at Blue Mountain geothermal field, where they used plug-and-perf multi-stage propped hydraulic fracturing stimulation technique for the first time in EGS reservoir (Norbeck et al., 2023). This EGS consisted of a horizontal doublet system, where the wells were landed at true vertical depth of approximately 7,700 ft (~2347 m) and the lateral sections were extended roughly by 3,250 ft (~1073 m). In our model, we varied the reservoir temperature uniformly within the range of 171 to 188 ℃ to account for uncertainty in reservoir temperature encountered in the field. One of the major deviations from the stimulation design used in the field and our model is that we stimulated all the fractures in a single stage, whereas field stimulation is carried out in multiple stages, e.g., Fervo Energy's site at Blue Mountain geothermal field consisted of 16 stages.

The GeoDT code used in this study is available in GitHub (Frash 2024). The model includes parameters that are randomly sampled from uniform or log-uniform distributions to account for the subsurface uncertainties. Some critical parameters used in the model are listed in Table 1. Initially, we set-up the model to answer the key question of the study, i.e., minimum proppant pack conductivity that should be targeted to achieve a flow rate that can produce positive net power from the system during multi-stage hydraulic fracturing stimulation. Later we investigated the impact of design parameters, such as number of stages (or perforation clusters), number of production wells and well spacing on the minimum proppant pack conductivity required in EGS. In total we modeled 13 different EGS scenarios with approximately 4000 realizations each. The simulation took about 8 hours to 72 hours to run in a desktop computer depending on the input parameters used in the model such as number of perforation clusters, production wells, and well spacing.

Table 1: Model parameters

S.N.	Parameter	Min	Max	Distribution	Unit
1	Propped Fracture Permeability	1.00E-01	1.00E+05	loguniform	Darcy
2	Sand ratio in frac fluid	0	0.034		m3/m3
3	Production Well Count	1	4	-	ea
4	Perforation clusters	25	200	-	ea
5	Perforation Diameter	0.02	0.02	-	m
6	Perforation per cluster	6	6	-	
7	Target injection rate	0.005	0.5	loguniform	m3/s
8	Well spacing	50	800	-	ea
9	Reservoir Size (Half)	1000	1000	-	m
10	Reservoir Depth	2300	2300	-	m
11	Thermal Gradient	74.3	81.7	uniform	C/km
12	Rock Density	2550	2950	uniform	kg/m3
13	Rock Thermal Conductivity	2.27	3.58	uniform	W/m2
14	Rock Specific Heat Capacity	0.74	1.2	uniform	kJ/kg-K
15	Surface Temperature	0	0		C
16	Surface Pressure	0.101	0.101	-	Mpa
17	Rock Young's Modulus	55	62	uniform	Gpa
18	Rock Poisson's Ratio	0.26	0.4	uniform	
19	Minimum Earth Stress Coef.	0.3	0.6	uniform	Pa/Pa
20	Intermediate Stress Coef	0.4	0.8	uniform	Pa/Pa
21	Minimum Stress Azimuth	85	115	uniform	deg
22	Azimuth's uncertainty	1.5	1.5	-	deg
23	Minimum Stress Dip	-15	15	uniform	deg
24	Dip's uncertainty	1.5	1.5	-	deg
25	Fracture Slip-Length Scaling	0.001	0.063	-	m/m
26	Fracture Dilation-Slip Scaling	0	0.01	-	m/m
27	Fracture Hydraulic-Dilation Scaling	0	2	-	m/m
28	Fracture compressibility	2.00E-09	1.00E-07	-	1/pa
29	Proppant Compressibility	2.00E-09	1.00E-07	-	1/pa
30	Fracture initial hydraulic aperture	1.00E-08	1.00E-04	-	m
31	Boundary hydraulic aperture	1.00E-04	1.00E-03	-	m
32	Fracture Stranding Scale factor	0.0625	1	-	m/m
33	Well inclined Azimuth	95	95	-	deg

S.N.	Parameter	Min	Max	Distribution	Unit
34	Well inclined Dip	2	2	-	deg
35	Well inclined proportion	0.9	0.9	-	m/m
36	Well inclined length	990	990	-	m
37	Well intervals	1	1	-	
38	Casing inner radius	0.18	0.18	-	m
39	Casing outer radius	0.2	0.2	-	m
40	Borehole radius	0.25	0.25	-	m
41	Well hydraulic roughness	80	80	-	
42	Cement thermal conductivity	2	2	-	W/m2
43	Cement Specific Heat Capacity	2000	2000	-	kJ/m3-K
44	Generator Efficiency	0.85	0.85		
45	Lifespan of production	10	10	-	yr
46	Production Wellhead Pressure	1	1	-	MPa
47	Injection Water Temperature	15	25	uniform	C
48	Convection Coefficient	3	3		
49	Water Density	920	932	uniform	kg/m3
50	Water Viscosity	0.2	0.2	-	cP
51	Production well drawdown	0	0	-	MPa
52	Solver's Pressure Increment	0.02	0.02	-	Mpa
53	Maximum Injection pressure	s3-1.0	s3-1.0	-	MPa
54	Fracture Friction Angle	20	45	-	deg
55	Fracture Cohesion	1	6	-	MPa
56	Hydraulic Fracture Cohesion	15	35	-	deg
57	Hydraulic Fracture Friction Angle	0.1	0.4	-	MPa
58	Electric Sales	0.1372	0.1372	-	$/kWh
59	Drilling Cost	2763.06	2763.06	-	$/m
60	Drilling Pad Cost	590000	590000	-	$
61	Power Generation Cost	2025.65	2025.65	-	$/kW
62	Exploration Cost (Geophysics)	2683.41	2683.41	-	$/m
63	Operation Cost (maintenance)	0.03648	0.03648	-	$/kWh
64	Earthquake Penalty (Coefficient)	2.00E-04	2.00E-04	-	$/Mw
65	Earthquake Penalty (Exponent)	5	5	-	$/Mw

3.RESULTS AND DISCUSSIONS

We start by investigating the minimum propped fracture permeability required to produce positive net power in Blue Mountain geothermal field. For this simulation, we used the same design parameters as in field, e.g. doublet system with well spacing of 120 m, total perforation clusters of 102 with six perforations per cluster. The purpose of this simulation is not to match the field data rather to serve as a baseline for comparison and understand the impact of various design parameters on minimum fracture permeability required for long term power production. Our model did not consider the uncertainty that could be caused due to presence of natural fractures in the sub-surface. GeoDT calculates the average net power per year (kW) assuming binary power plant for each realization, which we used as a metric to determine the optimum propped fracture permeability in this study (Figure 1). It is worth noting that, we report propped fracture permeability instead of fracture conductivity in this study. GeoDT assigns constant propped fracture permeability to all the fractures in each realization. However, the individual fracture conductivity varies based on the width of the fracture. GeoDT calculates individual width of the fracture, which can be multiplied by the fracture permeability to get the conductivity.

When the propped fracture permeability was low most of the target flow rate, especially higher target, was not achieved during the simulation and resulted in value smaller than 0.005 m^3/s. This is due to the limit on injection pressure, which was set at 1.0 MPa lower than the minimum principal stress (S_3). Any flow rate smaller than 0.005 m^3/s is omitted from the analysis as this flow rate is smaller than the lower range of assigned target and is not economic for energy production from EGS. Our simulation results indicate the power produced from the EGS generally increases with the propped fracture permeability and flow rate. The optimal region where the average net power production is positive is highlighted in Figure 1. Average power production per year is positive when the propped fracture permeability is greater than 200 D with the corresponding flow rate range between 0.015 m^3/s and 0.05 m^3/s. When the propped fracture permeability increases the upper range of the flow rate that can produce positive power increases while the lower range remains constant at 0.015 m^3/s. Our simulation results suggest, minimum propped fracture permeability of 200 D is required to achieve a flow rate that could produce net positive power in the EGS model loosely based on Blue Mountain geothermal site. The propped fracture width ranged between 0.05 mm and 0.2 mm, which resulted in a minimum fracture conductivity ranging from 30 mD-ft to 130 mD-ft for the net positive average power production. The observed conductivity in the Blue Mountain geothermal field ranged between 300 to 400 mD-ft and an average flow rate of 0.037 m^3/s. The average net electricity produced from the system was ~1300 kW for 37 days test period (Norbeck and Latimer, 2023). Again, our model used in this study does not consider exact field parameters such as exact stress regime, natural fractures and faults, which could significantly help to improve EGS performance in some cases. However, our simulation results suggest that when the flow is in optimum range and uniformly distributed through all the fractures, the produced water temperature increases initially due to near well bore heating, which was also observed in the Blue Mountain geothermal field during the 37 days of circulation test. In such case when the flow is uniformly distributed through all the fractures, thermal breakthrough was observed after ~ 4 years of operation which resulted in decline of power production from the reservoir (Figure 2(a)). Future study with history matching could provide crucial insights about the performance of the Blue Mountain EGS in long term.

The net power required for economic EGS depends on the reservoir depth and temperature, flow rate, number of production wells in the system, and well spacing. It is worth pointing out that positive net power does not necessarily mean economic system. Further analysis on net present value (NPV) that is based on revenue generated from electricity sell and cost associated with drilling, pumping, and seismicity risk show that net power higher than ~4500 kW is required for this system to generate profit without considering tax credits from the doublet EGS with well spacing of 120 m modeled in this study.

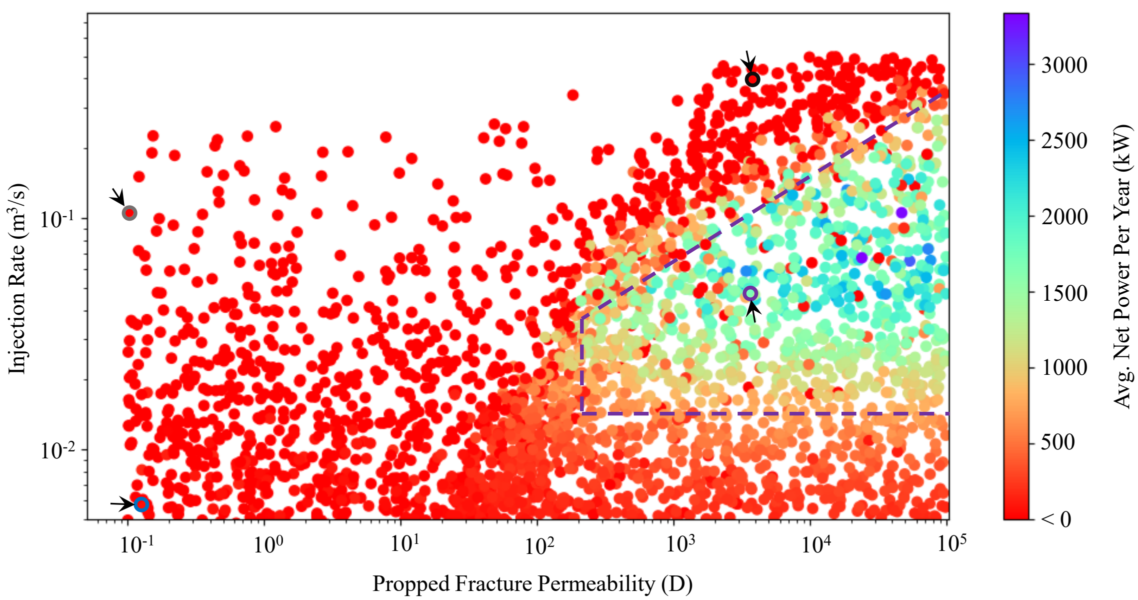
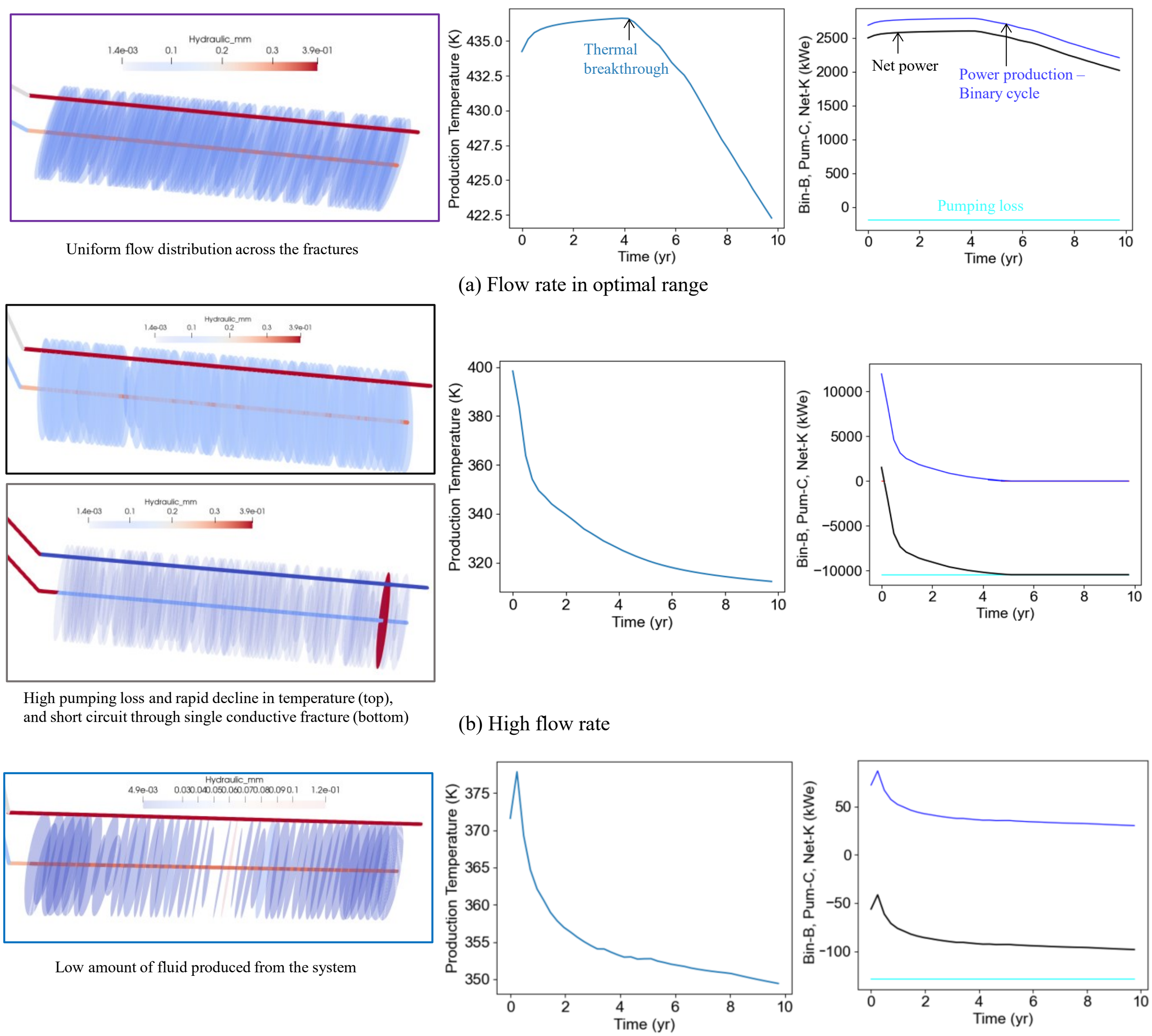


Figure 1: 3D scatter plot showing the net power output of the doublet EGS as a function of propped fracture permeability and flow rate. The minimum propped fracture permeability required for positive net power from the system is 200 D and the minimum flow rate required is 0.015 m^3/s.

The main objection of injecting proppant into the fracture in EGS is to increase the flow rate as higher flow rate is often considered to be better in terms of power production. However, our simulation results as well as previous studies (Frash et al., 2023a) consistently show that at higher flow rates, EGS performance becomes unpredictable. The EGS will be economical when operated within a range of flow rate, which depends on the propped fracture permeability of the fractures. We show an example of timeseries data and 3D visualization of fractures for realizations which resulted in positive power production at flow rate within optimal range, and negative power production under high and low flow rates in Figure 2. Upon careful inspection of the realizations, we found that high pumping cost and rapid decline in production temperature is the most common mechanism that could result in negative power production when the flow rate is high. Thermal short circuiting caused by single fracture contributing to the flow could also result in negative power production at high flow rate. When the flow rate is low, the total power production is low resulting in very small (or negative) average net power from the system. In the case where the flow rate falls in the optimum range and uniformly distributed through the fractures maximum surface area is available for heat exchange, thus producing positive net average electricity throughout its lifetime of 10 years.



(c) Low flow rate due to low proppant pack conductivity

Figure 2: 3D visualization of fractures and time series data for the realizations with (a) optimal flow rate, (b) high flow rate, and (c) low flow rate due to low fracture permeability. Uniform flow distribution across all the fractures at optimal rate is key for successful EGS. The color of the borders on 3D fracture visualization (left) represents the corresponding circled realizations shown in Figure 1.

3.1 Impact of number of perforation clusters

Perforation clusters are seed for the new fractures during multi-stage hydraulic stimulation of a reservoir. The number of perforation clusters on each stage directly impacts the effectiveness of new fracture creation during stimulation and hence the overall power production from EGS. We ran five simulations with 4000 realizations each by varying the number of perforation clusters in the model while keeping all other parameters constant. We used the similar approach as discussed above to investigate the impact of number of perforation clusters on the minimum propped fracture permeability required for positive average net power production. For comparison purpose, we show the plot of propped fracture permeability, flow rate, and average net power production for the perforation clusters of 25 and 200 in the same reservoir (Figure 3). The doublet EGS system modeled in this study shows that positive net power can be produced when the perforation clusters are as low as 25 if the propped fracture permeability is greater than 900 D. The permeability required for positive power generation decreases as the number of perforation clusters increases (Figure 4). With larger number of perforation clusters larger numbers of new fractures are created, thus decreasing the overall permeability required for positive net power production. In addition, larger number of new fractures will provide larger surface area for heat transfer and can accommodate larger flow rate under pressure limited injection strategy producing more power from the same system. Higher number of perforation clusters help to increase the power production potential of the system, however at high number of perforation clusters, the new fractures will start to interact with each other and do not contribute much value in terms of power production from the reservoir.

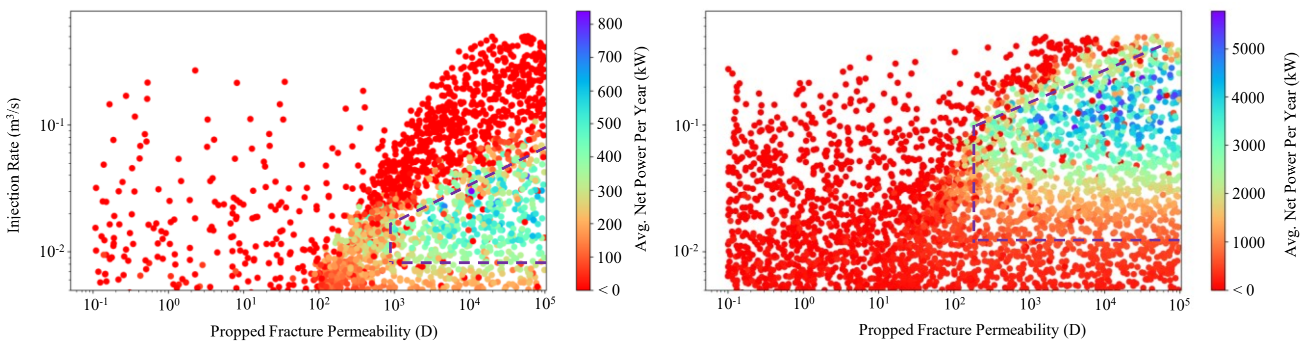


Figure 3: Scatter plot showing the region of propped fracture permeability and flow rate required for positive power generation for the perforation clusters of 25 (left) and 200 (right). The average net power produced form the system increases with the number of perforation clusters.

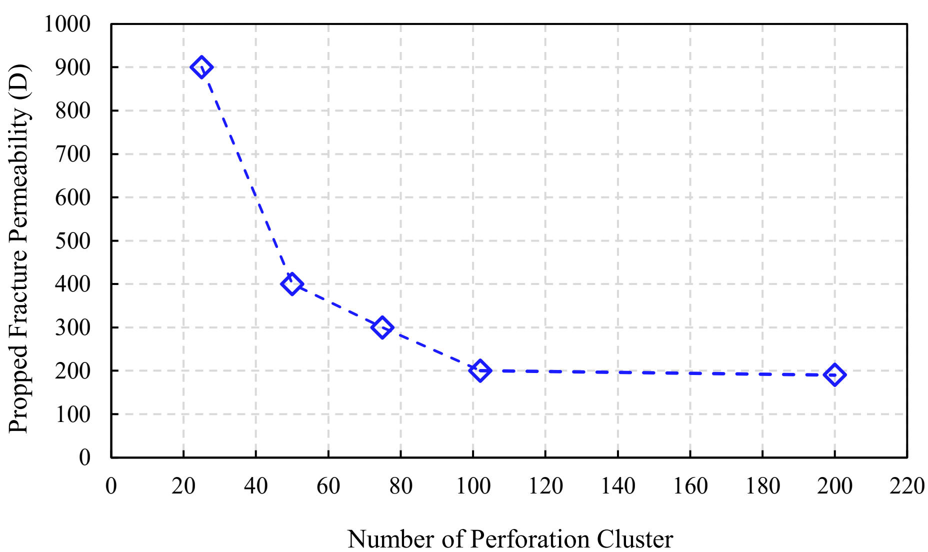


Figure 4: Minimum propped fracture permeability of the fractures required for positive power generation from the system decreases with increasing perforation clusters.

3.2 Impact of number of production wells

Conventional EGS system consists of a doublet system to minimize the drilling cost. However, previous studies have shown that more than one production well strategically placed around the injection well will not only help to increase the economics of an EGS but also reduce the risk of induced seismicity by halting the fracture growth (Frash et al., 2022, 2023a, 2023b). Thus, following the same line, we simulated the EGS with multiple production wells surrounding the injection well to investigate its impact on the minimum propped fracture permeability required for positive power production. For each number of production wells, we simulated 4000 realizations by keeping number of perforation clusters and well spacing constant at 50 and 120 m, respectively. Our simulation results showed that the minimum propped fracture permeability required for positive net power production remained constant at 400 D when the number of production wells was increased from one to four. However, adding production wells increased the net power produced from the system (Figure 5). Further investigation of the system indicated that the increase in power production did not increase the economics of the system due to the cost associated with drilling extra wells. The system with multiple production wells could be profitable if we increase the well spacing (Frash et al., 2023a).

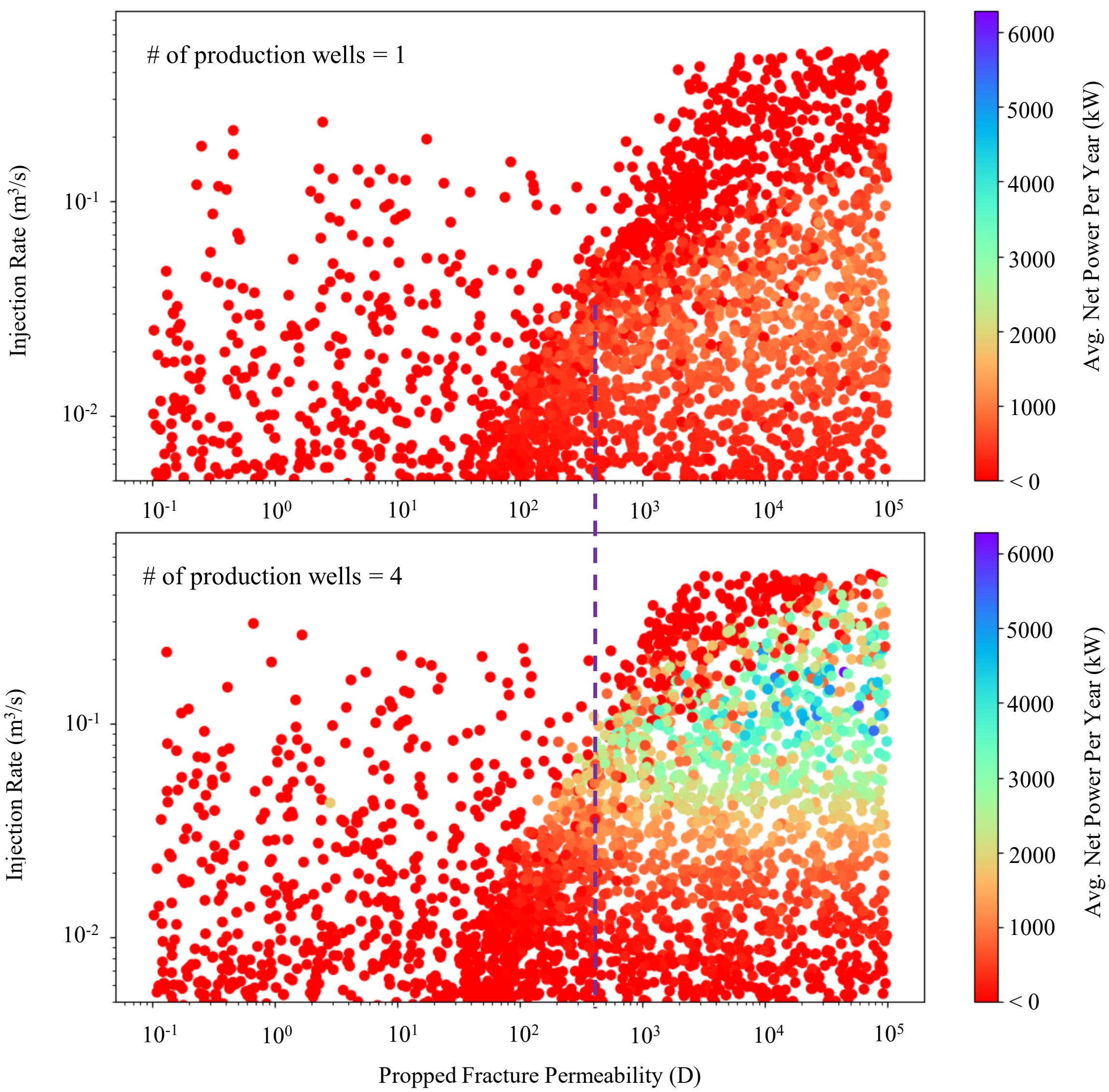


Figure 5: Increasing the number of production wells did not show significant impact on the minimum propped fracture permeability required for positive power generation from the system. The average net power produced from the system increased with increasing number of production wells.

3.3 Impact of well spacing

To investigate the impact of well spacing on the minimum propped fracture permeability required for positive net power production, we switched back to the doublet design with varying well spacing within the range of 50 to 800 m. The number of perforation clusters were kept constant at 50 during all simulations. The well spacing did not affect the minimum propped fracture permeability required for positive net average power production, which remained constant at 400 μm^2-cm for all the well spacing simulated in this study. However, increasing the well spacing led to increase in power production and improved the economics of the doublet EGS system. Further analysis on the NPV of the system shows the EGS starts to become profitable when the well spacing is larger than 400 m, permeability is greater than 800 D, and flow rate is greater than 0.08 m^3/s. For comparison, we have only shown the NPV plot of the system with well spacing of 120 m and 400 m in Figure 6. It is worth pointing out that, although increasing the well spacing resulted in increase in reservoir economics it should be kept in mind that this could also lead to larger magnitude seismic events due to the larger fracture size during stimulation.

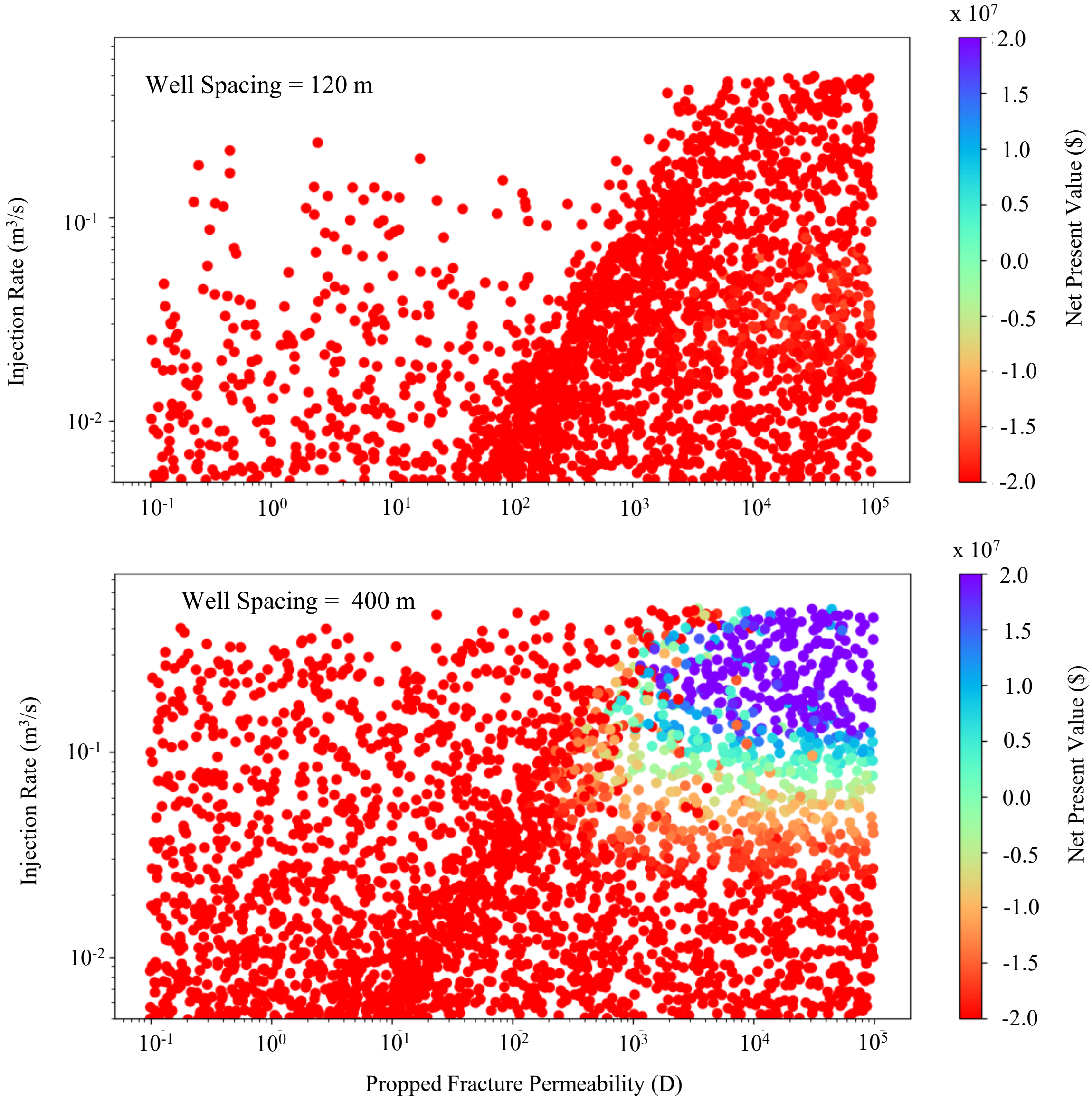


Figure 6: Increasing the well spacing did not affect the minimum propped fracture permeability required for positive power generation from the system but helped to increase the economics of the system. Our simulation results show, the doublet EGS with 50 perforation clusters modeled in this study starts to become profitable at well spacing of 400 m, propped fracture permeability of 800 D, and flow rate of 0.08 m^3/s.

4. CONCLUSIONS

In this study, we modelled hydraulically fractured and sand propped Enhanced Geothermal Systems (EGS) to investigate the minimum propped fracture permeability (or conductivity) that should be targeted for stimulation design. We also investigated the impact of design parameters such as number of perforation clusters, number of producer wells, and well spacing on the minimum propped fracture permeability. Our simulation results based on 4000 realizations per EGS scenario predicts that a minimum propped fracture permeability of 200 D, which equates to fracture conductivity ranging from 30 mD-ft to 130 mD-ft based on the fracture width, is required to produce positive net power from a doublet system with well spacing of 120 m and 102 perforation clusters over a 10-year lifespan. The optimal flow rate at fracture permeability of 200 D ranged from 0.015 m^3/s to 0.05 m^3/s, with the upper bound increasing with the fracture permeability. Having uniform distribution of flow through all the fractures is crucial for high performing EGS at optimal flow rate. The EGS performs poorly at high flow rate due to high pumping loss, rapid decline in production temperature, or thermal short circuiting. Alternatively, too low of flow rate will also result in insufficient energy for net positive power generation. The minimum propped fracture permeability required for positive net power generation from the EGS decreases as the number of perforation clusters is increased. The number of production wells and well spacing seems to have very little to no impact on minimum propped fracture permeability required for positive power generation. Increasing the number of production wells increased the total power generated from the system, but not the economics. On the other hand, increasing the well spacing improved both net power production and economics of the doublet EGS system.

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