

Pathways to Superhot and Superdeep: Lessons from Deep and Hot Geothermal Projects

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ABSTRACT

Next-Generation geothermal development is undergoing a fundamental transition to access deeper and hotter targets, aiming to maximize and increase energy production per well by orders of magnitude. At ‘superhot’ or ~350 °C+ conditions, wells can produce up to ten times more power than conventional geothermal systems, motivating this study to identify additional firm, abundant energy for power generation. This study utilizes reduced-order physical models grounded in analytical foundations quantifying how the interplay of fracture surface area, mass flow rate, and thermal properties dictates long-term project performance. Projects are categorized by development approach: Traditional EGS, Huff-n-Puff EGS, and closed-loop Advanced Geothermal Systems (AGS). These projects are critically assessed through their Connectivity (establishing hydraulic communication), Conductivity (maintaining open flow paths), and Conformance (ensuring uniform sweep). Analysis shows that past EGS projects suffered from a lack of control over one or more of these metrics. Lessons learned from deep and hot geothermal systems are then applied to an evaluation of superhot and superdeep geothermal resources for each Next-Generation geothermal classification. By treating the subsurface as an engineered heat exchanger, we demonstrate that maximizing effective sweep volume is the primary lever to delay thermal breakthrough and achieve sustainable power densities. Novel concepts to recover heat from superhot formations while reducing the complexities of drilling superdeep are introduced, including deep, vertically-oriented fractures and utilizing dense working fluids to reduce operational surface pressures and recover heat from deeper, hotter formations. This approach exploits fracture mechanics to access superhot resources while bypassing many technical and economic hurdles that typically challenge deep and hot drilling and completions.

1. INTRODUCTION: SUPERHOT AND SUPERDEEP GEOTHERMAL OPPORTUNITIES

Hydrothermal and hot dry rock resource estimates in the United States include over 13,000,000 EJ in the top 10 km of the U.S. crust. With reasonable investments in research and development by 2050, the U.S. could realistically achieve 100,000 MW (100 GW) of installed capacity in traditional hydrothermal geothermal and emerging Next-Generation Enhanced Geothermal Systems power plants (EGS) (Tester et al., 2006). Including the energy available at ‘superhot’ and including ‘superdeep’ depths greater than standard drilling limits (such as approximately 7 km or ~23,000 feet true vertical depth (TVD)), resource estimates increase dramatically. Including these resources, a 2024 DOE next-generation geothermal report projects that geothermal generation could increase 20-fold from current levels, reaching at least 90 gigawatts (GW) of capacity by 2050 of firm, flexible baseload power (U.S. Dept. of Energy, 2024). Within this larger context, we evaluate some of the hottest and deepest resources studied to review critical factors that can provide access to these higher-density energy supplies, also known as ‘superhot’ and ‘superdeep.’

Hydrothermal geothermal fields include high mass flow rates through complex porosity/permeability structures in faults and natural fractures. Wells often target water (brine) production and re-injection with significant km-scale offset providing heat recovery through subsurface flow, with water recycling to sustain continuous power generation (Dipippo, 2012). Fields also typically connect to shallow aquifers and are mostly at hydrostatic pressure. Key challenges for any development follow from these conditions, especially around connectivity, conformance of flow, and conductivity of the host rock and connections to deeper heat sources. Since the 1970’s and in test sites around the world, “next-generation” field tests have aimed at resolving these challenges within low-permeability Hot Dry Rock (HDR), moving beyond the requirement for rare, naturally occurring aquifers. This approach focuses on creating man-made and/or re-opening permeable pathways in the subsurface to achieve reliable heat transfer with conductivity. These Enhanced Geothermal Systems (EGS) utilize hydraulic stimulation to either reopen natural fractures or create new tensile networks in otherwise “tight” low permeability formations. By circulating working fluids through these engineered pathways, heat can be effectively transported from the subsurface to surface power plants for electricity generation (Tester et al., 2006).

Notable EGS test sites in the USA and Europe include Utah FORGE site (Moore et al., 2020), the Milford site in Utah (Allis et al., 2016), Blue Mountain EGS Demonstration in Nevada (Norbeck et al., 2023), and the Grimsel Test Site in Switzerland (Vogler et al. 2017). Fracture-based projects in particular build on work conducted by the U.S. Dept. of Energy at The Fenton Hill Hot Dry Rock (HDR) tests in New Mexico in the 1980s and early 1990s (Brown et al., 2012). Technology approaches vary in how heat is transferred to the surface, with notably different approaches in drilling, completions, and pressure management. “Closed Loop” systems do not use fractures to create heat conductivity surface area, while EGS approaches do.

1.1. Temperature and Depth: Superhot, Superdeep

Most conventional and next-generation geothermal power projects to date have targeted temperatures of 150 – 350 °C. This represents resources that are most easily accessible, although not all of the resources that power plants can harness most effectively. Figure 1 below summarizes the net power output of an off-the-shelf binary-cycle turbine for power, highlighting the increased performance associated with higher reservoir temperatures, particularly above 350 °C. The case described assumes 100 kg/sec of flow into the power plant, 25 °C ambient temperatures, and typical modern geothermal power plant efficiencies.

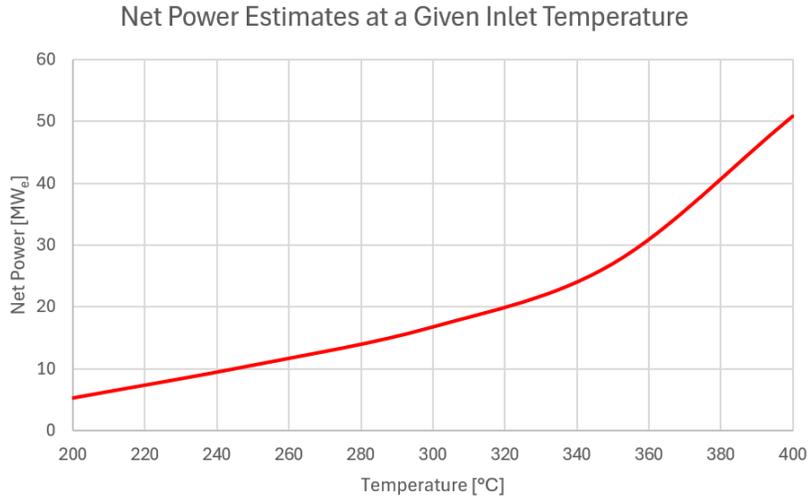


Figure 1: Power efficiency curves for a generic power plant cycle for geothermal energy production. The x-axis shows power plant inlet temperature (°C) from 200 - 400, y-axis shows gross power of the plant minus its parasitic load (Mwe). Curves include Organic Rankine Cycle (ORC) and Brayton cycles, each demonstrating increased efficiency above 350 °C.

Achieving higher temperatures (e.g. > 350 °C) provides a pathway to produce much higher net power output. Figure 1 shows that a plant operating at 350 °C produces 4-5 times as much power compared to one operating at 200 °C given the same fluid flow rate. The electrical efficiency of geothermal power plants also improves at high temperatures, dramatically increasing the power output under similar flow rate conditions. Provided production rates can be sustained at high temperatures, this allows for large-scale developments to be completed with fewer wells, rather than more wells required to target similar output in mid-enthalpy and lower temperature systems.

1.2 Temperature and Depth Classification

Current approaches in research and industry suggest classification of geothermal production according to temperature and depth in a few broad categories, including a range of mid to high target temperatures, as well as depth to these temperatures. This paper will classify projects according to the depths and temperatures found in Table 1. The categories used in this paper are tied in practical terms to current economic limitations introduced with depth as described by Anderson, et. al. (2025) and National Lab of the Rockies’ (previously NREL) annual reporting (NREL, 2024).

This analysis considers geothermal resources in the context of electricity generation potential. Accordingly, emphasis is placed on projects targeting reservoir temperatures able to sustain efficient power production. In addition, superhot geothermal resources are discussed as a frontier opportunity with substantial potential, using approaches discussed in Section 4. Within this framework, generalized temperature thresholds relevant to current economic viability versus superhot is distinguished as 150–350 °C versus > 350 °C. Past work (Vargas et al., 2022, CATF, 2024) has used 374 °C as the threshold for superhot resource; here ‘superhot’ temperatures are considered at a slightly lower range to include 350 °C given the substantial power increases made possible on a per-well basis even at this threshold, as reflected in Section 1.1, are significant enough to warrant distinction from “hot” resources.

Table 1: Classification of Geothermal Developments According to Temperature and Depth of Resource Targets.

	Hot (150 - 350°C)	SuperHot (> 350°C)
Shallow (< 4km)	Shallow, Hot	Shallow, SuperHot
Deep (4 – 6 km)	Deep, Hot	Deep, SuperHot
Superdeep (6 + km)	SuperDeep, Hot	Superdeep, SuperHot

1.3. Resource availability: USA Examples

Globally, superhot' potential can be found in vast portion of terrestrial regions, many of which are close to large human population centers (Vargas et al, 2022). As an example of the resource density and richness available, we present updated mapping of superhot conditions ($>350\text{ }^{\circ}\text{C}$) in the contiguous United States that relies on the Stanford Thermal Earth Model (STM), extrapolated to 10 km depths using geophysical data (e.g., heat flow, seismicity, and crustal thickness) (Aljubran and Horne, 2024a, 2024b). This study focuses on extrapolations and potential beyond the limited few active magmatic centers that cluster in Figure 2, such as Newberry Volcano, the Salton Sea, and other isolated volcanic areas.

Considering the Lower 48 USA / contiguous United States (CONUS) as an example area of interest, resource characterization is primarily underpinned by databases summarized in Anderson et al (2025) and the Stanford Temperature Model (Aljubran and Horne, 2024b). These studies utilize some of the latest available public data for over 400,000 bottom-hole temperatures, mapped extent of wellbore data and regional interpolations, and additional parameterization based on geothermal gradients with depth to $>6\text{ km}$. Anderson et al (2025) further delineate the areal extent of prospective geothermal systems based on mid-enthalpy "hot" resource thresholds of $180\text{ }^{\circ}\text{C}$, estimating that deep resources at this temperature could correspond to gigawatt-scale electricity generation potential within CONUS.

As shown in Figure 2, superhot resources are widespread in regions with Cenozoic-recent volcanism and tectonism, such as the Basin and Range, Rio Grande Rift, and Snake River plain. Very few locations in the L48 USA / CONUS provide $>350\text{ }^{\circ}\text{C}$ hot dry rock, with few, isolated areas at depths varying from 6 km in regional hotspots (e.g., Yellowstone) to 10 km in stable craton regions. Within 10 km of the surface, superhot conditions are accessible across $\sim 5\%$ of the CONUS (approximately $350,000\text{ km}^2$). Western states dominate access to superhot conditions within this depth interval. These results are likely to be updated in the near future, reflecting advances in data collection and analysis of deeper crustal features and improved local databases (e.g. Bhattacharya et al., 2026).

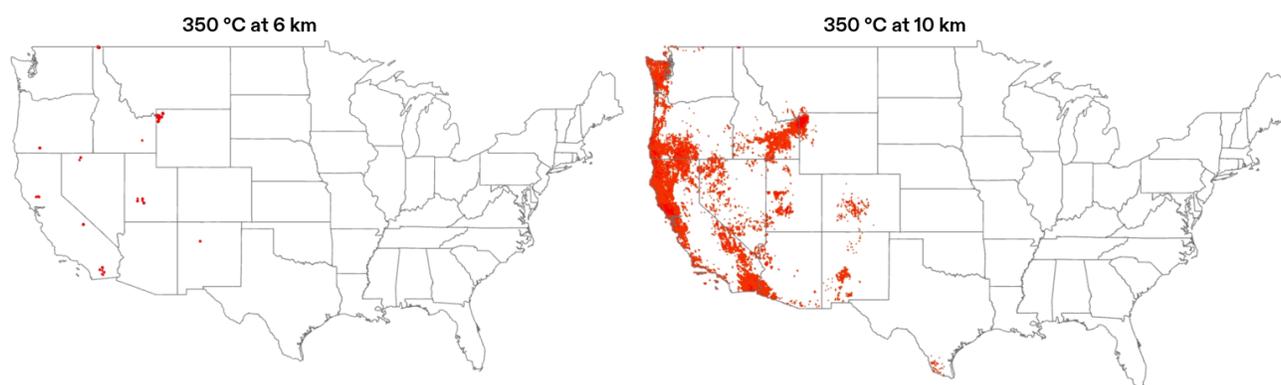


Figure 2: Maps of depth to $350\text{ }^{\circ}\text{C}$ isotherms in the continental USA at depths at 6 and 10 km. Legend: red ($>350\text{ }^{\circ}\text{C}$), values $<350\text{ }^{\circ}\text{C}$ are excluded. Each point represents 18 km^2 of land. Data adapted from STM predictions (Aljubran and Horne, 2024).

2. NEXT-GENERATION GEOTHERMAL OVERVIEW

2.1 Overview of Development Pathways

2.1.1 Huff-n-Puff EGS

To bypass the connectivity risk of "finding" connectivity between wells in the subsurface, some designs utilize a single wellbore for both injection and production. Single-well cyclic operations (huff-n-puff) minimize water loss through cyclic recovery. This has been demonstrated in sedimentary settings with pressure management under geopressured and hydrostatic conditions. Huff-n-Puff EGS is also known as Pressure Geothermal (Simpkins et al., 2023).

2.1.2 Traditional EGS

Traditional EGS requires both an injector and a producer well with open-loop circulation occurring through fractures that connect the wells. These fractures can be naturally occurring or created via stimulation. The core challenge is stimulating the rock between them to create a sustainable heat exchange in the subsurface. Theories addressing Hot Dry Rock's response to stimulation range across a spectrum from purely shear dilation of natural fractures maintaining aperture post-stimulation (i.e. self-propped), to planar, tensile hydraulic fractures with proppant (McClure and Horne, 2014). Building on drilling and completion advances from the shale revolution, increasingly horizontal multi-laterals have become a multi-well development design of choice.

2.1.3 Closed Loop AGS

Advanced Geothermal Systems (AGS) describe a conduction-dominated system with fluid flowing within wellbores and heat transfer occurring via conduction from Hot Dry Rock formation directly to the working fluid within the wellbore. In a multi-well closed loop system (See Figure 3), the thermosiphon effect reduces parasitic pumping (Longfield et al, 2022)

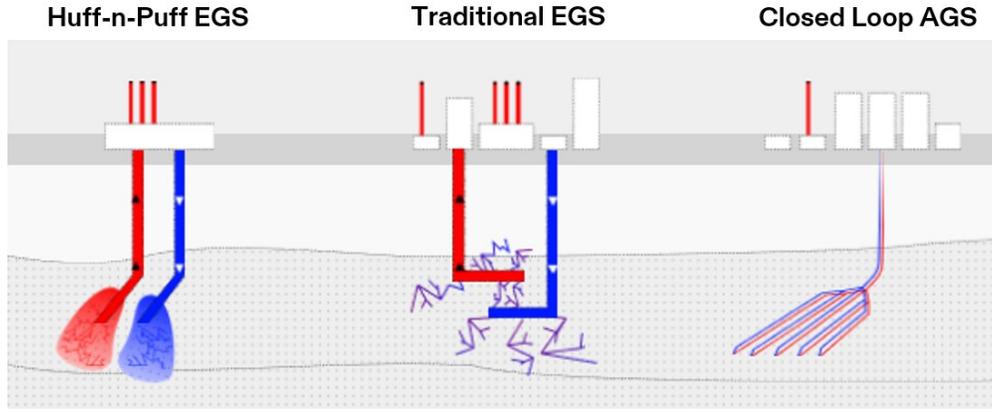


Figure 3: Next Generation geothermal technology approaches for subsurface heat exchange.

2.2 Modeling Geothermal Efficiencies: Connectivity, Conductivity, and Conformance

2.2.1 Foundational Concepts for EGS Heat Production

Simplified modeling that synthesizes many of the most critical factors affecting EGS development will be directly applicable to providing future understanding of efficient and commercial subsurface heat exchange and is especially critical for fractured development cases. The mathematical foundation for heat extraction from next-generation geothermal reservoirs was established by Gringarten and Witherspoon (1975), who idealized a stimulated hot dry rock reservoir as a series of parallel, vertical plates with uniform aperture, embedded in impermeable hot rock. Cold water is injected, flows parallel to the fracture planes, and extracts heat through conduction from the surrounding rock blocks. Their work was adapted by Tester and Smith (1977) to cover a realistic power production scenario. Tester and Smith's equation for power generation can be simplified to:

$$P_{\text{plant}}(t) = \eta_{th} \cdot \dot{m}_w \cdot C_{p,w} \cdot (T_r - T_{inj}) \cdot \left(1 - \text{erfc} \left(\sqrt{\frac{k_r \cdot C_{p,r} \cdot \rho_r}{t}} \cdot \frac{n_f \cdot A_f}{2 \dot{m}_w \cdot C_{p,w}} \right) \right) \quad (1)$$

where η_{th} is cycle thermal efficiency, \dot{m}_w is mass flow rate, $C_{p,w}$ is water heat capacity at T_{inj} , T_r is formation temperature, T_{inj} is injection temperature, k_r is formation thermal conductivity, $C_{p,r}$ is formation specific heat capacity, ρ_r is formation density, ρ_f is fluid density, t is time, n_f is the number of fractures, A_f is area of a single fracture, \dot{m}_w is mass flow rate.

Gringarten approach was developed to understand and predict the behavior of traditional EGS systems in hot, dry rock. It has been extended to predict Huff-n-Puff EGS as well (Rivas et al, 2026).

An example of thermal decline from a horizontal traditional EGS doublet with 100 kg/sec flowing uniformly between a variable number of fractures is given in Figure 4. In this case, the T_r is 200 °C, T_{inj} is 80 °C, ρ_r is 2650 kg/m³, ρ_f is 976 kg/m³, k_r is 2.5 W/m/K, $C_{p,w}$ is 4176 J/kg/K, and each fracture has a surface area of 72,000 m².

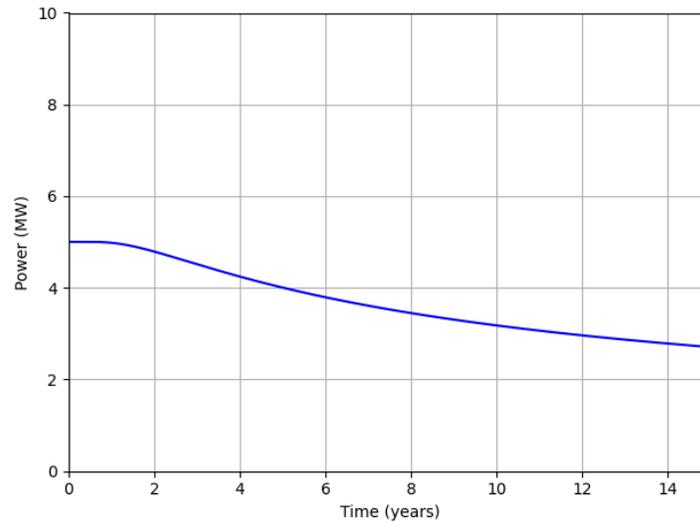


Figure 4: Net power production over time for a generic geothermal power plant, assuming production from a pair of horizontal EGS wells with working fluid flow across 50 fractures in 200 °C hot dry rock conditions. The x-axis shows power plant operational time in years; y-axis shows gross power of the plant minus its parasitic load (MW).

Based on Equation 1, high initial power is often counterweighted by sharp temperature decline; therefore, heat with heat removal from circulation must be balanced with heat supply from rock conduction. From the equation, the following relationships can be inferred:

- Effective fracture Surface Area ($n_f \cdot A_f$): Large surface area delays thermal drawdown. Surface area gains can be achieved through creating more access to the reservoir; this could be increasing the number of fractures (n_f) or the effective area of each fracture (A_f) in an EGS system.
- Mass flow rate (\dot{m}_w): Higher initial production temperature ($T_{p,i}$) but quicker thermal drawdown.
- Initial rock temperature (T_i): Higher T_i by increasing ΔT , positively shifting the power curve.
- Injection temperature (T_{inj}): Lower T_{inj} increasing ΔT , but limited in practice by surface cooling impracticality.
- Rock thermal properties: Higher conductivity k , dictated by lithology, supplies heat to the fracture face quicker, delaying drawdown.

In practice, two parameters dominate system behavior: the effective contact with the reservoir and the mass flow rate that can be sustained through that contact. Experience from next-generation geothermal field demonstrations shows that these factors are not merely conceptual considerations; deficiencies in either result in hindered circulation performance.

2.2.2 The 3 C's: Connectivity, Conductivity, and Conformance

Past analyses of stimulation and production testing and challenges identified issues of inter-well linkage, transmissivity maintenance, and avoiding short-circuiting as critical to an EGS project's successful recovery of heat (Pollock et al, 2021). Put another way, three of the key factors controlling reservoir performance in next generation geothermal are connectivity, conductivity, and conformance:

- **Connectivity:** An established hydraulic communication between injection and production points. Poor connectivity is defined by low effective fracture area ($n_f \cdot A_f$), high impedance (resistance to flow) and limited circulation rates (\dot{m}_w).
- **Conductivity:** Effectiveness of a flow pathway between the wellbore and fracture network. To maintain conductivity, open permeable fractures must resist closure stress, thermal effects, and geochemical reactions during operations; self-propping from shear dilation or emplaced proppant is commonly used for this end. Poor conductivity leads to high impedance, limiting circulation rates (\dot{m}_w) at a given pump pressure.
- **Conformance:** An even flow distribution between different fractures. Uniform fluid distribution across the stimulated volume to maximize heat sweep efficiency to contact maximum fracture surface area ($n_f \cdot A_f$). Channeling through a few dominant flow paths causes premature thermal breakthrough (Tester et al., 2006).

In a closed loop setting, conductivity, connectivity, and conformance as described above may not be the most appropriate metrics for judging the system given that fundamental architecture differs significantly from traditional EGS projects. For these closed loop systems:

- **Connectivity:** Each well in a closed-loop system is effectively isolated in the subsurface, connected only to itself.
- **Conductivity:** The thermal conductivity of the surrounding formation (k_r) replaces hydraulic conductivity as a controlling factor on the system's performance. Heat transfer relies entirely on conduction across the wellbore wall. The primary motivation for the radiator-like inflow-outflow multi-lateral well design is to maximize the available wellbore surface area for subsurface heat exchange.

Due to the minimal contact area with the reservoir, thermal drawdown is initially quite steep, reaching a plateau when the heat transfer to the wellbore balances with the conduction of energy migrating inward from the formation (Longfield, 2022).

- Conformance: Unlike with EGS, this is no longer about sweeping a reservoir between wells, but rather about ensuring balanced flow between each loop of a multi-lateral, radiator-style array to prevent thermal short-circuiting.

3. LEARNING FROM DEEP & HOT GEOTHERMAL TESTING

As summarized in Table 1, geothermal projects can mostly be classified as hot and deep, or super hot and super deep – most experiments have been hot and deep, a few deep and super hot. Looking at past projects will help to understand current challenges and predict ways to address higher temperature, pressure and geomechanical stress in superhot and superdeep settings. Superhot configurations will also be discussed for several classes of next-generation geothermal development.

3.1. Traditional EGS

3.1.1. Fenton Hill Phase I (1974-1980, New Mexico, USA)

The Fenton Hill geothermal project was the first geothermal project targeting Hot Dry Rock (HDR). Phase I targeted a shallower reservoir at approximately 2.7–3 km depth in Precambrian crystalline basement rocks in the Valles Caldera region of Northern New Mexico, with bottom-hole temperatures ~185–200 °C (achieving production temperatures up to ~190 °C during flow tests). The system used nearly vertical wells (EE-1 injector and GT-2 producer, later redrilled) with massive hydraulic stimulations to create a joint-dominated fracture network (Brown et al., 2012).

The project planned to circulate between separate injection and production wells through an engineered fracture network in low-permeability granodiorites and metamorphic rocks (gneiss, schist.). This configuration demands strong performance connectivity, conductance, and conformance to achieve viable heat extraction and power production. The project encountered challenges associated with all three C's:

- Connectivity: Initial connectivity was established between wells GT-2 and EE-1. However, it was technically challenging; the wells did not initially intersect the man-made fracture. Success was only achieved after sidetracking GT-2 (to GT-2B) into a fault connected to the EE-1.
- Conductivity: The reservoir was dominated by a single, high-angle vertical fracture. Initial low flow rates were achieved; impedance was very high and significant pumping pressure to maintain circulation.
- Conformance: Conformance was the primary failure point of the initial Phase I reservoir. In the 1978 January - April circulation test, the production temperature dropped from 175°C to 80°C in just 75 days, indicating a "short-circuit" where water traveled quickly through a single path without sufficient heat exchange surface (Brown et al., 2012).

Phase I demonstrated proof-of-concept circulation but highlighted fundamental barriers to commercial viability, yielding only short-term flow loops with low recovery factors.

3.1.2. Fenton Hill Phase II (1981-1995, New Mexico, USA)

Building on Phase I lessons, Phase II deepened the reservoir to 3.5–4.5 km (wells EE-2 and EE-3), accessing hotter rock with bottom-hole temperatures exceeding 230–330 °C in target zones. A larger stimulated volume (~1 km³ goal) was pursued through extended fracturing and directional drilling, aiming for higher enthalpy and power potential.

- Connectivity: Phase II captured a notable connectivity failure. Two deviated wells were drilled side by side with similar trajectories, assuming that fractures could be completed such that the fractures would grow horizontally toward each other. Instead, fractures completed in one well grew vertically along the natural stress field, missing the nearby wellbore entirely. Connectivity was only established after sidetracking EE-3 into EE-3A, a slanted trajectory designed to "catch" the fractures (Dash et al., 1989).
- Conductance: After the wells were connected, the reservoir showed a high flow impedance (inverse of conductivity) of 3.11 MPa/L/s. The parasitic power required to circulate water at these depths began to rival the energy produced, highlighting the need to ease a reservoir's resistance to flow in future experiments (DuTeau and Brown, 1993).
- Conformance: Phase II showed superior conformance compared to Phase I. The 115-day Long-Term Flow Test (LTFT) showed negligible thermal drawdown, suggesting that at these depths, the stimulation created a "fracture cloud" observed in near-wellbore microseismic data and a network of shear-strain release likely related to the opening of multiple joints rather than a single crack. This dramatically increased the heat-exchange surface area in the pressure-propped fracture network (Dash et al., 1989).

Phase II achieved the longest continuous HDR circulation (~1 year in LTFT) and valuable data on deeper/hot reservoirs, but ultimate performance fell short of economic thresholds due to compounded 3 C's issues (Brown et al., 2012; Duchane, 1995). Fenton Hill's legacy underscores the multi-well pathway's dependence on favorable natural fracture networks for connectivity and conformance, while deeper/hotter targets amplify conductance demands in high pressure and high temperature settings.

3.1.3. Habanero EGS Project (2000-2016, Cooper Basin, Australia)

The Habanero project in Australia's Cooper Basin represented one of the most ambitious multi-well EGS demonstrations in extremely hot dry rock conditions, targeting granitic basement at ~4.2–4.9 km depth with reservoir temperatures of 240–270 °C (Hogarth and Holl, 2015; Hogarth and Holl, 2017). The program involved a series of wells (Habanero-1 as initial injector/producer, followed by Habanero-3

and Habanero-4 for doublet configuration), with massive hydraulic stimulations and circulation tests that briefly operated a 1 MWe binary pilot plant. Despite achieving some of the highest flow rates and temperatures in HDR history, performance was constrained by the 3 C's in a fault-dominated regime.

- **Connectivity:** The wells were successfully connected by a few large, natural faults during stimulation activities.
- **Conductivity:** Maintaining conductance proved to be the downfall of project's commercial potential due to the Cooper Basin's harsh mechanical and chemical environment. The hot, hypersaline brine triggered significant scaling issues, specifically with silica and carbonate precipitates. These minerals began to choke conductive pathways both in the reservoir, making circulation attempts nearly impossible, requiring chemical and hydraulic interventions to reestablish permeability (Hogarth and Holl, 2015).
- **Conformance:** Flow confined to a few dominant paths (natural faults), bypassing much of the stimulated volume. Although temperature levels stayed constant during circulation, premature thermal decline likely would have been observed had the test operated longer.

3.1.4. ST-1 Deep Heat (2014-2022, Otaniemi, Finland)

The ST-1 Deep Heat project stands out as the deepest EGS attempt to date, drilling two wells to approximately 6.4 km in crystalline granite with bottom-hole temperatures around 120 °C (Kukkonen and Pentti, 2021). Although significantly cooler than the hot and superhot projects discussed elsewhere in this paper, its inclusion is warranted due to its record depth and implications for superdeep feasibility.

- **Connectivity:** Demonstrated that hydraulic communication is achievable at extreme depths (>6 km), with flow logs indicating inter-well linkage after stimulations (Kukkonen and Pentti, 2021). This represents a technical success in establishing basic circulation pathways in deep basement rock.
- **Conductivity:** The project's stimulated fractures in low-permeability granite exhibited rapid closure and insufficient sustained permeability despite shear activation, hindering the commercial success of the project. Post-stimulation injectivity/productivity remained low, with fractures failing to stay open long-term under high lithostatic stress, leading to high impedance and inadequate flow rates for the project's target power outputs.
- **Conformance:** Limited data suggest uneven distribution, though inconclusive given the minimal flows recorded.

The ST-1 wells experienced conductivity challenges at superdeep depths, as closure stresses nullified conductivity improvements from stimulation without additional support (e.g. proppants or pressure-propped conditions). While proving connectivity is possible beyond 6 km, it highlights the need for improved propping measures for future superdeep/superhot pursuits.

3.1.5. Utah FORGE (2015-present, Milford Valley, Utah USA)

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE, 2020) serves as the U.S. Department of Energy's flagship laboratory for EGS. Targeting the Roosevelt Hot Springs-associated granite pluton, the project has transitioned from site characterization to a full-scale demonstration of the "3 C's" using oil and gas-derived drilling and completion strategies. The laboratory utilizes a deviated doublet design: wells 16A(78)-32 and 16B(78)-32 were drilled to a vertical depth of approximately 2.6 km with lateral sections extending to 3.3 km MD. The reservoir temperature is roughly 232 °C, placing it in the high-enthalpy range suitable for binary cycle turbines and/or flash turbine power generation.

- **Connectivity:** Initial circulation tests in 2023 demonstrated that while a hydraulic link existed, it was commercially non-viable, with fluid recovery rates of only 3–5% (Moore et al., 2025). Following a massive commercial-scale stimulation in April 2024, connectivity improved by an order of magnitude. Subsequent circulation tests achieved fluid recovery rates of 70% to 90%, confirming that the engineered fracture network successfully bridged the 100-meter (330-ft) vertical gap between the injector and producer (Moore et al., 2025).
- **Conductivity:** The FORGE site has operated in both a propped and unpropped manner. During proppantless Phase I, stimulations using only water resulted in extremely high impedance and production rates of approximately 7 gpm. Proppant was added to 2024 stimulations as part of Phase II. The impact on conductance was immediate: production rates jumped to 378 gpm, with a sustained 30-day circulation test achieving 28 kg/s (Xing et al., 2025). This confirmed that in crystalline granite, a propping mechanism can prevent near-wellbore fracture closure and maintain conductance.
- **Conformance:** Equalizing the flow distribution between zones remains an area for optimization for the FORGE experiments and future EGS projects. In the 2024 tests, Stage 8 and Stage 10 accepted a disproportionate share of the flow (over 25% each), (Xing et al., 2025?). Future work is underway to address the conformance challenge.

3.1.6. Newberry Volcano EGS Demonstrations (2010-present, Deschutes National Forest, Oregon USA)

Learning from shallow superhot hotspots will be instrumental in determining the future of the industry. The Newberry Volcano EGS demonstration site in Oregon has provided access at relatively shallow depths (~ 3km) for testing superhot geothermal resources in the contiguous United States. Its unique volcanic geology enabled early exploratory drilling to encounter exceptionally high temperatures (320–330 °C) at approximately 3 km (Cladouhos et al., 2015). A primary test well underwent hydraulic stimulation during the 2010's. There are currently efforts underway focused on advancing the project to target deeper, even hotter rock at the site. Promising results from these tests relate to fracture creation in volcanic rock:

- **Connectivity:** Recent efforts have connected the original test well to a twinned well via hydraulic stimulation (Grubac et al., 2025).

- **Conductivity:** shear stimulation provided initial gains, but rapid closure and low sustained permeability in the targeted volcanic basement rock led to high impedance and insufficient flow. Stimulation increased reservoir permeability by two orders of magnitude, although there was still too much impedance for commercial flow rates (Cladouhos et al., 2015). During recent testing, propped stimulations were created in basalts and granodiorites at >300 °C to connect an injector and producer well pair (Grubac et al., 2025). This provides new insights into heat-resistant propping materials and potential connectivity at relatively shallow depths for superhot EGS.
- **Conformance:** Long-term circulation will provide information about the effective surface area utilized when flowing between the wells.

3.2. Huff-n-Puff EGS

EGS operations using separate wells that are not specifically connected in the subsurface began as a byproduct of failures to hydraulically connect two or more wells. By utilizing a single well for both working fluid injection and production, operators aimed to eliminate connectivity hurdles that had doomed many previous projects.

3.2.1. Fenton Hill Project (1974-1975, New Mexico, USA)

The first instance of a single-well EGS system was in the GT-2 wellbore at Fenton Hill. This experiment sought to address fluid loss to the formation.

- **Connectivity:** By utilizing a single-well configuration with a specialized completion, engineers implemented a massive hydraulic fracture at approximately 2,900 m TVD/MD. The breakthrough was the use of proppant (sand) to hold the fracture open after the initial injection, connecting to a much larger surface area.
- **Conductivity:** Unlike previous zones where fractures would "pinch" shut or allow fluid to dissipate into the far-field rock, the propped fracture in Zone 7 created a high-conductivity path that remained accessible.
- **Conformance:** The propped fracture design allowed for an unprecedented 98% fluid recovery rate during circulation tests (Brown et al., 2012). Additionally, pressure propping was successfully implemented by applying backpressure to the production well during circulation tests as described by Rivas, et. al. (2024).

3.2.2. Genesys Horstberg Project (2003-2016, Horstberg, Germany)

The Genesys project proved the viability of single-well concepts in low-permeability sedimentary rocks. The project plugged back a deep gas exploration well to test huff-n-puff EGS within a sandstone at ~3900 meters depth, reaching ~145°C (Jung, 2005). By utilizing a single-well design, the projects effectively bypassed the requirement for inter-well connectivity, the most frequent point of failure in geothermal doublets.

- **Connectivity:** Bypassed the need for a doublet by using a single well for both injection and production by utilizing "huff-n-puff" cycles alternating between injection and production.
- **Conductivity:** The project successfully created a massive fracture with high hydraulic conductivity without proppants, relying on self-propping effects of the host rock (Tischner, 2010).
- **Conformance:** By circulating fluid through a single fracture, all flow was within the intended zone. No thermal decline was observed during the short testing period (Jung, 2005). A single-well system with more fractures would be more robust to thermal decline at the potential cost of achieving equal flow through each of the fractures.

3.2.2. Genesys GEOZENTRUM Project (2009-2016, Hannover Germany)

The commercial-scale successor to Genesys Horstberg was a well was drilled to 3900 m TVD in Paleozoic-aged sedimentary rocks with a bottom hole temperature of 160 °C. It was operated in a similar huff-n-puff style as the Horstberg project. After a 6-month shut-in, a salt plug had developed in the well, highlighting the importance of formation water and working fluid geochemistry and its effects on the 3 C's (Tischner, 2010).

- **Connectivity:** Successfully connected two sandstone formations connected to single deep well (3,901 m) to access the target formation, before salt and other mineral precipitation from nearby saline connate aquifers ended the testing.
- **Conductivity:** a large and highly conductive fracture was created without the use of chemical additives, proving that sedimentary rock can support high fluid rate injection and flowback. "Self-propping" was possible in these sandstones, but conductivity degraded at lower pressures (Tischner, 2013).
- **Conformance:** No conformance issues with a single fracture design, although the fracture did not translate to high flow rates due to low effective matrix permeability in the sandstone targets.

3.3. Closed Loop AGS

A third approach for next-generation geothermal development is a closed-loop, or Advanced Geothermal System (AGS). The first commercial-scale closed-loop project being developed in Geretsried Germany has documented production beginning in 2026 (Kombrink, 2026). The project utilizes two vertical wells, each one kicking off into multiple horizontal and deviated laterals. The lateral well sections act as the core of the subsurface heat-transfer mechanism, targeting depths of 4.3 - 4.7 km and 150 °C (Longfield, 2022). As discussed in Section 2, the three C's are understood slightly differently when discussing AGS systems:

- **Connectivity:** Separate boreholes are connected to form a closed working fluid flow loop by drilling lateral sections connected at each well's terminus, meaning that each wellbore's surface area provides 100% of the area subject to heat exchange to into the working fluid, and harvested by the producing well.
- **Conductivity:** Thermal conductivity of the reservoir rock and flow rate in the wellbore determines the thermal drawdown of the system, and is the primary driver for heat recovery.
- **Conformance:** An equal flow distribution through each leg of the multi-lateral subsurface radiator is necessary to maintain thermal performance over time.

4. ADAPTING NEXT-GENERATION GEOTHERMAL TO SUPERDEEP & SUPERHOT

Methods for heat extraction from Hot Dry Rock have been summarized above. Below we describe challenges facing these different methods in superdeep and superhot conditions, defined as deeper than 6 km and hotter than 350 °C, respectively. This section will not focus on drilling and wellbore challenges, limitations and stability in these systems; for more information on the status and limitations of tools and technology in superhot temperatures and superdeep depths, see work by Cladouhos and Callahan (2023).

4.1. Evolving Paradigms for Superhot and Superdeep EGS

4.1.1. Superhot Traditional EGS

Open-loop circulation between separate injection and production wells through an engineered fracture network faces amplified technical barriers at temperatures greater than 350 °C and depths greater than 6 km:

- **Connectivity:** very few stress measurements have been taken in most development areas, even to indicate dominant regional stress orientations. This factor dictates the direction of fracture growth between wells, and in most places remains largely unknown. Lab scale experiments also suggest that fractures may propagate differently in Superhot and Superdeep fractures (Goto, 2024).
- **Conductivity:** Maintaining a high-conductivity flow path is at odds with intense chemical and mechanical conditions of superdeep and superhot reservoirs. For propped cases, prevalent commercial proppants are expected to degrade under superhot, high-pressure conditions (Cladouhos and Callahan, 2023; Grubac et al., 2025). Geochemical concerns observed in shallower projects such as Habanero (Hogarth and Holl, 2017) and Genesys (Tischner, 2010) may be exasperated by additional analytes coming into solution under high-pressure and high-temperature conditions, in addition to corrosive effects, diagenesis, and pore occlusion.
- **Conformance:** Even with successful fracture creation and accessible pore space, controlling the distribution of the working fluid is complicated by super-hot thermodynamic properties. Working fluids have a lower viscosity at higher temperatures, worsening flow anisotropy between different fractures with different conductivities. Challenges and mitigations to ensure more uniform conformance across large numbers of fractures and fracture sets prevalent in next generational EGS development are also complicated at < 350 °C and super deep conditions.

4.1.2. Alternative Superhot EGS Approaches

Superhot geothermal resources deliver far more energy per kilogram of fluid than EGS at hot temperatures, easing demands on flow rates and reservoir performance. This enables simpler, more creative well designs that would be impractical in cooler settings. One approach: a single, large, conductive fracture linking two vertical wells. This minimizes drilling and completion complexity by eliminating multi-stage fracturing a horizontal well in superhot and superdeep conditions. It also eliminates conformance challenges across multiple pathways by relying on one pathway.

In Figure 5, shows sustained power output per well) for a single fracture concept shows a pathway to reliable development (> 2MW power capacity for 15 years within some specific conditions (such as with mainly vertical wells and a single fracture). This designs around conformance, able to focus on creating a large fracture between the wells. This design would carry a much simpler completion than a horizontally-drilled well. Critically, this could allow broader utilization of fracture completions to target superhot resources. Each project would need many more wells if this design were selected.

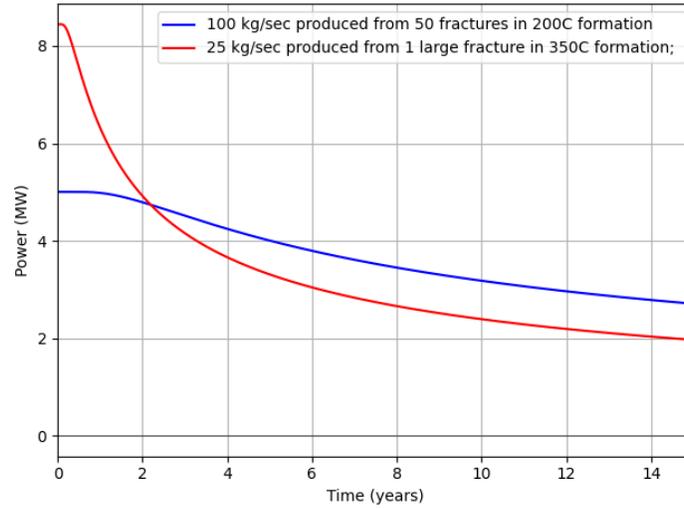


Figure 5 compares two scenarios: the case described in Figure 4 with two horizontal wells drilled into 200 °C formation with 50 fractures connecting them and a second case with two vertical wells connected by one fracture that is five times the size coming from the horizontal sections and flowing 25 kg/sec. This takes advantage of increased power plant efficiency at superhot temperatures, needing less flow rate Figure 5. Power production over time for a generic geothermal power plant. Blue Curve: production from a pair of horizontal EGS wells with working fluid flow across 50 fractures in 200 °C hot dry rock conditions. Red curve: power production from two nearly vertical wells connected across 1 large fracture at 350 °C. The x-axis shows power plant operational time in years; the y-axis shows gross power of the plant minus its parasitic load (MW).

4.3. Adapting Superhot, Superdeep Huff-n-Puff EGS

Huff-n-Puff systems can be adapted to operate at high-pressure conditions required for superdeep targets. If operating pressure-propped fractures, exceptionally high pressures will be needed at the surface to maintain fracture aperture. If the required pressures cannot be handled on the surface, a dense fluid could be used to increase bottom hole pressure at a given wellhead pressure, following standard approaches in managing fluid pressures. Brine was used over freshwater during the Habanero EGS project to increase the well’s bottomhole pressure (Hogarth and Holl, 2017).

Similar concepts can be applied to create buoyancy-driven, downward oriented fractures using a heavy working fluid from a wellbore. A “drill shallow, fracture deep” development strategy (Figure 6) seeks to decouple thermal resource access from drilling depth by exploiting the mechanics of hydraulic fracture propagation, especially to target deeper targets. Wells could be drilled to moderate depths where drilling cost and technical risk remain manageable, and hydraulic stimulation used to propagate fractures downward into hotter rock. This approach offers a potential pathway to access high-enthalpy resources at substantially reduced capital cost relative to ultra-deep drilling.

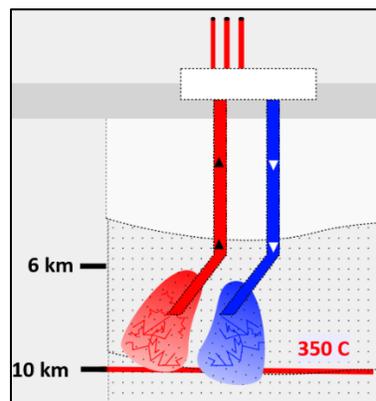


Figure 6: Conceptual model of a two-well huff-n-puff geothermal development with circulation switching cyclically between two nearly vertical or deviated wells (blue cold water charge phase, red warmed production phase). This scenario also describes superdeep fractures connected to deep (but relatively shallower) wells.

The feasibility of this concept is supported by fracture-mechanics theory describing the vertical stability of fluid-driven fractures. The direction of fracture propagation is governed by the balance between in-situ stress gradients, fracture fluid pressure, and buoyancy forces arising from density contrasts between the injected fluid and the surrounding rock (Weertman, 1971; Salimzadeh, 2020). In most sedimentary hydraulic-fracturing applications, injected fluids are less dense than the formation rock, and fractures exhibit a natural tendency to propagate upward.

Garagash and Germanovich (2022) investigated downward fracture propagation with a dense working fluid, demonstrating analytically and numerically that vertical hydraulic fractures can propagate stably downward when the fracture fluid density exceeds that of the surrounding formation. This work showed that downward-propagating fractures are dynamically stable and may be capable of connecting large vertical distances under sustained injection. Buoyancy and stress-gradient effects control whether a fracture tip accelerates upward, stalls, or migrates downward.

These mechanics imply that fractures initiated at intermediate depths may be engineered to grow preferentially into higher-temperature rock, increasing the effective heat-exchange surface area without requiring direct drilling into super-hot formations. Nevertheless, practical deployment remains constrained by uncertainties in fracture path control, interaction with pre-existing faults, and long-term fracture aperture evolution under high temperatures and high effective stresses. Conductivity through time of these downward oriented fractures also lacks a grounding in field observations in these conditions. These challenges suggest that the “drill shallow, fracture deep” paradigm should be viewed not as a universal replacement for deep drilling, but as a complementary heat extraction strategy whose viability depends strongly on local stress conditions, thermal gradients, and structural geology.

4.1.4. Superhot and Superdeep Closed Loop Development Scenarios

Superhot rock conditions have not yet been successfully targeted for closed loop developments deeper than 6 km and hotter than 300 °C. As summarized by Cladouhos and Callahan (2023), there are numerous drilling and completion challenges associated with drilling any superhot and superdeep wells, in addition to added complexities focused on multilateral as well as well-in-pipe designs. Wellbore stress conditions and open hole as well as casing or tubing collapse at great depths and pressures remain challenging. For well-in-pipe or vacuum insulated tubing (VIT), casing too heavy to support its own "string weight" or tensile limit becomes critical at internal pressures reaching approximately 22 MPa (3,190 psi). High thermal loads can also lead to collapse (Zhou et al., 2015).

5. CONCLUSIONS

Superhot and super deep development could unlock terawatt-scale additional energy potential. Reduced models of conduction and depletion, adapted from Gringarten and Witherspoon (1973) and Tester and Smith (1977), forecast net outputs of 5–10 MW per well pair over 30 years, factoring in thermal efficiency.

Approaches to making Superhot geothermal an economically and technically industry must overcome critical limitations approaching deep (> 7 km) targets and pressures for conformance, connectivity and fluid management in conductive fractures and permeability. With this in mind, leveraging proven oil and gas technologies to access superhot zones while maintaining borehole and working fluid stability could also be achieved with novel approaches in terms of conductive and cost-effective mud additives to water, significantly increased hook-load weight capacity for drilling rigs, as well as emerging solutions for improved casing integrity and high-pressure power plants.

Fracture extension facilitated by heavy working fluids may allow operators to better control propagation direction and manage high-pressure and high temperature (HPHT) conditions, reducing buoyancy effects and stabilizing fractures against closure. This creates an effective heat exchanger without exposing wellbores to extreme depths, minimizing thermal stress on equipment. Circulation could also occur in a huff-n-puff or closed-loop mode, with injected fluid absorbing heat from the deep fractures before production. This method could reduce CAPEX significantly compared to direct deep drilling while achieving super hot's energy density.

This updated analysis shifts focus from mid-enthalpy HDR to superhot resources, confirming vast potential in the USA limited primarily by innovation challenges as opposed to geology. Critical factors in achieving economic, superhot or superdeep geothermal development:

- Hot dry rock targets at > 350 °C and shallower than 10 km includes more than 5% or approximately 350,000 km² of the continental USA at ~10 km depth, widely expanding potential for geothermal development beyond traditional hydrothermal resources. Similar abundant resources have also been documented globally (Vargas et al., 2022).
- It is possible to achieve a 3-5x multiplier in heat and/or power recovery by targeting superhot (>350 °C) rocks, compared to traditional geothermal methods. This is likely to be critical to support additional CAPEX requirements for deeper targets (> 7 km).
- Scalable, single-well, single fracture concepts for superhot targets within 7 km depth from surface provide an attractive alternative to deep horizontal, multi-stage fracture developments by reducing CAPEX while maintaining project effectiveness by harnessing > 350 °C temperatures.
- Working fluids research and development are needed to provide engineered, economic heat-recovery tools, especially within the conceptual framework of fracture stimulation in superhot rock. This potentially includes novel nanoparticle mud additives in water/brines, and materials with beneficial conductivity in supercritical conditions and high temperatures.

Suitable development concepts must balance accessibility and economics, enabling lower-cost energy projects. Continued research and development in fracturing and fluids could unlock this resource, establishing SHR as a cornerstone of sustainable energy.

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