



**PREPARED BY:**

Harish Chandrasekar	Julio Quijano	Cory Draper
Alvaro Amaya	Orkhan Khankishiyev	Derek Dixon
Greg Szutiak	Shanti Swaroop Kandala	Rob Klenner
Sean Britton		
GreenFire Energy Inc.		

**Primary Authors**

Benson Gilbert

**Project Manager**

**California Energy Commission**

**Agreement Number:** EPC-21-015

Anthony Ng

**Branch Manager**

**TECHNOLOGY INNOVATION AND ENTREPRENEURSHIP BRANCH**

Jonah Steinbuck, Ph.D.

**Director**

**ENERGY RESEARCH AND DEVELOPMENT DIVISION**

Drew Bohan

**Executive Director**

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## PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency; renewable energy and advanced clean generation; energy-related environmental protection; transportation; and energy transmission and distribution.

In 2011, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned electric utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs to promote greater reliability, affordability, and safety for California electric ratepayers. EPIC investments advance these values by:

- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility-scale projects), and finally with a clean electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

*Advanced Geothermal System Commercial Demonstration at The Geysers, California* is the final report for the *Steam Dominated GreenLoop: Proof of Concept at The Geysers, California* project (EPC-21-015) conducted by GreenFire Energy Inc. The information from this project contributes to the CEC Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the [CEC's research website](http://www.energy.ca.gov/research/) (www.energy.ca.gov/research/) or [contact](mailto:ERDD@energy.ca.gov) the Energy Research and Development Division at [ERDD@energy.ca.gov](mailto:ERDD@energy.ca.gov).

## ABSTRACT

This report summarizes the results of a California Energy Commission-funded project that tested GreenFire Energy Inc.'s Advanced Geothermal System (AGS) in an existing legacy geothermal well within the southern portion of The Geysers geothermal field, a steam-rich geothermal field in Northern California. The goal was to demonstrate that existing wells can be upgraded using a pipe-in-pipe closed-loop system, and to evaluate its performance under real reservoir conditions.

Over a 90-day test period, the system was operated at various flow rates using water as the working fluid. The system was tested in both forward (water flows down the central insulated pipe and up the outer annulus) and reverse (water flows down the outer annulus and up the central insulated pipe) flow configurations, with reverse flow showing better thermal performance. A 30-day test at 330 gallons per minute yielded stable production (outlet) temperatures of about 311 degrees Fahrenheit (155 degrees Celsius) and sustained heat extraction rates of 7.4 megawatts of thermal power. At peak flow of about 400 gallons per minute, the system achieved around 9 megawatts of thermal power, which is equivalent to an estimated gross power production of around 1.1 megawatts of electric power when paired with a standard Organic Rankine Cycle power system.

The results in this report confirm that AGSs are both technically and economically viable for repurposing idle or underperforming geothermal wells. Based on extrapolated performance data and preliminary economic modeling, a full-scale 100 megawatts of electric power AGS project at The Geysers could be deployed within the next 4 to 5 years, with an estimated levelized cost of electricity of between \$90 and \$95 per megawatt-hour over a 20-year horizon. These estimates are subject to further technical, geologic, and commercial validation as described in the economic feasibility section of this report. California holds over 200 megawatts of electric power of additional potential in idle wells that could be tapped quickly using this technology, offering a scalable, low-impact pathway to expand the state's clean energy capacity.

**Keywords:** Advanced Geothermal System (AGS), Closed Loop Geothermal Systems (CLG), Downbore Heat Exchanger (DBHX), The Geysers

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# EXECUTIVE SUMMARY

## Background

California has established clean energy and climate goals, including reaching 100-percent zero-carbon electricity by 2045, as mandated by Senate Bill 100. To meet these goals, the state requires more sources of reliable renewable energy, especially those that provide steady baseload power when the sun isn't shining or the wind isn't blowing. Geothermal energy is one of the few clean energy sources that delivers this baseload, "always-on" power, known as firm energy. California has substantial geothermal potential, but conventional or traditional geothermal systems face technical challenges that limit them. These challenges are linked to the geological thickness of the Earth's crust, which historically required a specific thinness to allow for the economical access of geothermal energy. Beyond this crustal constraint, conventional or traditional geothermal technology expansion is often limited by reservoir availability, complex fluid management, and the broader implications for seismic stability and water availability. This project aimed to overcome those hurdles by implementing a new type of geothermal technology at The Geysers, a geothermal field in Northern California, which has been generating energy since the 1960s and currently has 15 operating geothermal power plants that draw from more than 350 wells.

## Project Purpose and Approach

This project tested a novel technology called Steam Dominated GreenLoop (SDGL), which is referred to in this report as GreenFire Energy Inc.'s (GreenFire) Advanced Geothermal Systems (AGS). Instead of pulling water or steam from underground, as is the case in conventional geothermal systems, AGS sends water through a sealed pipe-in-pipe coaxial setup to absorb heat from deep inside the earth. That heat is then used to generate electricity without disturbing underground fluids or re-injecting water. This is an important distinction from conventional geothermal methods because it:

- Supports lower maintenance energy production: The system harnesses geothermal energy in a manner that does not require maintenance of the geothermal reservoir.
- Protects the environment: Since no water or steam is taken out or injected back into the reservoir, the system provides reservoir pressure stability and has less impact on the steam reservoir.
- Can potentially work in non-productive areas: This method could be productive in places where there is heat but insufficient water or steam for conventional geothermal systems to produce energy.

## The Goals of the Demonstration Project Were To:

- Demonstrate that GreenFire's AGS technology can enable the geothermal industry to overcome specific technical issues that have historically impeded the development of geothermal power (such as fluid scarcity and reservoir pressure decline) in California, particularly in steam-dominated resources.

- Retrofit one geothermal production well with GreenFire’s AGS technology to test its performance.
- Assess the potential for the technology to deliver ratepayer benefits of greater electricity reliability and lower cost, with superior environmental attributes.
- Improve heat exchanger design: Advance the engineering of downbore heat exchanger systems to better capture and transfer underground heat.
- Explore future potential: Evaluate how well this approach could work at larger scales and in other locations, both at the Geysers and elsewhere in California.

### **The Objectives of the Project Were To:**

- Prove the system works efficiently: Show that the closed-loop setup can produce at least 80 percent of available heat from deep underground without losing either significant water or pressure in the steam zone.
- Match models to real results: Make sure the engineering designs and computer models match actual measured data during the test, within expected limits.
- Estimate future potential: Use the test results, resource data, and cost information to determine if this system could work for a larger project — one that could produce over 100 megawatts of electricity — and calculate expected electricity costs.

### **Key Results and Conclusions**

The project technology test was conducted over three months (90 days) with GreenFire’s AGS installed in an existing production well. The system was operated under a variety of flow conditions with water circulated through the system. The main improvements achieved are as follows:

During testing, the downbore heat exchanger system sustained outputs of up to about 9 megawatts of thermal power. The water circulating and exiting the system reached 311 degrees Fahrenheit (155 degrees Celsius), with a maximum mass flow rate of 24.2 kilograms per second in a closed loop. The water going back into the system averaged 155 degrees Fahrenheit (68 degrees Celsius). These results are based on validated field measurements taken during active operation. Temperatures were recorded at the points where water entered and exited the downbore heat exchanger system. The system also intermittently released small amounts of naturally occurring gases from the space between the AGS equipment and the well, which assisted in maintaining performance. Notably, the calculated steam flow rate entering the wellbore during the testing of the AGS was found to be approximately three times higher than the established steam production rate of the well during standard (recent) conventional flow periods.

The system demonstrated a significant increase in the estimated electric power potential of the existing well. Based on thermal performance data and modeled surface conditions, the well’s output was calculated to increase from roughly 0.5 megawatts of electric power (under conventional geothermal operation) to about 1.1 megawatts of gross electric power and 0.94

megawatts of net electric power using GreenFire's AGS configuration, paired with an Organic Rankine Cycle power system. While no power generation units were installed during this project, the modeled results indicate the potential to roughly double electric power production from the well. This substantial improvement highlights the scalable potential of the technology and its potential to improve the performance of existing wells and fields.

The system demonstrated stable heat extraction over the entire testing period, with a maximum output of about 9 megawatts of thermal electricity. Key observed metrics included:

- Stable downbore heat exchanger production (outlet) temperatures of the working fluid (water), which remained steady throughout the testing period. This stability indicates both effective heat absorption from the reservoir and reliable thermal performance.
- Stable pressure and flow dynamics, demonstrating that the system can maintain safe and reliable operation.
- No evidence of fluid leakage within the system, validating the system's closed-loop integrity.
- No evidence of seismic events, demonstrating that pressure changes in the rock induced by the system were minimal during the test period.

The data gathered during the test were high resolution and used to validate and refine GreenFire's predictive modeling tools. These models simulated thermal behavior, geological interactions, and long-term performance, which are critical for planning future development. The test results improved the accuracy of these tools, allowing developers and policymakers to make better-informed decisions about geothermal investment and development.

## **Knowledge Transfer and Next Steps**

GreenFire's support for this project included thermal modeling, design optimization, and system troubleshooting. Project teams can continue to consult with GreenFire to refine AGS configurations, interpret complex field data, and enhance overall system efficiency. Critically, the team continually reviews observed field performance and translates those findings into practical design improvements for upcoming development. GreenFire is additionally available to discuss project needs, review proposed designs, and deliver tailored technical support to help scale geothermal innovations.

GreenFire also conducts public engagements to raise awareness of the technology and its potential as a transformative clean energy solution. This has included the launch of a dedicated project page on the company website and a targeted media campaign designed to communicate the benefits of the technology to a broad audience — from policymakers and investors to local communities and industry stakeholders. These efforts positioned GreenFire's AGS as a scalable and innovative approach to geothermal development.

In addition to public-facing outreaches, technical findings from the project are expected to be shared through peer-reviewed papers and presentations at leading conferences, including the Geothermal Rising and Stanford Geothermal Workshop, which contributes to the broader scientific and engineering dialogue around next-generation geothermal technologies. The team

also plans to expand outreach through targeted briefings and roundtables with local stakeholders, including Sonoma County officials and Sonoma Clean Power, to specifically address replicability, permitting pathways, reservoir dynamics, and strategies to accelerate the adoption of AGSs across California and other regions.

## **Benefits to California Ratepayers**

This project benefits California IOU ratepayers by demonstrating a pathway to add firm, zero-carbon capacity from existing geothermal fields using GreenFire Energy’s closed-loop AGS technology. Results from the demonstration and techno-economic modeling indicate that a conceptual 112 megawatts of electricity AGS deployment at The Geysers could generate approximately 866,000 megawatt-hours/year, enough to serve over 100,000 California homes, while providing reliable peak and net-peak capacity.

Preliminary levelized cost of electricity estimates of \$90–\$95 per megawatt-hour suggest AGS could be competitive with other firm, low-carbon resources, while displacing fossil generation, reducing emissions, and supporting the Senate Bill 100-related clean energy targets. The project’s data, models, and lessons learned reduce performance and cost uncertainty, assisting utilities and regulators in planning a more reliable, affordable, and diverse clean energy portfolio.

# CHAPTER 1:

## Introduction

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### Context and Background

California's energy system is evolving rapidly to meet growing demand and ambitious climate mandates, including reaching 100 percent zero-carbon electricity by 2045 under Senate Bill 100.<sup>1</sup> Electricity use is rising due to population growth, the shift to electric vehicles and buildings,<sup>2</sup> and the increasing energy requirements of industries, including data centers and artificial intelligence (AI) infrastructure.<sup>3</sup> According to the state's 2024 projections, California must add more than 76 gigawatts of new electric power capacity by 2039 to meet demand and stay on track with climate goals.<sup>4</sup> This year's transmission plan reflects that need, highlighting the importance of expanding energy generation and delivery across the state.

To meet increasing demand and its climate goals, the state is retiring fossil fuel plants and adding more solar and wind power to the transmission grid.<sup>5</sup> While these renewable sources are essential, they are variable, meaning they don't always generate electricity when it is required. That is why California urgently seeks clean, firm energy sources that can provide reliable power around the clock.

Geothermal energy is one of the few clean energy sources that can deliver this kind of "always-on" power, known as firm energy. Despite the massive geothermal potential in the state,<sup>6</sup> conventional or traditional geothermal systems face technical challenges that limit their growth, which is why geothermal energy accounted for only 4.35 percent of the electricity that was actually delivered to customers and sold by the state's utilities in the year 2024 (after factoring in the power lost during transmission<sup>7</sup>). The technical challenges (hurdles) are primarily linked to reservoir availability, water availability, complex fluid management, and issues around reservoir pressure. This project aimed to overcome those hurdles by implementing a new type of geothermal technology called Steam Dominated GreenLoop (SDGL), which is referred to in this report as GreenFire Energy Inc.'s (GreenFire) Advanced Geothermal System (AGS), at The Geysers, a geothermal field in Northern California.

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<sup>1</sup> California Legislature. 2018. [Senate Bill No. 100: The 100 Percent Clean Energy Act of 2018](https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100). California Legislative Information. [https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill\\_id=201720180SB100](https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100)

<sup>2</sup> California Energy Commission. 2024. *Draft 2024 Integrated Energy Policy Report Update*. CEC-100-2024-001.

<sup>3</sup> Rhodium Group. 2025. [The Potential for Geothermal Energy to Meet Growing Data Center Demand](https://rhg.com/research/geothermal-data-center-electricity-demand/). Rhodium Group. <https://rhg.com/research/geothermal-data-center-electricity-demand/>

<sup>4</sup> California Independent System Operator. 2025. *2024-2025 Transmission Plan Draft*. California ISO

<sup>5</sup> California Energy Commission. 2024. [New Data Shows Investments to Build California's Clean Energy Grid of the Future are Paying Off](https://www.energy.ca.gov/news/2024-05/new-data-shows-investments-build-californias-clean-energy-grid-future-are-paying). California Energy Commission. <https://www.energy.ca.gov/news/2024-05/new-data-shows-investments-build-californias-clean-energy-grid-future-are-paying>

<sup>6</sup> Clean Air Task Force. 2025. [Unlocking California's Geothermal Potential: A Strategic Opportunity for Clean, Firm Power](https://www.catf.us/resource/unlocking-californias-geothermal-potential/). Clean Air Task Force. <https://www.catf.us/resource/unlocking-californias-geothermal-potential/>

<sup>7</sup> Jacobson, Mark Z., Daniel J. Sambor, Yuanbei F. Fan, Andreas Mühlbauer, and Mark A. Delucchi. 2025. "No Blackouts or Cost Increases Due to 100% Clean, Renewable Electricity Powering California for Parts of 98 Days." *Renewable Energy*, Volume 240.

The Geysers is a world-class geothermal field where heat from deep underground reservoirs is used to make electricity. It is the largest geothermal field in the world that runs on steam, and it has been operational since the 1960s. The Geysers field contains a substantial amount of underground heat that can be used to generate electricity by producing steam. However, for the system to sustain energy output, it requires sufficient water underground to convert that heat into usable steam. During the field's early production in the 1970s and 1980s, overproduction led to a drop in the geothermal reservoir pressure, which in turn caused a decline in power generation. To stabilize the power generation profile, The Geysers initiated a partnership in the 1990s and early 2000s with nearby municipalities like Lake County and Santa Rosa. Through this collaboration they began injecting recycled water — defined here as treated municipal water — into the reservoir. This injection of recycled water has proven to be highly effective; it assists in sustaining steam generation and maintaining long-term energy output, creating a beneficial outcome for both The Geysers and the participating counties. However, recycled water is not always available and does not address issues such as reservoir pressure, which can affect seismic stability.

The purpose of this project was to demonstrate that GreenFire's AGS technology can safely and effectively bring heat energy to the surface even when well conditions are not ideal for conventional geothermal production. This heat can then be used to generate electricity or support other heating requirements. In doing so, GreenFire's AGS technology supports California's clean energy goals, reduces greenhouse gas (GHG) emissions, and makes more efficient use of existing geothermal resources while maintaining reservoir water and pressure levels.<sup>8</sup>

This project represents a crucial step in scaling the AGS technology. It builds on an initial, successful pilot-scale demonstration project by GreenFire at the Coso geothermal field in Southern California.<sup>9</sup> That pilot project proved that the technology could be used to extract heat from a single, existing, idle geothermal well. This new project aimed to adapt that proven concept and demonstrate its commercial viability and scalability by applying it to a broader geothermal resource base, paving the way for wider future use.

## **How Geothermal Energy Works: Conventional versus GreenFire's AGS Technology**

Geothermal systems differ widely in how they produce usable heat. In conventional steam-rich fields like The Geysers, naturally occurring steam rises through the underground rocks (reservoir) and is produced directly at the surface to run turbines. Other geothermal fields are liquid-rich, where hot water — not steam — feeds the wells, and power is generated either by flashing that water to steam or by using an Organic Rankine Cycle. Some geothermal reservoirs require supplemental water injection to sustain pressure and replace the fluid withdrawn during power generation. In contrast, AGS technology operates as a closed loop; it does not rely on producing the natural fluids already in the rock. Instead, it circulates an

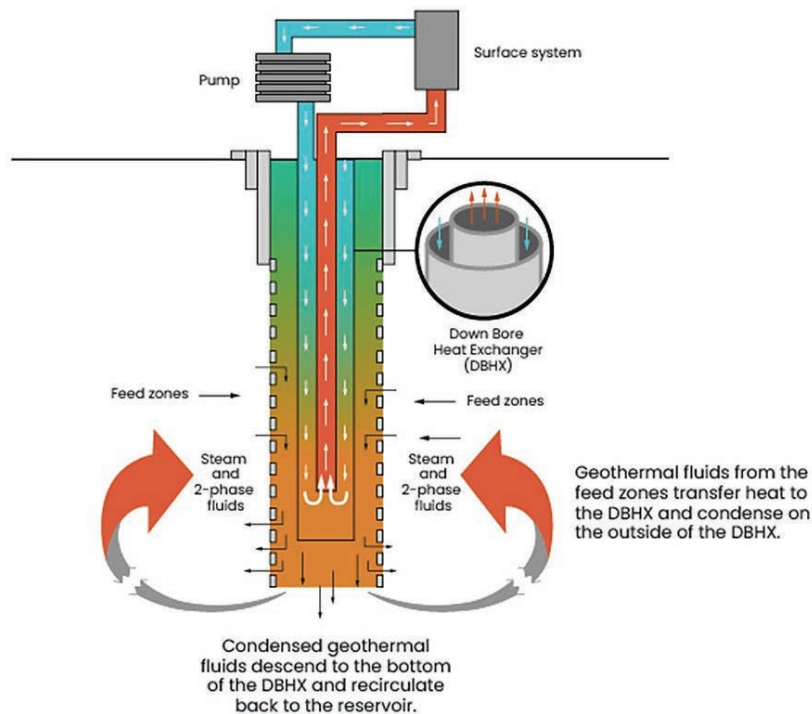
<sup>8</sup> ThinkGeoEnergy. 2022. "[GreenFire Energy awarded funding for demonstration project at The Geysers.](https://www.thinkgeoenergy.com/greenfire-energy-awarded-funding-for-demonstration-project-at-the-geysers/)" <https://www.thinkgeoenergy.com/greenfire-energy-awarded-funding-for-demonstration-project-at-the-geysers/>

<sup>9</sup> GreenFire Energy. 2020. *Closed-Loop Geothermal Demonstration Project: Coso, California*. California Energy Commission. Publication Number: CEC-300-2020-007.

engineered working fluid — typically water — inside a sealed pipe-in-pipe downbore heat exchanger, which extracts heat purely by conduction (heat transfers directly from the hot rock to the pipe, like heat moving from a stove burner to a metal pan) and convection (heat transfers from naturally moving subsurface fluid around the downbore heat exchanger) from the reservoir. This gives AGSs a unique advantage; the reservoir’s heat can be accessed regardless of whether sufficient fluid exists naturally to sustain conventional steam production. While GreenFire’s AGS can work when there is little to no underground water in the reservoir, the efficiency of the AGS in bringing heat energy to the surface would be lower. With little to no underground water, the methods of heat transfer the AGS could use would be more conduction dominated, meaning the AGS would require a larger size and longer vertical/ deviated sections to generate sizeable electric power. On the other hand, when sufficient water exists in the reservoir, the AGS is more efficient.

An example of the system is shown in Figure 1. Because the system doesn’t remove reservoir fluids, it also helps reduce costs and other impacts experienced from conventional geothermal systems.<sup>10</sup>

**Figure 1: Schematic of a DBHX Installed in a Well**



**Cold and hot fluids circulate through the annular space and central insulated tube. Steam from the reservoir condenses along the outside of the system and flows downward, with the condensed fluid recycling into the reservoir to recharge the system and nearby wells.**

Source: GreenFire, 2023<sup>11</sup>

<sup>10</sup> Higgins, Brian, Joseph Scherer, Alvaro Amaya, Harish Chandrasekar, and Andrew Van Horn. 2021. "Closed-Loop Geothermal in Steam Dominated Reservoirs." *Geothermal Resources Council Transactions*, Volume 45.

<sup>11</sup> Scherer, Joseph, Glenn Golla, Harish Chandrasekar, Alvaro Amaya, Hollis Chin, Steven Brown, Eric Sonnenthal, et al. 2023. *The GreenLoop Closed-Loop Geothermal (CLG) System: Optimizing Power Generation and Evaluating*

This technology also offers other advantages:

- Reduced requirement for reinjection wells, which reduces cost and environmental impacts
- Lower risk of induced seismicity; because the system doesn't remove reservoir fluids, it avoids the pressure drops that typically cause hydraulic-induced seismic events.
- Modular design, making it easier to install and scale
- Improved heat control, allowing real-time adjustments to optimize heat capture from the reservoir
- Works in challenging reservoir conditions, allowing geothermal energy expansion to corrosive or mineral-rich reservoir conditions that would clog conventional geothermal systems or require expensive materials
- Revives old wells, bringing low-producing or difficult-to-operate wells back into service, making the most of the existing resources
- Reduces geothermal exploration risk, providing a strong backup plan for geothermal developers by making new geothermal wells useful for energy production, even if they lack the natural fluid flow or pressure required by conventional systems.

## **Project Goals and Success Metrics**

The main goal of this project was to validate the commercial potential and operational performance of GreenFire's AGS technology under real-world conditions. Specifically, the project aimed to:

- Demonstrate that GreenFire's AGS technology can overcome specific technical barriers that have impeded the development of geothermal energy in California, particularly in steam-dominated resources.
- Retrofit one geothermal production well with GreenFire's AGS technology to test its performance.
- Deliver ratepayer benefits of greater electricity reliability and lower cost, with superior environmental attributes.
- Improve heat exchanger design: Advance the engineering of DBHX systems to better capture and transfer underground heat.
- Explore future potential: Evaluate how well this approach could work at larger scales and in other locations at The Geysers and elsewhere in California.

The project's initial performance metrics are summarized in Table 1. These metrics highlight three key variables that jointly define system performance:

1. The electric power produced per flowrate of effective water reinjected

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*Its Impact on the Reservoir.* Proceedings, The 9<sup>th</sup> Indonesia International Geothermal Convention & Exhibition (IIGCE).

2. The effective reinjection of water required to maintain the reservoir under sustainable production conditions
3. Reservoir water consumed per megawatt of electricity produced

When considered together, these parameters demonstrate the ability to simultaneously maximize energy extraction while ensuring long-term reservoir sustainability.

**Table 1: Key Performance Metrics for this Project**

Performance Metric	Performance Metric Unit	Benchmark Performance	Minimum Target Performance	Current Performance
Electrical power produced per flowrate of effective water reinjected	Megawatts of electric power per kilopounds-mass per hour [MWe/(klbm/h)]	0.022 Megawatts of electric power per kilopounds-mass per hour of water produced and reinjected	0.046 Megawatts of electric power per kilopounds-mass per hour <sup>12</sup> of water produced and reinjected	0.046 Megawatts of electric power per kilopounds-mass per hour <sup>13</sup> of water produced and reinjected
Effective reinjection percentage	Percent of produced geothermal water that is reinjected into the resource [%]	40–60 percent <sup>14</sup>	99 percent	99.84 percent
Reservoir water consumed per megawatt of electric power produced	Kilopounds-mass per megawatt year [klbm/(MW-year)]	63,282–94,923 <sup>15</sup>	632–949	3.9

Source: GreenFire, 2025

<sup>12</sup> See Table 2: Power produced is 0.94 MWe when the effective flow reinjected is about 2.6 kilograms per second resulting in 0.046 megawatts of electric power per kilopounds-mass per hour. The formula used for calculating the electric power produced per flowrate of effective water reinjected is electric power in megawatts divided by the produced flow rate in kilopounds-mass per hour, multiplied by the effective reinjection percentage.

<sup>13</sup> See Table 2: Power produced is 0.94 MWe when the effective flow reinjected is about 2.6 kilograms per second resulting in 0.046 megawatts of electric power per kilopounds-mass per hour. The formula used for calculating the electric power produced per flowrate of effective water reinjected is electric power in megawatts divided by the produced flow rate in kilopounds-mass per hour, multiplied by effective reinjection percentage.

<sup>14</sup> This range is based on Sanyal, Subir K., and Steven L Eney. 2011. *Fifty years of power generation at The Geysers geothermal field, California – The lessons learned*. Proceedings, 36<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California. More recent work by Sanyal, Subir K., Steven L Eney, Paul Brophy, and Edward Voge. 2025. *The Geysers: The oldest and largest geothermal power operation in the US*. Geothermal Power Generation (Second Edition), reports an average effective reinjection percentage of approximately 60–80 percent.

<sup>15</sup> The reservoir water consumed per megawatt of electric power produced is obtained by multiplying the steam consumption factor by the total number of hours in a year, and then multiplying the result by the effective reinjection percentage

## **Target Audience and Market Impact**

The results of this project will be useful to a wide range of stakeholders:

- Utilities and grid planners, like Pacific Gas and Electric Company (PG&E), which require reliable clean energy sources
- Policymakers and regulators, which are shaping the future of California's energy mix
- Geothermal energy operators and developers that want to expand projects in areas where conventional geothermal systems are not effective
- Investors and technology providers seeking scalable, cost-effective solutions

Factors that support adoption include AGS's lower environmental impact (due to its closed-loop system), ability to reuse existing wells, and flexibility in dry or hard-to-access geothermal zones. This project has the potential to unlock California's vast underground heat resources and make geothermal a bigger part of the state's clean energy future.

# CHAPTER 2:

## Project Approach

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### Technology Overview

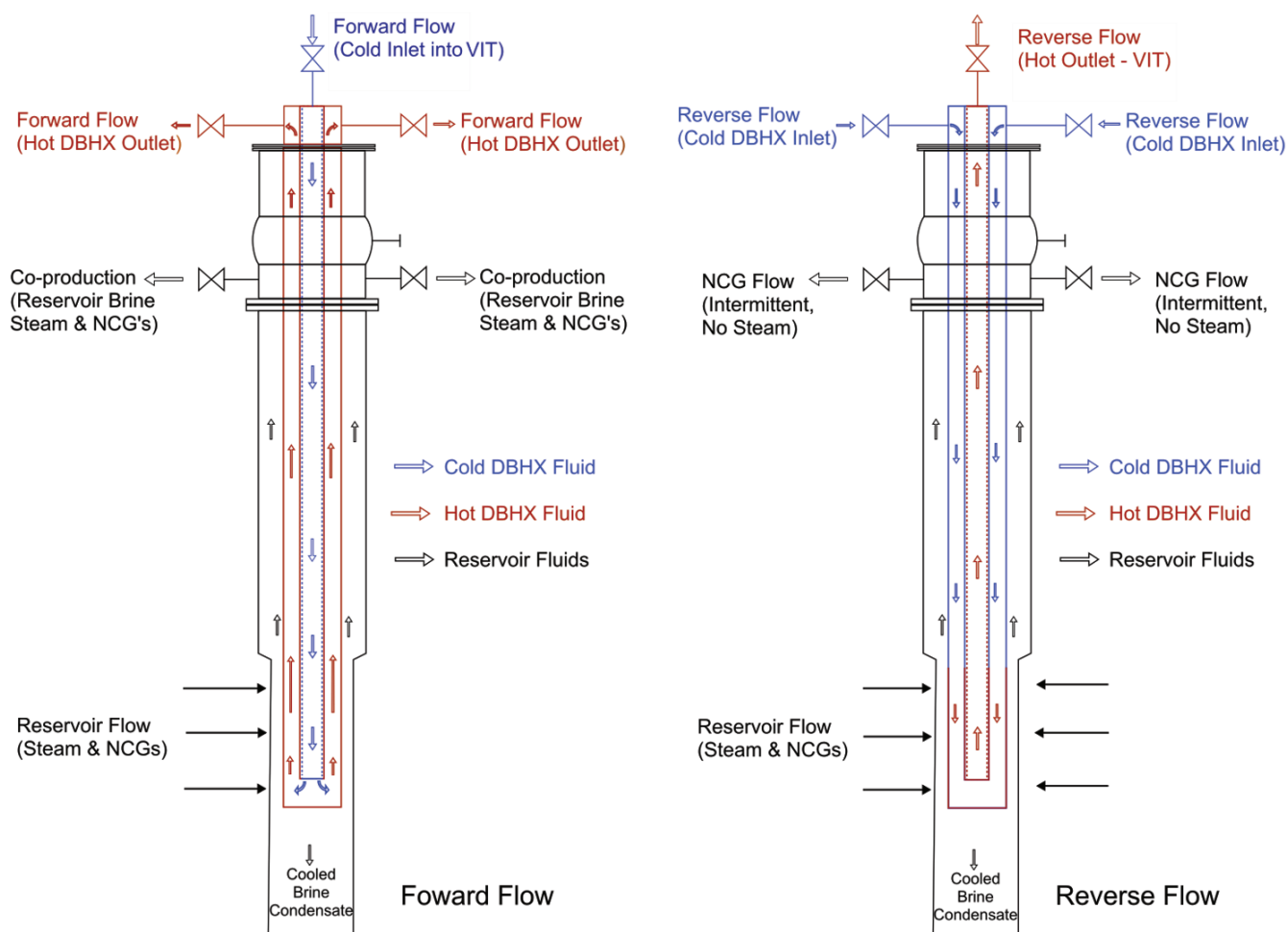
GreenFire's AGS is a closed-loop system designed for deep geothermal wells. These wells can be existing or new ones drilled specifically for this purpose. The system, installed deep in the well, is typically a sealed pipe-in-pipe setup held in place at the wellhead. This sealed pipe-in-pipe setup acts as a DBHX because its primary function is to exchange heat between the working fluid inside the pipes and the reservoir fluids and rocks. The process of operating the system is straightforward: a pump is used to move a working fluid down the DBHX (a general schematic of the system is shown in Figure 1). A range of working fluids can be used within the pipe-in-pipe setup to enable heat transfer (such as water), supercritical carbon dioxide, or other refrigerants. The specific fluid is chosen based on its thermodynamic properties, as well as the well's temperature, pressure, and other reservoir properties (water is often preferred because it is both readily available and affordable).

The system can be configured for either forward flow or reverse flow.

- Forward flow: In a forward flow configuration, the working fluid is pumped down the inner (central) tube of the DBHX. It then turns around at the bottom of the DBHX and flows back up through the annulus, which is the space between the inner and the outer pipes;
- Reverse flow: In a reverse flow configuration, the working fluid is pumped down the annulus and turns around at the bottom of the DBHX and flows back up the inner tube.

The inner (central) tube must be insulated to minimize heat loss in the system. Without insulation, the fluids produced from the DBHX cool down significantly, reducing the amount of energy available at the surface. A commonly used insulated tube is a coaxial vacuum insulated tube (VIT). A VIT is similar to a large thermos flask, or vacuum bottle. The vacuum acts as a powerful insulator, dramatically reducing heat transfer and improving the system's efficiency. Figure 2 illustrates the forward and reverse flow configurations of the system.

**Figure 2: DBHX Schematic in Forward Flow (Left) and Reverse Flow (Right) Configurations**



Source: GreenFire, 2025

Heat is transferred to the DBHX from reservoir fluids and/or the hot rocks adjoining the well. In a steam-dominated field like The Geysers geothermal field in California, the reservoir fluids are a mixture of steam and non-condensable gases (NCGs). Outside the DBHX, steam enters and is cooled by the relatively cold surface of the DBHX, causing it to quickly turn into liquid water, a process called condensation. This new liquid water, which is about 1,000 times denser than steam, then flows downward. Any remaining steam and naturally occurring NCGs flow upward. Depending on the DBHX flow configuration — forward or reverse — the annular space between the DBHX and the well casing can be vented either continuously (forward flow) or intermittently (reverse flow). In other words, the well co-produces a mixture of steam and NCGs in forward flow, requiring continuous venting from the annular space between the DBHX and the well casing. In reverse flow, NCGs rise through the well, cooling and shedding moisture. This configuration allows for intermittent venting only, as gas accumulation is slower. The NCGs are treated before being released or reinjected. More information on the NCGs and composition can be found in Appendix B.

Within the DBHX, the amount of heat the system captures is directly related to how fast the working fluid flows and its corresponding temperatures. Flow is measured using two common units: gallons per minute (GPM) or kilograms per second (kg/s). GPM is a volumetric measurement showing the number of United States gallons that pass a point in one minute, while kg/s is a metric measurement showing the mass of a fluid that passes a point in one second. Temperature in the DBHX is recorded in degrees Fahrenheit (°F) or degrees Celsius (°C) scales. A higher mass flow rate means the working fluid spends less time in the well, but the total heat extracted is typically greater. This is because a larger volume of fluid passes through the system, and even with shorter residence time, the cumulative energy carried by the flow increases. On the other hand, a lower mass flow rate allows the fluid to remain longer in the system, potentially absorbing more heat per unit volume. However, the total heat captured may be lower due to the reduced throughput. Overall, heat extraction in the DBHX is strongly influenced by mass flow rate — higher flow generally results in higher thermal output.<sup>16</sup>

## **Project Partners, Hosts, and Participants**

This project brings together a team of experts and resources from different organizations:

- GreenFire led the design, engineering, and modeling of the patented AGS closed-loop technology. GreenFire also managed the installation and testing process.
- Geysers Power Company, LLC, a subsidiary of Calpine Corporation, licensed the use of one of its geothermal wells.
- California Energy Commission funded the project as part of its mandate to support clean energy innovation and reduce greenhouse gas emissions.
- Lawrence Berkeley National Laboratory provided scientific oversight and assisted in validating the technical modeling and software tools used in the project.

In summary, the project was made possible by the combined field expertise of GreenFire, the technical innovation of Lawrence Berkeley National Laboratory, and the financial support of the California Energy Commission.

## **Step-By-Step Project Approach**

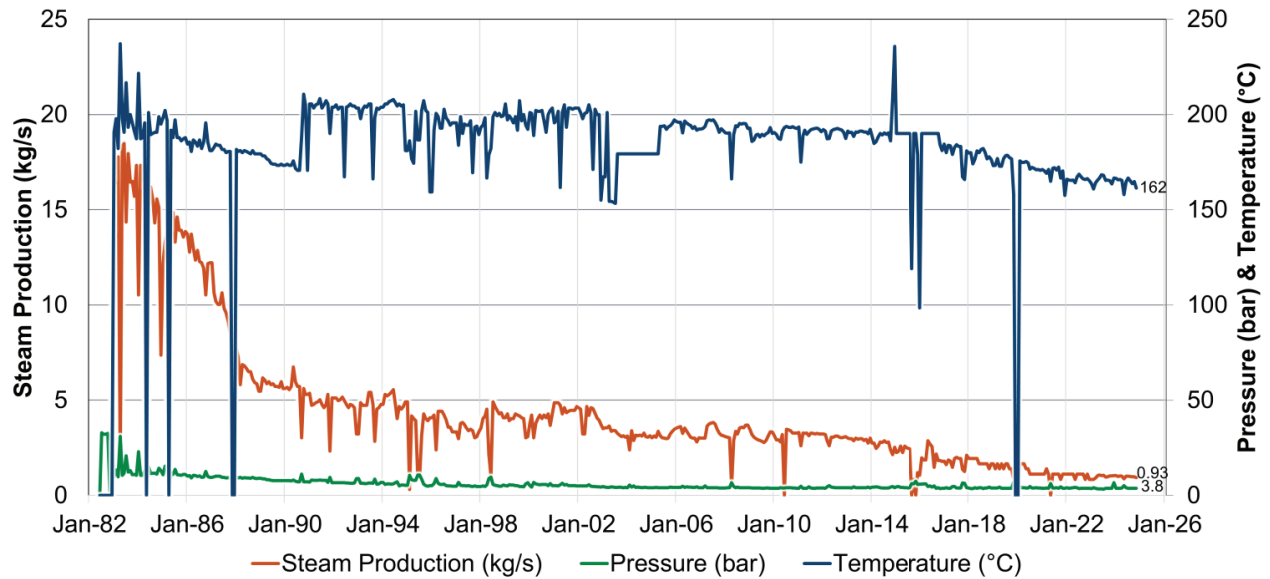
This project followed a structured timeline, starting with site selection and ending with system testing and data analysis. Below is an overview of six key steps:

1. Well identification and assessment: The chosen well for this test was DV-13, located at The Geysers geothermal field in California. The isolated well is a conventional producer with output that declined after more than 40 years of operation. The well retained a lot of heat, which made it a perfect candidate for GreenFire's AGS technology. Figure 3 illustrates the change in steam production rates (kg/s), production temperature (°C), and production pressure (bar) as a function of time since the year 1982.

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<sup>16</sup> Chandrasekar, Harish, Alvaro Amaya, Saul Molina, Ray Alvarado, Joseph Scherer, and Glenn Golla. 2023. *Comparison of Water, sCO<sub>2</sub>, and Organic Hydrocarbons as Working Fluids for the GreenLoop System and ORC Unit*. Proceedings, 48<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

**Figure 3: Production Data of Well DV-13 as a Function of Time since 1982 (Data Recorded at the Wellhead)**

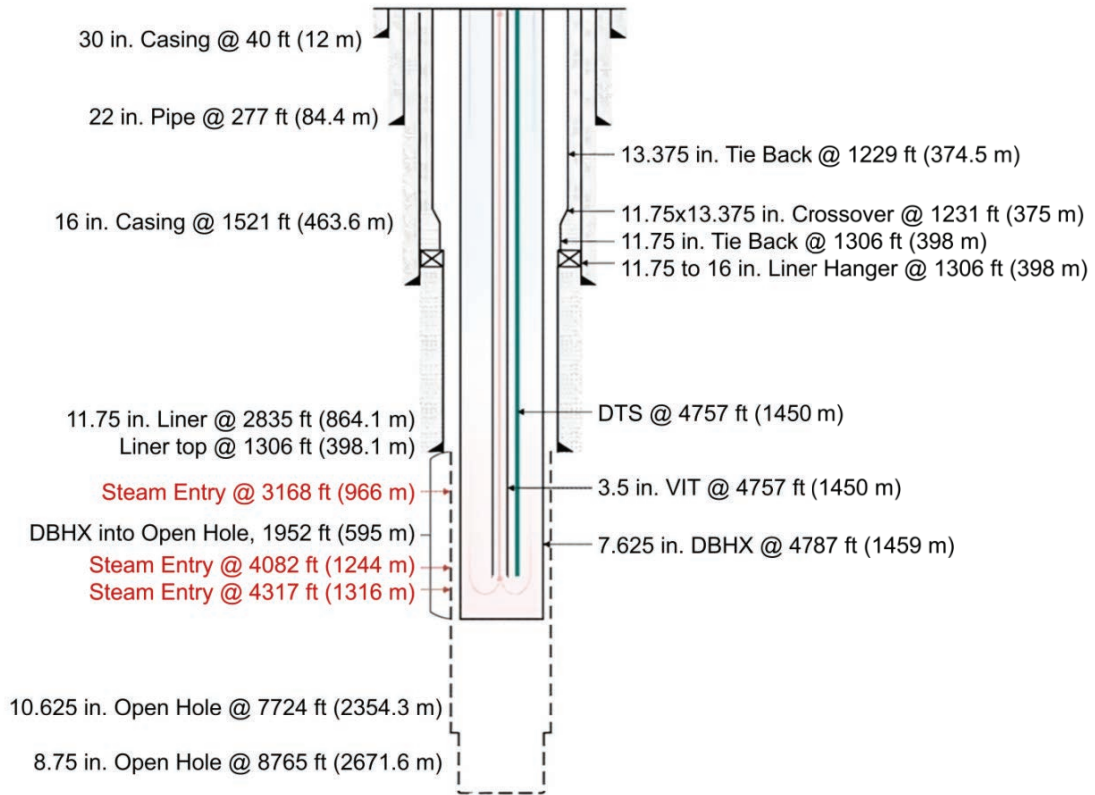


Source: California Geologic Energy Management (CalGEM), 2025

The well has three main sections. The top part has a metal pipe, or casing, with an outside diameter of 13.375 inches (in.), which is about 0.34 meters (m). This casing runs to a depth of 1229 ft. (374.5 m) from the surface. Below this, the casing reduces in size to 11.75 in. (outside diameter), which is about 0.3 m. This casing runs to about 2,835 ft. (864.1 m). Below that, the well is open with an uncased hole that is about 10.75 in. (0.27 m) wide. This section goes down to a depth of 7,724 ft. (2,354.3 m). The deepest section is another open hole, which is narrower at about 8.75 in. (0.22 m) wide. This part extends to a depth of 8,765 ft. (2671.6 m). A pictorial representation of the well with the DBHX is shown in Figure 4.

The DBHX setup has an outer casing with outside diameter of 7.625 in. (0.19 m). Inside, the VIT has an outer diameter of 4.5 in. and an inner diameter of 3.5 in. The DBHX length is around 4757 ft. (1450 m).

**Figure 4: Schematic of Well DV-13 and the DBHX Inserted within the Well**

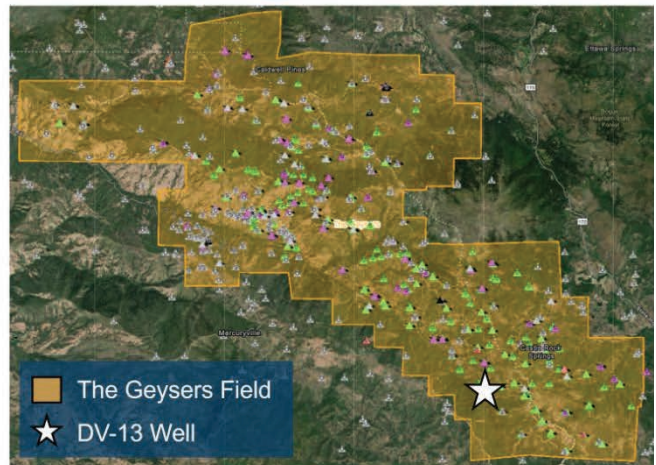
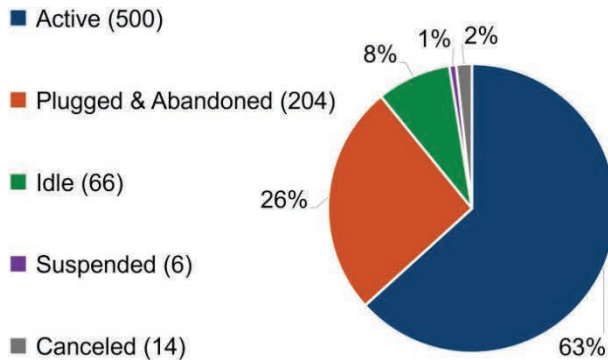


Source: GreenFire, 2025

The well is located in the southern part of The Geysers geothermal field marked by a white star, shown in Figure 5. The yellow region in the figure highlights the area of the geothermal field. There are currently about 500 active wells, along with 204 wells that have been permanently closed (plugged and abandoned), 66 wells that are idle, 6 wells that are suspended, and 14 wells that were canceled before completion.

**Figure 5: Location of Well DV-13 within The Geysers Geothermal Field (And the Current Status of Wells across the Field)**

**Status of Wells in Geysers**



Source: CalGEM, 2025

2. Host agreement and permitting: GreenFire worked closely with Calpine and local regulators to secure the necessary permits and agreements for executing the project in well DV-13 in The Geysers geothermal field. This included environmental reviews and safety planning to ensure the project met all legal and operational requirements.
3. Design of subsurface and surface equipment: The team designed a pipe-in-pipe DBHX that could be installed inside the existing DV-13 well. This system allows a working fluid (water, in this case) to circulate in a closed loop, picking up heat from the reservoir and returning it to the surface. The design of the DBHX places it next to areas in the well that produce steam. These areas, or "steam feed zones" are in the open, uncased part of the well, from about 3,169 ft. (966 m) to 4,317 ft. (1,316 m) down. There is another steam feed zone located near the bottom of the well, at 8,765 ft. (2,672 m).

To measure the temperature, a special fiber optic distributed temperature sensing (DTS) cable was attached to the outside of the VIT. This cable provided very detailed temperature readings, which gave valuable information about how and where the system was absorbing heat along the entire length of the DBHX.

4. Engineering, procurement, and construction: All the parts were engineered to ensure they would work together and efficiently transfer heat. The installation followed standard geothermal well control procedures, with small adjustments made for the unique closed-loop AGS design. On the surface, the facility involved several key components including a fin fan cooler, an expansion tank, pumps, valves, and monitoring instruments. This equipment allowed the team to control and measure fluid flow, temperature, and pressure throughout the test period, even when operating conditions were changed.
5. Field operations and installation: The installation process was carefully managed to protect both workers and the environment, safety protocols were followed throughout, and the system was installed without disturbing underground or reservoir fluids or causing further surface disruption.
6. Pilot system setup and commissioning: Once installed, the system was commissioned and tested under controlled conditions (Figure 6 presents the installed setup as it appeared upon completion). This included:
  - Monitoring flow rates, temperature, and pressure of the working fluid in the DBHX.
  - Adjusting working fluid parameters (flow rate, temperature, and pressure) to optimize heat recovery.
  - Ensuring stable operating conditions within the DBHX (near constant production temperatures and pressures).

**Figure 6: GreenFire’s AGS in Well DV-13 at The Geysers Geothermal Field**



Source: GreenFire, 2025

## Key Project Milestones

Several important milestones marked the progress of the project:

- Initial well assessment completion: Confirmed DV-13 as a suitable test site
- Permitting and host agreement finalized: Ensured legal and operational readiness
- Engineering design and procurement: Delivered both custom subsurface and surface systems.
- System installation and commissioning: Completed safely
- Performance testing and data collection: Provided real-world results for analysis
- Model validation: Simulation results were compared with measured field data collected during system operation to confirm alignment with observed thermal performance. While an initial model was developed before preliminary results were available, it was calibrated using actual data to ensure the simulation accurately reflected key system behaviors.

## Modeling and Analysis

To ensure the setup would work as planned, the project team used advanced computer modeling to simulate how heat would move from the reservoir into the system’s working fluid. This modeling was a critical part of designing the system, predicting how it would perform, and comparing those predictions with what actually happened in the field. To understand how well this process would work, the team built a detailed computer model that included the shape and size of the well, the properties of the rocks and fluids, and historical data from well DV-13 (the test site at The Geysers geothermal field).

The model built was designed to simulate four key aspects:

- Thermal behavior: How heat moves from the reservoir into the working fluid inside the DBHX

- Hydrological flow: How fluids in the reservoir move around the DBHX system
- Mechanical stress: How reservoir pressure and rock movement could affect the system
- Chemical reactions: How minerals and fluids interact over time.

Together, these are known as thermal-hydrological-mechanical and chemical (THMC) processes. Modeling all four assisted the team in understanding how the system would behave over time, under real-world conditions.

To run these simulations, the team used a set of powerful software tools called TOUGH codes developed by Lawrence Berkeley National Laboratory. TOUGH stands for transport of unsaturated groundwater and heat. These tools are widely used in geothermal research and allow scientists to simulate complex underground systems with high accuracy.

Different software modules of TOUGH were used for different parts of the modeling:

- TOUGH2 was used to simulate how heat and fluids move through the rocks to the DBHX.<sup>17</sup>
- TOUGH-REACT modeled chemical reactions that occur due to DBHX operations both in the well and near-well regions; this is important for understanding long-term performance and avoiding clogging or scaling.<sup>18</sup>
- TOUGH-FLAC was used to study mechanical stress and how the rocks could respond to temperature changes and fluid movement, both in the well and the reservoir.<sup>19</sup>

These tools allowed the team to test different scenarios, adjust system settings to ensure that the design would be safe, efficient, and reliable.

A big part of the modeling effort involved creating a detailed representation of the well and the surrounding rock layers, shown in Figure 7. This included:

- The pipe-in-pipe layout of the DBHX system.
- The flow paths for water going down and coming back up the DBHX.
- The cemented, open hole, and the steam feed zone(s) sections of the well.
- The thermal properties of the rock, including how well it conducts heat.
- The porosity and permeability of the rock, which affects how fluids move through it. Porosity refers to a measure of tiny pores or spaces within the rock. Permeability describes how easily fluids can flow through those spaces or how well they are connected.

The model was broken down into small sections (a process called meshing) so that the computer could simulate how heat and pressure change over time in each part of the system. The team also modeled the feed zones — key areas in the reservoir where most of the heat is

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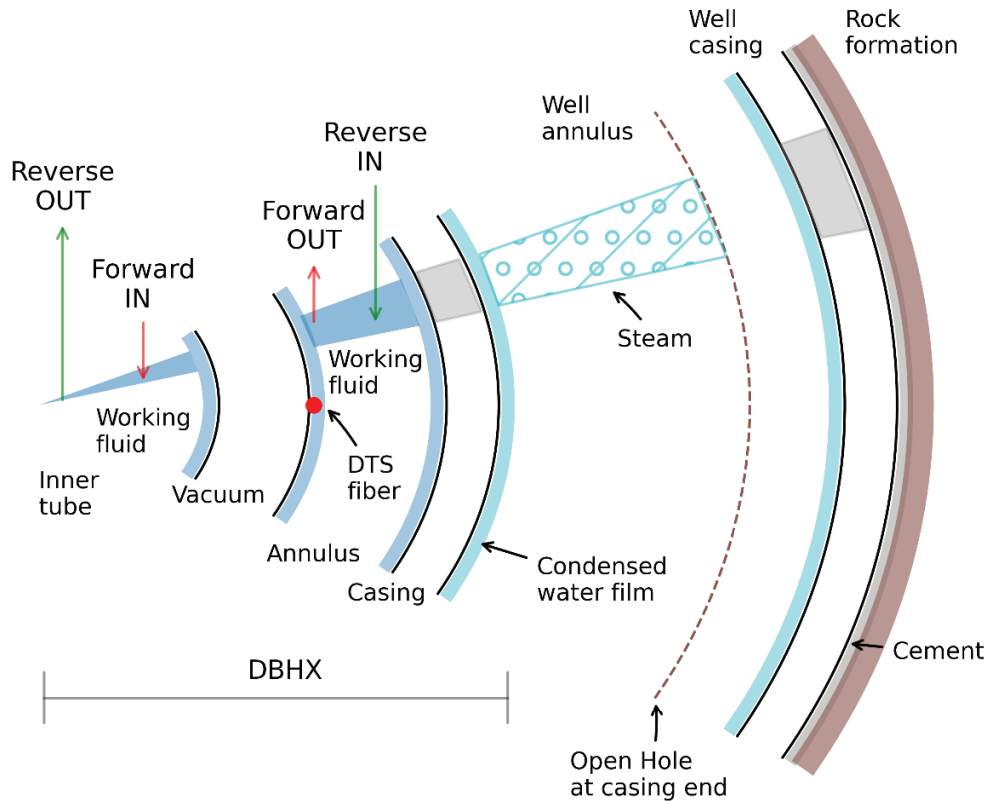
<sup>17</sup> Pruess, Karsten, Christophe Oldenburg, and Günther Moridis. 1999. *TOUGH2 User's Guide, Version 2.0*. Lawrence Berkeley National Laboratory Report.

<sup>18</sup> Xu, Tianfu, Eric Sonnenthal, Nicolas Spycher, and Karsten Pruess. 2004. *TOUGHREACT User's Guide: A Simulation Program for Non-Isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Geologic Media*. Lawrence Berkeley National Laboratory Report.

<sup>19</sup> Rutqvist, Jonny. 2017. "An overview of TOUGH-based geomechanics models." *Computers & Geosciences*, Volume 108.

concentrated. Understanding the location and depth of these zones helped optimize the design and placement of the DBHX.

**Figure 7: Top Close-Up Radial Cross-Sectional View of the DBHX Design, Shown within the DV-13 Well**



**The diagram also shows the two operational configurations of the DBHX: reverse flow (green arrows) and forward flow (red arrows)**

Source: GreenFire, 2025

By using these models, the team could:

- Predict how much heat the system would capture in megawatts of thermal power (MWth), which is a unit used to measure the rate of change in heat output. One megawatt thermal is equal to one-million watts of thermal power.
- Adjust flow rates and temperatures to get the best performance.
- Compare predictions to actual field data to improve future designs.

To ensure that the advanced computer model of the geothermal system matched what actually occurred during the demonstration, the team used a process called history matching. This means comparing the model's predictions — like temperature and pressure readings — with real data collected during the ninety (90) day test at well DV-13. If the numbers didn't match, the team adjusted the model accordingly.

For example, if the model predicted a lower or higher temperature than what was measured, the team would examine things like:

- How easily fluids move near the well (permeability).
- What the surrounding conditions were like (boundary conditions).

Energy balance equations were used to diagnose the source of model discrepancies. These equations allowed the team to track precisely how much heat was entering and leaving the system. When the energy didn't balance, the results pointed directly to the inaccurate parameter in the model — specifically, the flow rate of the water, the heat in the reservoir, or the efficiency of the heat transfer.

By carefully tuning these inputs, the team ensured that the model was not only mathematically accurate but also reflected the real-world behavior of the system.

To validate the thermal behavior of the system and the models, the team used basic energy conservation principles to look at both the heat source and the DBHX. The Darcy equation,<sup>20</sup> which connects the flow of steam from the heat source to the pressure difference, was used to determine how much heat energy was being extracted from the well. The relationship allowed the team to understand how much of the well's energy was available for heat extraction.

Next, a heat balance equation was used to estimate the thermal energy that was extracted by the DBHX. The heat the system extracted from the well's source must equal the heat produced by the DBHX. The team calculated the heat from the heat source from the energy released when the steam condenses. This heat must also match the heat absorbed by the working fluid (water) circulating within the DBHX.

These equations allowed the team to compare measurements from the surface — such as the flow rate and temperature rise — with the thermal energy extracted from the heat source deep inside the well.

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<sup>20</sup> Darcy, Henry. 1856. *Les fontaines publiques de la ville de Dijon*. Paris: Victor Dalmont.

# CHAPTER 3:

## Results

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The team ran a 90-day test of GreenFire’s AGS at well DV-13 to demonstrate how the technology works under real world conditions. The test was broken into three categories, based on duration:

- Short term (2 days)
- Medium term (3 to 7 days)
- Geothermal standard term (30 days)

This step-by-step approach allowed the team to understand how the system responded under different conditions, from quick startup checks to multi-day operations. The goal was to confirm that the system could reliably extract heat, stay mechanically stable, and handle changes in flow, temperature, and pressure. This was an important step in proving that the technology can be used to upgrade existing geothermal wells and reliably pull heat from the reservoir over time, under various conditions.

The results showed that the system is stable, flexible, and capable of operating across a wide range of flow rates and pressures. The consistent performance of the DBHX, supported by techno-economic modeling, suggests that GreenFire’s AGS is well suited for long-term geothermal energy production and scalable deployment.

### Tiered Testing Methodology

This section summarizes key results observed from the short, medium, and geothermal standard term tests. Table 2 and Table 3 summarize the thermal power (MWth) extracted from the system, calculated from the measured parameters of the DBHX. They also include the estimated electric power output (MWe) that could be generated if the system were connected to a surface power conversion unit. The tables also show the volumetric and mass flow rates in GPM and kg/s, respectively, within the DBHX.

The electric power estimates assume coupling of the system to an Organic Rankine Cycle (ORC) system. Organic Rankine Cycle units are commonly used in the geothermal energy industry and in waste energy recovery applications. They operate by using a specialized fluid with a low boiling point to absorb heat from the hot water coming out of the DBHX to drive a turbine, allowing electricity generation even from relatively low-temperature sources.

It’s important to note that The Geysers geothermal field does not currently use ORC systems. Instead, it relies on dry steam technology,<sup>21</sup> which is well-suited to the high-temperature steam naturally flowing out of the wells, conventionally. In dry steam plants, steam flowing from the wells is directly piped to turbines to generate electricity — no intermediate fluid or heat exchanger is required. In contrast, this system is designed to produce sustained heat in the form of hot water from the DBHX, not direct steam. The electric power values shown in

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<sup>21</sup> California Energy Commission. n.d. “[Types of Geothermal Power Plants](https://www.energy.ca.gov/data-reports/energy-almanac/data-renewable-energy-markets-and-resources/types-geothermal-power).” <https://www.energy.ca.gov/data-reports/energy-almanac/data-renewable-energy-markets-and-resources/types-geothermal-power>

the tables are not actual measurements — they are vendor-based estimates, intended to illustrate power generation potential if the system is paired with commercially available ORC technology. While power generation wasn't part of this project's scope, adding an ORC system is not a major hurdle. It is a well-established, off-the-shelf technology that can be integrated relatively easily to convert extracted heat into electricity. The estimated values reflect gross electric power, which represents the total output from the ORC system before accounting for internal parasitic loads (power requirements) such as pumps and cooling requirements. Net electric power, which is the usable output available for external loads or grid export, would be slightly lower than the gross electric power as it accounts for the described parasitic losses.

### Short- and Medium-Term Testing

The short-term tests, typically lasting from a few hours up to two (2) days, focused on verifying startup procedures, confirming baseline functionality, and observing initial heat exchange dynamics. This phase allowed for rapid iteration and system tuning, so the team could optimize flow rates, temperature profiles, and control parameters.

Medium-term tests extended from three (3) to seven (7) days and were aimed at capturing steady-state performance and assessing how the system responded to daily operational cycles. Key averaged results from the short and medium-term testing are given in Table 2. These tests provided insight into control system responsiveness, pressure stability, and any diurnal variability in thermal output — critical factors for predicting long-term reliability and efficiency.

Together, these early tests laid the groundwork for sustained operation, offering a clear picture of how the system behaves across both short bursts and multi-day cycles. They also helped refine the testing protocol for longer-duration tests.

**Table 2: Key Averaged Results from Short- and Medium-Term Testing**

DBHX Operational Mode	Duration (hours)	DBHX Flow Rate (GPM)	DBHX Flow Rate (kg/s)	Thermal Power (MWth)	Considered ORC Thermal to Gross Electric Conversion (%)	Estimated Gross Electric Power (MWe)	Estimated Net Electric Power (MWe)
Reverse	4	126	7.8	2.7	11	0.3	0.25
Forward	24	332	20.5	6.8	10	0.7	0.58
Reverse	77	392	24.2	8.8	12.5	1.1	0.94

Source: GreenFire, 2025

### Geothermal Standard Testing

As part of the 90-day test, the project included a thirty (30) day continuous test (a geothermal standard test) to evaluate how the system performs under extended, real-world conditions. Key averaged results from the geothermal standard term testing are given in Table 3. This

extended duration test followed industry practices<sup>22</sup> used by next-generation geothermal energy projects to assess whether the system can operate reliably over time.<sup>23</sup>

During this phase, the system was run at its optimized settings — meaning the flow rates, temperatures, and controls were all tuned for best performance. The goal was to simulate commercial deployment and evaluate the system’s ability to deliver stable, consistent heat.

This test was especially important because it provided a comparison to full-scale geothermal operations. It confirmed that GreenFire’s AGS is not only functional in short periods but is also resilient and stable over longer periods — an essential requirement for future power generation and commercial deployment.

**Table 3: Key Averaged Results from Geothermal Standard Term Testing**

DBHX Operational Mode	Duration (days)	DBHX Flow Rate (GPM)	DBHX Flow Rate (kg/s)	Thermal Power (MWth)	Considered ORC Thermal to Gross Electric Conversion (%)	Estimated Gross Electric Power (MWe)	Estimated Net Electric Power (MWe)
Reverse	30	330	20.4	7.4	12.5	0.9	0.83

Source: GreenFire, 2025

**Flow Performance and Thermal Output: What the Tests Showed**

During testing, the DBHX demonstrated it could operate across a wide range of flow conditions — from natural, pump-free circulation (thermosiphon mode) to high-powered pumped flow. In thermosiphon mode, the system ran without any pump, relying entirely on natural forces. As water heated up, it became lighter and rose (production fluid within the DBHX), while cooler water sank down (injection fluid within the DBHX) — creating a natural loop called thermosiphon. This setup achieved flow rates of about 120 GPM (7.4 kg/s) in reverse flow and 144 GPM (8.9 kg/s) in forward flow, proving that the system can operate without pumps, at relatively lower flow rates.

In active (pumped) mode, the flow rate was gradually increased from thermosiphon levels up to the pump’s maximum capacity of around 392 GPM (24.2 kg/s). This operating range allowed the team to test how well the system handled different flow rates, how stable it remained, and how it managed gases.

The operational strategy for the DBHX system provides unique flexibility that directly addresses energy demand and grid stability requirements. The system offers exceptional ramping capability because the thermal power extracted is easily controlled by adjusting the surface pump’s flow rate. This allows geothermal operators to quickly scale the system’s output up or down to meet fluctuating grid demands, which is a crucial function for

<sup>22</sup> Xing, Pengju, Kevin England, Joseph Moore, and John McLennan. Analysis of the 2024 Circulation Tests at Utah FORGE and the Response of Fiber Optic Sensing Data. Proceedings, 50<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California

<sup>23</sup> Fervo Energy. 2023. "[Fervo Energy Announces Technology Breakthrough in Next-Generation Geothermal.](https://fervoenergy.com/fervo-energy-announces-technology-breakthrough-in-next-generation-geothermal/)" <https://fervoenergy.com/fervo-energy-announces-technology-breakthrough-in-next-generation-geothermal/>

complementing intermittent sources like solar and wind. In thermosiphon mode the system runs without active mechanical power. However, the thermal output of the system is significantly lower than when the system is run in active mode, where the highest operating flow rate within the DBHX is enabled. This maximized flow extracts the highest possible thermal power from the reservoir, translating directly to the highest electrical generating capacity at the surface plant. This controlled flexibility allowed the team to prioritize either lower operating costs or maximum electrical output, with fast ramping based on real-time grid conditions.

### **Steam and Gas Behavior: Forward versus Reverse Flow**

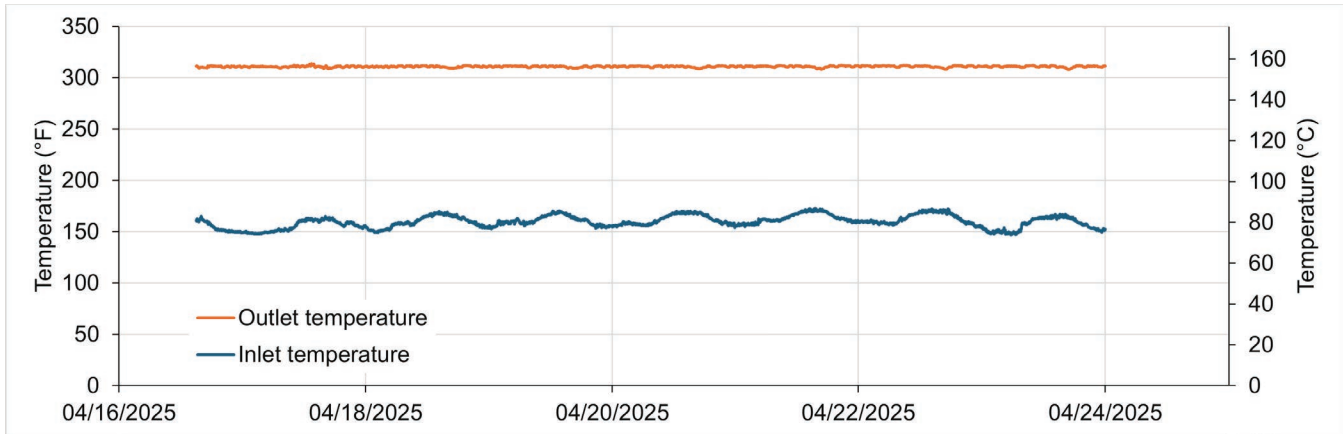
The way steam and NCGs behaved depended on the flow direction:

- In forward flow operational mode, steam from the reservoir moved into the space between the DBHX and the wall of the well. Some of that steam condensed around the DBHX, transferring heat into the system. At the same time, a portion of the steam and NCGs continued rising up through the same space. This meant the system could collect heat while also releasing steam and gases, a process called co-production.
- In reverse flow operational mode, the steam condensed around the DBHX, helping the system absorb heat. Meanwhile, only the NCGs kept rising up through the space between the DBHX and the well wall. This setup allowed the system to capture heat more efficiently without sending steam to the surface — just a small amount of NCGs was released intermittently for a very short duration (on the order of a couple of minutes), post chemical treatment (chemical abatement).

### **Choosing the Right Flow Rate for the Geothermal Standard Test**

For the 30-day test, the team chose a flow rate of about 330 GPM (20.4 kg/s). While higher rates were technically possible, running the pump near its limit for long periods could cause instability due to how the fluid interacted with the DBHX's internal design. So, 330 GPM was selected as a safe and realistic benchmark for future long-term, stable operations (typically decades long, 20-30 years of operations). Figure 8 shows a 10-day snapshot of the DBHX inlet and outlet temperatures during the 30-day test. The inlet temperature (blue line) fluctuated due to changes in outdoor conditions — daytime heat raised the inlet temperature, while cooler nighttime air brought it down. In contrast, the outlet temperature (orange line) remained stable at around 310°F (154°C). Figure 9 presents a snapshot from the fiber optic DTS data collected along the length of the system, mounted externally on the VIT. The black horizontal lines mark the depths corresponding to the end of the well casing and the three identified steam entry zones (feed zones). These data were recorded during the 30-day test period and illustrates how the system absorbs heat from the open hole section of the well, particularly where it is exposed to steam inflow below the casing.

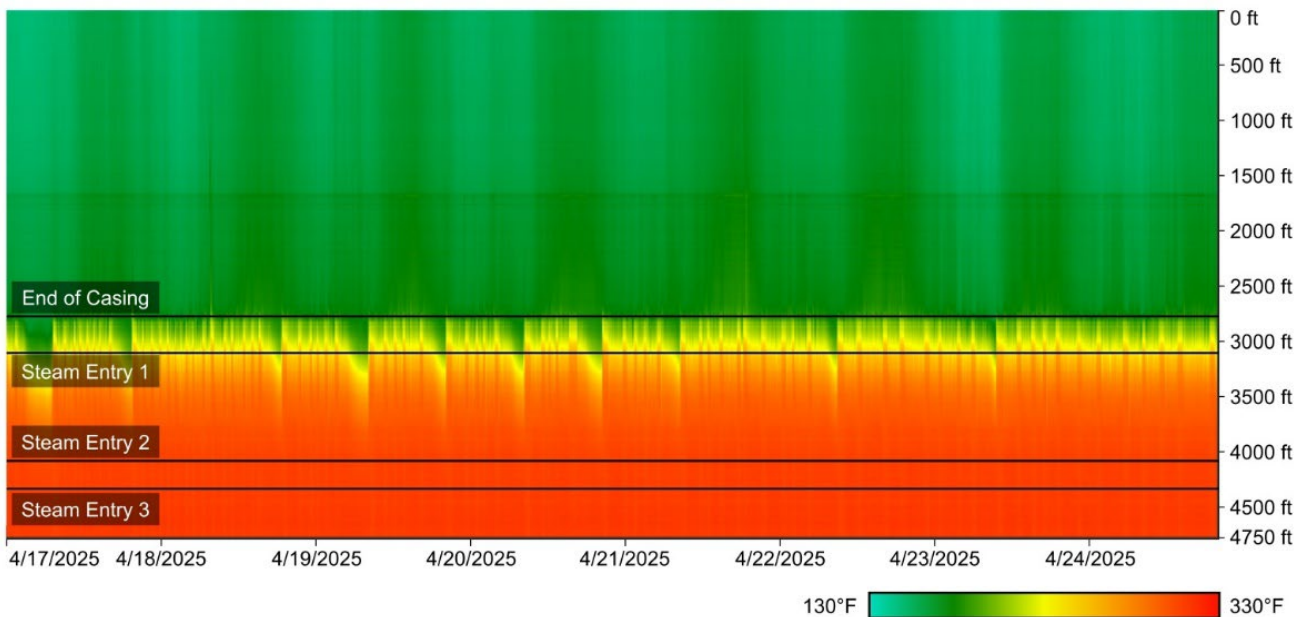
**Figure 8: Snapshot of the Approximately 10 days of DBHX Operations during the 30-Day Geothermal Standard Test with a Flow Rate of 330 GPM (20.4 kg/s)**



**The plot shows inlet temperatures (blue line) and outlet temperatures (orange line) in °F (left) and °C (right)**

Source: GreenFire, 2025

**Figure 9: Snapshot of the Fiber Optic DTS Data during the 30-Day Geothermal Standard Test with a Flow Rate of 330 GPM (20.4 kg/s)**



Source: GreenFire, 2025

**Reverse Flow Delivers Better Heat Performance**

Across all tests, the reverse flow operational mode consistently delivered better thermal results, with return fluid temperatures about 10°F (5.56°C) higher than in forward flow (the optimal conditions for operations are summarized in Table 3). This means that the system picked up more heat in the reverse flow operational mode, thanks to more efficient heat exchange. These findings match what other studies have shown about closed-loop geothermal

systems (albeit in different geothermal settings and operating conditions)<sup>24</sup>— reverse flow mode tends to perform better than forward flow when it comes to heat recovery.<sup>25</sup>

### **Stable Performance Across Flow Rates**

One of the most impressive results was how stable the production temperatures remained, regardless of flow rate, as observed through the temperature profiles plotted in Figure 10. In other geothermal setups and operating conditions — especially those in low-permeability rock — performance can vary significantly depending on how fast the fluid moves.<sup>26</sup> But in this case, the outlet temperature remained nearly constant, with only 1°F to 2°F (0.56°C to 1.11°C) of variation between low- and high-flow rates. The system also reached steady-state conditions quickly — within about 20 minutes — showing strong thermal connection with the reservoir. Figure 10 also shows the temperature profile of the well during conventional surface flow, along with DTS recorded temperatures within the DBHX, captured prior to the start of the 90-day flow test.

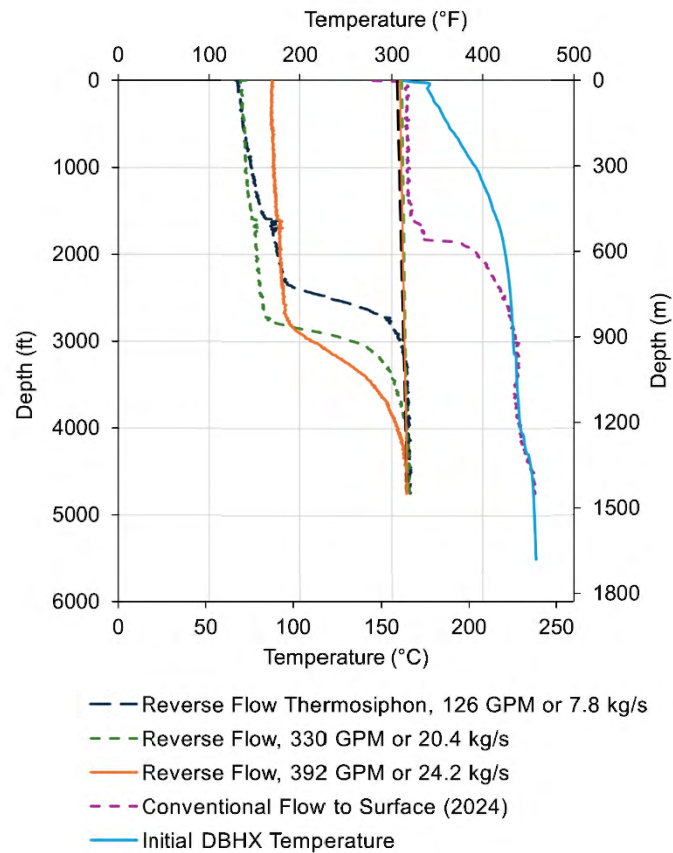
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<sup>24</sup> Holmberg, Henrik, José Acuña, Erling Næss, and Otto K. Sønju. 2016. "Thermal evaluation of coaxial deep borehole heat exchangers." *Renewable Energy*, Volume 97.

<sup>25</sup> Beckers, Koenraad, Nicolás Rangel-Jurado, Harish Chandrasekar, Adam J. Hawkins, Patrick M. Fulton, Jefferson W. Tester. 2022. "Techno-economic performance of closed-loop geothermal systems for heat production and electricity generation." *Geothermics*, Volume 100.

<sup>26</sup> White, Max, Yaroslav Yasylyv, Karl Beckers, Miguel Martinez, Pietro Balestra, Claudio Parisi, Clare Augustine et al. 2024. "Numerical Investigation of Closed-Loop Geothermal Systems in Deep Geothermal Reservoirs." *Geothermics*, Volume 116.

**Figure 10: Temperature as a Function of Depth during Different Operating Modes with the DBHX and Well DV-13**



Source: GreenFire, 2025

## History Matching Test Results with Computer Models

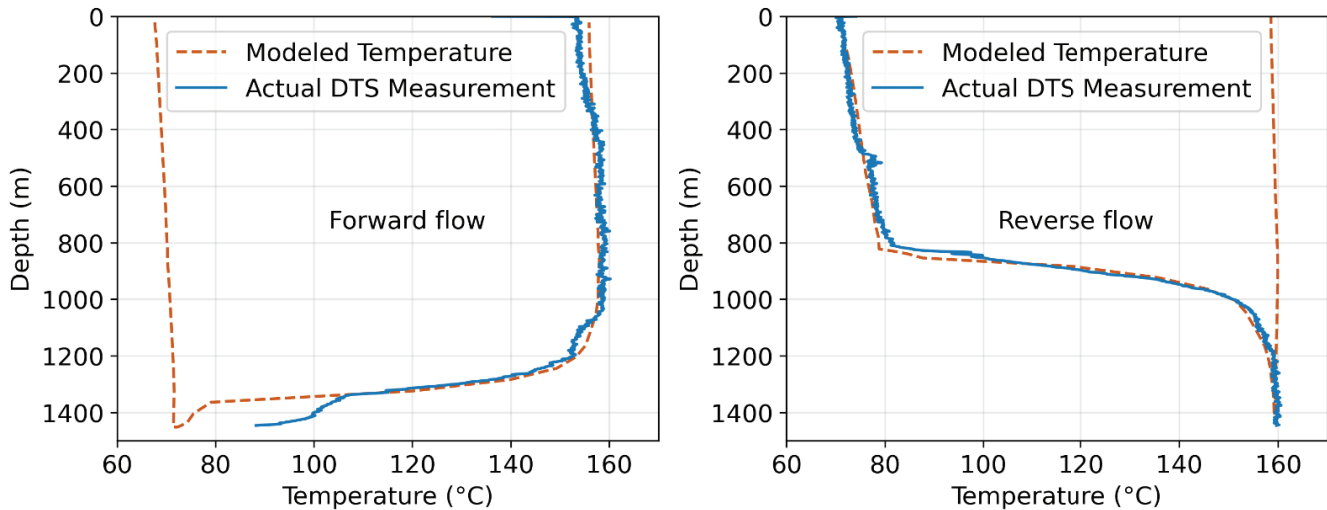
During the 90-day testing period, the team fine-tuned an advanced computer model to simulate how fluids moved through the system. One key comparison was made using data from the 30-day geothermal standard test at a flow rate of 330 GPM (20.4 kg/s), running in reverse flow operational mode.

Figure 11 shows how closely the computer model (orange) aligned with actual temperature readings from the DTS system (blue), for both forward flow (left) and reverse flow (right) configurations (operated at 330 GPM (20.4 kg/s) in the DBHX). Since the DTS system was installed outside the VIT, it recorded temperatures in the surrounding annulus – neither the hot fluid rising inside the tubing during reverse flow, nor the cold fluid descending during forward flow.

To obtain direct temperature measurements of the fluid entering and exiting the DBHX at the surface, the team used thermocouples. These small sensors measure temperature by detecting electrical signals created when two different metals are joined and exposed to heat. They are widely used in industrial settings because of their reliability and their ability to operate in harsh environments, which makes them well-suited for both geothermal systems and this demonstration.

Using these surface readings, the team matched the model’s predictions with actual production temperatures. The temperature drop across the VIT was small — with a temperature difference of only around 9°F (5°C) over the 1450 m length of the DBHX under various operating conditions, showing that the insulation both worked well and helped preserve heat as the fluid traveled upward.

**Figure 11: DBHX Temperature Profile as a Function of Depth (Modeled Temperature in Orange versus Actual DTS Measured Temperature in Blue) with 330 GPM (20.4 kg/s) under Forward Flow (Left), and Reverse Flow (Right) Configurations**



Source: GreenFire, 2025

## Chemical Modeling

Computer models were used to study how the chemistry of the reservoir fluids changed near the DBHX during operations. Similar to earlier published work,<sup>27</sup> the modeling showed that condensed water around the DBHX caused small, localized changes in fluid chemistry. Importantly, no signs of scaling (mineral buildup) or precipitation were detected through the computer model.

As the steam condenses around the DBHX, it absorbs acidic gases, creating a low-pH fluid that drains to the well bottom. This helps prevent scaling and accelerated rock breakdown. It was found that the chemical shifts that occurred mirrored the natural steam-condensate interactions already occurring in the reservoir, especially with injected condensate and wastewater. More details on the chemical modeling can be found in APPENDIX B of the report.

<sup>27</sup> Chandrasekar, Harish, Eric Sonnenthal, Alvaro Amaya, Jonny Rutqvist, Curtis Oldenburg, Glenn Golla, Fred Manuel, et al. 2023. "Coupled Thermal Hydraulic Mechanical and Chemical (THMC) Modeling of the GreenLoop System in the Southeast Geysers, California." *Geothermal Resources Council Transactions*, Volume 47.

## Mechanical Modeling

Stress simulations were run through computer models to see how the well materials and surrounding rock responded to heating and cooling cycles. These tests examined how the stress in the rocks changed over time.

The results showed that:

- Stress levels stayed within safe limits during startup, operation, and cool down.
- No damage or fatigue was observed in the well materials.
- Minimal uplift or sideways stress occurred in the surrounding rock due to the system's closed-loop design.

More details on mechanical modeling can be found in Appendix B of the report.

## Technical Challenges

The team encountered technical challenges, both anticipated and unexpected, which required adaptive strategies and on-the-ground problem solving. These issues included well integrity, weather impacts, instrumentation reliability, and surface system performance. The following summary outlines key challenges and practical solutions implemented to maintain testing continuity and data integrity:

- Installing equipment in an aging well: The Well DV-13 was over 40 years old, so extra precautions were taken to ensure safe installation. A new casing head and master valve were added to support the new setup. Backup casing materials (both smaller and tapered designs) were kept on site in case adjustments were required. After several checks confirmed the well's internal dimensions, the original design was installed successfully without requiring any down hole repairs.
- Weather-related and testing adjustments:
  - Heavy rain caused construction challenges.
  - Temperature variations between hot days and cool nights were managed proactively. Due to the limited cooling capacity available during the test, flow experiments were scheduled during cooler periods, using weather forecasts to optimize performance with only two surface coolers. In a full-scale deployment, the cooling system would be engineered to match the anticipated flow rates and account for seasonal and diurnal temperature variations expected at the site.
- Scale buildup in venting and injection systems during forward flow configuration: Mineral scale occasionally clogged injection ports, control valves, and sensors, especially during reverse flow and dry gas venting. The scale was water-soluble, so the team used soak-and-flush routines during non-venting periods to clean the system. This approach became part of regular maintenance to prevent future blockages. The scale buildup and blockages were totally avoidable with larger pipes and different injection ports at the surface.

- Improving flow measurement accuracy during co-production: Acoustic flow meters were initially deployed to measure the flow of the co-produced stream (steam and NCGs) during the forward flow configuration. These meters gave inconsistent readings at low flow rates. To resolve this, an orifice plate with pressure sensors was installed by modifying the existing piping. Once in place, the system provided reliable flow measurements.
- Power supply reliability and redundancy: Initially, one diesel generator powered all surface equipment. After a few unexpected shutdowns, a second generator was added. Equipment was split between the two generators to ensure that critical systems like coolers and pumps could continue running even if one generator failed.

## **Market and Policy Challenges**

In this initial one well retrofit project involving the installation of GreenFire’s AGS in well DV-13, there were no major market and policy challenges. Permitting was smooth and handled efficiently by the relevant agencies. Market-related issues were minor, mostly involving routine scheduling and pricing for specialized contractors.

However, scaling this technology for larger installations is expected to bring more serious market and policy hurdles. The most critical challenge in California is the new interconnection and deliverability process, which are the steps required to connect a new energy project to the grid and ensure it can reliably deliver power.

This process is managed by the California Independent System Operator (California ISO), the nonprofit entity responsible for operating most of California’s high-voltage electricity grid and coordinating how power projects connect and deliver electricity. Within the California ISO’s system, securing an interconnection agreement and full capacity deliverability status can take several years due to:

- High application volumes: A growing backlog of interconnection requests has overwhelmed queue management.
- Limited processing capacity: Staffing and infrastructure constraints at the California ISO and utility transmission providers slow down the review of technical system impact studies, interconnection study requests, and grid reliability assessments.
- Complex upgrade requirements: Many proposed grid connection points require detailed system impact studies and potential infrastructure upgrades.

These delays directly affect developers’ ability to secure financing. Without certainty around grid access and deliverability, projects struggle to prove they are “bankable,” which in turn delays procurement, construction, and commercial operation.

While permitting for the pilot was efficient, future large-scale deployments may face longer review times. Because GreenFire’s technology is relatively new, especially in terms of its subsurface and surface impact, regulators may require more time to understand and evaluate it. This could lead to longer approval timelines compared with conventional geothermal or other renewable energy projects.

## **Techno-Economic Insights and Expansion Pathways for GreenFire’s AGS at The Geysers and California’s Idle Well Portfolio**

Following testing and modeling activities, GreenFire conducted an analysis of a portion of The Geysers geothermal field to assess how existing geothermal wells (especially older, low-producing, or idle wells), could be repurposed to boost California’s supply of reliable, renewable energy using GreenFire’s AGS technology. The company examined how much power this technology could produce on a larger scale, how sustainable production practices could be applied, and what strategies could work for bringing unused wells back online across the state.

To accomplish this, the evaluation combined public data from the California Geologic Energy Management (CalGEM), California’s geothermal regulatory agency, with GreenFire’s quick evaluation tool for geothermal wells<sup>28</sup> to estimate potential capacity, identify cost-effective options, and highlight both short-term and long-term benefits. The findings are organized into four key sections:

- Power Density Analysis at specific locations at The Geysers geothermal field, using GreenFire’s AGS (analysis of MWe per unit area in kilometers squared, represented as MWe/km<sup>2</sup>)
- Economic modeling of GreenFire’s AGS at The Geysers
- GreenFire’s AGS technology potential in California’s idle geothermal wells
- Implementation approach for scaling statewide

### **Power Density Analysis at Specific Locations at The Geysers Geothermal Field, Using GreenFire’s AGS**

For the power density analysis, GreenFire selected 60 geothermal wells (combination of idle and producing wells) spread across a portion of the north, central, and southern regions of The Geysers geothermal field. Using insights from GreenFire’s DV-13 AGS project, combined with well data sourced from CalGEM’s publicly available database, the team calculated that the wells’ combined projected output using GreenFire’s AGS would be approximately 112 MWe and 100 MWe in gross and net electricity generation, respectively. On average, each of the wells in these zones can produce gross electric power between 2 and 2.5 MWe using GreenFire’s AGS technology when coupled to ORC units at the surface. The wells were grouped by well pads, clusters of wells that share surface infrastructure and reservoir conditions. This pad-level approach allowed GreenFire to identify patterns in performance and highlight opportunities to repurpose idle and lower-producing wells more efficiently using centralized ORC power plants. A summary of the findings is listed below:

- Portion of the North Region: 18 wells analyzed across 7 well pads generating a total net power of 32 MWe over 9.5 km<sup>2</sup>, leading to a power density of 3.37 MWe/km<sup>2</sup>

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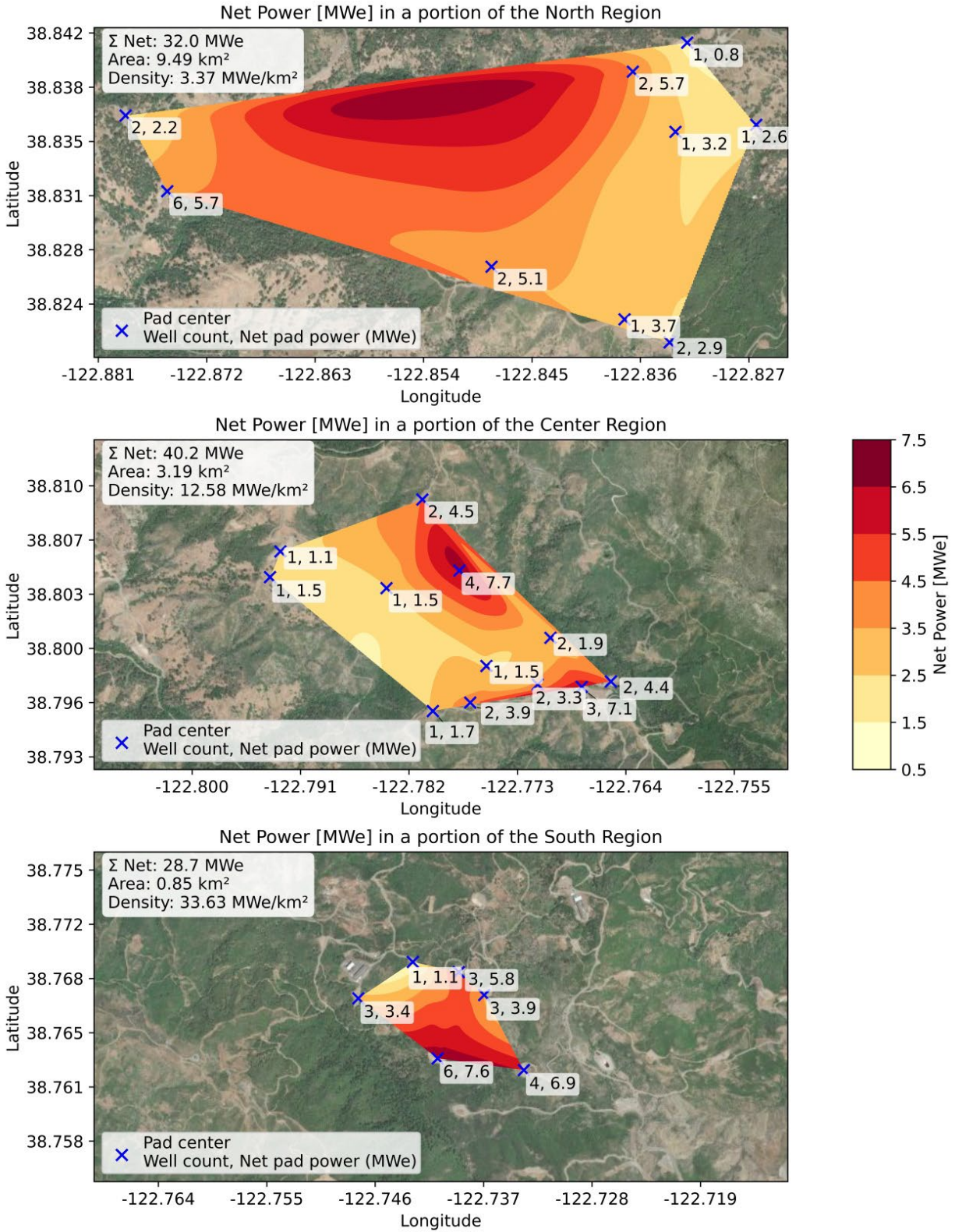
<sup>28</sup> Amaya, Alvaro, Harish Chandrasekar, Saul Molina, Steven Brown, and Joseph Scherer. 2024. *Heat Extraction Processes Using Unconventional Geothermal Technologies (GreenLoop) Applied in Different Reservoir Types*. Proceedings, 49<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

- Portion of the Central Region: 22 wells analyzed across 5 well pads generating a total net power of 40.2 MWe over 3.2 km<sup>2</sup>, leading to a power density of 12.58 MWe/km<sup>2</sup>
- Portion of the Southern Region: 20 wells analyzed across 3 well pads generating a total net power of 28.7 MWe over 0.9 km<sup>2</sup>, leading to a power density of 33.63 MWe/km<sup>2</sup>

Figure 12 provides graphical representation of net power distribution across the analyzed regions. Each cross mark in the figure indicates the center of a well pad included in the analysis. Below each cross mark, two numbers are annotated: the first denotes the number of wells within the pad, the second indicates the estimated net power potential, in MWe, which can be generated from the entire pad, using GreenFire's AGS technology coupled to ORC units at the surface. For example, the annotation "2,5.7" refers to a pad with 2 wells and a total estimated net power potential of 5.7 MWe.

By managing reinjection, controlling reservoir pressure, and optimizing operations across these clusters, the life of the reservoir can be extended. It is important to note that this analysis does not account for potential transmission constraints or grid integration challenges that may arise when delivering additional power. The purpose of this assessment is solely to illustrate the potential of GreenFire's AGS technology to generate approximately 100 MWe of net power.

**Figure 12: Net Power Distribution (MWe) Using GreenFire’s AGS Technology across 60 Wells, Spread across a Portion of the Northern, Central, and Southern Regions of The Geysers Geothermal Field**



Source: GreenFire, 2025

## Economic Modeling of GreenFire's AGS at The Geysers

The GreenFire team used the same conceptual 112 MWe gross AGS system just described for its economic model, using financial models and extrapolated performance data from the DV-13 demonstration. Preliminary modeling suggests the system could generate up to 866,000 megawatt-hours (MWh) annually under steady-state operations, which is equivalent to approximately 100 MWe of additional net capacity. If fully implemented, the system is projected to achieve a levelized cost of electricity (LCOE) of between \$90 and \$95 per MWh over a 20-year horizon. These preliminary LCOE estimates are based on early-stage assumptions and should be considered indicative of the potential economic viability of scaling GreenFire's AGS technology at The Geysers under favorable development conditions, with modeled costs broadly within the range of competitive renewable energy sources. Further technical, geologic, and commercial validation will be required to confirm both feasibility and scalability.

Key findings and considerations are listed below:

- The projection considers deployment of GreenFire's AGS technology across 60 existing wells across the northern, central, and southern regions of The Geysers field, over a 20-year period.
- Each well is expected to yield an average of 1.85 MWe, based on total system capacity.
- The modular nature of AGS retrofits enables phased deployment over 4 to 5 years, with streamlined permitting and infrastructure integration.

To evaluate the cost of producing electricity, GreenFire applied the LCOE metric. In simple terms, LCOE represents the average cost to produce one megawatt-hour of electricity over the project's lifetime, encompassing construction, maintenance, and operation. It provides a standardized basis for comparing energy technologies. For this system, the estimated LCOE of \$90-\$95 per MWh is competitive with other comparable renewable and baseload energy sources.<sup>29</sup>

These financial projections are preliminary as they are based on extrapolated data from the implementation of the AGS in well DV-13. Prior to commercial deployment in existing wells, further studies are required to confirm feasibility, including:

- Subsurface geology.
- Fluid chemistry and heat transfer behavior.
- Surface layout and infrastructure constraints including transmission, interconnection, and gathering system.

Economic outcomes may also vary depending upon financial models, ownership structures, power purchase agreements, and market strategies. GreenFire's AGS makes economic sense due to the following three key aspects:

- Lower operating costs: The system reduces fluid reinjection, cutting expenses.
- Greater cost competitiveness: Higher reliable output and lower costs make geothermal more scalable.

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<sup>29</sup> Lazard. 2025. [Lazard Levelized Cost of Energy+](https://www.lazard.com/media/uoynhon4/lazards-lcoepplus-june-2025.pdf). Lazard Webpage. <https://www.lazard.com/media/uoynhon4/lazards-lcoepplus-june-2025.pdf>

- Sustainable design: The systems are efficient and environmentally friendly, supporting long-term clean energy goals.

### **GreenFire’s AGS Technology Potential in California’s Idle Geothermal Wells**

By applying GreenFire’s patented AGS technology approaches to approximately 206 idle geothermal wells listed in the CalGEM database across California,<sup>30</sup> there is strong potential to bring the state’s non-producing geothermal assets back online. Preliminary analysis by idle well category, using different hybrid method approaches illustrated through the company’s wide patent portfolio (10 patent families, comprising 27 patents granted, 13 utility patents in process, and 5 provisional patents), suggests a total gross electric power estimate of about 242 MWe, assuming the systems are coupled to ORC units at the surface (Table 4). These early estimates show that each idle well could generate an average of around 1.3 MWe of gross electric power. That means renewable energy output can be increased using existing infrastructure, making it both affordable and scalable. This strategy supports two major goals: strengthening California’s energy supply and helping meet its clean energy and climate mandates.

**Table 4: Summary of Estimated Power Potential Using GreenFire’s AGS in California’s Idle Wells**

<b>Idle Well Categories</b>	<b>Number of Wells</b>	<b>Estimated Power Potential on a per-well basis</b>	<b>Estimated Electric Power (MWe)</b>
Low Temperature Wells	40	1	40
Steam Wells	27	3	81
Reinjection Wells	17	2.5	42.5
Exploration Low Temperature Wells	2	0.8	1.6
Exploration High Temperature Wells	2	2	4
Non-commercial Low Temperature Wells	56	0.5	28
Observation Wells	37	0.8	29.6
Thermal Gradient Wells	17	0.5	8.5
Water Wells	8	0.8	6.4
<b>Total</b>	<b>206</b>	<b>1.3</b>	<b>242</b>

Source: GreenFire, 2025

### **Implementation Approach for Scaling Statewide**

GreenFire’s AGS can co-exist and operate in a hybrid setup with conventional geothermal systems, making better use of existing wells and infrastructure. The system can be installed in parallel with existing systems, sharing surface infrastructure like pads, pipelines, and cooling

<sup>30</sup> ThinkGeoEnergy. 2023. [“About 1748 Geothermal Wells in the United States, Majority in California.”](https://www.thinkgeoenergy.com/about-1748-geothermal-wells-in-the-united-states-majority-in-california/) ThinkGeoEnergy Webpage. <https://www.thinkgeoenergy.com/about-1748-geothermal-wells-in-the-united-states-majority-in-california/>

systems. In addition, geothermal operators and developers can tune flow rates within the AGS to match grid demand or supplement conventional geothermal output during peak periods. This hybrid approach of operating geothermal fields assists in:

- Extending the life of the geothermal field.
- Lowering environmental impacts.
- Increasing overall energy output and flexibility.

In short, GreenFire's AGS adds a new layer of adaptability to geothermal operations: working with, not against, conventional geothermal systems.

# CHAPTER 4:

## Conclusion

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### **Benefits to California and California Ratepayers**

The successful execution of GreenFire’s AGS demonstration project at The Geysers represents a significant milestone in geothermal innovation, with broad implications for clean energy production, grid resilience, and decarbonization in California. GreenFire asserts this project validated the viability of the technology by proving the potential to double electric power production in an existing, marginally producing well at The Geysers geothermal field in Northern California. Over the course of a 90-day operational test, the system demonstrated stable, predictable thermal energy extraction without requiring substantial fluid production from the reservoir. During the test, mass flow rates of up to 392 GPM (24.2 kg/s) were achieved, delivering thermal outputs approaching 9 MWth. When paired with a standard ORC unit, this thermal energy could yield approximately 1.1 MWe of gross electric power. The economic modeling conducted as part of this project estimates an LCOE of between \$90 and \$95 per MWh, which is on par with other renewable generation and particularly other firm, dispatchable generation.

Based on these results, GreenFire’s AGS technology demonstrates strong potential to unlock hundreds of megawatts of geothermal power across California simply by retrofitting existing geothermal wells. Before commercial deployment, further studies are recommended to validate key technical and operational factors. These include a detailed assessment of subsurface geology, an evaluation of fluid chemistry and heat transfer behavior, and a review of surface layout and infrastructure constraints. With these considerations addressed, scaling the technology to reach 100 MWe is not only feasible; it could be realized within the next 4 to 5 years, unlocking substantial clean energy from California’s under-utilized geothermal resources.

Preliminary estimates suggest that, if GreenFire’s AGS technology were implemented in all 206 currently idle wells in California, the resulting output could account for up to approximately 15 percent of California’s total geothermal electricity generation. This projection assumes the retrofitting of existing idle or underperforming wells and does not include additional contributions that could be realized through deployment in newly drilled wells. Future site-specific assessments would be required to validate the technical and economic feasibility of such an expansion.

### **Project Relevance to California’s Clean Energy and Climate Goals**

The findings of this project directly support California’s ambitious energy and climate mandates, including carbon neutrality by 2045 and a 100-percent clean electricity grid. AGS offers a highly reliable and dispatchable renewable energy source that complements intermittent sources like solar and wind.

GreenFire's AGS technology offers distinct environmental advantages. It generates heat with minimal surface disturbance, avoids direct contact with reservoir fluids, and reduces the requirement for separate reinjection. While conventional geothermal operations have developed effective mitigation strategies for issues such as water usage, brine disposal, and surface impacts, AGS further reduces these concerns by design. AGS can be paired with ORC units at the surface for power generation, depending on site-specific requirements, highlighting the flexibility and environmental benefits of the approach, aligning with California's strong environmental stewardship values.

## **Implications for Commercial Markets, Utilities, and Policymakers**

The outcomes of the project indicate strong commercial potential for AGS technology in California and beyond. For utilities and independent system operators, the availability of firm, clean baseload power from geothermal sources reduces reliance on fossil fuel peaker plants and improves grid reliability. Unlike solar or wind, the AGS can also be adjusted to match demand, serving as an anchor for integrated energy portfolios and assisting in balancing the intermittency of other renewables.

For policymakers, the successful operation of GreenFire's AGS at The Geysers creates a new path for geothermal resource utilization that may require regulatory adaptation. This calls for thoughtful regulatory innovation to accommodate the growth of this technology in a way that maintains environmental oversight while enabling rapid deployment.

## **Lessons Learned and Opportunities for Future Development**

This project provided several important technical and operational insights. A key takeaway was the critical role of wellbore design and thermal insulation in minimizing heat loss and optimizing energy transfer. The DBHX demonstrated stable performance throughout the demonstration, confirming its suitability for long-term operation, particularly in steam-dominated geothermal reservoirs.

The deployment of high-precision temperature and pressure sensors allowed real-time tracking of system behavior and informed modeling and operational adjustments. The use of advanced history-matching methods and simulation enabled accurate reproduction of field conditions, providing a validated digital twin that can now be used to scale the system.

Future deployments would benefit from several enhancements. These include installing DTS fiber along the outer DBHX casing to monitor external thermal behavior and condensation effects, using duplicative flow sensors to distinguish steam from dry gas, and applying probe-style or flush-mounted meters to reduce plugging during reverse flow operations. The project also identified that NCG vent lines should be at least 4 inches in diameter to mitigate flow restrictions observed in field testing.

Strong collaboration with Lawrence Berkeley National Laboratory and other technical advisors proved instrumental in overcoming field-level challenges and refining the test configuration. These multidisciplinary partnerships underscore the importance of integrated scientific and engineering support in the development and commercialization of AGS.

## Market Opportunities and Commercial Scaling

The project results highlight multiple market pathways for AGS deployment in California and elsewhere:

- **Well repurposing:** Retrofitting idle, non-commercial, or low-producing geothermal wells with the AGS technology presents an immediate pathway to expand geothermal capacity. Based on preliminary analysis, this approach could unlock over 200 MWe of potential capacity in a relatively short timeframe, reducing both costs and permitting hurdles.
- **New purpose drilled wells:** New wells can be drilled with desirable characteristics (such as long lengths and large diameters) to dramatically improve the performance of AGS, providing high MWe on a per-well basis. This high-efficiency configuration is especially valuable for behind-the-meter applications where reliable, on-site energy is critical. For example, AGS-powered wells can support artificial intelligence (AI) data centers, military bases, and industrial campuses by delivering clean, dispatchable electricity directly at the point of use, reducing grid dependence, enhancing energy security, and enabling rapid deployment. With optimized well designs, AGS can provide scalable solutions that meet the growing energy demands of these strategic sectors.
- **Grid firming:** AGS is well-positioned to serve as a firming resource for renewable-heavy grids, offering utilities a flexible and low-carbon alternative to gas-fired generation.
- **Industrial heating:** The high thermal output of AGS (hot water output from the system) opens opportunities for decarbonizing industrial processes that rely on heat such as food processing, materials production, and water treatment.
- **Environmental and siting advantages:** The inherent minimal environmental impact of the AGS makes it highly suitable for distributed deployment including potential placement in urban and densely populated areas where conventional geothermal faces permitting and siting constraints. The AGS closed-loop design reduces its environmental footprint by reducing the requirement for large-scale reinjection wells and the associated piping that add cost and complexity to conventional systems. Although AGS may utilize existing wells, its closed-loop design minimizes interaction with the reservoir fluids, thereby facilitating deployment flexibility.

Together, these markets represent a multi-billion-dollar opportunity to scale geothermal energy in California and support a broader shift toward clean, resilient energy systems.

## Recommendations and Next Steps

To maximize the impact of this successful demonstration, the team recommends the following actions to accelerate AGS adoption and geothermal innovation:

### 1. Update Regulatory Frameworks

- Create a distinct regulatory classification for AGS to streamline permitting and ensure alignment.

- Clarify royalties, land use rights, and environmental compliance requirements for AGS projects.

## **2. Support Continued Research and Development**

- Fund additional full field demonstrations (including power generation units) in different geological settings, including sedimentary basins and other regions.
- Investigate hybrid configurations combining AGS with energy storage or other renewables.

## **3. Incentivize Repurposing of Idle Wells**

- Establish incentive programs for retrofitting abandoned oil, gas, or geothermal wells with AGS technology to accelerate near-term deployment.
- Provide cost-share grants or tax credits to reduce capital barriers for early adopters.

## **4. Expand Workforce Training and Education**

- Develop curriculum and certifications focused on AGS design, installation, and operation in collaboration with academic institutions and trade organizations.
- Prepare a skilled workforce to meet growing industry demands.

## **5. Integrate into State Energy Planning**

- Include AGS technology in the California Energy Commission's geothermal roadmap and long-term energy scenarios.
- Prioritize AGS in clean energy procurement and resource adequacy strategies.

## **Closing Perspective**

This project marks a turning point in geothermal innovation, demonstrating that heat can be sustainably accessed and transported without disturbing underground reservoirs. By proving the feasibility and success of GreenFire's AGS at The Geysers, the team has opened the door to a more scalable, sustainable, and flexible future for geothermal energy in California. The insights gained and partnerships forged through this effort provide a strong foundation for continued advancement and broader commercialization of AGS technologies.

With thoughtful policy support, continued technical innovation, and strategic investment, California can lead the nation and the world in deploying next-generation geothermal systems to help meet climate goals, enhance grid reliability, and ensure long-term energy security.

# List of Terms/Glossary

Term	Definition
AGS	Advanced geothermal system (The SDGL is one form of AGS developed by GreenFire, also referred to as GreenFire’s AGS.)
AI	Artificial intelligence
bar	Unit of measure for pressure
California ISO	California Independent System Operator
CalGEM	California Geologic Energy Management
CEC	California Energy Commission
Chemical treatment	(or chemical abatement); process of eliminating or reducing harmful chemical pollutants from an environment to protect human health and ecosystems
°C	Degrees Celsius
°F	Degrees Fahrenheit
DBHX	Downbore heat exchanger
DTS	Distributed temperature sensing (term for a special fiber optic cable)
EOS	Equation of state
EPIC	Electric Program Investment Charge
ERDD	Energy Research and Development Division
EWASG	Equation-of-State for Water, Salt and Gas
FLAC	Fast Lagrangian Analysis of Continua
ft.	Feet
GPM	Gallons per minute
GreenFire	GreenFire Energy, Inc.
in.	Inches
ISOs	Independent system operators
kg/s	Kilograms per second
kilopounds-mass per hour	A kilopound-mass per hour represents a mass flow rate, meaning how many thousands of pounds (kilo-pounds) of a substance pass a point each hour; it is essentially a large unit for measuring the flow of liquids or gases. Conversion values for reference: 1 kilopound-mass = 453.592 kilograms 1 kilopound-mass per hour = 0.125998 kilograms/second Source: GreenFire, 2025
klbm	Kilopound-mass

<b>Term</b>	<b>Definition</b>
klbm/h	Kilopound-mass per hour
km	Kilometers
LCOE	Levelized cost of electricity
m	Meters
MW	Megawatt
MWe	Megawatts of electricity
MWe/km <sup>2</sup>	Megawatts of electricity per square kilometer
MWh	Megawatt hour
MWth	Megawatts of thermal power
NCEDC	Northern California Earthquake Data Center
NCG	Non-condensable gas
ORC	Organic Rankine Cycle
%	Percent
PG&E	Pacific Gas and Electric Company
pH	<i>Power of hydrogen ions</i> , pH is a figure expressing the acidity or alkalinity of a solution on a logarithmic scale on which 7 is neutral, lower values are more acid, and higher values are more alkaline.
REACT	Reactive chemistry is a term for a specific software tool used to analyze reactive chemistry within a set of powerful software tools called TOUGH codes, developed by the Lawrence Berkeley National Laboratory.
Recycled water	Treated municipal water
SDGL	<i>Steam Dominated GreenLoop (SDGL)</i> technology refers to the sum of equipment used to extract energy from a steam dominated reservoir production well and transfer it to surface mounted heat exchange equipment used for power generation.
THC	Thermal-hydrological-chemical
THMC	Thermal-hydrological-mechanical and chemical
TOUGH	<i>Transport of unsaturated groundwater and heat (TOUGH)</i> , a term for a set of powerful software tools called TOUGH codes, developed by the Lawrence Berkeley National Laboratory).
VIT	Vacuum insulated tube

# References

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- Amaya, Alvaro, Harish Chandrasekar, Saul Molina, Steven Brown, and Joseph Scherer. 2024. *Heat Extraction Processes Using Unconventional Geothermal Technologies (GreenLoop) Applied in Different Reservoir Types*. Proceedings, 49<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.
- Battistelli, Alfredo, Claudio Calore, and Karsten Preuss. 1997. "The simulator TOUGH2/EWASG for modelling geothermal reservoirs with brines and non-condensable gas." *Geothermics*, Volume, 26
- Beckers, Koenraad, Nicolás Rangel-Jurado, Harish Chandrasekar, Adam J. Hawkins, Patrick M. Fulton, Jefferson W. Tester. 2022. "Techno-economic performance of closed-loop geothermal systems for heat production and electricity generation." *Geothermics*, Volume 100.
- California Energy Commission. n.d. "[Types of Geothermal Power](https://www.energy.ca.gov/data-reports/energy-almanac/data-renewable-energy-markets-and-resources/types-geothermal-power)." California Energy Commission. <https://www.energy.ca.gov/data-reports/energy-almanac/data-renewable-energy-markets-and-resources/types-geothermal-power>
- California Energy Commission. 2024. "[New Data Shows Investments to Build California's Clean Energy Grid of the Future are Paying Off](https://www.energy.ca.gov/news/2024-05/new-data-shows-investments-build-californias-clean-energy-grid-future-are-paying)." California Energy Commission. <https://www.energy.ca.gov/news/2024-05/new-data-shows-investments-build-californias-clean-energy-grid-future-are-paying>
- California Energy Commission. 2024. *Draft 2024 Integrated Energy Policy Report Update*. CEC-100-2024-001.
- California Independent System Operator. 2025. *2024-2025 Transmission Plan Draft*. California ISO
- California Legislature. 2018. [Senate Bill No. 100: The 100 Percent Clean Energy Act of 2018](https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100). California Legislative Information. [https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill\\_id=201720180SB100](https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100)
- Clean Air Task Force. 2025. [Unlocking California's Geothermal Potential: A Strategic Opportunity for Clean, Firm Power](https://www.catf.us/resource/unlocking-californias-geothermal-potential/). Clean Air Task Force. <https://www.catf.us/resource/unlocking-californias-geothermal-potential/>
- Chandrasekar, Harish, Alvaro Amaya, Saul Molina, Ray Alvarado, Joseph Scherer, and Glenn Golla. 2023. *Comparison of Water, sCO<sub>2</sub>, and Organic Hydrocarbons as Working Fluids for the GreenLoop System and ORC Unit*. Proceedings, 48<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.
- Chandrasekar, Harish, Eric Sonnenthal, Alvaro Amaya, Jonny Rutqvist, Curtis Oldenburg, Glenn Golla, Fred Manuel, et al. 2023. "Coupled Thermal Hydraulic Mechanical and Chemical (THMC) Modeling of the GreenLoop System in the Southeast Geysers, California." *Geothermal Resources Council Transactions*, Volume 47.
- Darcy, Henry. 1856. *Les fontaines publiques de la ville de Dijon*. Paris: Victor Dalmont.

- Fervo Energy. 2023. "[Fervo Energy Announces Technology Breakthrough in Next-Generation Geothermal](https://fervoenergy.com/fervo-energy-announces-technology-break-through-in-next-generation-geothermal/)." <https://fervoenergy.com/fervo-energy-announces-technology-break-through-in-next-generation-geothermal/>
- Garcia, Julio, Craig Hartline, Mark Walters, Melinda Wright, Jonny Rutqvist, Patrick F. Dobson, and Pierre Jeanne. 2016. "The Northwest Geysers EGS Demonstration Project, California: Part 1: Characterization and reservoir response to injection." *Geothermics*, Volume 63.
- GreenFire Energy. 2020. *Closed-Loop Geothermal Demonstration Project: Coso, California*. California Energy Commission. Publication Number: CEC-300-2020-007.
- Higgins, Brian, Joseph Scherer, Alvaro Amaya, Harish Chandrasekar, and Andrew Van Horn. 2021. "Closed-Loop Geothermal in Steam Dominated Reservoirs." *Geothermal Resources Council Transactions*, Volume 45.
- Holmberg, Henrik, José Acuña, Erling Næss, and Otto K. Sønju. 2016. "Thermal evaluation of coaxial deep borehole heat exchangers." *Renewable Energy*, Volume 97.
- Jacobson, Mark Z., Daniel J. Sambor, Yuanbei F. Fan, Andreas Mühlbauer, and Mark A. Delucchi. 2025. "No Blackouts or Cost Increases Due to 100% Clean, Renewable Electricity Powering California for Parts of 98 Days." *Renewable Energy*, Volume 240.
- Lazard. 2025. "[Lazard Levelized Cost of Energy+](https://www.lazard.com/media/uounhon4/lazards-lcoeplus-june-2025.pdf)." Lazard Webpage. <https://www.lazard.com/media/uounhon4/lazards-lcoeplus-june-2025.pdf>
- Pruess, Karsten, Christophe Oldenburg, and Günther Moridis. 1999. *TOUGH2 User's Guide, Version 2.0*. Lawrence Berkeley National Laboratory Report.
- Rhodium Group. 2025. [The Potential for Geothermal Energy to Meet Growing Data Center Demand](https://rhg.com/research/geothermal-data-center-electricity-demand/). Rhodium Group. <https://rhg.com/research/geothermal-data-center-electricity-demand/>
- Rutqvist, Jonny, Pierre Jeanne, Patrick F. Dobson, Julio Garcia, Craig Hartline, Lawrence Hutchings, Ankit Singh, Donald W. Vasco, and Mark Walters. 2016. "The Northwest Geysers EGS Demonstration Project, California – Part 2: Modeling and interpretation." *Geothermics*, Volume 63.
- Rutqvist, Jonny. 2017. "An overview of TOUGH-based geomechanics models." *Computers & Geosciences*, Volume 108.
- Sanyal, Subir K., and Steven L Eney. 2011. *Fifty years of power generation at The Geysers geothermal field, California – The lessons learned*. Proceedings, 36<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California
- Sanyal, Subir K., Steven L Eney, Paul Brophy, and Edward Voge. 2025. "The Geysers: The oldest and largest geothermal power operation in the US." *Geothermal Power Generation (Second Edition)*.
- Scherer, Joseph, Glenn Golla, Harish Chandrasekar, Alvaro Amaya, Hollis Chin, Steven Brown, Eric Sonnenthal, et al. 2023. *The GreenLoop Closed-Loop Geothermal (CLG) System*:

*Optimizing Power Generation and Evaluating Its Impact on the Reservoir*. Proceedings, The 9<sup>th</sup> Indonesia International Geothermal Convention & Exhibition (IIGCE).

Sonnenthal, Eric, Nicolas Spycher, Tianfu Xu, and Liange Zheng. 2021. *TOUGHREACT V.4.12-OMP and TReactMech V.1.0 Geochemical and Reactive-Transport User Guide*. Lawrence Berkeley National Laboratory Report

ThinkGeoEnergy. 2022. "[GreenFire Energy awarded funding for demonstration project at The Geysers](https://www.thinkgeoenergy.com/greenfire-energy-awarded-funding-for-demonstration-project-at-the-geysers/)." <https://www.thinkgeoenergy.com/greenfire-energy-awarded-funding-for-demonstration-project-at-the-geysers/>

ThinkGeoEnergy. 2023. "[About 1,748 Geothermal Wells in the United States, Majority in California](https://www.thinkgeoenergy.com/about-1748-geothermal-wells-in-the-united-states-majority-in-california/)." <https://www.thinkgeoenergy.com/about-1748-geothermal-wells-in-the-united-states-majority-in-california/>

White, Max, Yaroslav Yasylyv, Karl Beckers, Miguel Martinez, Pietro Balestra, Claudio Parisi, Clare Augustine et al. 2024. "Numerical Investigation of Closed-Loop Geothermal Systems in Deep Geothermal Reservoirs." *Geothermics*, Volume 116.

Xing, Pengju, Kevin England, Joseph Moore, and John McLennan. *Analysis of the 2024 Circulation Tests at Utah FORGE and the Response of Fiber Optic Sensing Data*. Proceedings, 50<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California

Xu, Tianfu, Eric Sonnenthal, Nicolas Spycher, and Karsten Pruess. 2004. *TOUGHREACT User's Guide: A Simulation Program for Non-Isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Geologic Media*. Lawrence Berkeley National Laboratory Report.

# Project Deliverables

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The primary product deliverables in the key technical tasks of this grant agreement are listed below.

## Task 2: Well, Reservoir, and Systems Modeling

- SDGL Model Report (draft and final)

## Task 3: Well Engineering

- Well Engineering Design Drawings and Specifications Report

## Task 4: Surface Systems Engineering

- Process Flow Diagram
- Process and Instrumentation Diagram
- Surface Systems Engineering Design Drawings and Specifications Report

## Task 5: Site Work - SDGL Equipment Installation

- SDGL Equipment Installation Report

## Task 6: Project Testing and Operations

- Test Plan
- Testing and Operations Report

These project deliverables, including interim project reports, are available upon request by submitting an email to [pubs@energy.ca.gov](mailto:pubs@energy.ca.gov).



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# **APPENDIX A: Geothermal Site Description, DBHX Data, Construction Photos and Site Diagrams**

**April 2026 | CEC-500-2026-009**



# Appendix A: Geothermal Site Description, DBHX Data, Construction Photos and Site Diagrams

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## Geothermal Site Location

The DV-13 well site is located about 0.65 miles from the Unit 18 power plant (Figure A.1). The well site sits on a ridge, with a steep drop into the valley on its west side. The attached map shows this local terrain, with the well location marked by a yellow star.

**Figure A.1: Location of Well DV-13 and All the Wells within  
The Geysers Geothermal Field**



**Location of the well DV-13 indicated by the yellow star along with the Socrates Unit 18 power plant. The top right hand corner photo shows all the wells in The Geysers geothermal field and the yellow star on the bottom left of the field indicates the location of the well DV-13.**

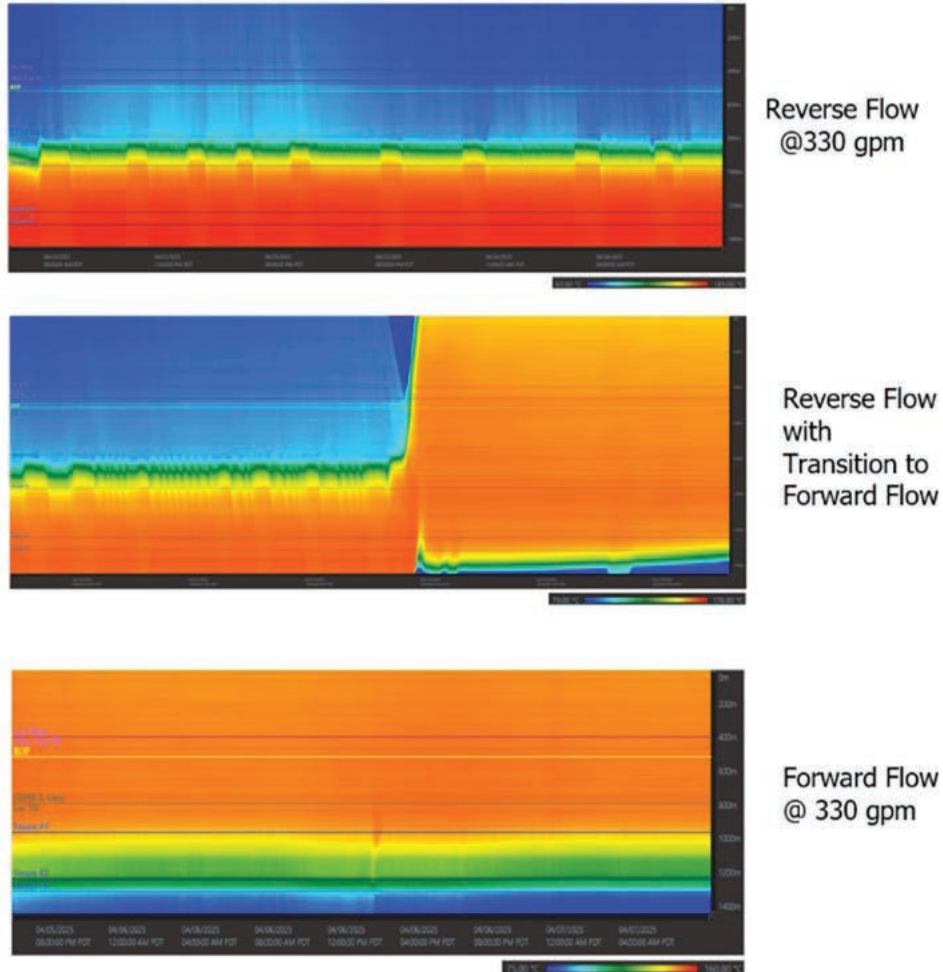
Source: GreenFire, 2025

## DBHX Data

DTS real time data feed observed during specific instances during the 90-day testing program. The DTS cable was attached to the outside of the VIT and hence, was used to track

temperature changes occurring over the depth of the annulus between the VIT and the DBHX casing. The visualization of the data is shown in Figure A.2.

**Figure A.2: Temperature Plots as a Function of Depth Observed during Reverse Flow Operational Mode at 330 GPM (Top Plot), Reverse Flow with Transition to Forward Flow (Middle Plot), and Forward Flow at 330 GPM (Bottom Plot)**



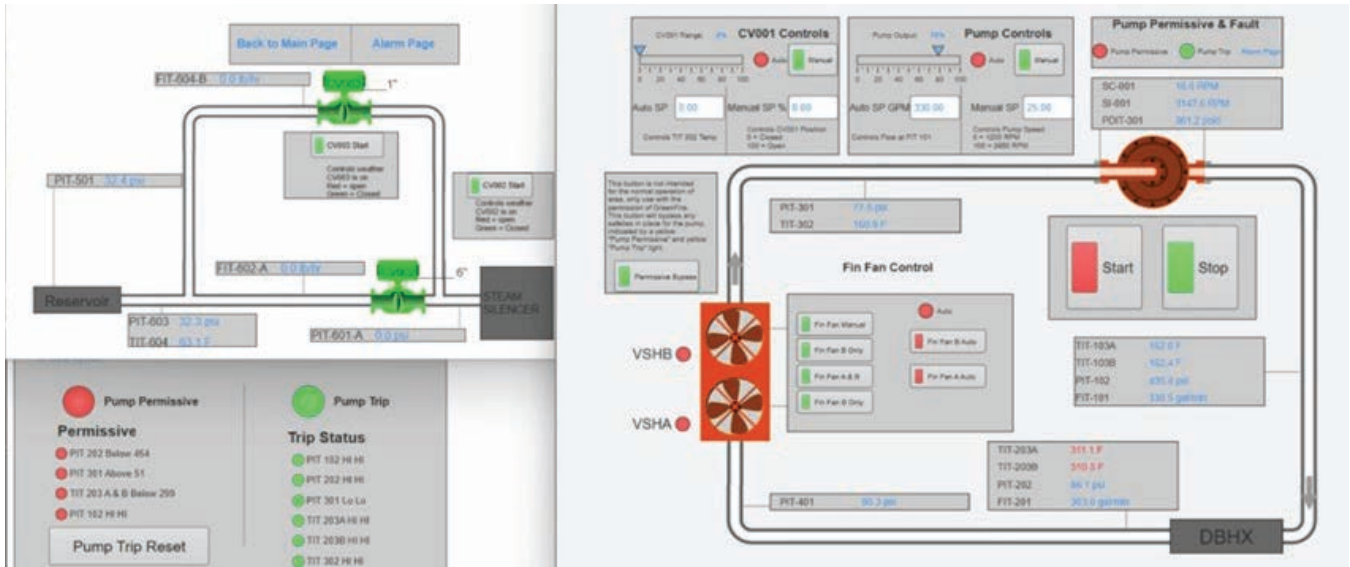
Three plots are shown here with the first (top) one being temperature as a function of depth observed during reverse flow operational mode at a flow rate of 330 GPM (20.4 kg/s) within the DBHX. The second plot shows reverse flow with transition to forward flow operational mode. The last plot shows forward flow operational mode at a flow rate of 330 GPM (20.4 kg/s).

Source: GreenFire, 2025

## Real-Time Data and Control Screen Layout

A real-time data monitoring and control system was set up in a way that enabled remote monitoring and controls. Key parameters such as temperature, pressure, and flow rates in various lines could be monitored and adjusted as desired remotely. A snapshot of the real-time data monitoring and control system is shown in Figure A.3.

**Figure A.3: Snapshot of the Real-Time Data Monitoring and Control System Setup for the AGS in Well DV-13**



Source: GreenFire, 2025

## Surface System and Wellsite Photos

The photographs in Figure A.4 through Figure A.8 illustrate the following:

- The wellhead connects to the surface piping. A stand for the DTS is positioned near the wellhead (Figure A.4)
- A silencer is visible in the background, designed to reduce noise from the well (Figure A.5)
- Chemical containers are located to the right and back of the layout, near the NCG lines that lead to the silencer. These containers hold chemicals used for gas treatment (Figure A.5)
- The pumping system, colored blue, is situated on the left side of the layout (Figure A.4)
- A control unit and coolers are part of the system's surface equipment (Figure A.6 and Figure A.7)
- One photo captures the venting of steam during a forward flow operational mode test, demonstrating how the system releases excess steam (Figure A.8)

**Figure A.4: Picture of the Well, Wellhead, Surface Piping System, Silencer and the DTS Stand**



**Picture of the well, surface piping system with the silencer visible in the background. The DTS stand can be seen towards the right, close to the wellhead.**

Source: GreenFire, 2025

**Figure A.5: Picture of the Surface Circulation Loop, Control Units and Chemical Containers**



**Picture of the surface circulation loop and control units. Chemical containers are also visible on the right side of the picture, used for gas treatment.**

Source: GreenFire, 2025

**Figure A.6: Picture of the Air Cooler on the Left Side and the Entrance to the AGS Control Unit on the Right Side**



Source: GreenFire, 2025

**Figure A.7: Layout within the Control Unit of the AGS**



Source: GreenFire, 2025

**Figure A.8: The Complete Surface System of the AGS Captured during a Forward Flow Operational Mode Test, Demonstrating How the System Releases Excess Steam**



Source: GreenFire, 2025



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# **APPENDIX B: Thermal-Hydrological-Mechanical and Chemical (THMC) Modeling**

**April 2026 | CEC-500-2026-009**



# Appendix B:

## Thermal-Hydrological-Mechanical and Chemical (THMC) Modeling

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The team built a native-state model first to represent the geothermal reservoir in its natural, undisturbed condition, before any extraction begins. The team used rock layers and their thermal (Figure B.1) and water-related (Figure B.2) properties as inputs for the model. Specific thermal-hydrological properties for the well DV-13 were based on prior studies done in 2016<sup>1</sup> and 2023.<sup>2</sup>

Since the only temperature data available for the well DV-13 was from when the well was flowing (disturbed condition), the team ran the model with two scenarios:

- High-temperature reservoir at The Geysers
- Low-temperature reservoir at The Geysers

The models successfully matched the static temperature readings from other wells and the flowing wellbore temperatures from DV-13 (Figure B.3 and Figure B.4). Out of the two models, it was found that the low-temperature reservoir native state model was representative of the conditions observed in the reservoir region around DV-13 and therefore was chosen as the baseline model for further DV-13 simulations. The high-temperature reservoir model is more representative of the conditions observed in the North-West area of The Geysers geothermal field.

The models also showed a zone rich in carbon dioxide forming under the caprock (Figure B.5). This is consistent with the total carbon dioxide buildup observed by the team during the DBHX testing, which affects the total gas pressure. However, it is important to note that when comparing the high and low-temperature reservoir models, the former shows a relatively larger zone of carbon dioxide accumulation below the caprock. The low-temperature reservoir model showed a maximum of 91 percent mass fraction of carbon dioxide in the gas phase. These processes were captured using the TOUGH-REACT simulator version 4.184 (update from version 4.12).<sup>3</sup> The simulator uses an equation of state (EOS) approach to define fluid components and their phases. To capture the evolution of carbon dioxide and water in the gas phase, as well as dissolved carbon dioxide and sodium chloride in the liquid phase a specialized EOS called EWASG (Equation-of-state for water, salt and gas) had to be used.<sup>4</sup>

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<sup>1</sup> Rutqvist, Jonny, Pierre Jeanne, Patrick F. Dobson, Julio Garcia, Craig Hartline, Lawrence Hutchings, Ankit Singh, Donald W. Vasco, and Mark Walters. 2016. "The Northwest Geysers EGS Demonstration Project, California – Part 2: Modeling and interpretation." *Geothermics*, Volume 63.

<sup>2</sup> Chandrasekar, Harish, Eric Sonnenthal, Alvaro Amaya, Jonny Rutqvist, Curtis Oldenburg, Glenn Golla, Fred Manuel, et al. 2023. "Coupled Thermal Hydraulic Mechanical and Chemical (THMC) Modeling of the GreenLoop System in the Southeast Geysers, California." *Geothermal Resources Council Transactions*, Volume 47.

<sup>3</sup> Sonnenthal, Eric, Nicolas Spycher, Tianfu Xu, and Liange Zheng. 2021. *TOUGHREACT V.4.12-OMP and TReactMech V.1.0 Geochemical and Reactive-Transport User Guide*. Lawrence Berkeley National Laboratory Report

<sup>4</sup> Battistelli, Alfredo, Claudio Calore, and Karsten Preuss. 1997. "The simulator TOUGH2/EWASG for modelling geothermal reservoirs with brines and non-condensable gas." *Geothermics*, Volume, 26

**Figure B.1: Rock Properties Considered for THMC Modeling**

	Caprock	Graywacke (NTR)	Hornfels (HTR)	Felsite
Permeability (m <sup>2</sup> )	1 × 10 <sup>-18</sup>	5 × 10 <sup>-14</sup>	2 × 10 <sup>-14</sup>	1 × 10 <sup>-15</sup>
Porosity (%)	0.01	1.5	1.0	1.0
Thermal cond. (W/(m °C))	3.2	3.2	3.2	3.2
Specific heat (J/(kg °C))	1000	1000	1000	1000
Bulk modulus (GPa)	3.3	3.3	3.3	3.3
Shear modulus (GPa)	2	2	2	2
Thermal expansion coefficient (°C <sup>-1</sup> )	1 × 10 <sup>-5</sup>	1 × 10 <sup>-5</sup>	1 × 10 <sup>-5</sup>	1 × 10 <sup>-5</sup>

Source: Rutqvist et al., 2016

**Figure B.2: Saturated Thermal-Hydrological Properties Considered for THMC Modeling**

Material	$k$ (m <sup>2</sup> )	$\phi$	K-rel	$\lambda$	$S_{lr}$	$S_{ls}$	$S_{gr}$	P-Cap	$\lambda$	$S_{lr}$	$1/P_0$ Pa <sup>-1</sup>	$k_T$ (w, d) W m <sup>-1</sup> K <sup>-1</sup>	Cp J kg <sup>-1</sup> C <sup>-1</sup>
Top Surface	2.55x10 <sup>-13</sup>	0.20	VG-C	0.4103	0.30	1.0	0.05	VG	0.4103	0.145	7.189x10 <sup>-6</sup>	2.0, 1.5	1.0x10 <sup>25</sup>
Near Surface	2.55x10 <sup>-15</sup>	0.10	VG-C	0.4103	0.30	1.0	0.05	VG	0.4103	0.145	7.189x10 <sup>-6</sup>	2.5, 1.75	952.9
Caprock	2.55 × 10 <sup>-18</sup>	0.02	VG-C	0.4103	0.30	1.0	0.05	VG	0.4103	0.145	7.189x10 <sup>-6</sup>	3.22, 2.415	952.9
Reservoir	2.55 × 10 <sup>-14</sup>	0.02	VG-C	0.4832	0.01	1.0	0.005	VG	0.4832	0.0001	7.189x10 <sup>-6</sup>	3.22, 2.415	952.9
Fracture Zone	2.55 × 10 <sup>-12</sup>	0.021	VG-C	0.4832	0.01	1.0	0.005	VG	0.4832	0.0001	7.189x10 <sup>-6</sup>	3.22, 2.415	952.9
Hornfels	2.55 × 10 <sup>-15</sup>	0.02	VG-C	0.4103	0.30	1.0	0.05	VG	0.4103	0.145	7.189x10 <sup>-6</sup>	3.22, 2.415	1.0x10 <sup>25</sup>

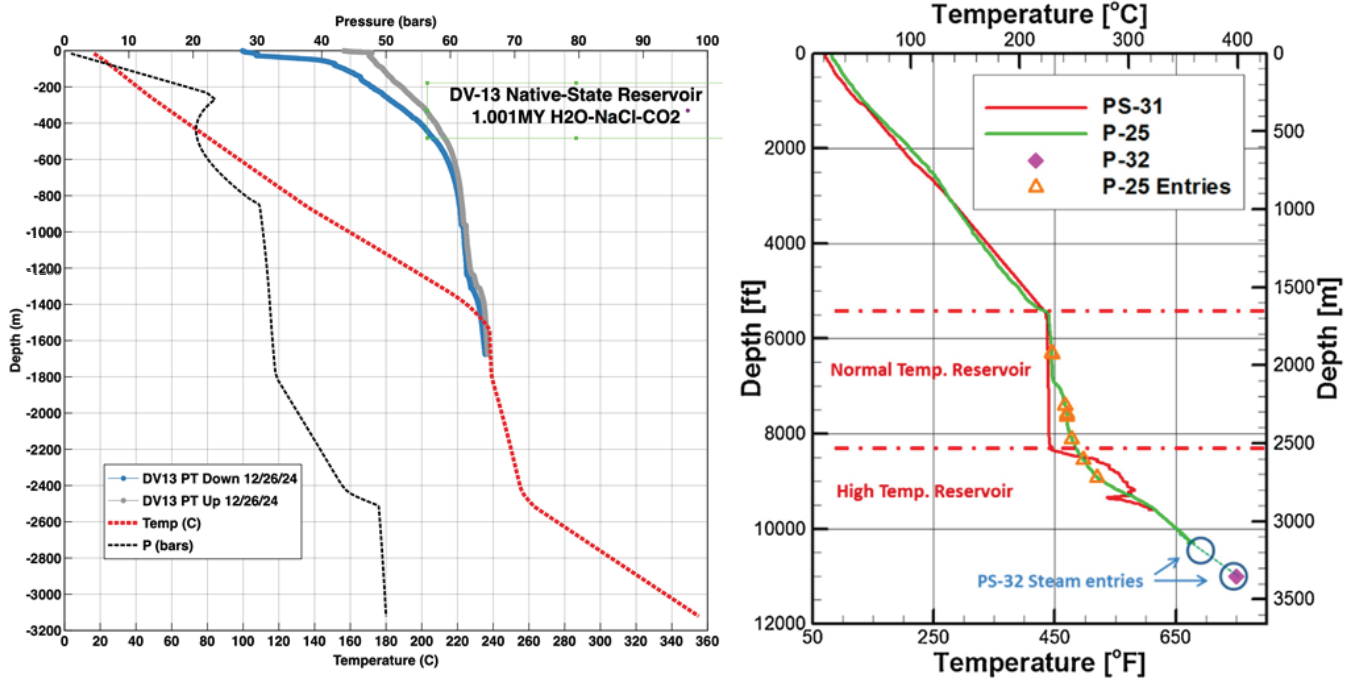
w, d: wet, dry

VG-C: van Genuchten for liquid, Corey for steam

Note: Cp values of 1.0e25 are used to fix temperature at top and base of model

Source: Lawrence Berkeley National Laboratory, 2025

**Figure B.3: Simulated High-Temperature Reservoir Condition Temperature and Pressure Profiles as a Function of Depth (Left), versus Well Temperatures Recorded as a Function of Depth in High-Temperature Wells (Right)**

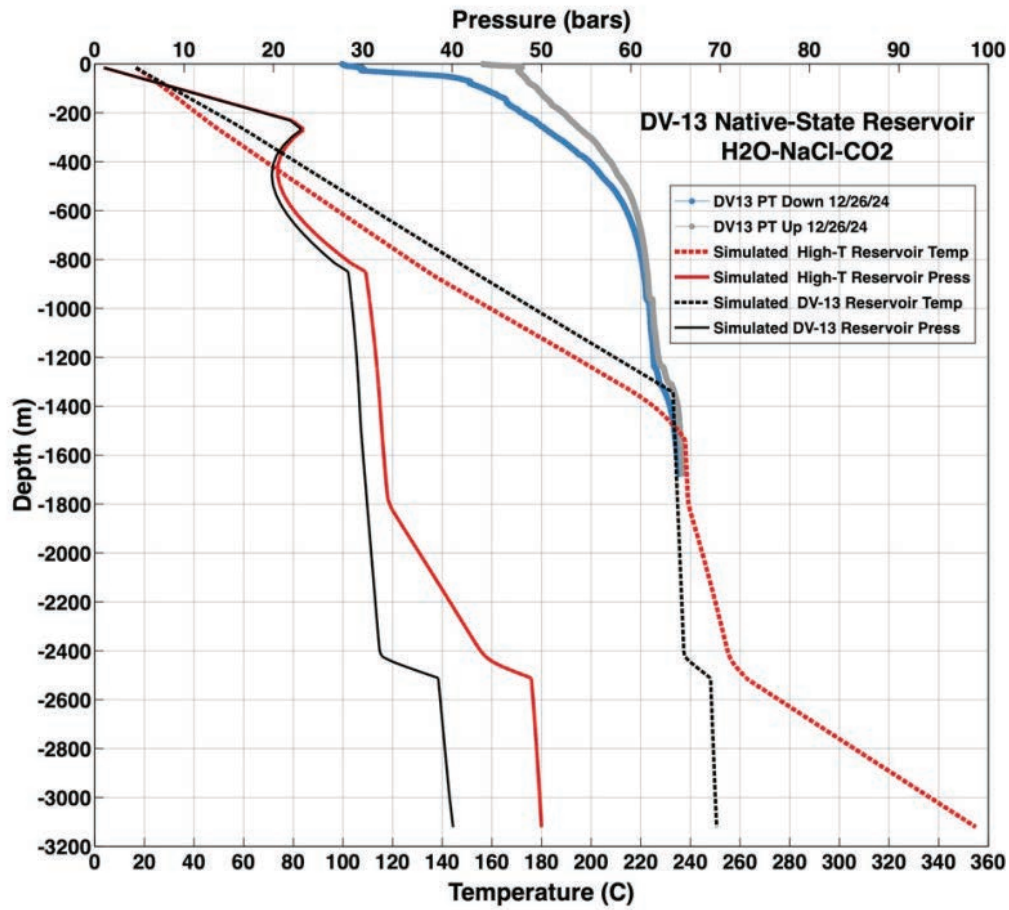


**Simulated native-state temperature (dashed red line) and pressure profiles (dashed black line) as a function of depth for the high-temperature reservoir condition. The temperature profiles (left) showed a good match with the static temperature (right) of the wells recorded in a prior work done in 2016 with high-temperature wells.<sup>5</sup>**

Source: Lawrence Berkeley National Laboratory (2025) and Garcia et al. (2016)

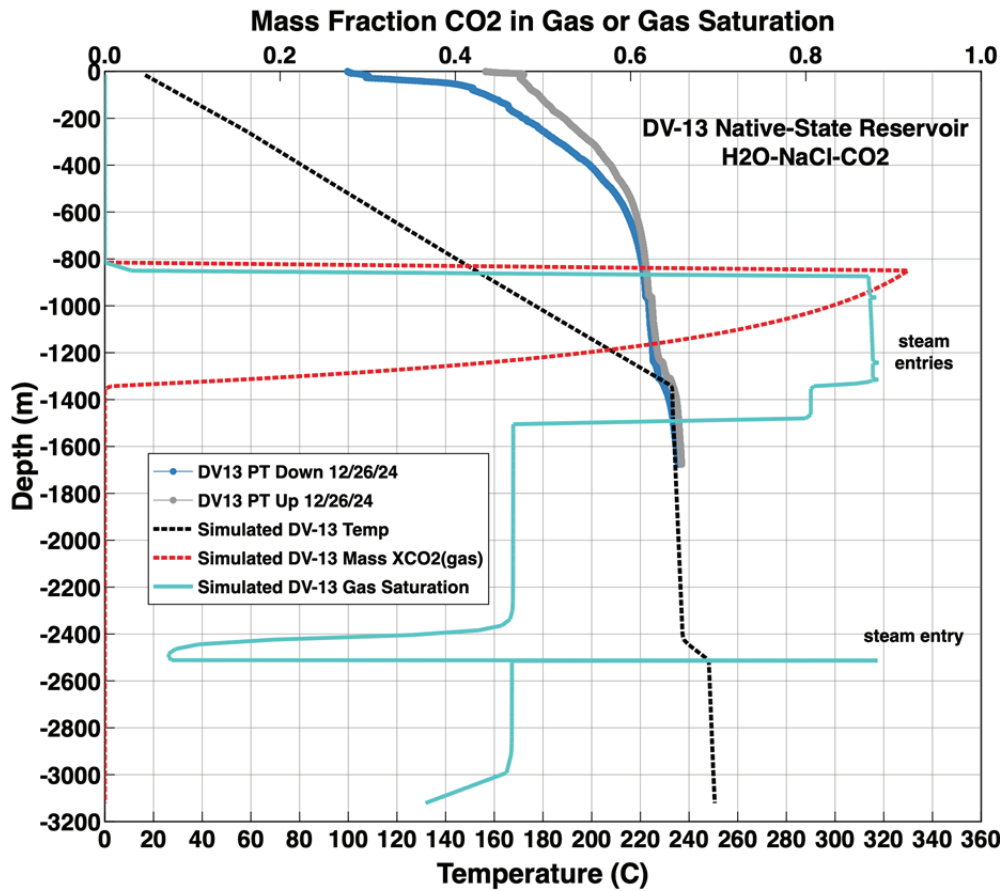
<sup>5</sup> Garcia, Julio, Craig Hartline, Mark Walters, Melinda Wright, Jonny Rutqvist, Patrick F. Dobson, and Pierre Jeanne. 2016. "The Northwest Geysers EGS Demonstration Project, California: Part 1: Characterization and reservoir response to injection." *Geothermics*, Volume 63.

**Figure B.4: Simulated Temperature and Pressure Conditions of the High Temperature (Red Dashed and Solid Line Respectively) and Low-Temperature (Black Dashed and Solid Line Respectively) Reservoir Scenarios as a Function of Depth**



Source: Lawrence Berkeley National Laboratory, 2025

**Figure B.5: Simulated Temperature, Carbon Dioxide Mass Fraction and Gas Saturation as a Function of Depth, Where the Pressure Conditions of the Low-Temperature Reservoir Conditions Are Representative of the Area Around Well DV-13**



Source: Lawrence Berkeley National Laboratory, 2025

Table B.1 shows the mix of gases found around the bottom of the DBHX in well DV-13. Compared to the figures from the native state EWASG simulations, the Thermal-Hydrological-Chemical (THC) analysis showed slightly less carbon dioxide and NCGs, but more methane, at a lower temperature of about 333°F (167°C). In this case, the DBHX was operating in the reverse flow operational mode at a flow rate of around 20 kg/s, which affects the results.

**Table B.1: Simulated Gas Compositions at the Base of the DBHX in Well DV-13 through Thermal Hydrological and Chemical Modeling**

Gas	Mole Fraction NCG	Mole Fraction in Steam
CO2	0.4274	0.08325
CH4	0.5550	0.10811
H2S	0.0112	0.00218
NH3	0.0013	0.000253

Gas	Mole Fraction NCG	Mole Fraction in Steam
H2	0.0051	0.000997
HCl	1.5e-14	2.9e-15
HF	1.7e-12	3.3e-13

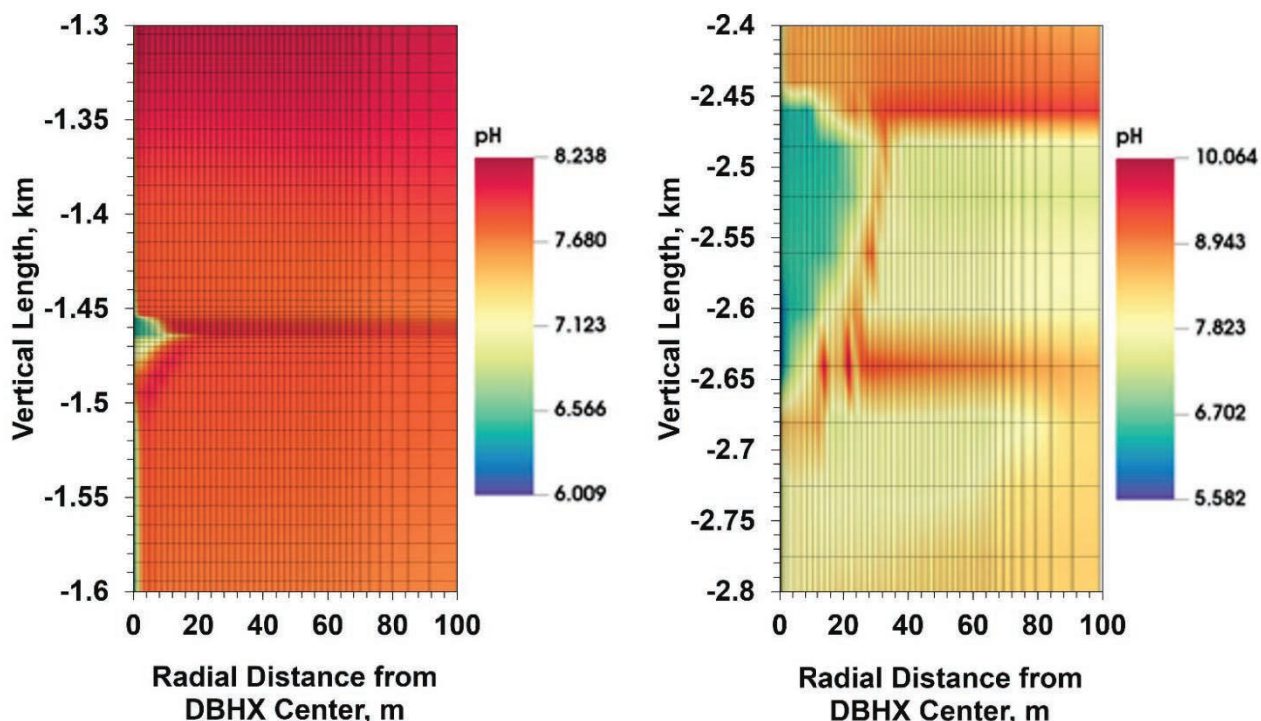
**NCG Gas Fraction = 0.1948**

Source: Lawrence Berkeley National Laboratory, 2025

The chemical changes in the well are mostly caused by condensation (the model results are visualized in Figure B.6). As steam cools and condenses, it pulls in acidic gases like carbon dioxide, hydrochloric acid, and hydrofluoric acid. This creates a more acidic (lower pH) fluid that drains to the bottom of the well. That acidic fluid prevents mineral scaling and speeds up the breakdown of surrounding rock compared to the natural conditions.

Still, these changes are just small shifts from the natural steam circulation and condensation already happening in the reservoir—especially since injected condensate and wastewater also similarly capture acid gases. Further details on the chemical modeling framework can also be found in the prior published work.<sup>6</sup>

**Figure B.6: Simulation Results of pH in the Near-Well Region at the Base of the DBHX (left) and at the Base of the Well (Right) in the Long-Term Reverse Flow Operational Condition**



Source: Lawrence Berkeley National Laboratory, 2025

<sup>6</sup> Chandrasekar, Harish, Eric Sonnenthal, Alvaro Amaya, Jonny Rutqvist, Curtis Oldenburg, Glenn Golla, Fred Manuel, et al. 2023. "Coupled Thermal Hydraulic Mechanical and Chemical (THMC) Modeling of the GreenLoop System in the Southeast Geysers, California." *Geothermal Resources Council Transactions*, Volume 47.

Mechanical modeling was also done to study how temperature changes affect the rock and well structure over time. In conventional geothermal systems, both pressure and temperature can cause stresses in the rocks. But in this case—using the AGS—no fluid is injected into the ground, so pressure changes are minimal. That means temperature is the main factor influencing mechanical stress.

Temperature of the surrounding rock after 3 months, 5 years and 30 years of continuous DBHX operations in DV-13 was analyzed. The biggest cooling effect happens near the bottom of the well, around 2,600 m deep, where condensed water collects (Figure B.7). In that zone, the rock cools (decreases in temperature) by about 144°F (80°C). Smaller cooling zones also appear near the bottom of the casing, and at the two feed zones at depths of around 800 m, 960 m and 1300 m respectively.

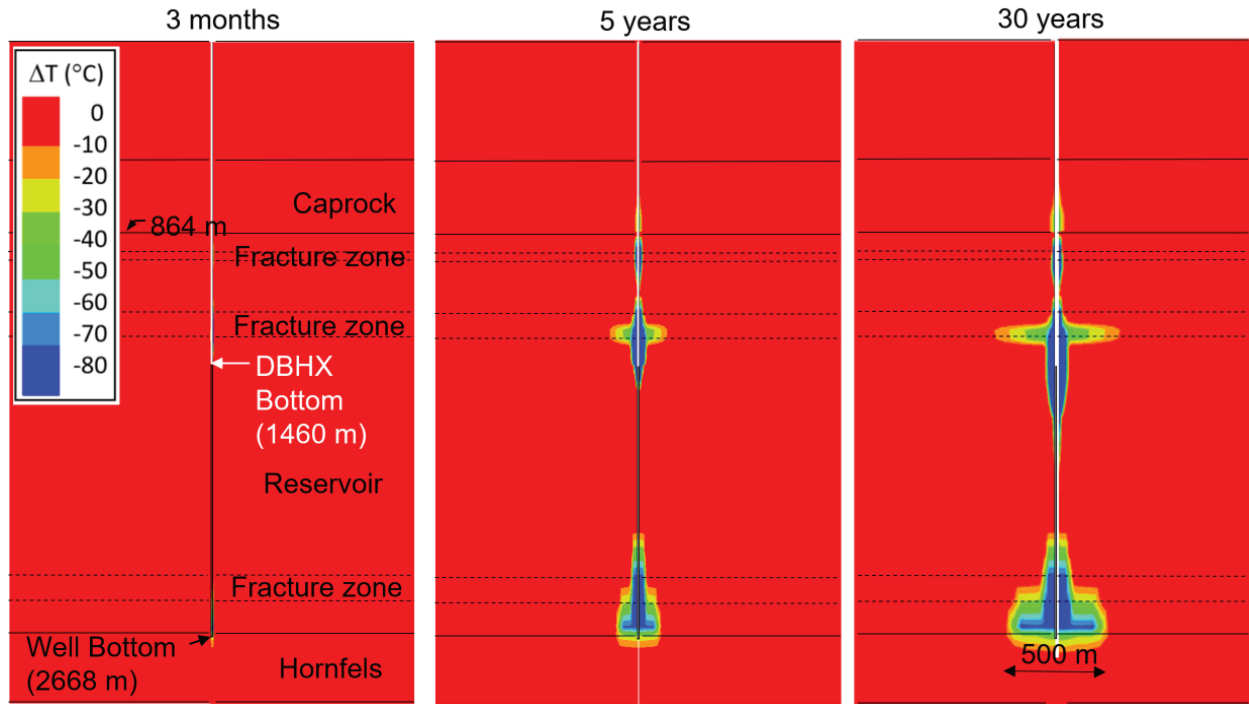
As the rock cools, it contracts slightly, which can change the stress in the surrounding formation. These stress changes were calculated (Figure B.8 and Figure B.9) using a method called the Coulomb criterion, which estimates the potential for small earthquakes, or microseismic events. This same method has been used in past studies to evaluate seismic activity around injection wells at The Geysers geothermal field.

The team checked the public seismic data from the Northern California Earthquake Data Center (NCEDC) and found no signs of increased seismic activity near the well during the test. In fact, no microseismic events were recorded close to the well DV-13.

The volume of rock affected by cooling increases with time of operations of the DBHX. A larger volume means there's a higher chance of encountering a fracture that could slip. But the amount of stress and temperature change doesn't increase—it stays about the same as during the 90-day test. So, the lack of seismic activity during the pilot may suggest that no major increase in microseismic events is expected over the long term.

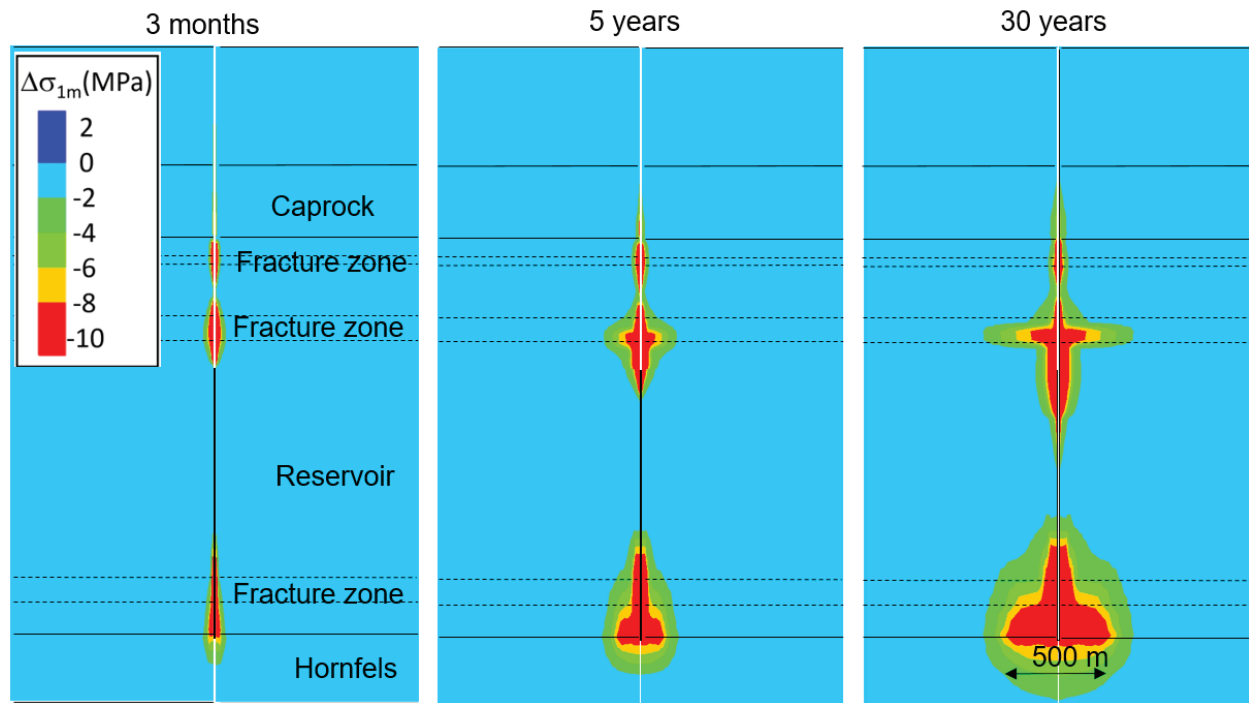
In addition, from 3 months to 30 years of DBHX simulations, there's no major change in stress that would damage the well or create new fractures (Figure B.10).

**Figure B.7: Simulated Temperature Changes in the Host Rock Surrounding the Well DV-13**



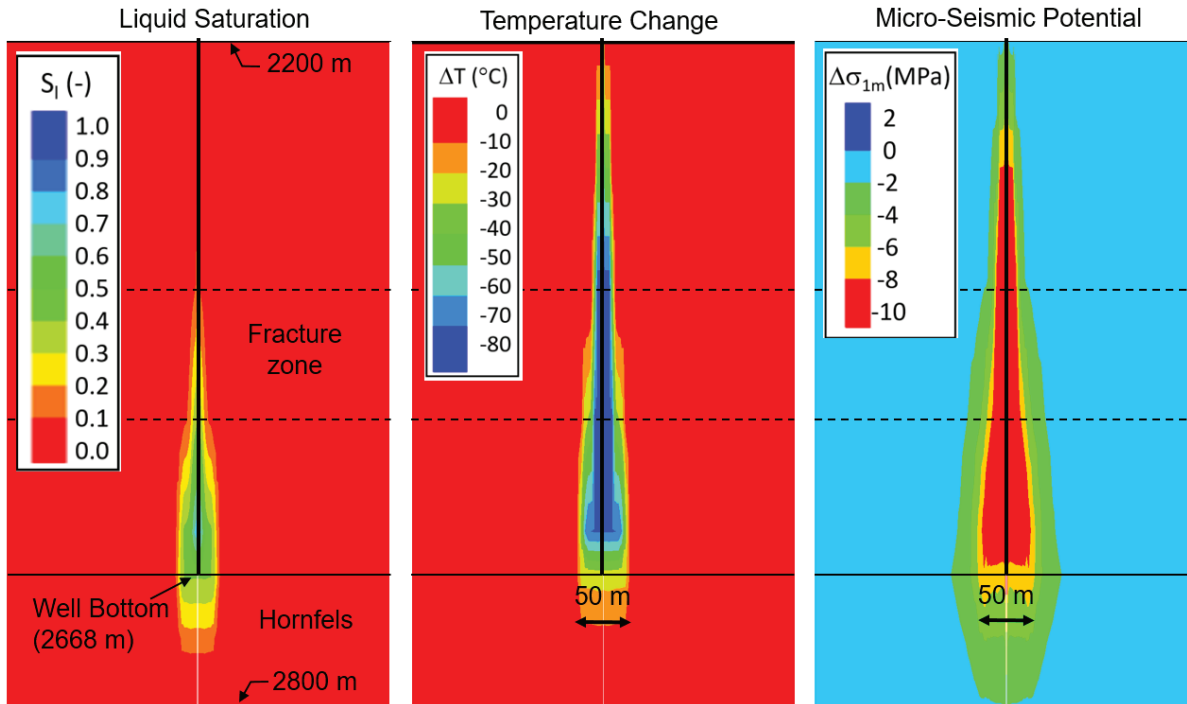
Source: Lawrence Berkeley National Laboratory, 2025

**Figure B.8: Simulated Microseismic Potential Caused by Cooling Stresses in the Host Rock Surrounding the Well DV-13**



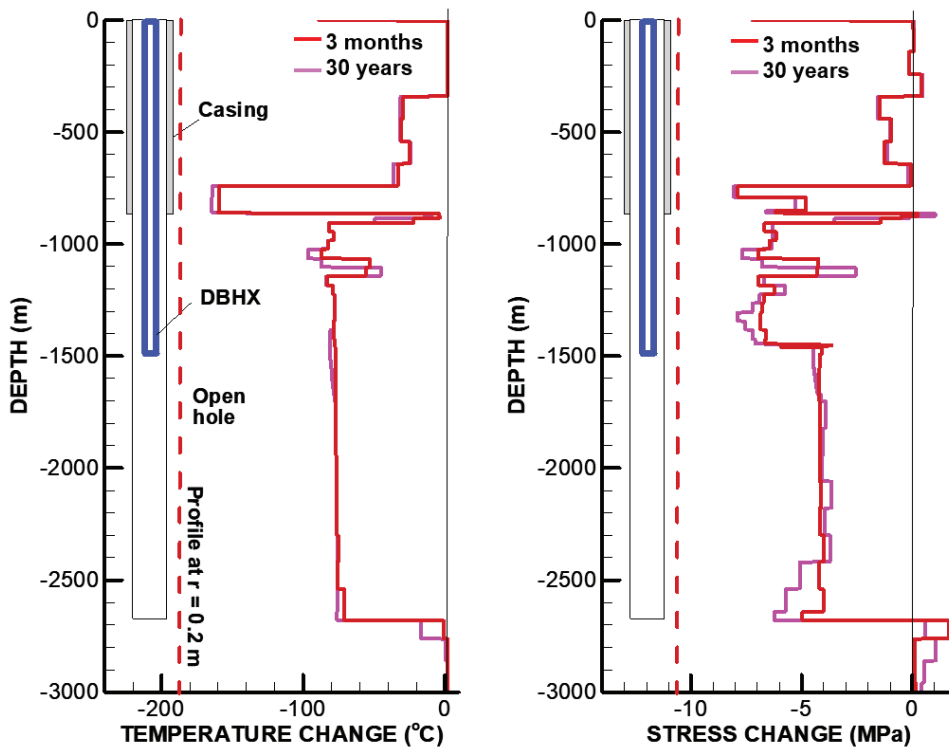
Source: Lawrence Berkeley National Laboratory, 2025

**Figure B.9: Simulated Liquid Saturation, Temperature Changes and Microseismic Potential near the Bottom of the Well DV-13**



Source: Lawrence Berkeley National Laboratory, 2025

**Figure B.10: Simulated Temperature and Cooling Stress Changes along the Well DV-13 at a Radius of about 0.2 m (7.87 in.)**



Source: Lawrence Berkeley National Laboratory, 2025