California Energy Commission

CONSULTANT REPORT

Closed-Loop Geothermal Demonstration Project

Confirming Models for Large-Scale, Closed-Loop Geothermal Projects in California

Prepared by: **GreenFire Energy Inc.**

Gavin Newsom, Governor
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PREFACE

The California Energy Commission's Geothermal Grant and Loan Program is funded by the Geothermal Resources Development Account providing funding to local jurisdictions and private entities for a variety of geothermal projects.

This report on the *Closed-Loop Geothermal Demonstration Project* is the final report for the Geothermal Grant and Loan Program Agreement Number GEO-16-004, completed by GreenFire Energy Inc. The information from this project contributes to the overall goals of the Geothermal Grant and Loan Program to:

- Promote the use and development of California's vast geothermal energy resources.
- Address any adverse impacts caused by geothermal development.
- Help local jurisdictions offset the costs of providing public services necessitated by geothermal development.

ABSTRACT

The project team investigated using a closed-loop heat extraction technology to unlock the vast geothermal regions of California that cannot be accessed by conventional hydrothermal systems due to insufficient water and subsurface permeability. The project team installed and measured the performance of a downbore heat exchanger in a field-scale closed-loop geothermal power system. Water and supercritical carbon dioxide were circulated in the system as alternatives for transporting heat to the surface where power generation was simulated.

The team conducted onsite testing in May and December 2019 using Well 34-A20 in Coso (Inyo County, California). Construction included the insertion of 1,083 feet of vacuum-insulated tubing inside a liner that was plugged at the bottom to form the downbore heat exchanger.

The tests consisted of circulating the selected fluid while varying the flow rate and working fluid injection conditions. The team measured output temperature and pressure.

Testing with water as the working fluid created enough steam potential to generate 1.2 megawatts of gross electric power and conformed well to the modeled prediction. Equally important, project testing clearly demonstrated that downbore heat exchangers can produce power from inactive wells.

Next, GreenFire circulated supercritical CO_2 in the downbore heat exchanger while coproducing brine to the surface. This test sought to verify GreenFire Energy's supercritical CO_2 process modeling techniques and illustrate the potential for power generation where conditions prevent the use of conventional hydrothermal technology.

The results confirmed the utility of a supercritical CO_2 closed-loop system to harvest heat in hot, dry rock. The research suggests 1) commercial projects may now be considered using the technology to retrofit existing underperforming geothermal wells and 2) new wells can be considered for drilling to depth in hot, dry rock at field-scale for commercial power production.

Keywords: California Energy Commission, GreenFire Energy, closed-loop, supercritical CO_2, Vacuum Insulated Tubing, Coso, noncondensable gases

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Introduction

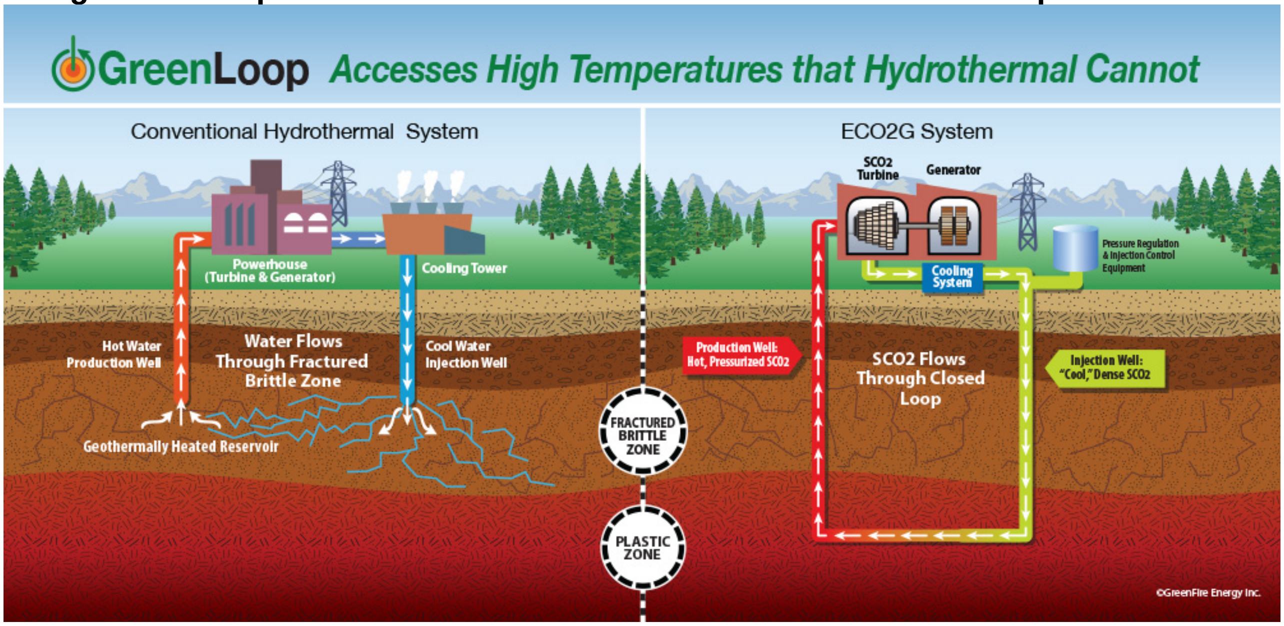
Despite rapidly rising demand for renewable energy and the abundance of geothermal resources in California, geothermal power generation is declining. Figures compiled by the California Energy Commission (CEC) show that gigawatt-hours generated between 2001 and 2018 decreased (13,525 vs. 11,528), mainly because of natural well degradation and the dearth of new geothermal projects. This paradox is clear evidence of a fundamental problem that prevents the geothermal industry from expanding to meet the twin demands of clean power generation and grid balancing for intermittent power.

Geothermal power generation in California is severely restricted with conventional “hydrothermal” technology, which requires abundant water and highly permeable subsurface rock structures. Because sites with the rare combination of sufficient heat, water and permeability have already been developed, such combinations are increasingly difficult to find. In short, the lack of geothermal sites with the necessary conditions has effectively limited the number of sites that can be developed with conventional technology. Further, conventional geothermal development is hampered by an unattractive business model characterized by high upfront risk, an extremely long period before revenue is generated, and only modest return on investment.

Reinvigorating geothermal development in California will require a substantially different technology and a better business model. To address these interrelated problems, GreenFire Energy has developed a “closed-loop” geothermal power technology that eliminates the need for subsurface permeability and large quantities of water. Closed-loop geothermal involves the creation of a sealed well traversing the subsurface rock strata through which heat transport fluid can freely circulate. Because no fluid is lost in a closed system, obtaining environmental permits is less expensive and time consuming. Closed loops further make possible the use of alternative heat transport fluids, such as supercritical CO_2, that can be used to reduce the power otherwise consumed by pumping water through the system.

Figure 1 depicts the difference between conventional hydrothermal systems and closed-loop systems. The diagram on the left illustrates how most hydrothermal projects depend on large amounts of water flowing down an injection well, then through highly permeable rock to collect and transport heat, and then into a production well that conducts the hot water to the surface. The closed-loop system, depicted in the right panel, does not need subsurface permeability because there is a sealed, engineered pipe that conducts the heat transport fluid through the rock strata and then up to the surface. Closed-loop systems have two immediate advantages. First, they make possible the use of alternative heat transport fluids that may be superior to water under various conditions. Second, closed-loop systems can access heat from high-temperature resources (where permeability is generally very limited), which translates into more efficient power generation.

Figure 1: Comparison of Conventional Geothermal vs. Closed-loop Geothermal



Source: GreenFire Energy

This report describes the first field-scale test of closed-loop geothermal power generation technology. To date, the primary obstacle to the success of closed-loop geothermal technology has been the lack of a field demonstration. Though mathematical modeling predicts success, "real-world" operation is required to attract funding for field-scale commercialization. This demonstration project is valuable in overcoming the final obstacles to commercial development not only of well rehabilitation projects but, more importantly, field-scale, closed-loop geothermal projects using wells drilled into hot, dry rock.

Project Purpose

Although previous modeling by GreenFire indicated that resources with hot, dry rock can be economically developed using closed-loop heat extraction technologies, this indication had yet to be proven.

Accordingly, the project goal was to prove that a closed-loop geothermal power plant using supercritical CO_2 can operate successfully at field scale. The project team used measurements taken during the testing to validate and improve GreenFire's thermodynamic models of closed-loop geothermal projects. These models will be essential to expanding significantly California's geothermal industry to the hot, dry rock regions that are inaccessible with current hydrothermal technology.

The project consisted of a field-scale demonstration of a closed-loop geothermal system using a downbore heat exchanger (DBHX) to extract heat. A downbore heat exchanger is a tube-in-tube assembly inserted into a geothermal well to circulate a fluid that absorbs heat for transport to the surface. The project team evaluated heat extraction using water and supercritical CO_2 as alternative heat transport fluids. The team took careful measurements of each experiment to build a dataset to guide development of field-scale, closed-loop geothermal projects in California. Further, because the project was conducted using an existing but idle geothermal well, this project demonstrated that many inactive geothermal wells in California can be restored to productivity.

Objectives

The specific project objectives were to:

- Use an underperforming hydrothermal well at the Coso known geothermal resource area.
- Design, build, and operate a closed-loop technology demonstration plant.
- Collect enough data to guide development of commercial closed-loop projects.

Testing Overview

In independent tests, water and supercritical CO_2 were circulated through a 330-meter, tube-in-tube downbore heat exchanger hung from the wellhead. During testing, the team "coproduced" a mixture of brine and steam to the surface along the surface of the DBHX to increase convective heat flow. The team coproduced brine at four flow rates (including zero flow), while alternatively circulating water and supercritical CO_2 inside the DBHX at different flow settings.

Conclusions and Recommendations

The results obtained from this test lead to the following conclusions:

- Closed-loop technology using supercritical CO_2 as the transport fluid shows promise for large-scale geothermal projects in hot, dry geothermal resources.
- Water can also be effectively used in some closed-loop systems as a transport fluid in hot, dry geothermal resources.
- Closed-loop systems can restore some idle wells to productivity.
- Additional research and field-scale demonstration should be done with supercritical CO_2, other refrigerants, and water to optimize closed-loop geothermal architecture and handling procedures.

Benefits to California

Senate Bill 100 (De León, Chapter 312, Statutes of 2018) creates a mandate for California to transition to clean energy resources instead of fossil fuels. With closed-loop geothermal technology, geothermal can play an important part in that transition while providing baseload generation, which improves grid reliability and supports increasing amounts of intermittent renewable energy resources. In May 2019 the California Public Utilities Commission set a target of an additional 2,500 megawatts (MW) of geothermal capacity by 2030.

At present, however, growth is limited due to a scarcity of geothermal sites that have enough water and permeability for conventional "open-loop" projects. In other words, further development of California's geothermal resources requires a technology that doesn't depend on water or subsurface permeability.

Because closed-loop geothermal technology overcomes both these limitations, it is crucial to the expansion of the enormous geothermal resources in California that remain undeveloped.

This project demonstrates that closed-loop geothermal technology, using water or alternative heat transport fluids, can enable California to provide renewable, baseload, or flexible power on a larger scale.

CHAPTER 1: Developing Geothermal Energy in California

What Is Geothermal Energy?

Geothermal energy is the largest potential source of renewable and continuous energy on earth and offers at least two magnitudes more energy than coal, gas, and oil combined. A well-known study by scientists at Idaho National Laboratory concluded that using just 2 percent of the geothermal energy potential in the United States would be enough to supply all current U.S. power consumption for 2,500 years.[1]

Geothermal energy is the natural heat created at the earth's core by the decay of radioactive elements. That heat flows upward toward the surface through the movement of molten rock. In known geothermal resource areas (KGRAs) molten rock or steam reaches the surface in the form of volcanoes, hot springs, steam vents, or mud pots. However, because geothermal regions composed of hot, dry rock often exhibit no surface manifestations, an estimated 70 percent of geothermal resources have yet to be discovered.

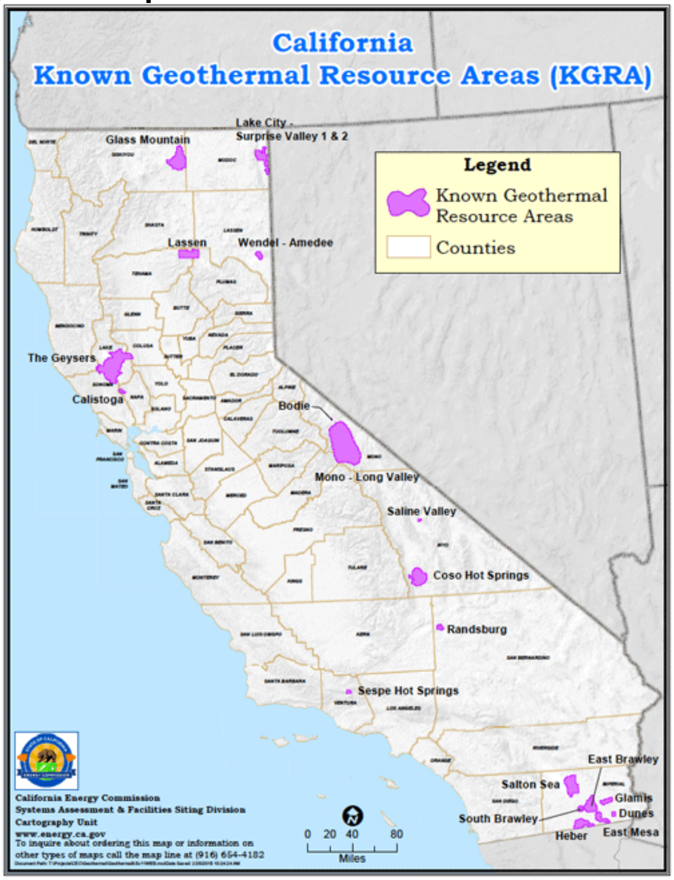
For more than 100 years, and in many regions of the world, geothermal heat has been converted to electric power. This usage is distinguished from "direct use," where geothermal heat can also be used directly for such purposes as warming buildings, agricultural hot houses, or even public swimming pools

California Has Abundant Geothermal Resources

Due to its location on the Pacific Ocean's famous "ring of fire" and residing over tectonic plate conjunctions, California contains the largest amount of geothermal electric generation capacity in the United States. In 2018, geothermal energy in California produced 11,528 gigawatt-hours (GWh) of electricity. Combined with another 700 GWh of imported geothermal power, geothermal energy produced 5.91 percent of the state's total system power. There are 43 operating geothermal power plants in California with an installed capacity of 2,730 megawatts (MW).

1 *The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century*; Idaho National Laboratory, 2006.

Figure 2: Map of California Geothermal Resources



Source: California Energy Commission

California Is a Leader in Geothermal Energy Production

Although the first geothermal power generation project was developed in Italy in the early 1900s, California developed the world's largest geothermal project at The Geysers starting in the 1970s and continued to add projects rapidly through the end of the century.

As Figure 2 indicates, many parts of California contain geothermal resources. Other than The Geysers, the largest concentrations are in the Salton Sea area in extreme Southern California and in the volcanic regions around Mammoth Mountain and at Coso.

Consequently, California has been the center of the global geothermal industry, with many of the leading geothermal engineering companies located in the state. Nevertheless, because of market conditions and the dearth of new geothermal projects in California contrasted with new opportunities in other regions, much of that expertise is being employed overseas.

How Is Geothermal Power Produced?

Using conventional methods, efficient power generation requires a geothermal resource of at least 302°F (150°C). Although there are many geothermal features on the surface, such as geysers, hot springs, and mud pots, these are rarely sufficiently large and hot for efficient power generation. Consequently, conventional geothermal power generation requires moving subterranean heat upward from 1 to 4 kilometers deep using water as the heat transport mechanism.

All conventional hydrothermal projects require geothermal reservoirs, and the most productive have a large supply of hot water trapped in a geothermal reservoir. To tap the water found in geothermal reservoirs, developers drill wells that are generally 1 to 3 kilometers deep.

Conventional Hydrothermal

Heat is extracted by production wells that may produce hot water through natural pressure or by pumping. The hot water often flashes to steam, which is used to drive a turbine. In other configurations, the hot water is run through a heat exchanger that transfers the heat into a "working fluid" used to drive turbines.

After the heat is extracted, a portion of the water produced from the resource is generally condensed and returned underground by injection wells. The water then is reheated and may migrate toward a production well to complete the cycle.

Conventional hydrothermal systems suffer two important constraints. First, there must be a high level of subsurface permeability to allow the flow of water through hot rock. Second, hydrothermal projects rely on large volumes of "process water" to transport heat to the turbine. But much of that water is unavoidably lost to hidden fractures in the surrounding rock, so makeup water is continually required. Heat extraction is a direct function of the amount of water flow between injection and production wells for a given temperature.

Engineered Geothermal Systems

To address the permeability problem, the U.S. Department of Energy and the geothermal industry have experimented with a technology called enhanced geothermal systems (EGS). EGS uses hydraulic fracturing to create small fractures that collectively increase permeability within a geothermally heated reservoir. Large volumes of water are then circulated through the system to create an artificial version of a conventional hydrothermal reservoir.

Despite more than three decades of investment, research, and experimentation, EGS has yet to attain commercial viability. Hydraulic fracturing is not only complex, risky, and expensive, but the resulting system still requires enormous water resources. EGS projects require substantial volumes of water not only for the hydraulic fracturing process, but, on a continuous basis, for heat transport through the system and to make up for significant fluid loss into the surrounding rock formations.

Why Has Geothermal Development in California Dramatically Slowed Down?

For a variety of interrelated reasons, geothermal development in California is declining. First, the best and most obvious sites for conventional hydrothermal projects – those with the rare combination of enough heat, water, and permeability — have already been developed. For example, the Coso geothermal area boasts a huge area of very hot rock but lacks the water to fully develop the resource. Second, a combination of federal policies, combined with state subsidies and battery storage mandates, have accelerated the development of solar and wind projects and associated battery storage. This sort of government support is also needed for the geothermal industry. Third, geothermal is more expensive, and geothermal plant operators must pay property taxes. In contrast, solar energy projects do not pay property taxes, giving the industry a competitive advantage. Fourth, compared to wind and solar projects, feasibility studies for geothermal projects are significantly more expensive and complex. Finally, conventional hydrothermal projects require six to seven years before first revenue compared to fewer than two years for most wind and solar projects. Further, even excellent hydrothermal resources degrade over time. For example, at peak, The Geysers had a gross capacity of about 1,500 MW. Now, due to well degradation, water issues, and other problems, actual capacity is only about 750 MW.

Closed-Loop Geothermal Is Important to California's Energy Future

Expanding the Scope and Efficiency of Geothermal Power Generation

The heat available from California's geothermal resources is effectively unlimited, so with improved technology, geothermal power can become a more significant part of California's electricity portfolio. That potential led the California Public Utilities Commission to target installation of an additional 2,500 MW of geothermal capacity by 2030.

Because GreenFire's closed-loop geothermal technology system overcomes the limitations associated with low subsurface permeability and water availability, it can enable a vast expansion of geothermal power generation. In fact, ensuring enough flow of heat from the geothermal resource to the surface using an appropriate heat transport fluid is the core rationale for closed-loop geothermal systems. This flow of heat is crucial because, in general, hot, dry rock formations contain more than 90 percent of existing geothermal heat. Such formations are not only too impermeable for conventional hydrothermal operation, but generally such regions have significantly higher temperatures than more shallow and permeable formations. In short, closed-loop systems provide the heat transport required by EGS and conventional hydrothermal systems but without relying on natural permeability or the availability of large water resources.

Further, because closed-loop systems are sealed to prevent fluid loss, it becomes economically possible to consider using more costly alternative fluids, such as sCO_2, instead of water as the transport fluid. SCO_2 and other refrigerants may be superior to water for heat transport and power generation. Although properly sealed and cemented closed loops are unlikely to leak, some fluids, such as water and CO_2, occur naturally in most geothermal areas and would not pose an environmental risk. Also, various sealing systems can be employed to fix or prevent leaks. Regardless of the choice of transport fluid, closed-loop systems enable power generation in areas where water is limited.

Closed-loop systems are also capable of removing more of the heat from a given geothermal site. This capability is important because, according to the U.S. Geological Survey (USGS), hydrothermal projects generally remove only about 10 percent of the available heat from a given resource. This occurs because heat can be removed only from those portions of the resource that have natural fractures to allow fluid flow; the rest of the heat is stranded. In contrast, GreenFire research shows that closed-loop wells can be spaced at close intervals for intensive heat extraction. By accessing a higher percentage of available heat, closed-loop systems reduce the levelized cost of energy (LCOE) and provide higher returns on project development expenditures, fixed assets, and transmission.

Additional Advantages of Closed-Loop Geothermal Systems

Efficiency, Flexibility, and Scalability

- Modular construction can scale more precisely to the resource or the power demand.
- Modular deployment allows variable output to meet fluctuating grid requirements.
- The transport fluid remains free of chemical reactions and contamination that can occlude or corrode well casings and surface equipment.
- Where enough water (brine) is present (in other words, not in hot, dry rock), the brine can be induced to flow upward around the closed loop to add convective heat to the system.

Grid-Balancing Capability

- Baseload power complements solar and wind, which are available less than 30 percent of the time

Environmental Advantages

- Does not affect subterranean water supply.
- Does not release greenhouse gases to the surface.
- Does not induce earthquakes.
- Does not cause soil subsidence.
- Safe for wildlife on the ground or in the air.

Unique and Superior Resiliency and Security

- Resilient: Recent 7+ magnitude earthquakes near Coso did not interrupt power generation at the Coso Operating Company or damage the GreenFire demonstration project.
- Secure: Largely underground, the system is less susceptible to terrorist or military attack.

CHAPTER 2: Project Overview

Project Scope

This project explored the ability of a closed-loop, downbore heat exchanger to produce geothermal power using sCO_2 and water as alternate working fluids. The data generated from the experiment validate and improve GreenFire's closed-loop geothermal models. These models are essential to guiding the large-scale commercialization of closed-loop geothermal that will reinvigorate California's moribund geothermal industry.

The project team considered several idle geothermal wells at Coso for the demonstration project. The team selected Well 34-A20 because of these attributes:

- Good structural integrity with undamaged well casing
- Previously productive but currently idle
- Bottom hole temperature > 392°F (200°C)
- Brine flow of at least 2.6 gallons (10 liters) per second
- Accessible for construction and equipment installation

Project Steps

Preliminary Well Assessment

Coso is known as a significant high-temperature geothermal resource constrained by a limited water supply. Although Coso wells tend to be very hot – generally more than 392°F (200°C) bottom hole temperatures – power generation is limited because this high desert area has limited water availability. As these conditions are representative of geothermal conditions in much of California, Coso was an obvious choice to demonstrate a closed-loop system.

Agreement With Coso Operating Company

GreenFire worked closely with Coso Operating Company to create an agreement to use Well 34-A20 for the demonstration project subject to GreenFire obtaining required permits and meeting conditions related to construction and site restoration. In return, Coso Operating Company agreed to provide a significant amount of matching contributions for the project in the form of in-kind services, donated materials, and payments to third-party contractors.

Permitting

As the Coso area is already a producing geothermal area and fully permitted for such use, existing permits at the Coso geothermal field applied to the project and simplified permitting compliance. However, for this project, a California Environmental Quality Act notice of exemption was obtained from the Great Basin Unified Air Pollution Control District.

Contract With Veizades & Associates as Project Manager

After having discussions with and receiving proposals from several geothermal engineering companies, GreenFire selected Veizades & Associates as the initial project manager to provide the surface system design and arrange construction of key portions of the project. Veizades has had significant onsite experience at the Coso geothermal field and other geothermal projects around the world.

Detailed Well Assessment

One of the first tasks undertaken by Veizades was a detailed analysis of Well 34-A20, including a review of all well records and new measurements of well attributes such as temperature, pressure, brine flow, and brine composition.

Engineering and System Design

Because of the many unknowns involved in designing a field-scale, closed-loop, downbore heat exchanger (DBHX) system, the project team considered and analyzed different configurations before choosing the best way to construct the project. This complexity was increased because the physical system needed to accommodate the high pressures associated with supercritical CO_2 (sCO_2) over a more conventional water-only system. To ensure leak-free working fluid circulation in the closed-loop and avoid the possibility of damaging the well casing, a 7-inch (17.78 centimeters) liner was inserted inside the casing.

Procurement

The special requirements of the project necessitated a special procurement process for the unusual and custom components. For example, the sections of coaxial vacuum-insulated tubing (VIT) comprising the DBHX required custom threading to achieve joints capable of dealing with the weight of the joined tubing and the pressure of sCO_2. Coso Operating Company was extremely helpful in managing the procurement and identifying alternative sources and types of components for the project. Equipment started arriving on site in December 2018.

Construction

Although Well 34-A20 was already drilled and cased, it needed modifications to enable the insertion of the VIT string and the installation of necessary equipment.

- Cement equipment pads needed to be poured to support the surface equipment. Figure 3 shows the equipment pad during installation of the tubing and surface equipment.

Figure 3: Equipment Pad and Partial Installation

Source: Coso Operating Company

- The most important construction task was the installation of 1,082 feet (330 meters) of 7-inch (17.78 centimeters) casing into the well and placement of the slightly shorter VIT into the 7-inch casing. This process is shown Figure 4.

Figure 4: Installation of Vacuum-Insulated Tubing

Source: Coso Operating Company

Testing

- **Water:** Because water is the transport fluid for conventional hydrothermal projects, it was important to establish a baseline for closed-loop systems using water as the transport fluid. However, in this project water was used not only as the transport fluid but also as the working fluid for water testing.

- **Supercritical sCO_2:** Supercritical carbon dioxide (sCO_2) is carbon dioxide in a phase that is neither liquid nor gas but has properties of both in that it is dense like a liquid but entirely fills a volume like a gas. The critical point for carbon dioxide is a sufficient combination of temperature and pressure to cause it to achieve this phase. The fluid is referred to as "supercritical" when the carbon dioxide temperature and pressure remain sufficient. Supercritical CO_2 is one of a class of fluids used as refrigerants because it is highly compressible without going through a phase change that releases or requires energy. Because of these properties, sCO_2 creates a stronger "thermosiphon" that moves the sCO_2 through the system because of the high-density differential between the descending cool and ascending hot columns of sCO_2. Supercritical CO_2 was proposed as an alternative to water as the transport and working fluid because the strong thermosiphon can reduce or eliminate the parasitic power loss associated with pumping water. Also, for deeper and hotter wells, the density differential and related thermosiphon effect are expected to get stronger.

CHAPTER 3: Project Design, Construction, and Equipment

Setting and Equipment Layout

The setting for the project is shown in Figure 5 below. The above-ground surface equipment consists of a heat rejection system and a feed pump or compressor.

Figure 5: Installation at Well 34-A20 at Coso

Source: GreenFire Energy

Figure 5 shows the demonstration equipment during testing when the well was flowing brine and the closed-loop downbore heat exchanger was flowing with water as the working fluid. In the figure, the wellhead is in the center of the photo, with the inlet and outlet of the closed loop at the top of the wellhead. The vessel on the left is the closed-loop water holding tank. The vessel on the right is the well silencer. The blue water tanks in the background are used to store freshwater, used for makeup water.

Figure 6 shows a view of the installation from the opposite direction looking across the surface equipment. Much of the foreground of this photo is equipment required for the circulation of sCO_2. The silencer in the upper right is the tank that holds the water circulating inside the closed loop when water was tested as the working fluid. Seen at the base of the water tank from right to left: (1) the blowdown line to the sump, (2) the feedwater pump inlet, (3) the level indicator, and (4) the return two-phase flow line to the silencer.

Figure 6: Surface Equipment Layout

Source: GreenFire Energy

The feedwater pump is not seen in the image because it was installed underground to account for net positive suction head inlet pressure requirements for the pump. The closed-loop water path is clockwise in the picture, from the tank to the well, then back around to the closed-loop water pressure control valve (PCV 2). PCV 2 can be seen at the top of the image just to the right of the wellhead. All the equipment on the left side of the concrete pad is for circulating sCO_2 (air compressor, chiller, feed pump, blower, heat exchanger, and water-pressure control valve for cooling).

In the foreground is the surface heat exchanger. Just past the surface on the left side (front to back) is the feed pump, the chiller (to keep the supply pump from prematurely vaporizing the CO2 while it is loaded), the supply pump, the compressor (used to power the feed pump), and the electrical panel. The center of Figure 6 at the back shows the well with three connections (top to bottom): the VIT inlet, the DBHX outlet, and the well outlet (to the atmospheric flash tank silencer shown in Figure 5.) The insulated pipe works in the middle of the picture with the yellow-handled valves make up the rest of the surface equipment (shown in detail in later figures). The DBHX flow PCV is just visible on the right side beyond the heat exchanger.

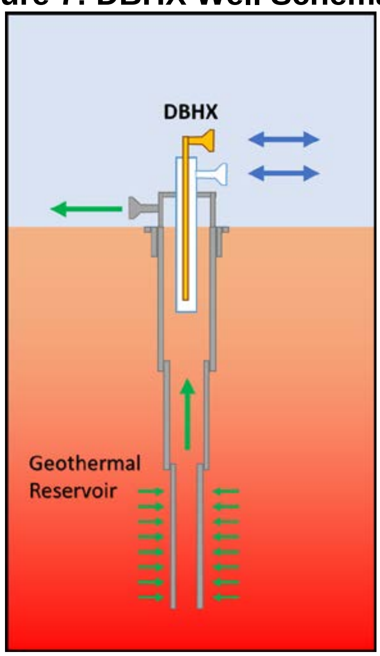
Downbore Heat Exchanger

A downbore heat exchanger is simply a tube-in-tube assembly installed into an existing well. The DBHX is hung from the existing wellhead. Modifications to the wellhead are provided so that the transport fluid can be introduced into the DBHX. Transport fluids can be water, supercritical carbon dioxide (sCO_2), or other refrigerants.

The DBHX consists of a liner inserted into the well with a plugged end at the lowest point. The geothermal brine can flow around this liner and may be produced to the surface. Inside the plugged liner, a VIT is installed, extending nearly to the bottom of the liner. The transport fluid is circulated to the bottom of the DBHX. The flow direction of the transport fluid can be selected depending on the characteristics of the transport fluid. The transport fluid extracts heat from the flow of coproduced geothermal fluid rising in the outer annulus, or ring, between the well casing and the DBHX (Figure 7).

The DBHX is designed to remove enthalpy, the total heat content, from the geothermal resource as the geothermal fluid is produced. Enthalpy is calculated as the internal energy of the system plus the product of pressure and volume. The chief advantage of the DBHX is that the transport fluid is exposed to the higher brine temperatures near the bottom of the DBHX relative to the temperatures at the exit of the well (at the surface). As such, the transport fluid can reach the surface at a higher temperature than the produced geothermal brine. When water is used as the transport fluid in the DBHX, the net effect is to produce steam that does not contain non-condensable gases (NCGs). NCGs include undesirable gases such as hydrogen sulfide and CO_2 that contribute to air pollution or global warming if released into the atmosphere. Similarly, when sCO_2 is used as the transport fluid, the sCO_2 is heated and available to make power directly.

Figure 7: DBHX Well Schematic



Source: GreenFire Energy

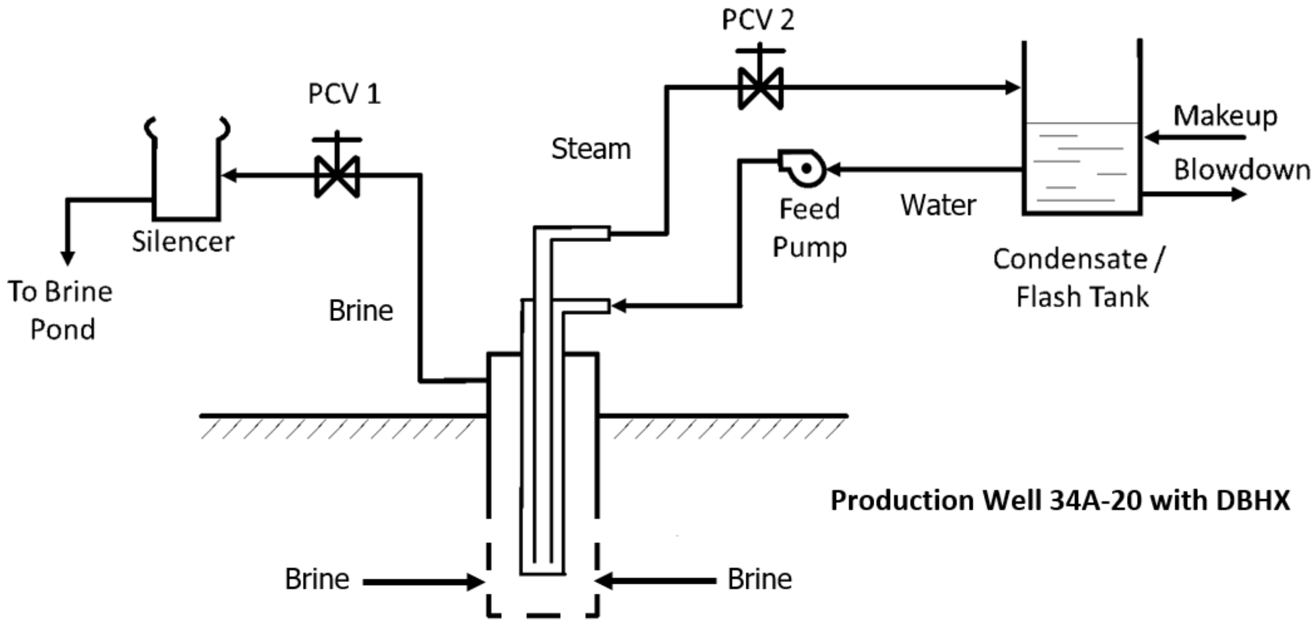
A key decision was made to add a 7-inch (17.78 centimeters) casing to the well. Although Well 34A-20 was determined to have good integrity, adding the casing avoided the possibility of problems arising from gaps or variations in the existing casing that might affect heat transport or the long-term well survivability after being exposed to high-pressure CO_2. The team installed a 7-inch liner, capped at the bottom, into which the VIT was inserted. This installation not only assured the consistent flow of working fluids but allowed brine to flow in the annulus around the 7-inch liner to increase heat transfer into the VIT.

CHAPTER 4: Tests Conducted With Water as the Transport and Working Fluid

This project included tests to determine the performance of water as the heat transport and working fluid in a closed-loop geothermal system.

Figure 8 shows a process flow diagram for water flow in the DBHX. The flow direction for water in the DBHX is (1) down the annular portion of the DBHX and (2) up the center of the VIT. By flowing in this direction, the water flows counter to the geothermal temperature gradient, thus maximizing the water production temperature and enthalpy extraction from the well. Brine flows around the DBHX and travels upward to the surface while heat is extracted into the DBHX.

Figure 8: DBHX Process Flow With Water



Source: GreenFire Energy

Two parameters can be varied in this arrangement: (1) the flow rate of geothermal brine produced to the other silencer (using a pressure control valve “PCV 1”) and (2) the flow rate of water through the closed-loop system (using PCV 2).

The flow of geothermal brine to the silencer (through the pressure control valve, PCV 1) was analyzed for (1) the flow rate of steam, (2) the flow rate of brine, (3) the NCG content in the steam, and (4) the chloride and sodium content in the brine. From these data and pressure, the enthalpy can be deduced.

Because the steam is removed from the loop, makeup water is required. Outside the DBHX, a silencer (normally used to reduce the noise caused by venting steam) is repurposed as a water-holding tank to maintain water level. Water is circulated from this tank, through the DBHX, and returns to the tank. A portion of the returning water flashes to steam at atmospheric pressure. A small portion of the tank water is blown down to the sump to reduce salinity buildup. The makeup water is equal to the portion of steam generated plus the small volume of water lost in the blowdown process.

The flow of water through the closed loop is provided by the feed pump, and the flow rate is controlled by the downstream PCV 2. The circulating water generally flashes across PCV 2. A small portion of blowdown is controlled (~5 gallons per minute [GPM]), and makeup water is added to maintain an appropriate level in the water tank.

Testing Procedures

Data are presented in Table 1 below for the closed-loop DBHX flowing with water while producing the well in May 2019. The well was cycled through three different brine production rates: low, medium, and high (described below). Likewise, the water in the closed-loop DBHX was circulated with three circulation rates: low, medium, and high, which correspond to about 41, 74, and 133 thousand pounds per hour (Kph). NCGs averaged 23 percent by weight of the produced flow. The project team investigated six combined flow conditions (four of which had simultaneous well flow rate and enthalpy measurements).

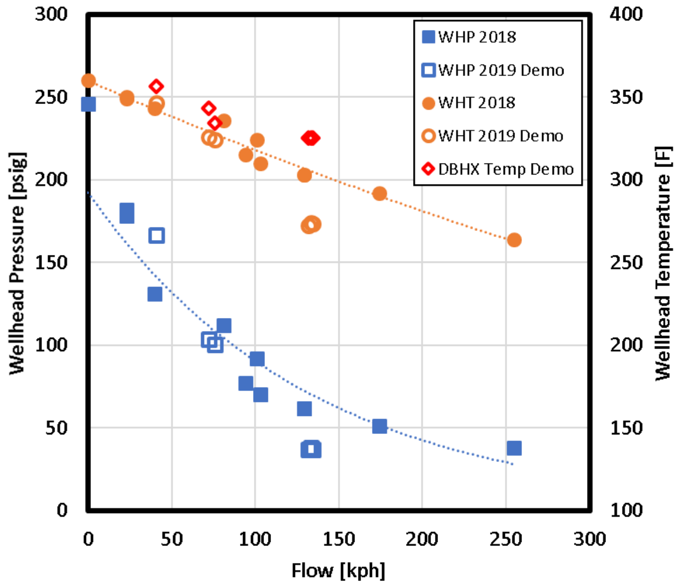
Table 1: Test Cases

Test Number	Well Flow	Closed-Loop Flow	Enthalpy Testing
1	High	High	Yes
2	High	Medium	No
3	High	Low	Yes
4	Medium	Low	No
5	Medium	Medium	Yes
6	Low	Medium	Yes

Source: GreenFire Energy

In December 2017 (before the DBHX was installed), the research team performed a well-flow test to measure wellhead pressure (WHP) and wellhead temperature (WHT). Those data points are plotted in Figure 9 using closed symbols versus the total well flow rate. Similarly, the WHP and WHT data corresponding to the test conditions in Table 1 during DBHX testing are depicted as open symbols. The red open diamonds in Figure 9 represent the closed-loop DBHX water-exit temperature for the corresponding well-flow conditions. For every case, the water returns from the well at a higher temperature than the geothermal brine that exits the well because the geothermal brine and closed-loop water flow countercurrent to each other. The closed-loop water flows downward to the bottom while absorbing heat from the upflowing geothermal brine and then returns to the surface through the VIT.

Figure 9: Wellhead Pressure and Temperature vs. Total Well Pressure



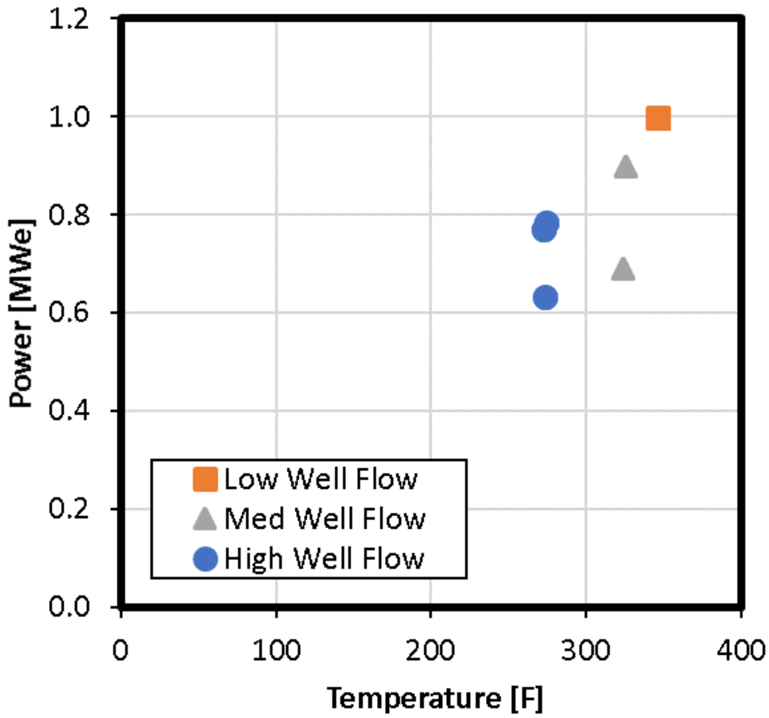
Source: GreenFire Energy

The change in enthalpy to the closed-loop transport and working fluid can be compared to the change in enthalpy of the brine for Tests 1, 3, 5, and 6 of Table 1, where enthalpy testing was simultaneously performed. This comparison is valid because the liquid measured in the well flow had virtually no dissolved solids. The data indicate that the well was producing steam and NCGs only, and that the measured liquid is steam condensed by the flow. Simply taking the latent heat of vaporization multiplied by the measured liquid flow exiting the well, yields enthalpy extraction of 8.9, 7.5, 9.0, and 9.2 MW thermal for tests 1, 3, 5, and 6, respectively.

At the same time the enthalpy was being measured, the project team also measured the closed-loop water flow rate inlet temperature and pressure. The closed-loop flow is always a liquid before it encounters control valve PCV2. The enthalpy increase in the closed-loop flow is a simple calculation of the specific enthalpy difference entering and leaving the closed-loop multiplied by the flow rate, which are calculated as 9.4, 7.6, 10.4, and 11.3 MW thermal for the same four tests, respectively. The average deviation between these data points and the ones in the paragraph above is 10 percent, which is reasonably close.

Although the experiment uses an atmospheric pressure silencer as a holding tank for the recirculated water, it is simple to determine the amount of steam that would be produced at the Coso steam gathering system pressure. At the exit of the DBHX, the water pressure is well above the saturation pressure for the produced temperature. This means that the DBHX water is 100 percent liquid. As such, the enthalpy can be calculated using temperature and pressure only. To determine the flashed quantity at the Coso gathering system pressure, the quality is then calculated using the same enthalpy and the gathering system pressure. Coso's low-pressure turbines with about 30 kph of steam produces 1 megawatt of electricity. The power predictions are plotted in Figure 10 versus the wellhead temperature. The data shown in Figure 10 do not include a parasitic power loss of about 130 kW attributable to the feedwater pump.

Figure 10: Power Potential for Water Flash to Steam vs. Wellhead



Source: GreenFire Energy

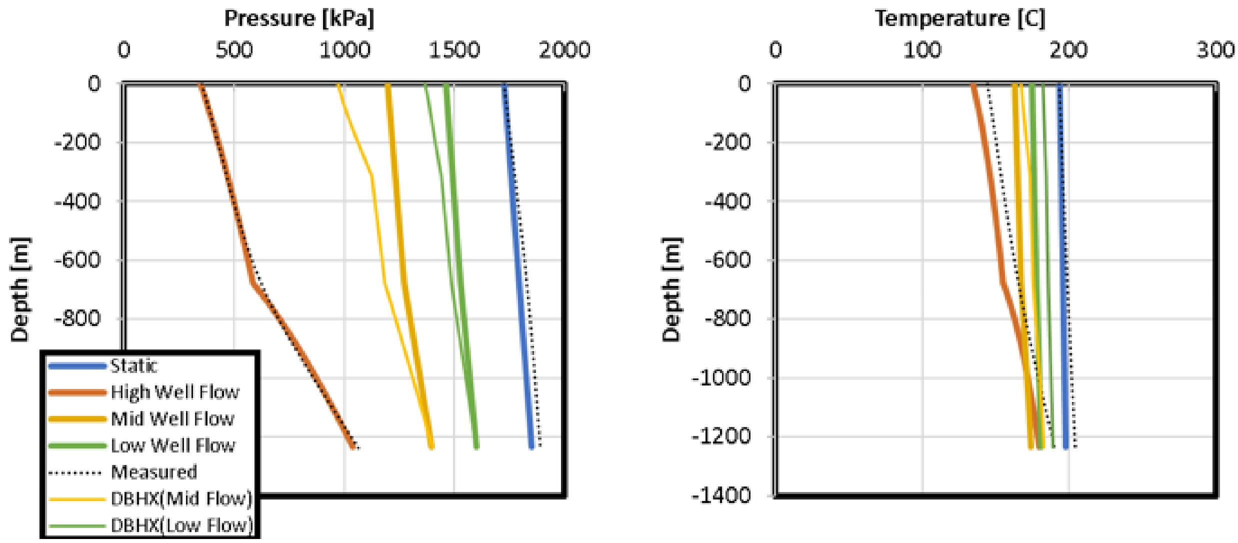
As expected from the modeling, and as clearly shown in Figure 10, more power is produced when the rate of coproduced geothermal brine is reduced. This raises the temperature of the brine that meets the closed-loop downhole heat exchanger, allowing the heat exchanger to absorb more heat.

Well-Flow Modeling and Measurements

In December 2017 (before the DBHX was installed), the research team performed well productivity testing, including downhole flowing and static surveys. The measured downhole temperature and pressures are plotted in Figure 11 using dotted lines. As expected, both the temperature and pressure are lower when the well is flowing.

For each of the well flow conditions in Table 1, the closed-loop flow was modeled while modeling the geothermal brine flow (orange for high, yellow for medium, and green for low well flow). The bold orange line ("High Well Flow") is the modeling data that corresponds to the flowing well survey. Both the temperature and pressure follow the measured values. Likewise, the bold blue line ("Static") is the modeling data that correspond to no flow being produced by the well. Again, the downhole temperatures and pressures closely match the measured values.

Figure 11: Temperature and Pressure vs. Depth for Measured and Modeled Data



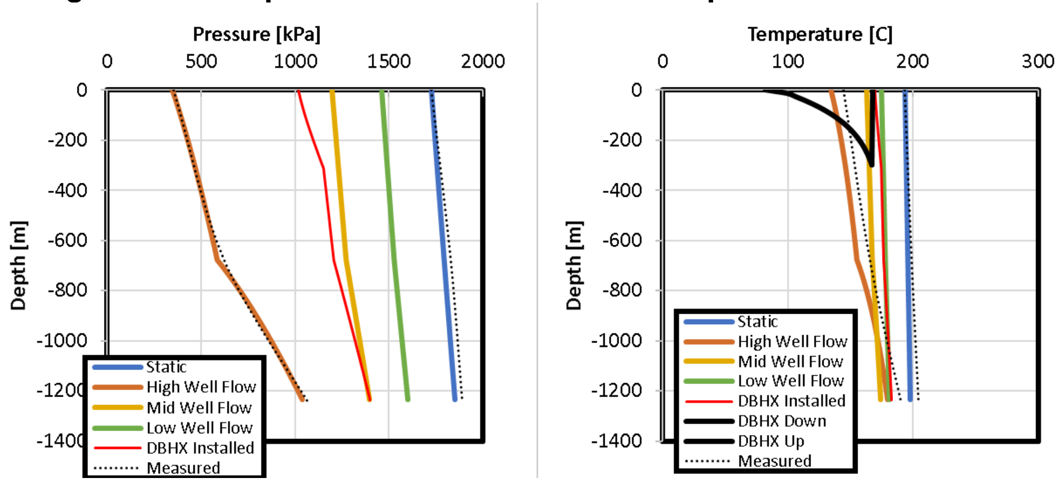
Source: GreenFire Energy

For the mid- and low-flow cases, only surface temperature and pressure were measured and the plotted data in Figure 11 represent modeled data only. The thin lines of the same color are for the same flow rates but with the DBHX installed. The DBHX creates more pressure drop in the well, and this is seen as a higher change in pressure from the bottom of the well to the exit of the well (for the same flow).

For each of the well flow conditions in Table 1, the closed-loop flow was modeled while modeling the geothermal flow. Figure 12 shows one such condition, where the closed loop has the flow corresponding to "Test 4" in Table 1. The light red line shows the modeled conditions with the closed-loop in operation. These data can be directly compared to the yellow line (Med Well Flow) data modeled using the same well flow but without the closed-loop heat exchanger. The bold black lines in the right image in Figure 12 are the temperature within the DBHX, showing increasing temperature as the water flows downward and constant temperature as water is extracted through the VIT.

Also, the differences between the thin yellow line in Figure 11 (with no flow in the DBHX) and the thin red line in Figure 12 (with DBHX flow) are minimal, as it is largely the steam quality of the well flow that is changing the most (not pressure or temperature).

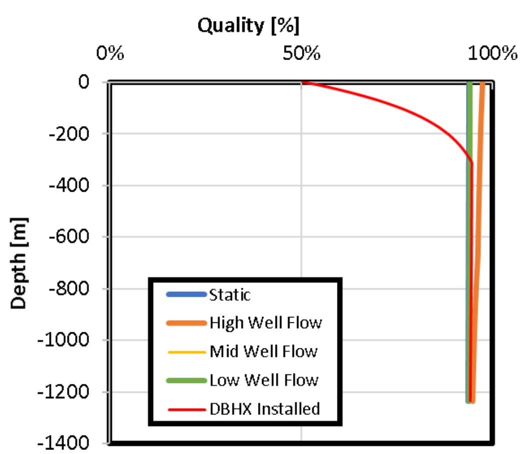
Figure 12: Temperature and Pressure vs. Depth for One Test Case



Source: GreenFire Energy

In Figure 13, the quality of each flow of brine, using the same color scheme as for Figure 12, is plotted versus depth. This figure shows that in all cases the brine flow leaving the well is nearly 100 percent quality (or dry steam). But with the closed-loop heat exchanger installed, the steam quality drops markedly. The steam converts to liquid water on the well side of the heat exchanger, and a matching enthalpy rise occurs inside the heat exchanger. By passing a large flow rate of water through the closed loop, a portion of this water is flashed to steam at the system pressure for each circulation. As discussed above, the portion of flashed closed-loop steam is roughly equal to the portion of condensed geothermal steam.

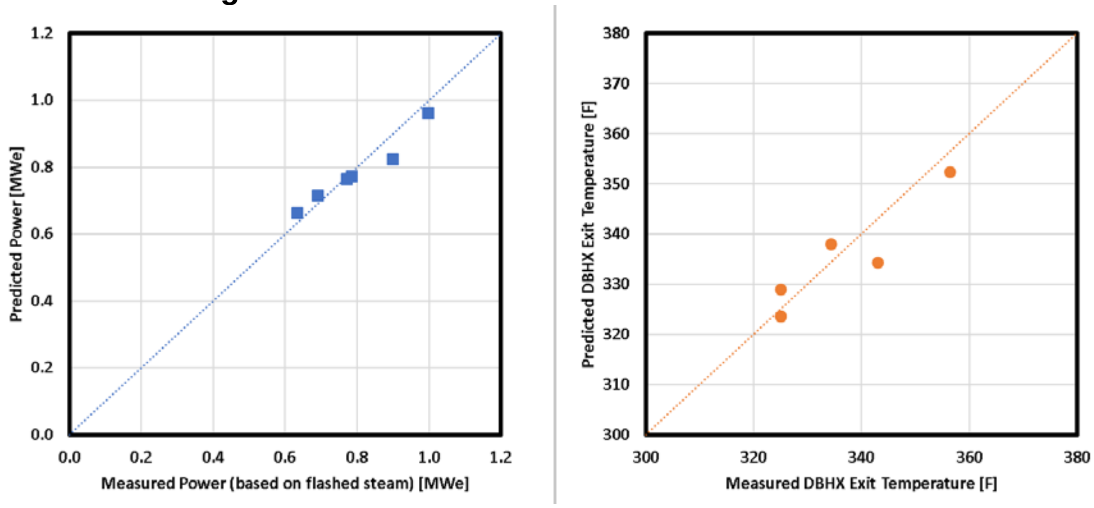
Figure 13: Steam Quality vs. Depth



Source: GreenFire Energy

In Figure 14, the predicted power is plotted versus the measured power (as deduced by the quantity of steam produced by the coproduced brine for each test) for all six test conditions in Table 1. Also, the predicted closed-loop outlet temperature is plotted versus the measured temperature. The model inputs for each case require only the following information: the closed-loop water circulation rate, the closed-loop water inlet temperature, the well production rate, and wellhead pressure. The dotted lines in Figure 14 represent X=Y. The closer the datum is to this line, the more representative the model predicts the measured results. The power data plotted in Figure 14 do not include the parasitic power required for the pump, which is ~130 kW.

Figure 14: Power Predictions vs. Measurements

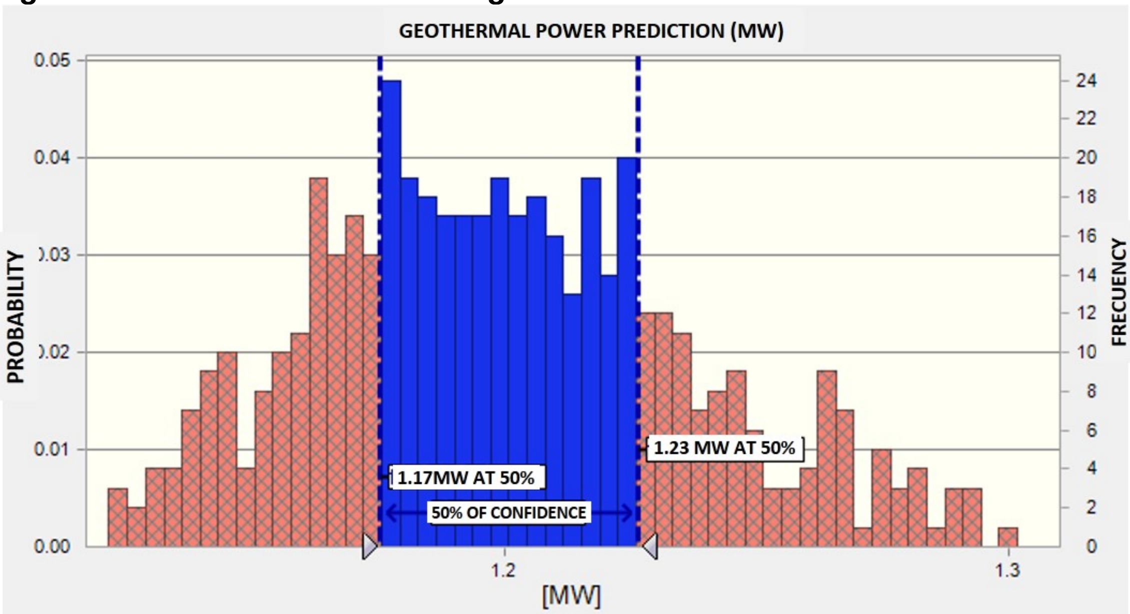


Source: GreenFire Energy

Optimization

The team considered 18 variables that could be modified to optimize power output (see the list of variables in Appendix A). A method called "Principal Component Analysis" was used to determine which of these variables have the greatest effect on power generation. Then using one-dimensional thermodynamic equations containing the "principal" variables, the team ran multiple simulations using random values for the principal variables (a method called Monte Carlo simulation). These virtual tests revealed that the system could be optimized to produce 1.2 MW, with ±0.3 MW of interval at 50 percent confidence. This result is shown in the probability histogram of Figure 15. Both methodologies consider that virtual test conditions can increase power produced by about 20 percent.

Figure 15: Power Estimates Using Monte Carlo Simulation and 1-D Modeling



Source: GreenFire Energy

Conclusions of Testing With Water as the Transport and Working Fluid

The primary goals of the testing with water as the transport and working fluid were to demonstrate the effectiveness of a closed-loop heat exchanger under various operating conditions and verify the accuracy of modeling before the tests. Both purposes were realized as the modeling results successfully predicted about the same production rate of steam as was measured in the field.

Installing a DBHX into a well that coproduced steam generated the equivalent of about 1 MW net electrical power using water as the transport fluid. The parasitic power loss was about 13 percent of the production potential. Makeup water was required at about 30 kph, which for this well could be produced from the condensate leaving the well silencer.

To further investigate the performance of the DBHX, the research team created a geothermal power coproduction equation as a function of flows using statistical modeling. The analysis suggests that, with optimization of system components, up to 1.2 megawatts of electric power (MWe) could be produced using 12 kph of brine flow and 510 gallons per minute (GPM) of closed-loop flow.

Additional analysis using Monte Carlo simulation method in combination with 1-D thermodynamic closed-loop modeling equations estimated the power production limits of this optimized configuration at between 1.18 MWe and 1.24 MWe with 50 percent confidence. This result represents an increase of 20 percent over the power measured through testing. The good “fit” between the results estimated by these two methods validates the results. Principal Component Analysis, with Bayesian statistical modeling techniques and Monte Carlo resampling analysis, confirms the 1-D thermodynamic analysis set forth above, can be used for optimizing performance, and is described in Appendix A.

CHAPTER 5: Tests Conducted With Supercritical CO_2 as the Transport and Working Fluid

Overview

The primary goal of this demonstration was to verify GreenFire Energy's supercritical CO_2 process modeling assumptions and illustrate the power production potential of closed-loop geothermal technology at different conditions (Amaya et al. 2020).

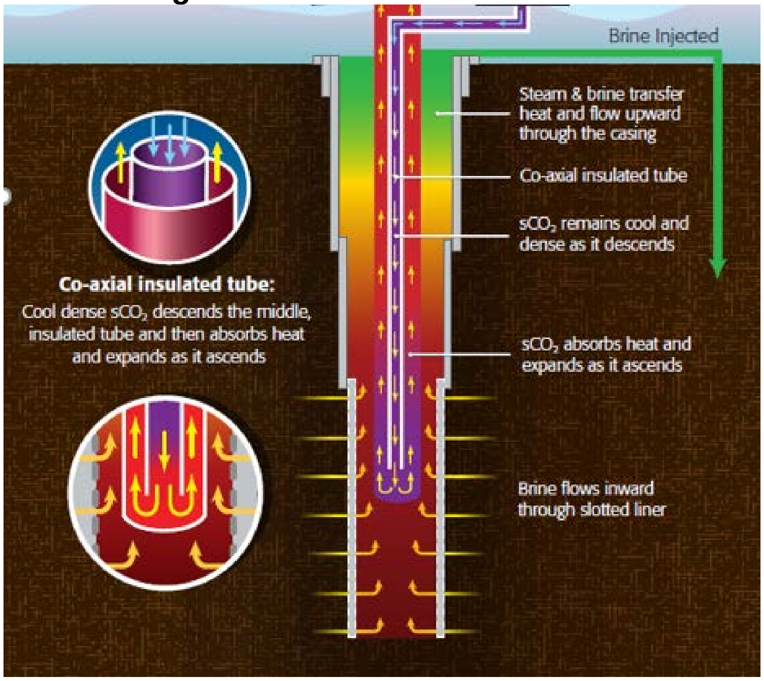
In this demonstration, sCO_2 was circulated through a 1,083 feet-long (330 meters) tube-in-tube DBHX, hung from the wellhead. During testing, the well coproduced steam at four flow rates (including zero flow), combined with five flow settings of circulated sCO_2.

Fluid Flows

The DBHX was hung from the existing wellhead with modifications so that the working fluid can circulate through the DBHX independent of the production of brine outside the VIT. The DBHX consists of a liner plus VIT. The liner had a plugged end at the lowest point. Inside the plugged liner, the VIT was installed, extending nearly to the bottom of the liner. The geothermal brine flows around the DBHX while it is produced to the surface.

Figure 16 shows the flow of geothermal fluid (brine) upward within the well and the flows of sCO_2 within the DBHX inserted into the well. The geothermal brine flows into the well and then upward along the DBHX to the surface. Supercritical CO_2 flows downward through the inside of the VIT and then returns in the annular region between the VIT and the liner. The blue arrows indicate the flow of the sCO_2 (inlet to the center of the VIT and outlet from the annular region of the DBHX). The system is designed to maximize heat transfer from the geothermal brine through the liner and into the sCO_2 in the closed loop. Conversely, the VIT is used to prevent, when possible, heat transfer between the upflowing and downflowing sCO_2. At the bottom of the VIT, the upflowing closed-loop fluid conditions are equal to the exit conditions for the downflowing closed-loop fluid.

Figure 16: Well Flow Schematic



Source: GreenFire Energy

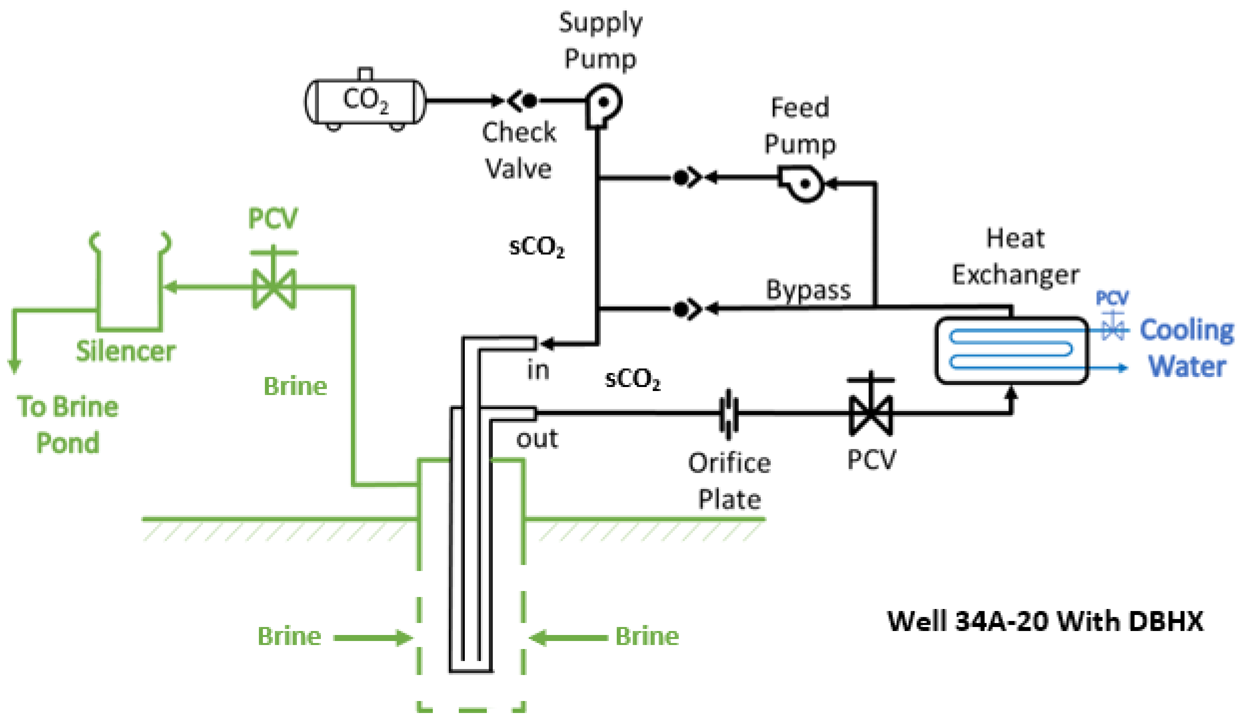
Process Flow Diagram

Figure 17 shows a process flow diagram with sCO_2 as the working fluid in the DBHX. The sCO_2 flow is depicted in purple; the cooling water flow is represented in blue; and the coproduced brine flow is shown in red as it enters the system and green as it exits. The cooling water is required to reject excess heat from the sCO_2 stream before it is recirculated in the DBHX.

Once started, the circulation of the sCO_2 is maintained as a result of a “thermosiphon” effect caused by the density differential between the cold, dense sCO_2 flowing down the center insulated pipe and the heated, expanded sCO2 flowing upward through the annulus. By flowing in this direction, the sCO_2 retains high density all the way to the bottom of the DBHX, and this density allows a strong thermosiphon to build up, maximizing the sCO_2 enthalpy production to the surface. (Although flowing the cold, dense sCO_2 downward through the annulus would have the advantage of reaching a higher temperature at the bottom of the DBHX, modeling showed that the expanded sCO_2 turning the corner and reversing direction at the bottom of the DBHX slowed down due to friction caused by high velocities, resulting in less power potential).

Because of costs and availability, a supercritical expander turbine with a generator was not used in this study to generate power directly. Instead, the sCO_2 was expanded across a control valve. To calculate the power that would be generated had a turbine been installed, the project team measured the thermodynamic state of the sCO_2 before and after the DBHX together with the measured sCO_2 mass flow rate accounting for the surface system pressure loss (including the piping, heat exchanger, and control valve/orifice plates).

Figure 17: Process Flow Diagram for Supercritical CO_2



Source: GreenFire Energy

Control Parameters

As shown in Figure 17, the equipment design for testing with sCO_2 required three PCVs that allow three control parameters to be varied:

- the flow rate of geothermal brine produced to the silencer (using the green PCV)
- the flow rate of sCO_2 through the closed-loop system (using the black PCV)
- the flow rate of cooling water (using the blue PCV)

Generally, after setting the well flow (green PCV), the well was allowed time to come to equilibrium. Then the sCO_2 flow control valve was stepped from 100 percent to 20 percent open in five equal steps.

The project team then analyzed the flow of geothermal brine to the silencer to measure (1) the flow rate of steam, (2) flow rate of brine, and (3) NCG content in the steam (23 percent wt). From this data and pressure, the enthalpy can be deduced. The flow rate of sCO_2 through the closed loop is measured using an orifice plate with a differential pressure measurement.

Figure 18 shows the sCO_2 supply pump in operation during startup and commissioning.

Figure 18: Supercritical CO_2 Injected Into the Well Just After Opening

Source: GreenFire Energy

Process Modeling for Supercritical CO_2 as Working Fluid

Modeling the Surface Equipment

In a field-scale, commercial application, the above-ground surface equipment consists of a turbine (or expander), heat rejection, and an optional feed pump (compressor). The turbine is driven by the pressure of geothermal fluid (water to steam or a change in state of a refrigerant) expansion. Because the power potential of the system depends upon the temperature difference between the cold fluid injected into the closed loop and the hot fluid entering the turbine, it is necessary to "reject" residual heat from the fluid before it is reinjected. In a field-scale application, the heat rejection is modeled using either ambient air or an evaporative water-cooling system in relation to local weather conditions (temperature, pressure, and humidity). A compressor is necessary to pressurize the fluid to the degree necessary for optimal power production.

For this demonstration, the turbine was simulated using isenthalpic (no change in enthalpy) expansion of the hot, compressed steam or sCO_2 across a control valve. The compressor was sized only to start the cycle, that is, for a small portion of the expected flow. Once the thermosiphon was established, the circulating sCO_2 bypassed the pump. To model the surface equipment, GreenFire used an isentropic efficiency assumption for the turbomachinery, typically, in the 80 percent to 85 percent range of isentropic efficiencies. For this project, a large water reservoir functioned as the heat rejection component.

Closed-Loop Modeling

GreenFire used a 1-D process model built in Microsoft Excel® to model the steady-state, closed-loop flow. This model considered conservation of mass and energy and included isentropic compression and expansion as the working fluid moved up or down the well. Friction caused by fluid movement in the well (the "Darcy" friction factor) was calculated using the well-known Haaland equation (Haaland, 1983). Friction manifests itself in the model as pressure drop. Heat transfer was modeled as 1D conduction through solid sections and as convection to fluids. The ratio of convective to conductive heat transfer (the “Nusselt number”) was calculated using the simplifying “Dittus-Boelter equation” (Bergman, 2011). Heat loss to the overburden was small and not modeled. Gas and liquid properties are called from the National Institute of Standards and Technology database using CoolProps, an Excel plug-in.

A one-dimensional, finite-volume, steady-state implicit solution scheme was used to solve the equations described above (similar to the Euler Method which calculates an approximate solution to a differential equation problem that cannot be solved by traditional methods) by considering the DBHX as a series of small lengths abutting each other. For each small length interval of the DBXH, the “next” position was calculated using two thermodynamic variables from the previous length interval, from which all other thermodynamic variables were calculated using the current position. By using a sufficiently small length interval, this solution method converged to the explicit solution. For the data presented in this report, the well was modeled with 100 intervals, 23 of which contain the DBHX.

There were three flows to be considered: the downflowing closed-loop sCO_2, the upflowing closed-loop sCO_2, and the coproduced geothermal brine. The boundary conditions were defined for the inlet of each of the three flows according to temperature, pressure and flow rate. Heat transfer from the geothermal brine to the working fluid in the closed-loop, as well as through the VIT (between the upflow and downflow working fluid), was also considered. Because the upflowing closed-loop sCO_2 conditions were equal to the exit conditions for the downflowing closed-loop sCO_2 (as the fluid “turns the corner”), the modeling solution required iteration.

The VIT did not have a continuous internal nor external diameter due to having a joint every 10 m. To account for this disruption to the flow in the friction calculation, the project team modeled the VIT with a slightly smaller inside diameter and a slightly larger outside diameter (for example, ~10 percent). More details can be found in previous works (Fox and Higgins, 2016; Higgins et al., 2016).

A relevant question is whether the system design, in terms of potential power output, was optimized for the attributes of this well. To investigate this question, the project team applied principal component analysis (PCA) and Bayesian statistics modeling techniques to the experimental data results. This process involved optimizing power production as a function of operational variables resulting from specific control valve settings for the sCO_2 and the coproduced brine. This power production function was validated by coupling the thermodynamic 1-D process model system equations and a Monte Carlo simulation method. This produced a statistic modeling capability that could consider the effects of other design variables such as the length of DBHX, the sCO_2 inlet temperature, and sCO_2 inlet flow. For more information, refer to Appendix A.

Results for Supercritical CO_2 as the Working Fluid

Data are presented in Table 2 below for the closed-loop DBHX flowing with sCO_2 while producing the well in May 2019. The well was cycled through three brine production rates:

low, medium, and high, as shown in Table 2 below. Likewise, the closed-loop was circulated with five control valve settings (20 percent, 40 percent, 60 percent, 80 percent and 100 percent). In total, the authors investigated 15 combined flow conditions in May 2019.

Table 2: Well and Closed-Loop Test Settings

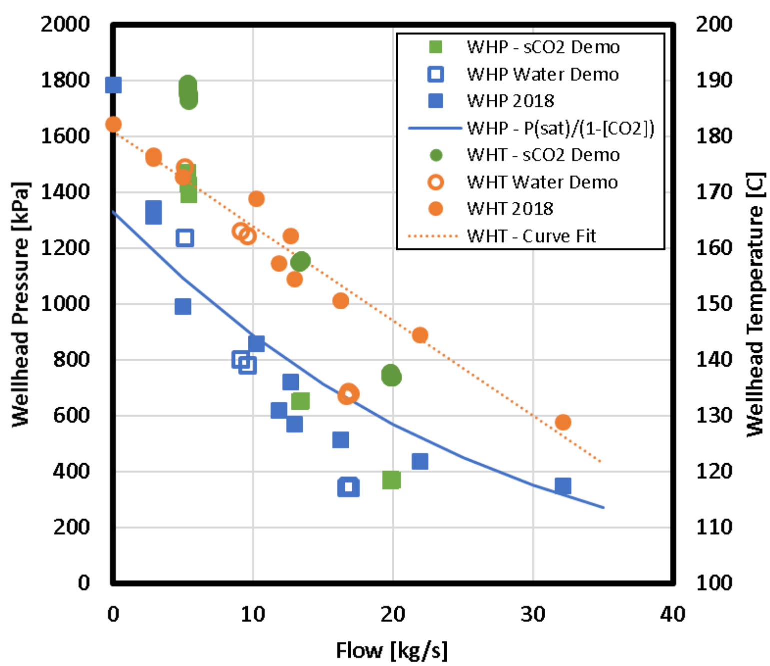
Test Numbers	Well Flow (kg/s)	Closed-Loop PCV Set Point (percentage)
A1-A5	20	20, 40, 60, 80, 100
B1-B5	13	20, 40, 60, 80, 100
C1-C5	5.4	20, 40, 60, 80, 100

Source: GreenFire Energy

Well-Flow Data

The project team collected several data sets of well-flow data. Figure 19 shows production wellhead pressure (WHP, left) and wellhead temperature (WHT, right) plotted versus total well flow (as measured in the brine collection system using an orifice plate with a two-phase flow correlation).

Figure 19: Wellhead Temperature and Pressure vs. Well Flow



Source: GreenFire Energy

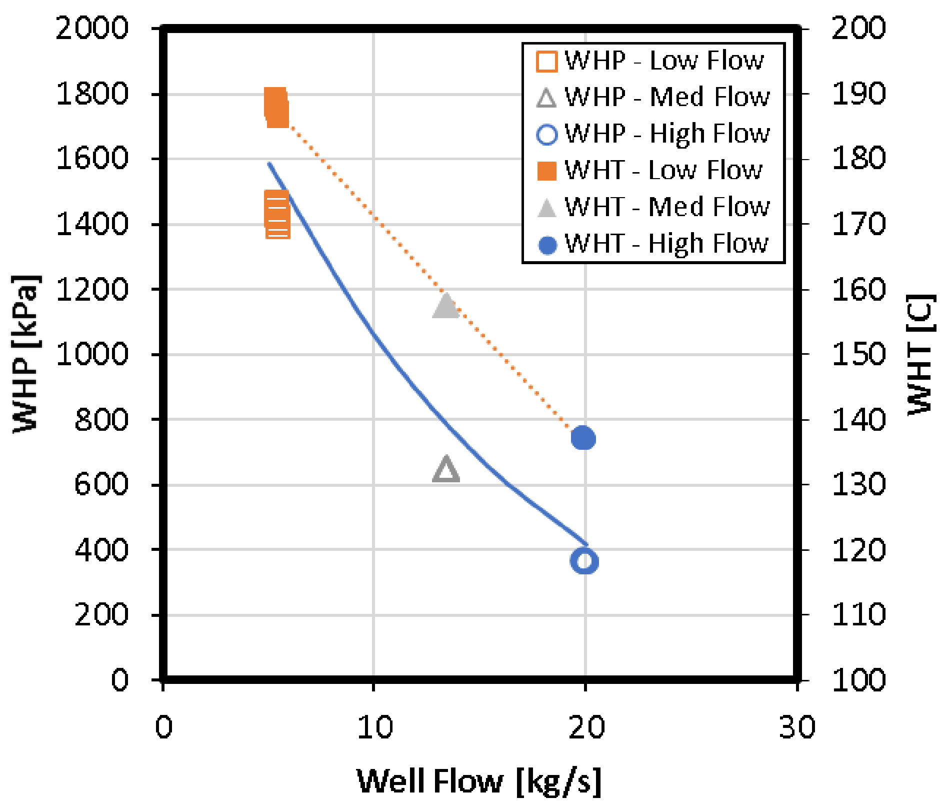
The dashed line is a linear curve fit to the temperature. The solid line is the saturation pressure (including NCGs) calculated at the curve-fit temperature. The round symbols are the temperature measurements, and the square symbols are the pressure measurements. The datum measured during the sCO_2 testing is in green. The non-green symbols represent data collected during well assessment in January 2018 and well testing that occurred during the water circulation portion of this demonstration (Higgins et al., 2019). Generally, the well brine production during sCO_2 testing was similar to the production during previous testing. This well produces saturated steam with high levels of NCGs, averaging 20 percent to 25 percent by weight.

The lines in Figure 19 represent the saturation curve of steam calculated with 23 percent NGCs (as CO_2). As the well was closed in, the flowrate of the produced stream was lowered, so the wellhead pressure and temperature simultaneously increased. The orange dotted line shows the relationship of wellhead temperature versus flowrate. For each temperature, the project team calculated the saturation pressure and plotted it versus the flowrate (blue solid line). This saturation pressure accounted for the 23 percent CO_2 concentration in the well flow. These two lines demonstrate that, as expected, the increase in wellhead temperature for lower well flow is the saturation temperature of the well at the increased wellhead pressure. This accounts for the concentration of NCGs.

Well-Flow Data During Closed-Loop DBHX Demonstration While Flowing Supercritical CO_2

Figure 20 shows the geothermal resource WHP and WHT as a function of the three well flow rates (5.4, 13, and 20 kg/s). This is simply the green data from Figure 19.

Figure 20: Wellhead Temperature and Pressure vs. Three Flow Rates



Source: GreenFire Energy

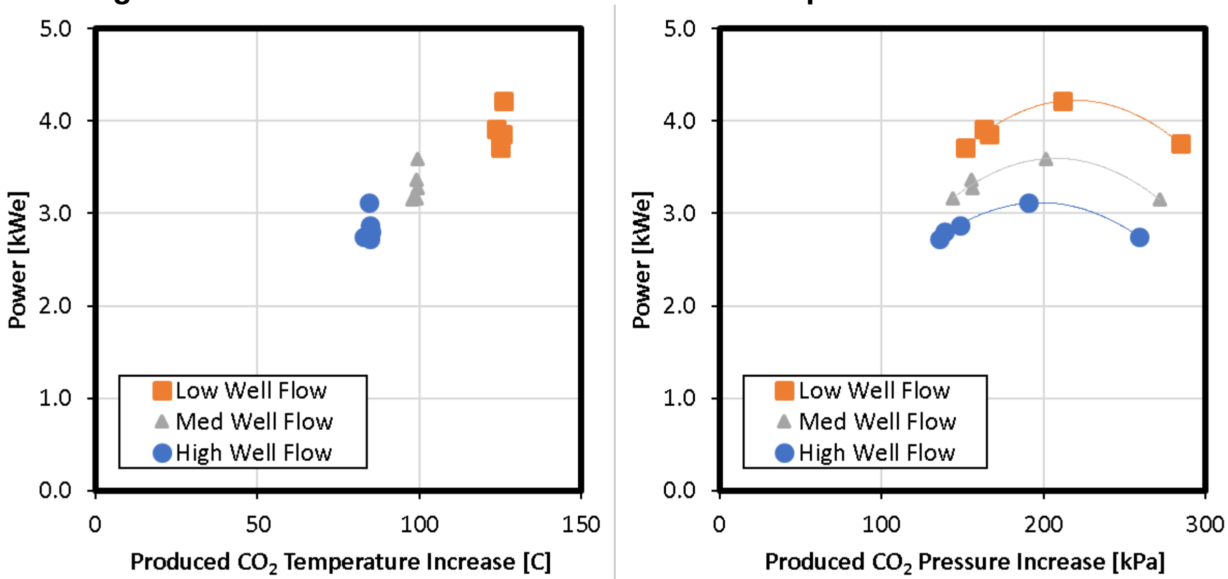
Figure 20 also portrays the relationship between WHP (open symbols) and WHT (closed symbols) of the geothermal flow plotted versus the geothermal produced flow. The dashed line is a linear curve fit to the temperature. The solid line is the saturation pressure (including NCGs) calculated at the curve-fit temperature.

The calculated power is plotted in Figure 21 versus the produced temperature increase and versus the produced pressure increase. As discussed above, to calculate the electric power potential of the circulating sCO_2, GreenFire used a simple isentropic efficiency assumption. Another assumption was made regarding the pressure drop required through a field-scale installation of the surface equipment (primarily the surface heat exchanger). The team based the turbine inlet thermodynamic conditions on the measured pressure and temperature of the sCO_2 exiting the DBHX. With an isentropic efficiency calculation for the turbine work, the team also assumed the turbine outlet pressure is equal to the DBHX inlet pressure plus 70 kPa (about 10 pounds per square inch [psi]) to account for the surface heat exchanger and piping pressure drop.

The data in Figure 21 show that more power can be generated when the rate of coproduced brine is reduced (that is, "low well flow"). Power output increases because low well flow increases wellhead pressure which in turn raises the temperature of the brine that flows around the closed-loop DBHX, thereby allowing the DBHX to absorb more heat. However, as prior modeling suggested, more power is not produced when the sCO_2 differential pressure is highest because this is associated with a substantially lower circulation rate of sCO_2 within the DBHX. The key conclusion is that the highest power production is achieved by striking a balance between a high DBHX circulation rate and high produced differential pressure.

Unfortunately, in the May 2019 testing, due to a disruption in freshwater availability, the sCO_2 return temperature at the inlet of the DBHX was 36°C when it should have been closer to the critical point temperature (31.1°C). This 5°C temperature difference near the critical point reduced the sCO_2 density by nearly 60 percent. The reduced density reduced the formation of the thermosiphon and resulted in less power than expected. This is discussed in detail later.

Figure 21: Power Production vs. Increased Temperature and Pressure



Source: GreenFire Energy

Well-Flow Modeling

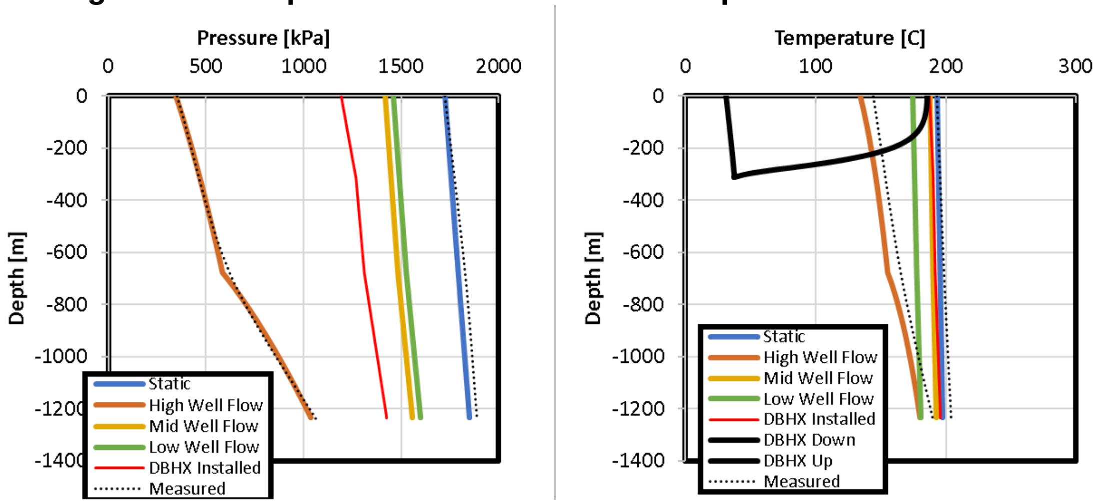
As previously mentioned, during well productivity testing, the project team performed downhole flowing and static surveys without the DBHX in place. The measured downhole temperature and pressures are plotted in Figure 22 using dotted lines. As expected, the temperature and pressure are lower when the well brine is flowing.

Figure 22 also depicts the modeled downhole temperatures and pressures for several well-flow conditions that nominally correspond to the conditions in Table 1 (orange for "high," yellow for "medium, and green for "low" well flow). The bold orange line ("high well flow") illustrates the modeling data corresponding to the flowing well survey. The temperature and pressure follow the measured values. Likewise, the bold blue line ("static") illustrates the modeling data corresponding to no flow produced by the well. Again, the downhole temperatures and pressures closely match the measured values.

For the mid- and low-flow cases, the project team measured only surface temperature and pressure, and the data plotted in Figure 22 represent modeled data only. For each of the well flow conditions in Table 1, the closed-loop flow was modeled while modeling the geothermal flow.

Figure 22 shows one such condition, corresponding to the highest power potential modeled. The bold black lines in the right image in Figure 22 are the temperature within the DBHX, showing a small temperature increase as the sCO_2 flowed downward inside the VIT but a large temperature rise as it flowed back up the annular region between the VIT and the DBHX outside liner. Due to the flow direction, the geothermal brine and sCO_2 arrived at the surface at about the same temperature (compare the top of the red and black lines in the right figure).

Figure 22: Temperature and Pressure vs Depth for One Test Case

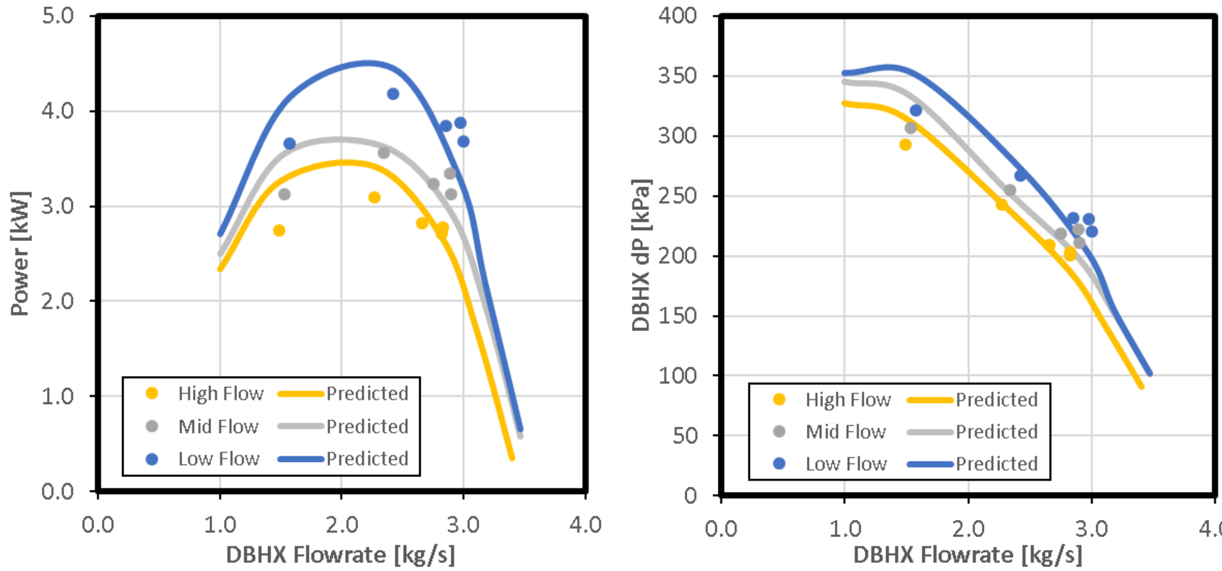


Source: GreenFire Energy

Demonstration Results Versus Modeling

Each data point from the demonstration (Table 2) was modeled. Additional points were also modeled considering higher and lower sCO_2 flowrates through the DBHX. These data (as points) and predictions (as lines) are plotted in Figure 23. These data again demonstrate that maximum power is not produced by the maximum recirculation rate of sCO_2 through the DBHX, nor is it produced when the thermosiphon is strongest. Rather, maximum power occurs at a point between the maximum circulation rate and maximum thermosiphon pressure production.

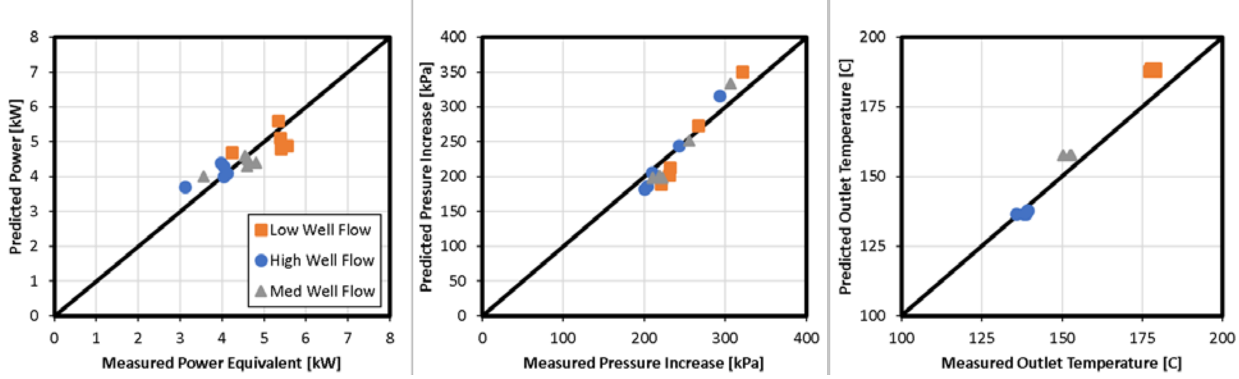
Figure 23: Supercritical CO_2 Power Production vs. Flowrate



Source: GreenFire Energy

As an indication of how well the modeling compares to the measured data, the modeled data points are plotted versus the measured points in Figure 24. "Measured power equivalent" was calculated using the enthalpy difference as described above. Generally, the predicted data followed the measured trends.

Figure 24: Predicted Pressure and Temperature vs. Measured Values



Source: GreenFire Energy

Retesting Supercritical CO_2 as the Working Fluid

Because the reinjection temperature was hotter than desired during the May 2019 testing, GreenFire Energy retested the circulation of sCO_2 as working fluid in December 2019. This testing sequence followed a similar testing plan.

Table 3 presents data for the closed-loop DBHX flowing with sCO_2 while producing the well in December 2019. The well was cycled through four brine production rates: low, medium, high, and a zero-well-flow condition, as shown in Table 3 below. (These are slightly different from Table 2). The closed-loop was circulated with four control valve settings (20 percent, 40 percent, 60 percent, and 100 percent for a total of 12 combined well and closed-loop flow conditions. At conclusion, a zero well flow test was also conducted.

Table 3: Well and Closed-Loop Test Settings

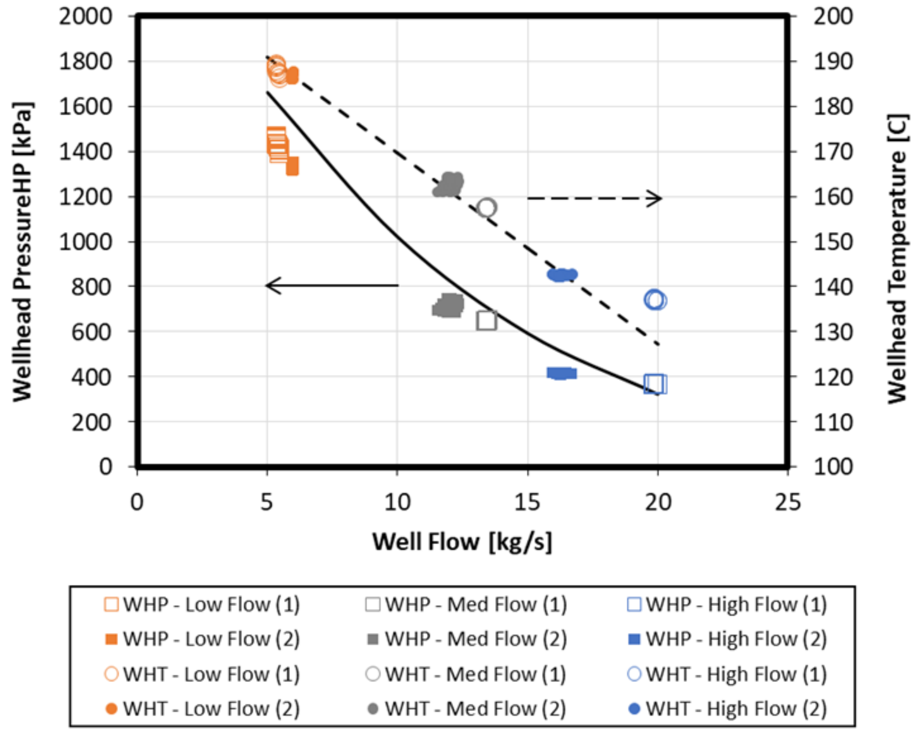
Test Numbers	Well Flow (kg/s)	Closed-Loop PCV Set Point (percent)
D1-D4	6.0	20, 40, 60, 100
E1-E4	12.0	20, 40, 60, 100
F1-F4	16.3	20, 40, 60, 100
O	0.0	90-100

Source: GreenFire Energy

Well-Flow Data During Closed-Loop DBHX Demonstration While Flowing Supercritical CO_2

Figure 25 shows the WHP (square symbols) and WHT (round symbols) as a function of the well-flow rates tested in May 2019 (1) (opened symbols) and the flow rates tested in December 2019.

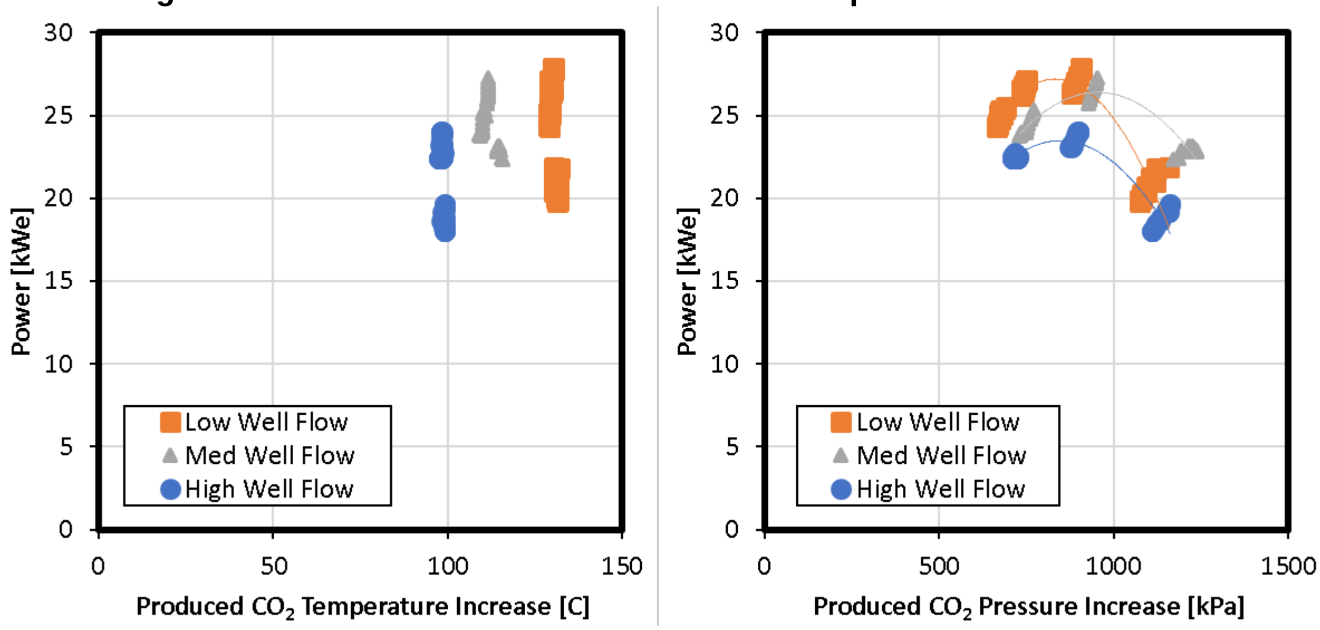
Figure 25: Well-Head Temperature and Pressure vs. Flow Rates



Source: GreenFire Energy

Indeed, the power production was substantially higher during retesting. The retested data are plotted in Figure 26. Again, the data show that more power can be generated when the rate of coproduced brine is reduced (that is, "low well flow"); however, the effect is not as pronounced as seen in the May 2019 data.

Figure 26: Power Production vs. Increased Temperature and Pressure

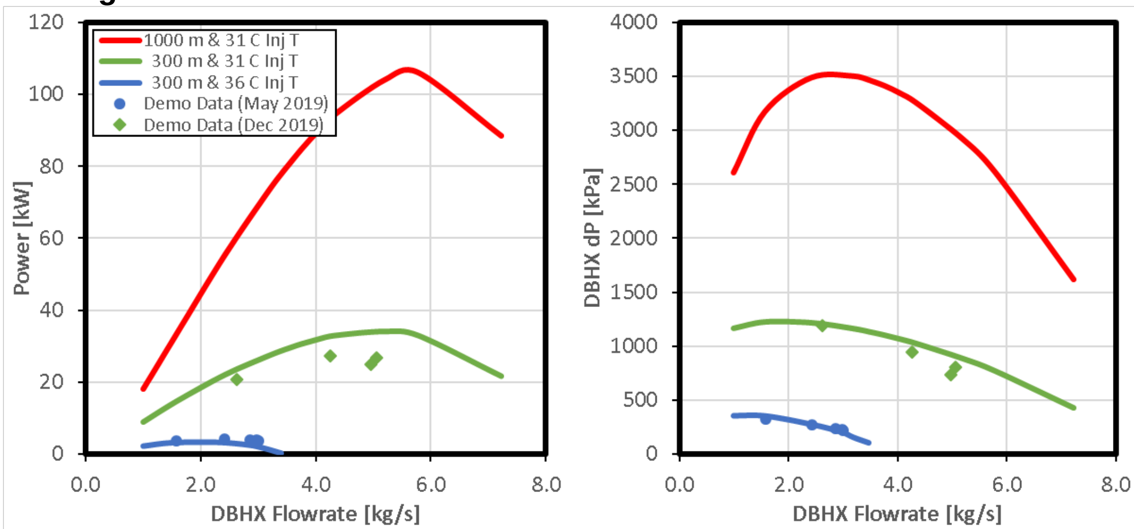


Source: GreenFire Energy

Modeling Injection Temperature and Deeper Wells

An additional testing modification that we considered (but did not implement due to costs) was to make the DBHX longer (i.e. extending deeper into the well). Instead of being limited to the installed system of 1,083 feet (330 m) deep, the project team modeled potential performance as if instead the DBHX was 3,280 feet (1,000 m) deep. The data in Figure 27 show that a colder sCO_2 inlet temperature and a deeper DHBX contribute to significantly higher power generation. This figure also shows that the measured data for both testing sequences (May 2019 and Dec 2019) conform closely to prior modeling.

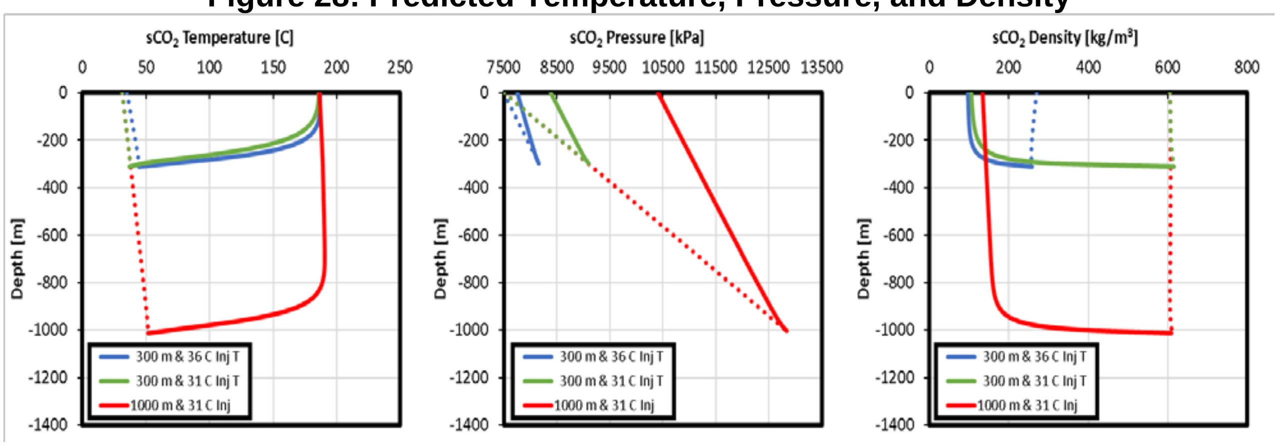
Figure 27: Estimated Power Production With Amended Conditions



Source: GreenFire Energy

Figure 28 illustrates the relationship between the predicted downhole temperatures (left), downhole pressure (middle), and downhole density (right) of the circulating sCO_2 as plotted versus depth for three DBHX scenarios. The dotted lines indicate downflow, and the solid lines indicate upflow.

Figure 28: Predicted Temperature, Pressure, and Density



Source: GreenFire Energy

Consider the rightmost figure first. This figure shows the density of the sCO_2 as it recirculates through the DBHX. The dotted blue line shows that under the demonstration conditions, the density is around 260 kg/m^3 as it enters. It slightly loses density as it reaches the bottom of the VIT (due partly to heat transfer through the VIT, which is not entirely adiabatic, and largely to frictional pressure losses).

The red and green lines show injection at the lower temperature (higher density), and here the density did not change as much as the sCO_2 descended the VIT. Since the density was so much higher at the lower temperature, the velocity was proportionally lower; therefore, there was less frictional pressure loss (hence a more vertical line). As the sCO_2 returned to the surface, the deeper well produced more pressure. This production is seen in the red line as a higher density at the surface (even through the returning temperature is similar).

The middle image in Figure 28 shows the cumulative pressure built up as the sCO_2 descended the VIT and the pressure loss as the less-dense sCO_2 returned in the annular region of the DBHX. The combination of a lower inlet temperature and the deeper DBHX (both shown in red) built up a lot more pressure.

Zero-Well-Flow Data

An important test to validate the modeling techniques used by GreenFire in predicting power production was determining the heat extraction and power production when the brine in the well was not flowing. Halting the brine flow ("shutting in the well") means that there is no longer convective heat transfer into the sCO_2 as it flows from the bottom of the well upward along the casing of the DBHX. Halting the brine flow is important because evaluating closed-loop performance without convection can be used to approximate the conditions in hot, dry rock that comprise most geothermal resources.

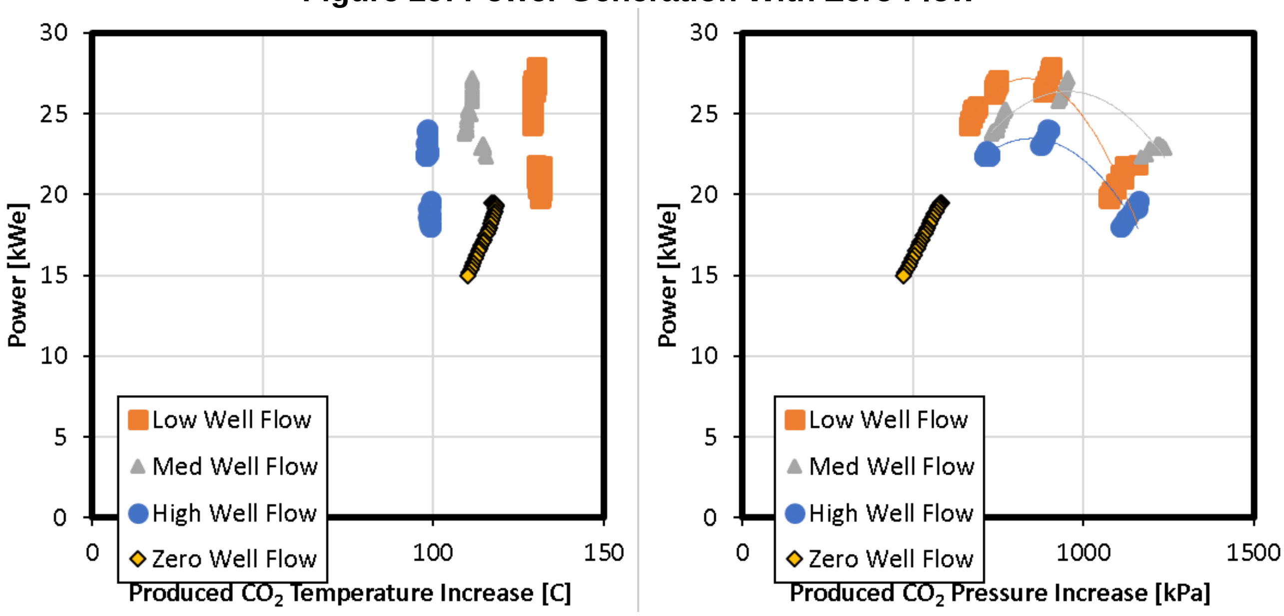
Of course, an important difference between the tested conditions and actual hot, dry rock conditions is that the annular region between the casing of the test well and the casing of the DBHX will not exist in the hot, dry rock context. Instead, in the hot, dry rock context, the well casing (together with the cement holding the well casing in place) will be the only barrier between the geothermal resource rock and the working fluid in the DBHX. (Filling the annular region around the DBHX with cement or another material having a thermal conductivity similar to the resource was not permitted.)

Hence, to approximate true hot, dry rock conditions, the project team shut in the well to capture the "zero-well-flow" data over a selected period. If the period of zero well flow is too long, the annular region between the well casing and the DBHX casing would effectively insulate the DBHX from the heat in the geothermal resource. Conversely, if the zero-well-flow period is too short, heat from the brine still residing in the system would continue to be transferred by convection to sCO_2 in the DBHX.

Consequently, the zero-brine-flow condition was tested at the end of the testing program. While the well was still hot, the well was "shut in" (in other words, no brine flow was allowed), and the sCO_2 within the DBHX continued flowing as the well cooled. In Figure 29, each black/yellow diamond represents power as a function of temperature and pressure increase, respectively. As expected, the data line shows the progress of the data, which is always in the same range, but at a somewhat lower level, than the produced during the high-well-flow coproduction tests. Hence, the team determined that the zero-flow condition testing period was long enough to eliminate the higher heat transfer from the upflowing geothermal brine in the annulus, but short enough so that the air in the annulus would not act to simply insulate the DBHX from the geothermal resource.

As shown in Figure 29, the flowing conditions were hottest (low well flow, shown by the orange squares, produces the hottest condition) just before the well was shut in. The first zero-brine-flow conditions (when the well was hottest) are the data with the highest power estimates (~ 22 kWe). When the well is no longer flowing, the energy extracted by the DBHX comes from the residual heat in the well casing and the remaining, static steam and brine in the annular region between the well and the DBHX. As a result, the testing confirmed that the modeling techniques used by GreenFire to predict power production of sCO_2 under zero-brine-flow conditions is also valid for predicting power production in hot, dry rock as well. Further, the modeling of scenarios using U-loop systems (as shown in Figure 30) by the conduction heat transfer mechanism in hot, dry rock can be simulated with the model validated in this project and suggests a promising future for this emerging technology.

Figure 29: Power Generation With Zero Flow

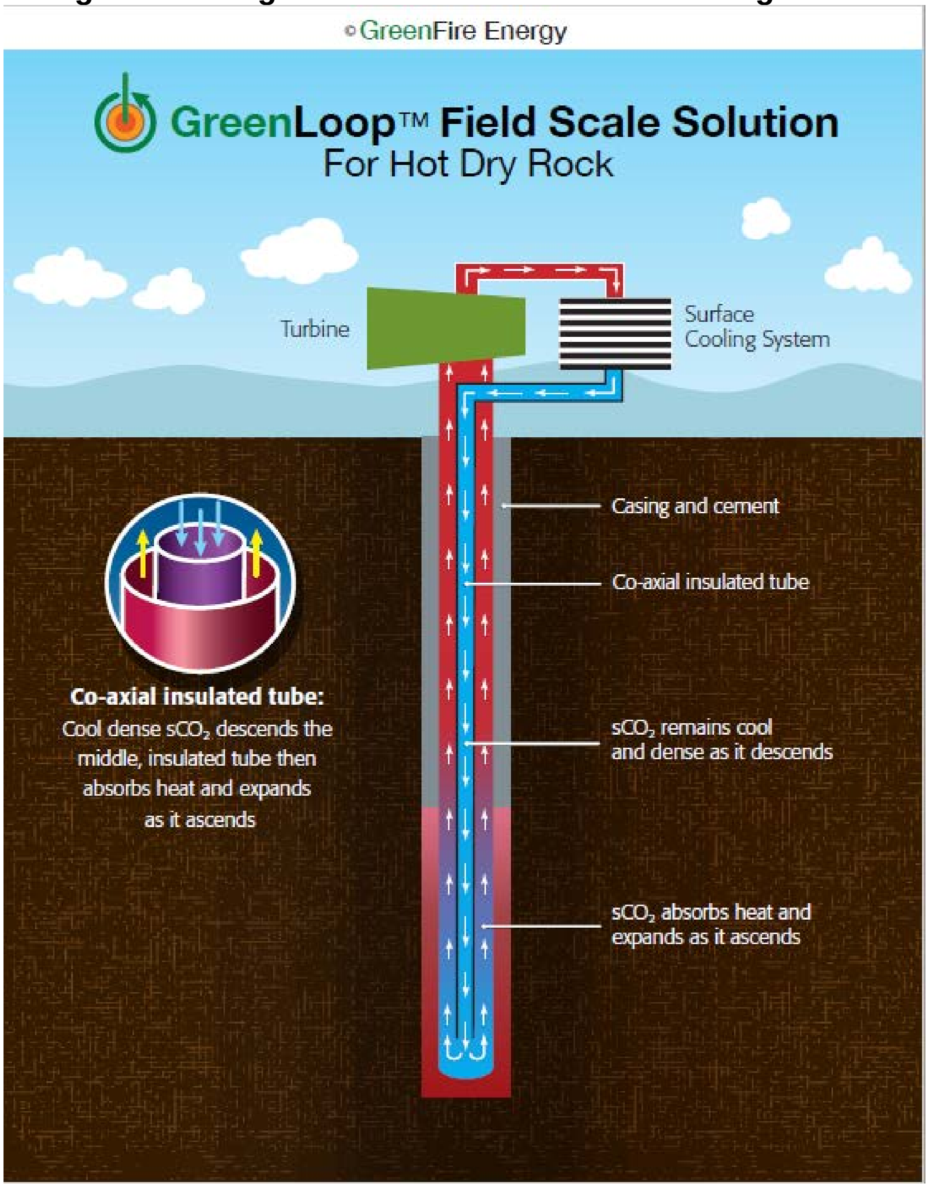


Source: GreenFire Energy

Field-Scale Application of Closed-Loop Geothermal Development

A major objective of this project was the validation of GreenFire's modeling to predict performance of a DBHX in hot, dry rock. In a field-scale application of closed-loop geothermal technology, the DBHX could be used in a variety of well configurations, depending on the heat and rock characteristics of the geothermal resource. In the simplest configuration, a tube-in-tube assembly (which must be coaxial but may be a VIT as described or some other type of insulated pipe) is inserted into a well with no annular region between the VIT and the well casing. Heat was absorbed directly through the conduction of heat from the rock, through the well casing, and then into the working fluid. Figure 30 below shows a well with the coaxial tube configuration.

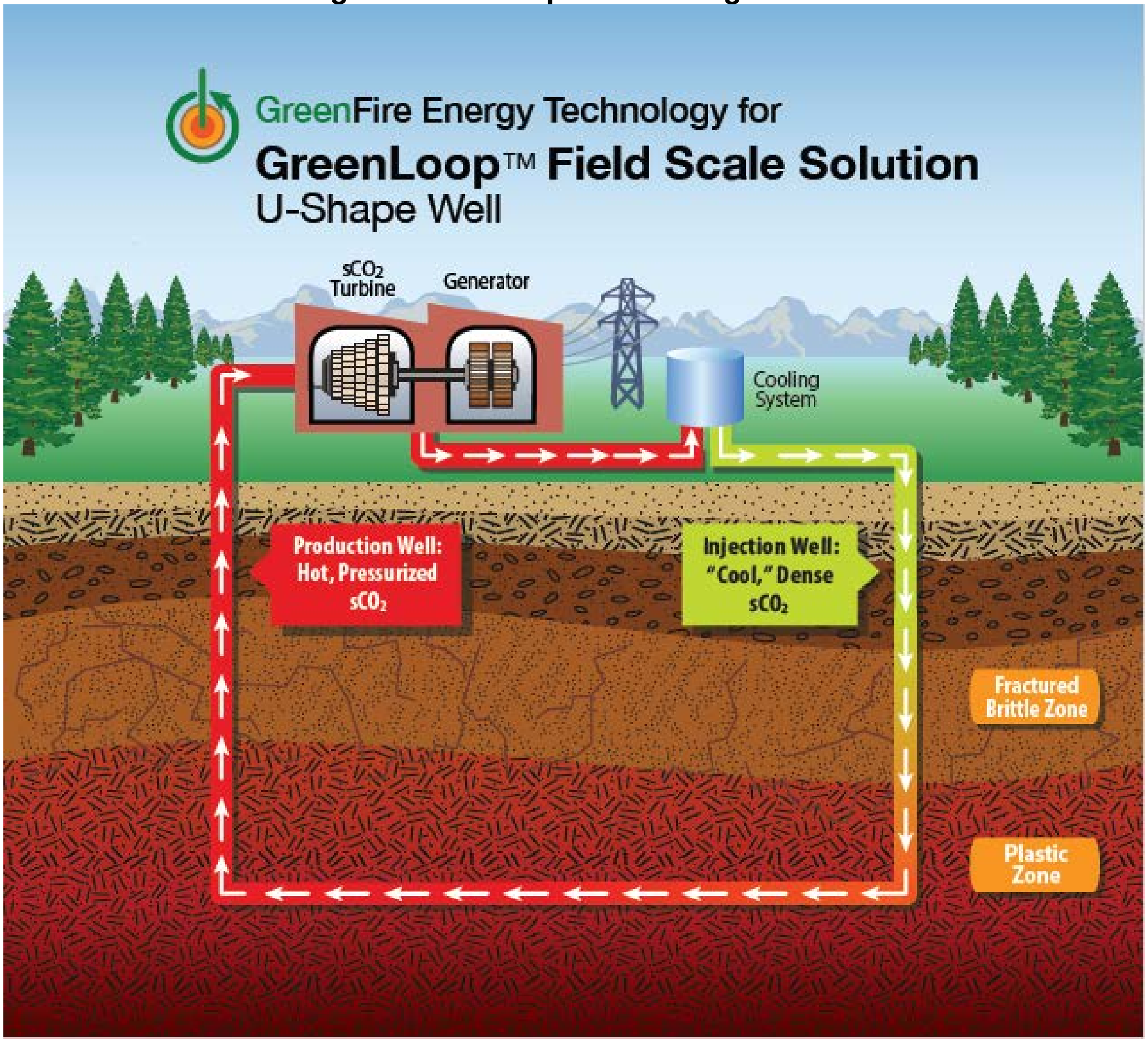
Figure 30: Single Well With Coaxial Tube Configuration



Source: GreenFire Energy

In addition to installing an insulated pipe inside a single bore well to create the DBHX, other architectures are possible, including, for substantially improved technical and economic performance, two wells connected at the bottom in a "U-Loop" configuration. This design removes the expense and potential longevity and maintenance issues associated with using VIT. The sCO_2 continuously circulates, simply going down one well, then returning to the surface through the second connected well. Figure 31 shows a diagram of the "U-Loop" configuration.

Figure 31: U-Loop Well Configuration

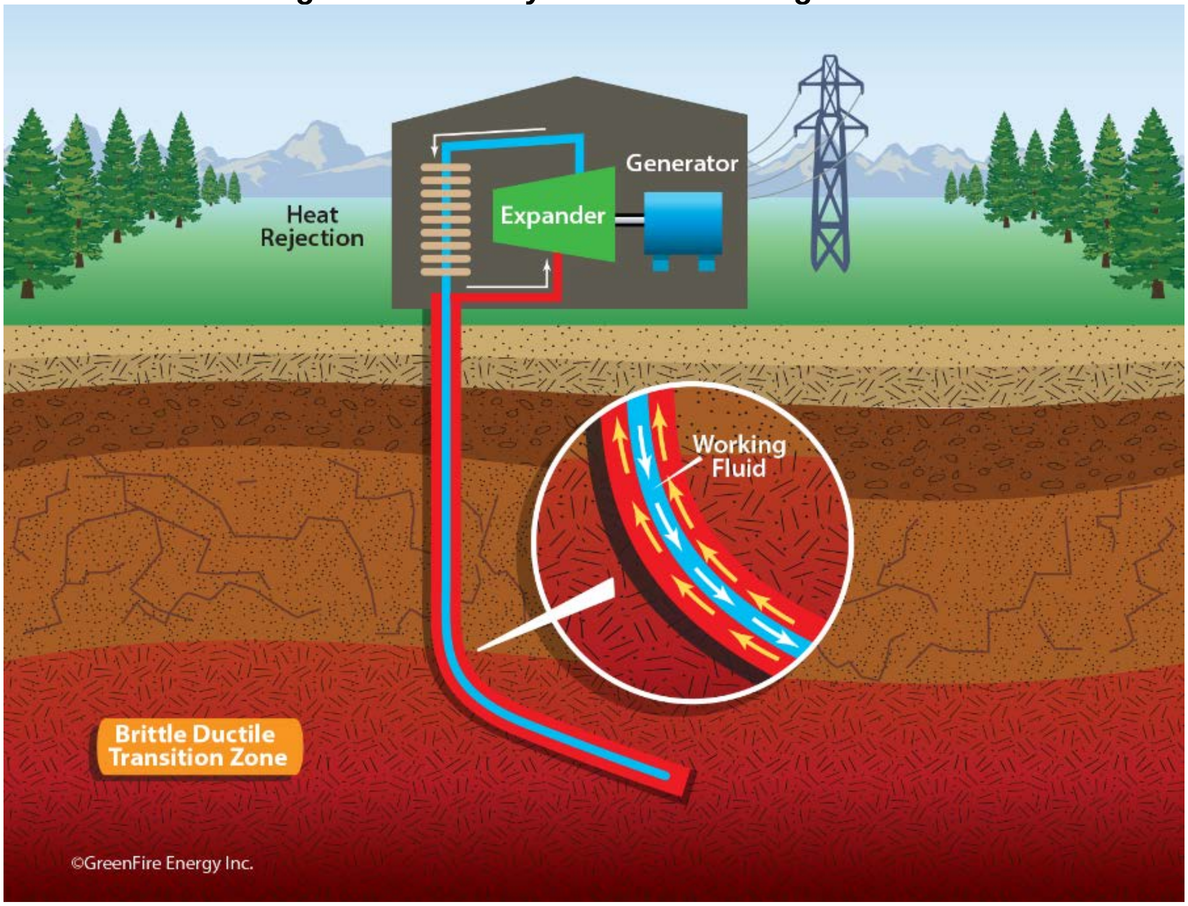


Source: GreenFire Energy

Despite the significant advantages of a "U-Loop" configuration, connecting two deep bores at high temperatures (where closed-loop geothermal produces more power at lower cost) may present technical challenges. Various current research projects, public and private, specifically address these challenges, causing GreenFire to be optimistic that U-loop closed-loop configurations at high temperatures are, or will soon become, possible.

However, to be conservative and demonstrate that closed-loop geothermal power production is economical using only drilling technologies that are commonly employed, much of GreenFire's modeling in hot, dry rock is based on using a "hockey stick" configuration, as shown in Figure 32. This coaxial configuration includes an insulated tube inserted into a well similar to the Coso demo project. The main difference occurs at the depth where a targeted temperature is found. At that point, the well is drilled to become increasingly horizontal so that the end portion of the well remains at a specified resource temperature or follows a targeted thermal contour.

Figure 32: Hockey Stick Well Configuration

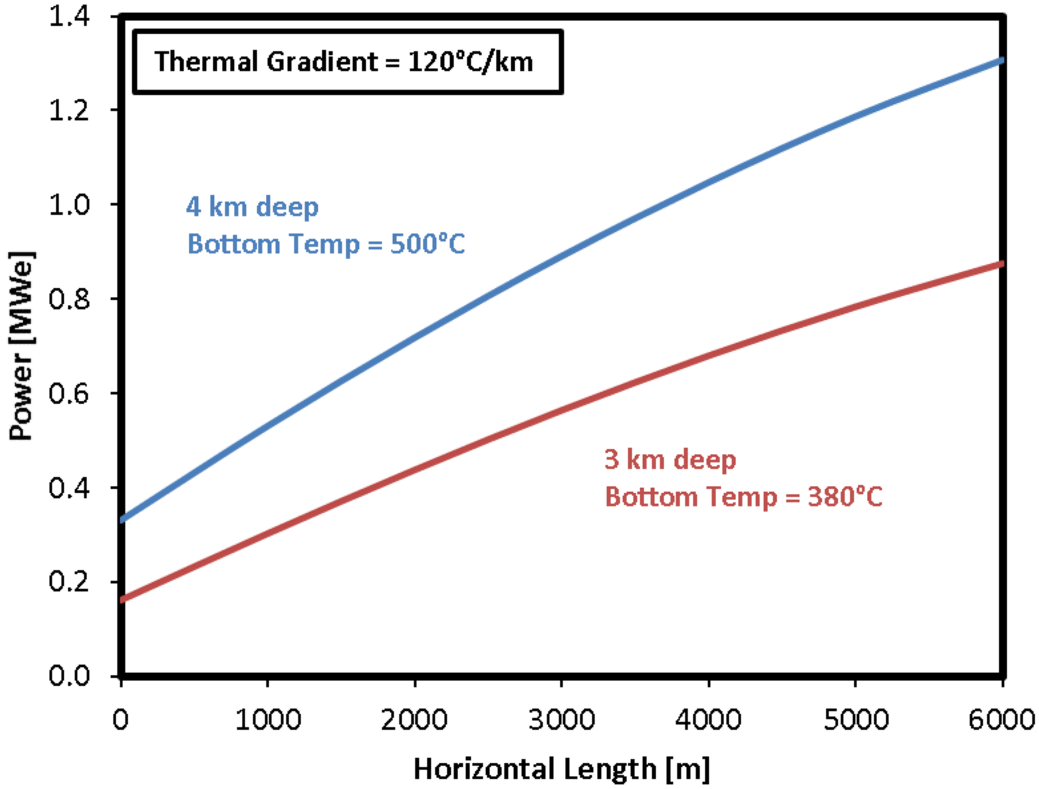


Source: GreenFire Energy

GreenFire's hot, dry rock modeling uses the same assumptions that were validated with the demonstration results but assumes no water or convection of heat in the geothermal resource. Instead, the authors assume that heat transfer to the DBHX is due only to conduction directly from the resource. The method has been reviewed in previous papers (Fox and Higgins, 2016; and Higgins et al., 2016). The authors have also used thermal gradient and rock analysis data from Coso to estimate the power production potential from a purpose-drilled well at Coso, in a location with little permeability, so heat transfer occurs by conduction only.

Consider Figure 33, which shows the modeled power potential of a field-scale closed-loop system using the same modeling assumptions verified at Coso, and installed in an impermeable geothermal resource with a thermal gradient of 240°F (120°C)/km. The modeled well described below is a "U-Loop" configuration. Generally, the vertical portion of the well is used to reach a sufficient depth for high resource temperature and developing a strong thermosiphon. The horizontal portion of the well is used to harvest heat from the resource into the sCO_2. Generally, longer, deeper, and hotter closed-loop well systems produce geometrically more power. Although convection of water in the resource across the well will add substantial power, none has been assumed in this modeling.

Figure 33: Power Potential Plotted Versus Horizontal Length Without Convection

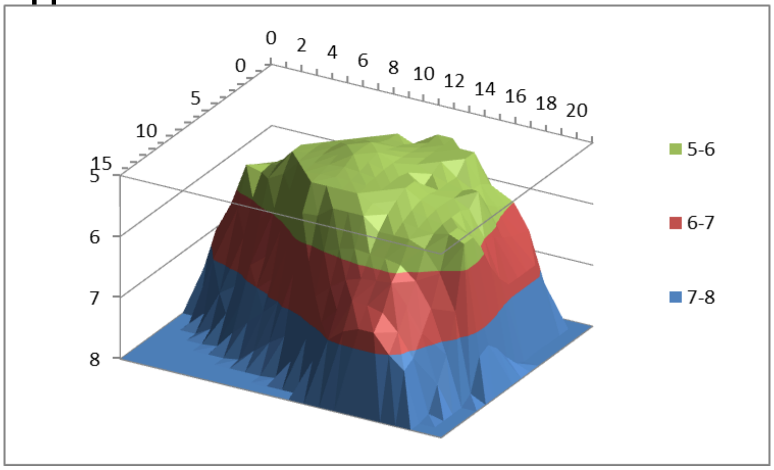


Source: GreenFire Energy

Understanding the performance of closed-loop wells in hot, dry rock enables a field-scale analysis of new closed-loop development for the Coso geothermal field. The first task was to estimate the potential for additional power generation that closed-loop geothermal technology creates. This task required two studies. The first study investigated the maximum intensity of closed-loop geothermal in a given area. In other words, the project team addressed the question of how closely closed-loop geothermal wells can be placed without adversely affecting each other. GreenFire research found that several wells can be initiated from a well pad and not thermally interfere with one another so long at the bottoms of the wells are at least 263 feet (80 meters) apart.

The second study addressed how much power could potentially be generated from the Coso geothermal area using closed-loop geothermal wells and assuming no heat-convecting water flowing within the resource. GreenFire used geophysical information of the Coso resource to build a 3D image of the heat resource. Figure 34 below shows the resource model that was constructed with 0.62 miles (1 km) depth intervals from 3.1 miles to 4.96 miles deep (5 to 8 km). Using existing information about the temperature gradient at Coso, estimates were then made of the temperature at each level of the model. Beyond 4 km with an average gradient of 100°C/km, the team determined that temperatures ranged from 932°F (500°C) to 1472°F (800°C).

Figure 34: Approximate Coso Geothermal Resource Isotherm vs. Depth



Source: GreenFire Energy

The authors' analysis shows the ability to access hotter temperatures means more of the overall resource can be used. For example, maximum exploitation of 800°C temperatures at Coso would theoretically produce an astounding 39 GWe of electric power. As would be expected, restricting wells to lower temperatures reduces the potential power generation. So, if the maximum bottom-hole temperature is set at 500°C, the potential power generation drops to a still extraordinary 19 GWe. When current limitations on drilling and materials are considered, as well as an acceptable LCOE, then the potential is much lower but still very high and in the range of 1 to 2 GWe.

To address the well cost and LCOE calculations, GreenFire had previously constructed a sophisticated closed-loop well cost model with involvement by Baker Hughes. To be conservative, and despite rapid progress on new drilling and completion technologies that substantially reduce costs, GreenFire used costs and drilling performance data pertaining only to existing drilling tools and techniques used in the drilling industry. In particular, GreenFire used only documented rates of penetration that have been proven in the field.

As demonstrated by the Coso demonstration project, subsurface fractures and permeability are not required for closed-loop power production. Therefore, GreenFire assumes a relatively homogenous geothermal resource for drilling purposes and that various economies of scale can be obtained in large projects. GreenFire's well-cost model is proprietary, and a description of it and the well-cost assumptions used in modeling full-scale commercial projects is beyond the scope of the demonstration project. However, under appropriate confidentiality arrangements, GreenFire is willing to share such information showing the potential of closed-loop geothermal technology in an appropriate hot, dry rock resource, such as Coso, at competitive LCOEs**.**

Conclusions of Supercritical CO_2 Testing

Additional analysis using PCA revealed the variables that can be changed to optimize power generation. The research team devised a geothermal power coproduction equation (as shown in Figure 37) for sCO_2 as a function of key operations variables including control valve settings, inlet pressure, and inlet temperatures. This equation, when combined with 1-D thermodynamic modeling results and Monte Carlo resampling results, was then used to develop a general equation that can be used to optimize power production in a wide range of real-world geothermal scenarios, including hot, dry rock. (See Appendix A for more information about the PCA equation). The PCA with Bayesian statistical modeling techniques and Monte Carlo resampling analysis confirm that the 1-D thermodynamic analysis can be used for optimizing performance and is detailed in Appendix A.

According to the Coso demonstration results reported at Higgins et al. (2019) and Amaya et al. (2020), the closed-loop DBHX system installed at Coso geothermal field using water as the working fluid delivered roughly 1 MWe net power. For sCO_2, the power delivered was much less than that produced with water. However, these test results are not directly comparable because the water was pumped through the system. In contrast, a key goal of sCO_2 experiments was to test power potential using only the thermosiphon to move the sCO_2 through the system. The thermosiphon force was optimized by controlling inlet properties including the temperature, which was tested at different conditions in May and December 2019. While modeling suggests that increasing inlet pressures and flow will produce much more power, varying the inlet compression process was outside the scope of this project. Hence, sCO_2 flow rate was much lower than the water flow rate — only between 6 and 18 percent of the total water flow rate — thereby delivering much less heat for power production.

However, both experiments produced useful results that validate the modeling technique. This validation increases confidence that the modeling technique can accurately forecast results across a wider range of conditions. Indeed, similar GreenFire modeling done with different assumptions indicates that using sCO_2 as the working fluid can result in superior power production to using water as the working fluid.

CHAPTER 6: Conclusions and Recommendations

Conclusions

This closed-loop geothermal project, the first of its type, signals a fundamentally different trajectory for geothermal power generation in California and elsewhere. Closed-loop geothermal technology has the potential to enable much greater energy extraction from California's existing geothermal projects, making geothermal power generation feasible in the vast California geothermal resources where conventional geothermal is not.

Because of the cost and risk associated with this project, conventional technology financing was not available; consequently, the project would not have been possible without a grant and support from the California Energy Commission. With the project complete and technical papers submitted for presentation and publication, closed-loop geothermal technology will likely attract both strategic and financial investment for commercial development. For example, partially as a result of this project, GreenFire is advancing discussions with various major geothermal operators and globally diversified energy companies.

Validation of GreenFire Proprietary Models for Closed-Loop Geothermal Wells

Test results validated the utility of the proprietary thermodynamic models created by GreenFire to predict the performance of closed-loop geothermal wells using either sCO_2 or water as alternative heat transport and working fluids. Testing further confirmed that a thermosiphon can be established to circulate supercritical CO_2 through a closed-loop geothermal well to add to produced power and avoid parasitic pumping losses.

These test results confirm that GreenFire's proprietary model for closed-loop geothermal wells can be usefully applied to predict closed-loop power generation from the diverse types of geothermal resources present in California. These types include the dry steam wells of The Geysers, the hypersaline wells near the Salton Sea, or the hot, dry rock found in Coso.

Although the demonstration was performed on an existing well with coproduction of brine to increase power generation, enough measurements were made to also validate previous estimates of heat extraction from closed-loop wells with no brine flow. In other words, this scenario simulated the performance of a field-scale closed-loop system in hot, dry rock.

The results of this project (when combined with previous GreenFire research) further demonstrate that closed-loop geothermal can produce more power from a given resource than conventional hydrothermal technology. An analysis of the Coso geothermal field, which has a producing capacity of about 140 MW, shows that with intensive closed-loop development production could be roughly 10 times greater, or between 1 and 2 GWe.

Validation of Closed-Loop Geothermal Wells for Well Rehabilitation

In addition to validating the thermodynamic models for closed-loop geothermal projects in hot, dry rock, this project had the significant benefit of demonstrating how inactive geothermal wells can be rehabilitated to produce power. Since on average more than 20 percent of geothermal wells fail either at the outset or over time from declining production, a technology that can cause such wells to become productive represents a significant opportunity to reduce the risk and improve the yield of geothermal projects in California and around the world.

Test Well 34A-20 at Coso was inactive due to high NCG concentrations. This used well provided the opportunity to test closed-loop geothermal technology without the cost and time necessary to drill a new well. GreenFire Energy successfully installed and operated a DBHX that proved that at least some inactive wells can be made productive with downbore heat exchangers.

Benefits to California

Harnessing California’s tremendous geothermal potential could significantly assist the state in meeting its goals for renewable energy production in general and for geothermal power generation specifically. Equally important, California’s geothermal resources may provide enough stable power to offset the intermittency of wind and solar power as they become a larger portion of California’s energy portfolio. These geothermal resources can provide a clean alternative to expensive battery storage. Further, closed-loop geothermal provides secure, resilient power that may be particularly attractive to U.S. military bases, data centers, refineries, and chemical processing plants, all of which contribute significantly to California’s growing economy. Finally, closed-loop geothermal offers California an environmentally superior alternative form of renewable energy as it is more land-efficient and less visible than wind and solar, eliminates seismic and subsidence risks associated with conventional geothermal and oil and gas technologies, and is safer for wildlife due to the limited above-surface equipment.

Recommendations for Additional Work

Because the modeling approach estimated the heat transfer in the demonstration system with considerable accuracy, GreenFire can confidently model other closed-loop well configurations in combination with a cost-benefit analysis to determine commercial project viability. These models will also enable an investigation into further improvements in closed-loop well technology.

GreenFire has either planned or already initiated investigation of the following potential enhancements of its closed-loop system:

- Adding various “fins” or heat pipe appendages to substantially increase heat transfer to the closed-loop well
- Cost-effective well-completion methods in high-temperature environments
- Conductive grouts and cements
- Advanced materials for well casings and insulated pipe

- Downbore pumps that derive motive power directly from the thermosiphon effect to economically pump mineralized brine or hydrocarbon resources
- Coproduction of energy from the closed-loop together with mineralized brine to power and the efficient extraction of minerals, including lithium
- Using energy produced from the closed-loop to further compress the working fluid and store thermal energy in the well and geothermal resource to allow flexible time-of-day delivery of energy when intermittent renewable energy sources cannot supply power to the grid
- Using refrigerants other than sCO_2, or mixtures of such fluids, as the closed-loop working fluid, to optimally match the pressure and temperature characteristics of geothermal wells and resources

Next Steps

This demonstration project has confirmed the validity of closed-loop modeling and provided the geothermal industry with the basis for considering well-retrofit projects and new field-scale geothermal projects using closed-loop geothermal technology. It is expected this will enable the geothermal industry to expand beyond its current constraints, use a much greater portion of the global geothermal resource, and more intensively and efficiently harvest energy from geothermal sites.

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GLOSSARY

Abbreviation, Acronym, or Term	Definition
Adiabatic	A process that occurs without loss or gain of heat
Btu	British thermal unit
BLM	Bureau of Land Management
°C	degrees Celsius
CA	California
Cal EPA	California Environmental Protection Agency
CAISO	California Independent System Operator
CO_2	carbon dioxide
Coso	Coso Geothermal Area
$	US dollar(s)
Darcy friction factor	Predicts the frictional energy loss in a pipe based on the velocity of the fluid and the resistance due to friction.
Dittus-Boelter Equation	A simplified way to calculate the ratio of convective to conductive heat transfer across a boundary. (See Nusselt Number)
Downbore	Inside a drilled well
DBHX	Downbore Heat Exchanger
Energy Commission	California Energy Commission
Enthalpy	A thermodynamic quantity equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume.
Euler Method	A numerical procedure for solving ordinary differential equations with a given initial value
°F	degrees Fahrenheit
ft.	foot, feet
hr.	Hour

Haaland Equation	A method of calculating the friction caused by laminar and turbulent flow in pipes
Isenthalpic	A process that occurs without any change in enthalpy
Isentropic	An idealized thermodynamic process that is both adiabatic and reversible. The work transfers of the system are frictionless, and there is no transfer of heat or matter.
kPa	1,000 Pascals pressure
Kph	1000 pounds per hour
kWh	kilowatt hour
LCOE	Levelized Cost of Energy: a measure of the average net present cost of electricity generation over the lifetime of the system.
Monte Carlo Simulation	A statistical methodology for determining probable outcomes using repeated simulations using different values for key variables
MWth	million watts of thermal energy
MWe	million watts of electrical power
Nusselt Number	The ratio of convective to conductive heat transfer across a boundary
PCA	Principal Component Analysis: a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of linearly uncorrelated variables call “principal components”. This analysis reveals which variables have the greatest impact on the outcome of a given process.
PCV	pressure control valve
Psig	Pounds per square inch per gauge. A measure of pressure.
sCO_2	supercritical carbon dioxide
Supercritical CO_2	Supercritical CO_2 is a fluid state of carbon dioxide where it is held above its critical point (i.e., critical pressure and temperature). The density at that point is similar to that of a liquid and allows for the pumping power needed in a compressor to be significantly reduced, thus significantly increasing the thermal-to-electric energy conversion efficiency
WHP	well-head pressures

WHT	well-head temperature
Veizades	Veizades & Associates
VIT	vacuum insulated tubing (co-axial)
U.S. DOE	United States Department of Energy
USGS	United States Geological Survey

APPENDIX: Information on Modeling

Modeling with Monte Carlo Simulations

One of the primary purposes of this project was to validate and improve existing models of closed-loop geothermal power cycles. However, modeling of this type is highly complex and uses methods and terminology that will be beyond the reach of the average reader. This appendix is included to enable those who are familiar with sophisticated modeling techniques to understand the additional modeling statistical modeling that GreenFire has done using both water and sCO_2 as working fluids. This modeling validates the 1-D modeling described in the body of this Report and highlights the processes that GreenFire will use to optimize future closed-loop geothermal installations.

Optimization of a geothermal power co-production function for both sCO_2 and water as the working fluid has been calculated using a statistical modeling methodology “Principal Component Analysis” (PCA) followed by a “Monte Carlo” simulation.

A PCA and Bayesian statistics modeling techniques were applied to the experimental data to optimize an objective function of power production. The purpose was to determine the optimal operational variables for specific closed-loop working fluid and brine well flows. This power production function has been validated by using a coupling between the thermodynamic 1-D process model system equations and a Monte Carlo simulation methodology to produce a statistic modeling forecast of the optimal variable conditions expected in a “virtual” test.

PCA is a technique that transforms all the variables and all the observed results of our testing at Coso into dimensionless vectors and scores. The principal component vectors create a new axis where the integrated information can be plotted and optimally analyzed. The variables used in this PC Analysis are summarized in Table 4.

Table 4: List of PCA Variables

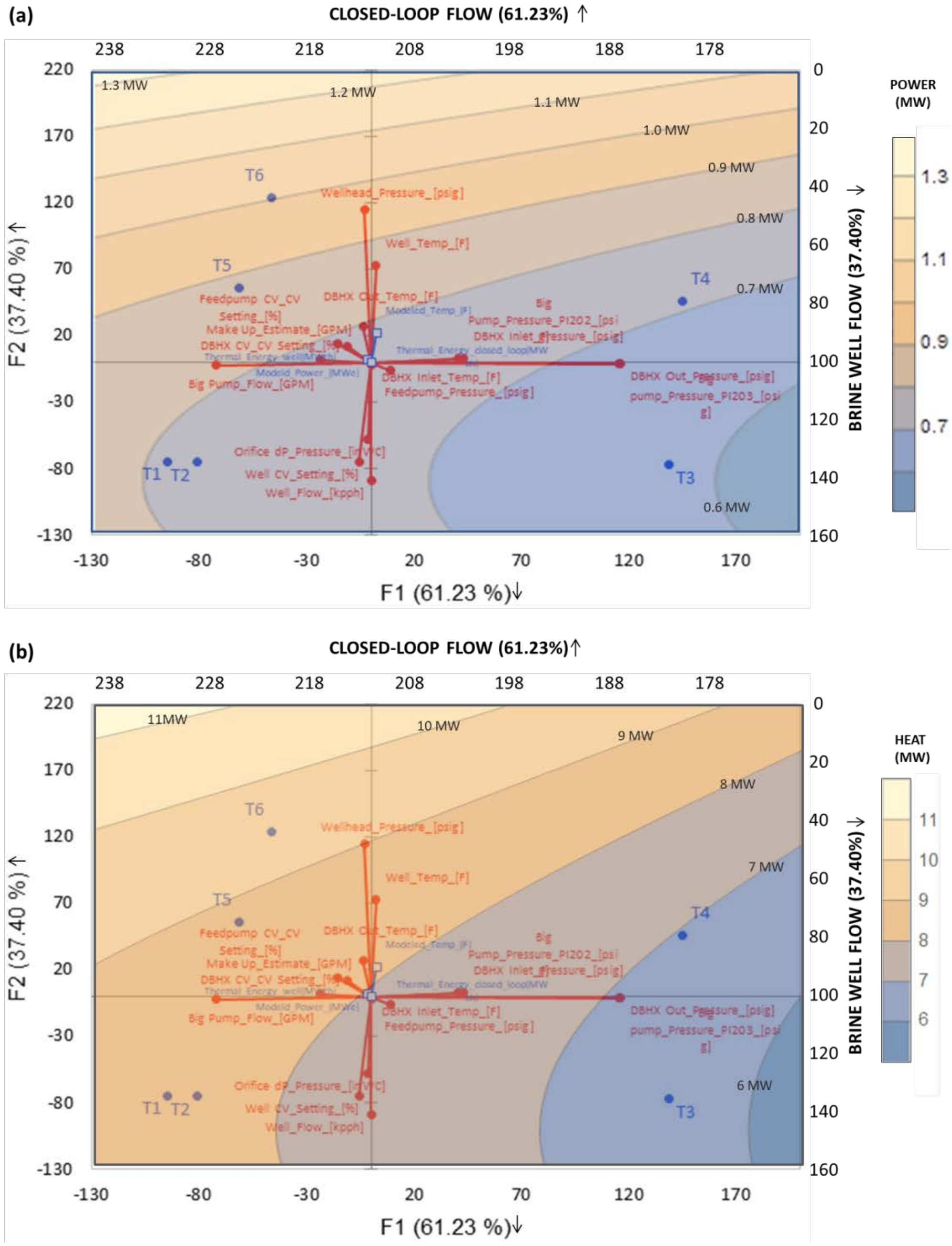
Variable Name	Unit of Measurement
Wellhead pressure	Psig
Big pump flow	GPM
DBHX out temperature	Degrees Fahrenheit
Feedpump control valve setting	Percent of maximum flow
Make up water estimate	GPM

Variable Name	Unit of Measurement
DBHX inlet temperature	Degrees Fahrenheit
Feedpump pressure	Psig
Big pump pressure (PI202)	Psig
DBHX inlet pressure	Psig
Orifice dP pressure	Psig
Well control valve setting	Percent of maximum flow
Well flow	Kpph
DBHX out pressure	Psig
Big pump pressure (PI203)	Psig
Well temperature	Degrees Fahrenheit
Water tank level	Inches
Big pump amps	Amps

Source: GreenFire Energy

Figure 35 is a biplot PCA schematic for water as the working fluid; it displays variables and observations analyses at the same time. Loadings and scores are plotted together on the same PC axes (defined by experimental flow rates) over the spatial domain ([a] by power production in MWe and [b] by Heat Power release in MWth).

Figure 35: PCA Analysis for Water as Working Fluid



Source: GreenFire Energy

Figure 35 shows the principal component axes for closed-loop flow (horizontal) and brine well flow (vertical) and energy output contours (in MW) in an overlay source plot. The statistical modeling process consists of three steps. In the first step, the six experimental sets of conditions (each represented by 18 operation variables) were analyzed. PC1 (which accounts for 61.2 percent of variance) and PC2 (which accounts for 37.4 percent of the variance) together comprise 99 percent of all the observed information.

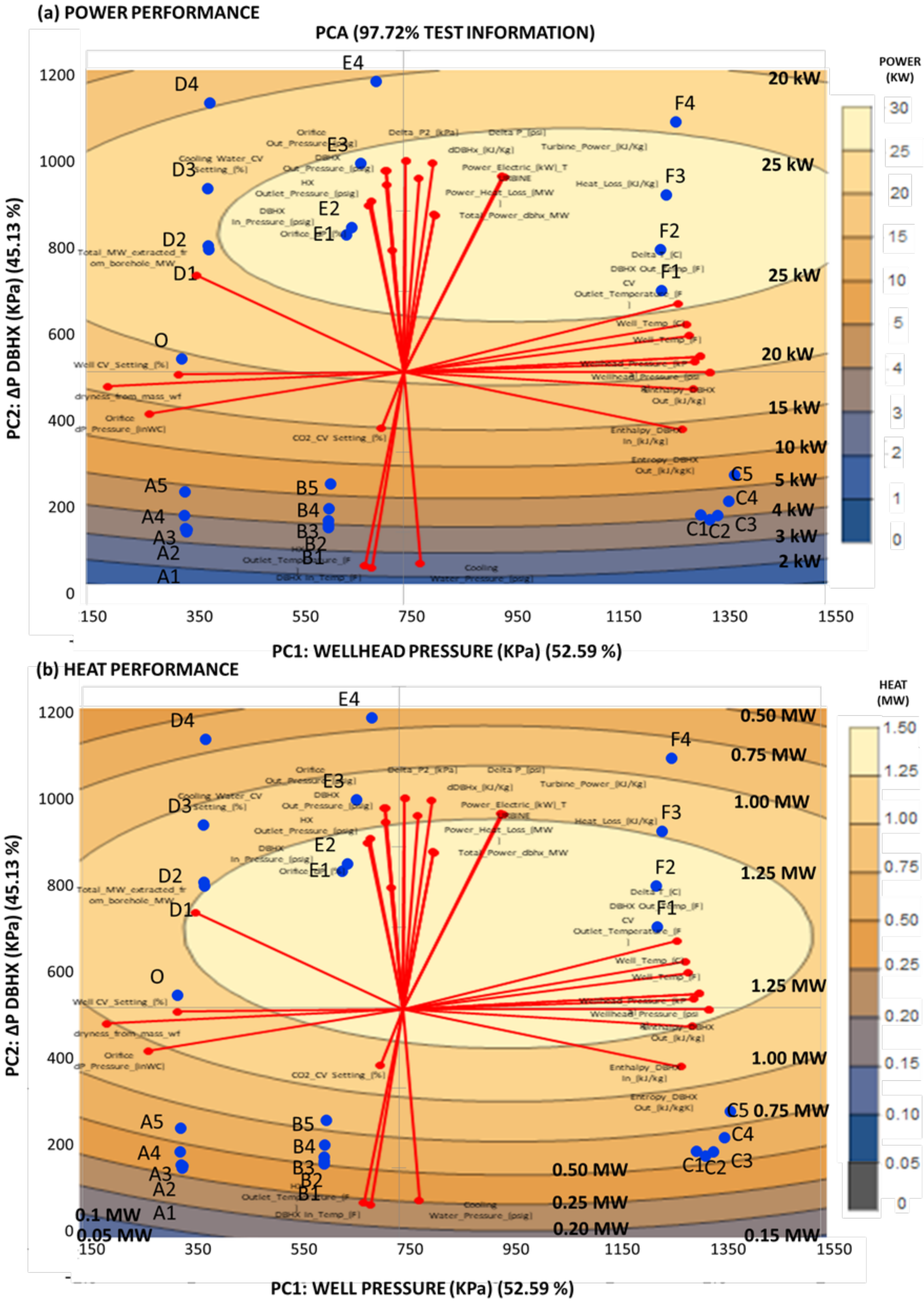
In the second step of the analysis, the principal component axes are correlated with specific variables or processes to understand the orthogonal space where the variables and the experimental data are shown as vectors (variables) and observed scores placed as blue dots (T1 to T6), respectively. This second step found that well and closed-loop flows are the main variables that control all the processes. PC1 is an inverse linear function of closed-loop flow (see the horizontal axis) and PC2 shows an inverse linear function of well flow (see vertical axis in Figure 35).

In the third step, the orthogonal dimensionless space is transformed through a power equation measured in MW (as a function of flows or the principal components). This source is overlain on the space in the biplot graph shown in Figure 35.

The same PCA methodology was used for sCO_2 experiments, but in this case, the principal component variables were the DBHX change in pressure and wellhead pressure respectively, instead of flow rates as was shown in water analysis.

The sCO_2 results are shown in Figure 36. This figure depicts the DBHX Electric Power contour in MWe (a) and the DBHX Heat Power contour in MWth (b).

Figure 36: PCA Analysis of sCO2 as the Working Fluid



Source: GreenFire Energy

Axis PC1 reflects the well pressure and accounts for 52.6 percent of variance and axis PC2 reflects the change in pressure and accounts for 45.1 percent of the variance; together they comprise 97.7 percent of all the observed information variance. The explanation of the graphics characteristics of Figure 36 are similar to the already explained on the Figure 35 because the same methodology was followed, and because variables (red lines) oriented in the vertical axis are important to control DBHX performance as well variables oriented in horizontal axis are important to control Well performance, the most important controlling variables can be simulated at different scenario using a Monte Carlo simulation methodology.

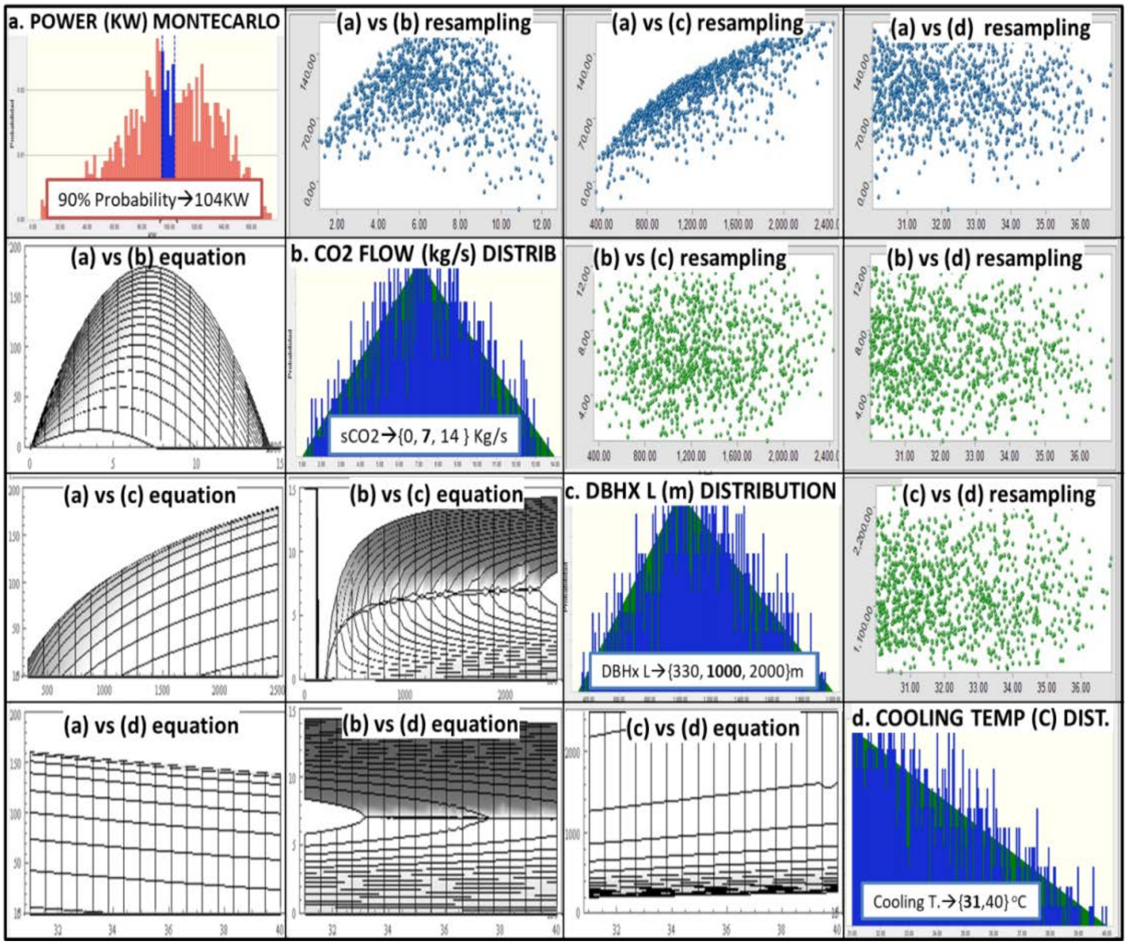
Figure 37 shows the Monte Carlo resampling simulations using the DBHX length, the cooling temperature, and sCO_2 flow rate as control variables. Finally, we arrive at a power production function that considers the effect of these synthetic variables in the process.

The modeling distribution results are displayed in the diagonal graphs of Figure 37: a) power output, b) sCO_2 flow input to be tested, c) DBHX length to be tested, and d) cooling temperature to be tested.

Figure 37 predicts that, using sCO_2 in pilot-scale, 104 KW net power can be obtained for a DBHX of 3,281 feet (1000 m) in length and 88°F (31°C) of cooling temperature. This result assumes no pumping; the thermosiphon is the motive force of the process. Above the diagonal graphics in Figure 37, six other biplot figures show the random resampling conditions in blue and green dot.

Consequently, below the diagonal graphics in Figure 37 the corresponding six results are obtained by equations. The equations shown in the first column summarize the Monte Carlo simulation and can be used to forecast experimental conditions. Similarly, these equations can be used to continue optimizing conditions, designing, validating experiments and forecasting results. For the case of water (see Figure 15) Monte Carlo simulations shows 1.2 MWe optimized power; the differences in water and sCO_2 and Water testing were discussed at the end of the Chapter 5.

Figure 37: Monte Carlo Simulation and 1-D Modeling



Source: GreenFire Energy

Experimental Power Forecasting for sCO_2 using Monte Carlo Simulation and 1-D Modeling