New Opportunities and Applications for Closed-Loop Geothermal Energy Systems

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ABSTRACT

Geothermal energy, the world's most abundant continuous heat supply, is available worldwide. Renewable geothermal energy systems generate clean, reliable, secure, and resilient electric power. Despite burgeoning demand for power, geothermal energy growth has been paradoxically low due to the limitations of legacy hydrothermal technology. However, attempts to use enhanced geothermal systems (EGS) to remedy legacy limitations have yet to succeed, due to the complexity of finding, fracturing, and maintaining the subsurface resources to allow the adequate flow of heated geo-fluids.

In contrast, Closed-Loop Geothermal (CLG) energy systems overcome permeability and flow issues by circulating fluid through sealed wells and pipes. CLG systems are defined as commercial-scale installations that provide geothermal heat for power generation, energy storage, or industrial applications by using an enclosed down-hole heat exchanger (DHX) or sealed pipes recycling a working fluid. CLG technologies transfer subsurface heat into a thermal transport fluid continuously circulating within the sealed wellbore. The versatility of carbon-free CLG applications is evidenced by the wide variety of different well and pipe configurations that can be evaluated to optimize site-specific costs and performance and by the use of different working fluids, such as water and supercritical CO_2 (sCO_2).

This paper first focuses on how CLG expands the range of clean geothermal power generation to include significant, but previously inaccessible, geothermal resources and how CLG enables retrofits of unproductive geothermal and oil and gas wells. It then discusses the unique ability of CLG to provide both continuous renewable electric power and precise flows of heat at high pressure to increase the efficiency and reduce the costs of high-value industrial applications, such as hydrogen production and lithium extraction from brines, all while reducing emissions of global greenhouse gases (GHG).

1. Introduction

The advent of Closed-Loop Geothermal (CLG) technologies expands the potential production and consumption of geothermal energy in fundamental ways:

- Closed-loop systems can operate in a much broader range of temperatures and rock compositions than conventional hydrothermal projects. Applications can range from relatively low-temperature sedimentary zones to hot dry rock formations. This wide range not only increases the number of viable geothermal projects but also allows the use of high-temperature resources (≥300°C) that dramatically increase power output.
- CLG energy systems can produce power from previously unproductive geothermal wells and from played out oil and gas wells in hot strata.
- The baseload and flexible power generation capabilities of CLG can help stabilize the electric grid with reliable, resilient, sustainable energy, capacity, and ancillary services.
- On-site production can provide secure, continuous commercial, industrial, and military uses for heat and power.
- CLG systems can enhance industrial processes, including high-value lithium extraction and hydrogen production, while lowering GHG emissions.

CLG energy systems are made possible by: 1) significant capability and cost improvements in deep (especially horizontal) well drilling, logging, construction, and materials that enable completions into high-temperature regions, greatly expanding the magnitude of useful global geothermal resources, 2) advances in high-temperature cement and well casing that increase long-term well integrity, 3) significant research and modeling of the thermodynamic properties of closed-loop systems that show long-term resource life and viability for CLG systems, 4) testing the efficiency of different closed-loop well architectures across a broad spectrum of geophysical conditions using different working fluids, such as water and supercritical CO_2 (sCO_2), and 5) the pressing need for clean energy to reduce global carbon emissions.

Conventional and closed-loop geothermal systems can provide thermal and electric energy. However, worldwide estimates indicate that only 2% of the earth's geothermal resources reside in permeable regions useful to conventional geothermal technologies (Geiser, 2016). Consequently, enormous resources of geothermal energy remain untapped in hot dry rock below the permeable layer. A 2006 study of U.S. geothermal potential compared the 2.8 GW of geothermal capacity to more than 25 GW of additional resources that were identified, and an additional 90 GW suspected to be available (Tester, 2006). In short, global geothermal energy potential is orders of magnitude larger than today's usage. However, today's geothermal industry requires technological advances to capture this potential.

At year-end 2019, installed geothermal power generation capacity in 27 countries was 15.4 GW. U.S. nameplate capacity reached 3.7 GW, and projects planned or in development could make geothermal energy available in up to 82 countries (Richter, 2019).

Because California has some of the best geothermal sites in the world (Hulen et al, 2002, Kaspereit et al, 2016), the state leads the world in geothermal power with an installed capacity of 2.73 GW in 43 operating power plants (Elders et al., 2019). Despite this potential, the number of net gigawatt-hours generated between 2001 and 2019 decreased (13,984 GWh vs. 11,434 GWh), mainly because of declining production at existing plants and the lack of new projects.

The Geysers Known Geothermal Resource Area (KGRA) provides a vivid example: the site now produces only about half the power today compared to its peak in the 1980s.

Worldwide, the geothermal power industry has expanded since the 1960s by accessing prime sites and generating economically competitive electric power. This expansion eventually forced the development of less attractive sites with many well failures. This trend significantly reduced the attractiveness of expanding geothermal power and exacerbated negative perceptions of the geothermal business model, including high upfront risk, a long lag before revenue generation, and modest returns on investment (Scherer et al., 2020).

Since the 1970s, government-funded research to resolve these problems has focused on developing enhanced geothermal systems (EGS). EGS attempts to increase subsurface formation fractures to permit sufficient geofluid flow rates through permeable rock layers (U.S. DOE et al., 2019). Despite significant government-sponsored research, EGS has been largely unsuccessful in establishing and maintaining hot rock fracture pathways and avoiding cool-water break-through.

New research, development, and demonstration directions recommend using supercritical geothermal resources (Reinsch et al., 2017; Stimac et al., 2017) and developing closed-loop geothermal technologies (Moncarz et al., 2017; Brown, 2000; Oldenburg et al., 2016).

2. Closed-Loop, Renewable Geothermal Electric Power Generation

2.1 Closed-Loop Configurations for Geothermal Power Generation

Many hot geothermal prospects locations lack sufficient subsurface permeability or water to be developed. Multiple researchers (Law et al., 2014; Geiser et al., 2016; Fox et al., 2016; Higgins et al., 2016; Raihi et al., 2017; Higgins et al., 2019; Amaya et al., 2020) have proposed closed-loop geothermal systems to ensure fluid flow in both the permeable layer and exploit the deeper hot rock layer.

CLG technology requires the creation of a sealed well in the subsurface geothermal rock strata. Within this closed system, a heat transport fluid continuously circulates to absorb and deliver heat. No fluid is injected into or extracted from the rocks, so environmental permits are substantially less expensive and time-consuming to obtain. Closed loops also make possible the use of alternative heat transport fluids that create a strong thermosiphon, such as sCO_2, thereby reducing the parasitic power loss associated with pumping. Compact turbomachinery is also scalable with sCO_2, reducing capital costs.

The diagram on the left in Figure 1 illustrates how conventional hydrothermal and EGS projects require large amounts of water pumped down an injection well, then through highly permeable rock as the geofluid collects and transports heat, and into a production well that produces fluid back to the surface via convection as brine or steam. The closed “U-Loop” shown on the right does not need subsurface permeability, because an engineered sealed pipe well system conducts the working fluid through hot rock and up to the surface for power generation.

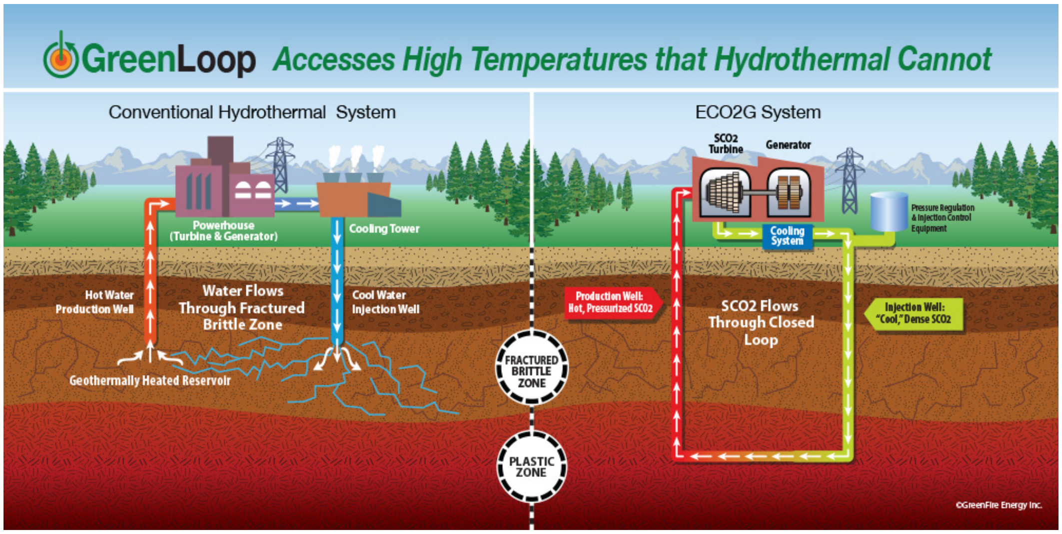

Figure 1: Comparison of conventional geothermal vs. closed-loop geothermal (GreenFire Energy).

In a straightforward configuration, a tube-in-tube assembly (an insulated concentric tube, frequently vacuum insulated tube [VIT]) is run into the well. Heat is absorbed via conduction from the rock through the well casing, and then into the working fluid. Figure 2 shows a deep vertical well with the concentric tube configuration circulating sCO_2.

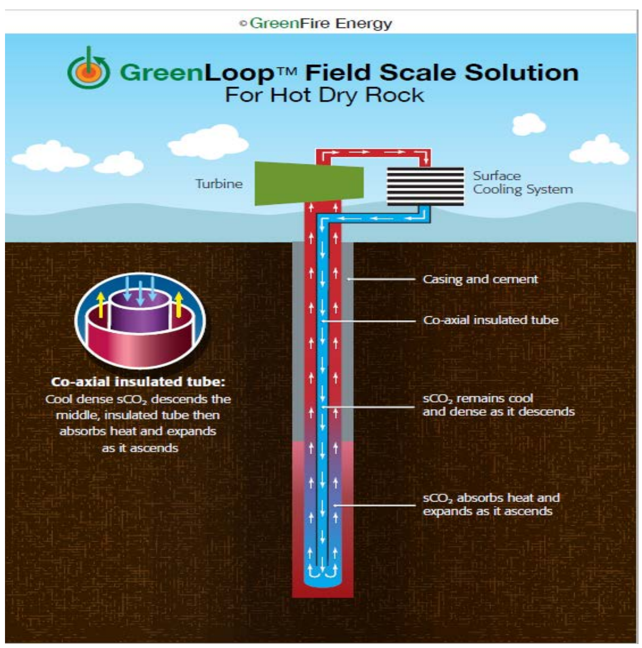

Figure 2: Single well with a concentric tube heat exchanger configuration.

Figure 3 illustrates a highly deviated well design, where the well bore kicks off directionally at the top of the hot geothermal target zone, increasing the surface area for heat transfer by angling through the target zone temperature gradient or following a thermal contour to bottom-hole depth. Multiple onsite deviated wells can increase the energy extracted from a high-quality resource.

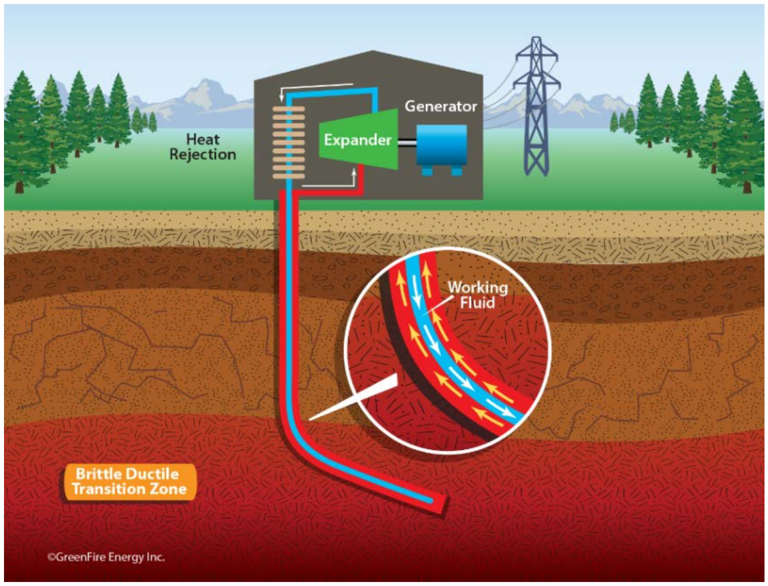

Figure 3: Closed-loop concentric pipe-in-pipe deviated well configuration.

Today's sophisticated wells can have operating lives of 20-40 years with low yearly operating expense. The upstream hydrocarbon industry now drills, completes and produces extreme gas and oil wells from reservoir formation depths over 9,750 m (32,000 ft) with bottom-hole temperatures above 500°F (260°C) and/or bottom-hole pressures to 30,000 psi (207 MPa) (Sathuvalli, 2018). The horizontal length of a single wellbore can be over 6.6 miles (10.7 km). Wells can be drilled in any direction, including a U-shape. Multilateral wells can be drilled and completed, where downhole multiple 'branch' horizontal wellbores emanate from a single 'mother' wellbore drilled from the surface. These advances enable oil and gas and geothermal wells to be used in both new and retrofit applications.

2.2 A Demonstration of Closed-Loop Geothermal Power Technology for Applications in Hot Dry Rock

During 2019, GreenFire Energy Inc. conducted a field demonstration of a CLG system at Coso, California (Higgins et al., 2019; Amaya et al., 2020). The project used a DHX to extract heat from an existing unproductive well. Despite useful enthalpy and satisfactory well integrity, conventional hydrothermal well 34-A20 was not useable for power generation because of high concentrations of non-condensable gases. GreenFire's well modifications included the insertion of a VIT string and installation of surface equipment. Two different working fluids were tested: water and sCO_2.

Figure 4 shows the above-ground equipment in September 2019. The project team conducted tests with varying parameters to build a dataset and calibrate models that could guide the development of future field-scale projects. An extensive description of the project and its results were presented in a California Energy Commission (CEC) report (Scherer et al., 2020).

Figure 4: GreenFire Energy's 2019 demonstration project at the Coso Geothermal Power Plant, Coso, CA.

Due to budget constraints, the closed-loop DHX in this demonstration was only 1,000 feet long. An obvious question is how power generation might increase with a longer well? Figure 5 shows the modeled power potential of a field-scale U-Loop system of increasing lengths installed in a geothermal resource with a thermal gradient of 248°F (120°C)/km. Although convective heat transfer from water in the resource moving across the well would add substantial power, no convection was assumed in these calculations.

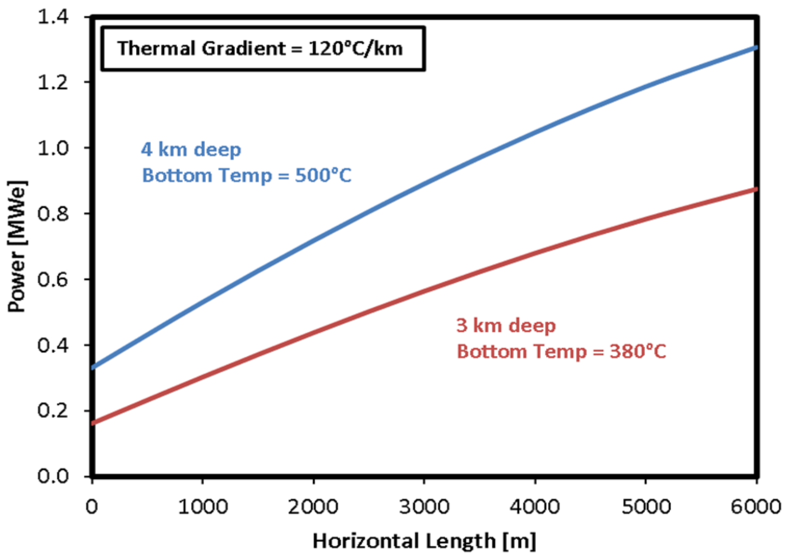

Figure 5: Power potential vs. horizontal length without convection.

Because closed-loop wells can be placed wherever there is heat, another question involves maximum well density without thermal interference. Provided that wellbores through the thermal target zone are at least 263 feet (80 meters) apart, calculations showed that multiple wells could be drilled from a single well pad without thermal interference.

Another relevant question is how much more power could be extracted from the Coso KGRA using CLG wells. Hotter temperatures can geometrically increase power output. By applying the average Coso temperature gradient of 100°C/km, to estimate temperatures below the 4 km depth of existing wells, it was determined that temperatures beneath Coso range from 932°F (500°C) to 1472°F (800°C).

Even if the maximum bottom-hole temperature for drilling deep wells is capped at 500°C, the potential power generation at Coso is an extraordinary 19 GW_e. When current limitations on drilling and materials are considered, plus an acceptable levelized cost of electricity (LCOE), the potential capacity at Coso with intensive closed-loop development is in the range of 1 to 2 GW_e, compared to its current capacity of about 0.145 GW_e. Measurements of CLG performance parameters during the Coso demonstration confirmed the accuracy of GreenFire's geothermal models to predict closed-loop power generation from diverse types of geothermal resources, including dry steam wells at The Geysers, hypersaline wells near the Salton Sea, and hot dry rock at Coso. Commercial CLG projects in Asia and Europe are now being modeled and designed for implementation.

Because power generation is a function of thermal surface area, the industry continues investigating the potential to multiply heat conduction via well configurations that increase down-hole surface area, such as an inverted tree-like configuration of fluid-conducting pipes. GTherm investigated various well architectures to increase down-hole surface area, developing a proprietary "heat rod" technology utilizing special fluids to conduct and concentrate heat at the center stem (GTherm, 2014).

2.3 Other Applications for CLG Energy Systems

2.3.1 A Closed-Loop Multilateral-Pipe Energy System for Power and District Heating

In addition to power generation, geothermal energy is well-suited for district heating and greenhouse applications, as reviewed by M. Soltani (Soltani et al., 2019). Eavor Technologies, Inc., a Canadian company, is developing CLG systems to produce both power and heat, primarily in low heat sedimentary basins at pressures higher than 10 MPa and temperatures less than 180°C (Eavor, 2020). Eavor's demonstration project near Rocky Mountain House, Alberta, was designed to generate industrial-scale electricity or sufficient heat to supply the equivalent of 16,000 homes from a single installation. Its technical objectives were to achieve:

- The ability to drill and intersect a multilateral closed loop with two laterals,
- The ability to simultaneously drill and seal the wellbores, creating a closed-loop isolated from the surrounding formation that does not leak fluid nor allow formation fluids to ingress into the closed-loop system,
- Prove that the subsurface heat transfer and thermosiphon effect match expectations.

Eavor’s CAD$10M demonstration project broke ground in August 2019, and successfully completed tests satisfying the technical objectives in September 2019. The demonstration project constructed multiple horizontal pipes connecting two vertical wells about 2.4 kilometers deep with lateral wellbores several kilometers in length (Figure 6.) Because there is no casing on the laterals, wellbores must be sealed below ground, so that the working fluid re-circulates without losses.

In May 2020, Eavor and Enex Power signed a letter of intent to use CLG to revitalize a project in Geretstried, Germany, where two exploratory wells had failed to find sufficient hot hydrothermal water to enable the economic development of a conventional geothermal project. Other projects are now being developed to scale-up output and bring down unit costs.

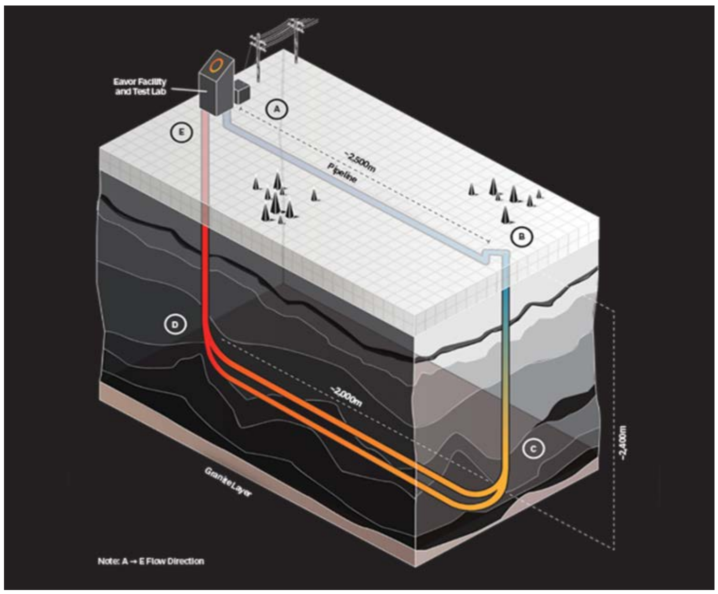

Figure 6: A simple Eavor-Loop™ configuration with lateral pipes several kilometers long connected and sealed at depth to inlet and outlet wells.

2.3.2 Retrofit of CLG Down-Hole Heat Exchangers (DHX) to Increase Power Generation at Under-Producing Geothermal Wells

In the U.S., 80% of geothermal wells now operating were drilled before the year 2000. Many were dry holes when first drilled, failed mechanically, or have experienced severe declines in production. In addition, conventional geothermal wells were drilled that failed to produce adequate power, due to a variety of problems common to legacy hydrothermal projects, including inadequate brine production, high non-condensable gases (NCG), low wellhead pressure, corrosive brine, and/or insufficient resource permeability. A study commissioned by the World Bank concluded that approximately 22% of all geothermal wells worldwide have “failed” (World Bank, 2013). Although some wells can be cured using various “workover” techniques, these are usually expensive and involve additional drilling.

A better option - CLG well retrofits - might be used to enable unproductive wells to generate more power with less risk and lower costs. This is increasingly appealing, because the cost of plugging and abandoning wells has escalated. The possibility of fixing new wells that fail to produce power by using low-cost closed-loop retrofit technology is an effective way to mitigate new project risks (Higgins, 2019). CLG retrofits may also reduce geothermal emissions experienced with geothermal brines at some conventional hydrothermal geothermal sites (Yanagisawa, 2017; von Düring, 2016).

A typical hydrothermal well retrofit solution is illustrated in Figure 7, which shows a closed-loop DHX inserted into an existing well. The working fluid circulates from the steam turbine back to the bottom of the DHX and extracts more heat on its upward path from the flow of co-produced geofluid rising in the outer annulus between the well casing and the DHX.

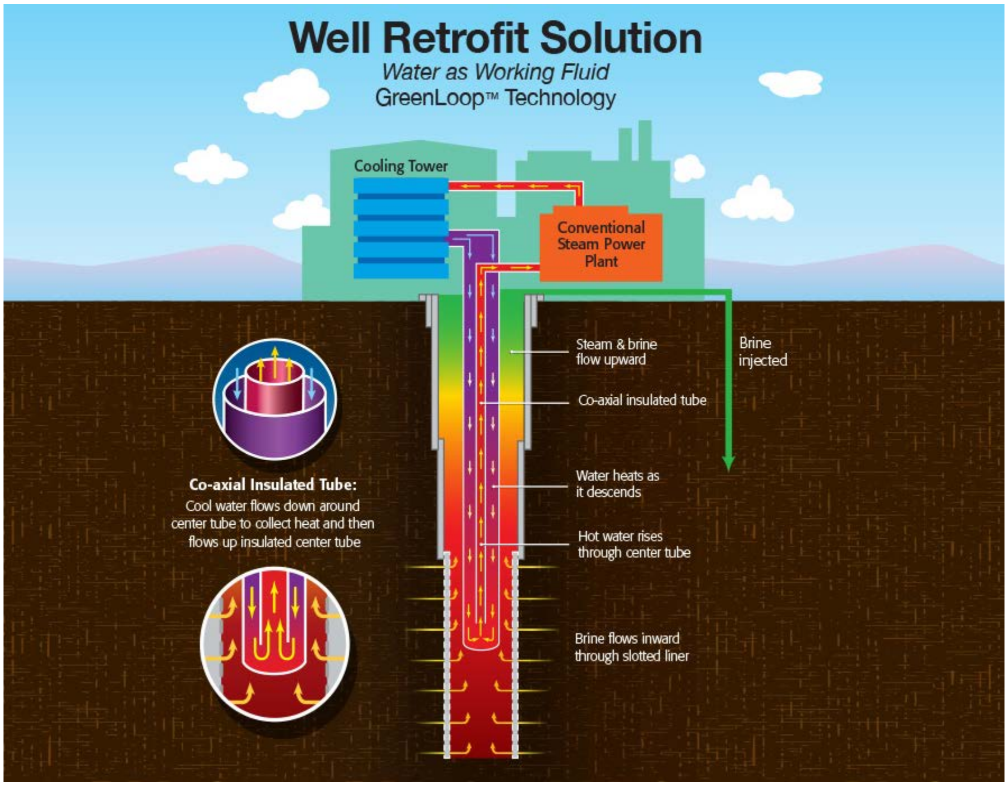

Figure 7: A closed-loop geothermal well retrofit. The DHX fluid can flow in either direction, depending on the working fluid. Water flows down the annulus and up the center, or sCO_2 flows down the center and is heated more as it flows up the annulus. Cooling water is required to reject excess heat from circulating sCO_2.

The chief advantage of the DHX is that the working fluid is exposed to the higher brine temperatures near the bottom of the DHX relative to temperatures near the surface. Hence, the working fluid reaches the surface at a higher temperature than the produced geothermal brine. When water is used as the working fluid, a key benefit is producing steam that does not contain contaminants transported from the subsurface, like NCGs, salts, radioactive isotopes, or metals. Similarly, when sCO_2 is the working fluid, heated sCO_2 generates power via expansion. Details of GreenFire Energy's Coso demonstration using a DHX are discussed in Higgins et al., 2019, Amaya et al., 2020, and Scherer et al., 2020.

2.3.3 Retrofit of Oil and Gas Wells for Power Production and Pumping in Suitable Oil and Gas Reservoirs

Today, there are nearly 100,000 well pads in the U.S. Permian basin alone, as well as millions of abandoned wells throughout the world. Many wells could be candidates for DHX or another method of transporting geothermal heat to the surface, rather than being idled. Repurposing existing hydrocarbon gas & oil wells for geothermal operations, including the combined production of geothermal heat with hydrocarbons, is a recently re-visited idea (Alimonti, 2020).

Three different business models are envisioned for combining CLG with oil and gas wells. First, is the idea of inserting a DHX in a defunct oil well to generate power for pumping oil from producing wells in the same field. This could be economical where diesel generators are used to power oil field pumps.

Second, geothermal heat might be used directly to pump oil or co-extract methane. One potential solution comes from the Gravity Head Pump (GHP) developed by GeoTek (GeoTek, 2015). A GHP is a down-hole pump that takes heat from the surrounding rock to create a thermosiphon that powers the mechanism. This innovation avoids the cost of electricity that would otherwise be used for submersible or surface pumps and is particularly interesting for off-grid sites. Third, a CLG system could be inserted into suitable non-productive oil wells to repurpose them for electric power generation. Because the wells are already drilled, and the subsurface is well-understood, the most expensive component of conventional geothermal power generation is avoidable. Another advantage is that repurposing such wells can indefinitely defer the substantial costs of abandonment.

These different approaches share the common challenge of transferring enough enthalpy to be cost-effective. CLG casing strings must be large enough to provide sufficient heat transfer across the down-hole tubulars and annuli into the working fluid. Because the largest percentage of oil and gas wells have 5-1/2-inch casing or less and have smaller inside diameter than typical geothermal >7.5-inch casing sizes, a tube-in-tube DHX may only be applicable when it's dimensionally possible.

DHX feasibility for oil well retrofits must be determined with accurate thermodynamic models and analytical engineering design tools. Geo-technical and well data are needed to evaluate possible retrofit designs, costs, and performance. Required heat transfer values and wellbore sizes for optimal thermal efficiency can be calculated for different diameter and length combinations. Well design is an iterative process where the variables of heat transfer are compared with the circulated fluid flow within the mechanical and dimensional limitations of well construction materials and components.

2.3.4 Advantages of Geothermal Electricity Generation for Energy and Grid Balancing

The need to reduce global GHG has led to rapid additions of variable wind and solar power. Due to their intermittency, maintaining reliable electricity service requires many changes to grid operations and tariffs, and often leads to plans relying on battery storage technologies with unproven duty cycles, costs, and uncertain lifetimes. Unlike intermittent solar and wind, geothermal systems operate continuously and reliably - night and day, rain or shine, in winds, and calm. Geothermal plants can deliver baseload and flexible power required for grid reliability, supply diversity, and electricity grid balancing by providing needed capacity, energy, and ancillary services (Thomsen, 2019; Orenstein and Thomsen, 2017; Matek, 2015; Luckhardt, 2016; Sepulveda, 2018; Jenkins, 2020).

An intriguing prospect would combine hydrogen production and geothermal power generation to balance supply and demand in the electricity grid. In California and elsewhere, over-generation by solar and wind occurs when intermittent electricity supplies exceed power demand. This oversupply not only causes a curtailment of power plants and falling wholesale prices, but also requires added available resources for ramping up generation when wind and solar become unavailable. In this case, geothermal power could be controlled to produce hydrogen continuously or only during grid oversupply periods, when wholesale power prices are too low.

2.3.5 Advantages of Geothermal Energy Systems Compared to Alternatives

Conventional geothermal systems generally have lower lifecycle environmental impacts than other electric generating technologies (Heath, 2016; Sullivan et al., 2010; Menberg et al., 2016; Matuszewska et al., 2019; Paulilloa et al., 2020; Basosi et al., 2020). One significant benefit is geothermal's small land footprint in comparison to other renewables. Estimated relative aggregate lifecycle environmental footprints (RAF) analyzed using lifecycle assessment methods (LCA) are shown in Figure 8.

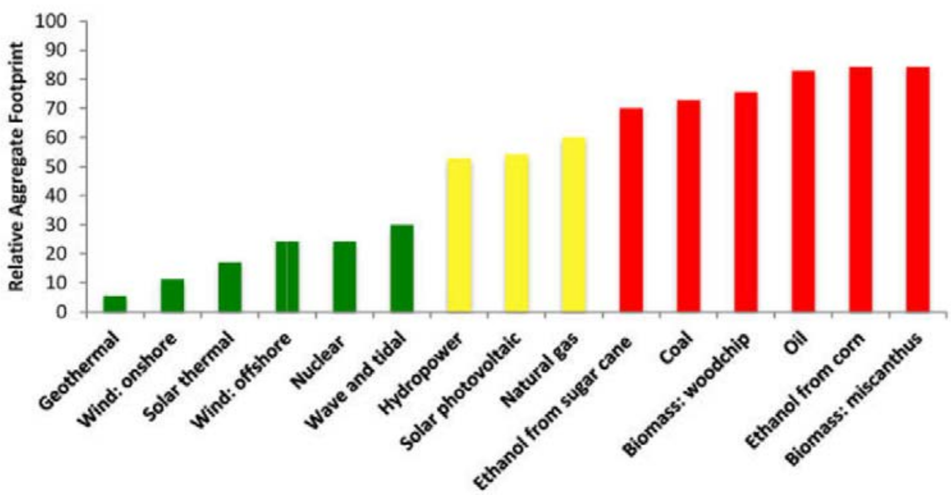

Figure 8: Relative lifecycle aggregate footprints (RAF) of different energy sources (Matuszewska et al., 2019).

CLG technologies also have important environmental advantages over conventional hydrothermal and EGS:

Air & Water Quality

- Consume little or no process water,
- Produce carbon-free emissions,
- Reduce problems with saline and corrosive brines inside the system,
- Have fewer effluent & waste disposal problems and permitting issues, and
- Do not interfere with subsurface water, such as hot springs and onsens.

Public Safety & Environmental Soundness

- No surface subsidence,
- No waste streams,
- No hazardous chemicals, and
- No risk of induced seismicity.

3. Potential Hydrogen Production Processes Using Closed-Loop Geothermal Heat and Power

Because hydrogen creates water and heat when it combines with oxygen (instead of GHG and other fossil-fuel pollutants), it is a highly attractive fuel for power, heat, and transportation, as well as being valuable for various industrial processes. Today, most hydrogen is consumed by on-site industrial applications for refining, ammonia production (which comprises 55% of global use), treating metals, and electric power generation. Pipelines transport hydrogen to storage and end-users, sometimes blended with natural gas. End-users include public transportation, diesel trucks, light-duty fuel cell vehicles (FCV), maritime facilities that refuel trans-oceanic ships, and steel mills.

Commercial hydrogen production processes have varying costs and environmental impacts. Steam Methane Reforming (SMR) using natural gas is the predominant process, producing "Grey Hydrogen" via pyrolysis, which releases significant CO_2. Electrolysis of water is a more expensive process that does not directly produce CO_2 but requires substantial electricity, often generated by fossil fuels. By comparison, "Green Hydrogen" is produced from zero-carbon feedstock utilizing non-carbon emitting renewable or nuclear energy, while "Blue Hydrogen" production relies on natural gas accompanied by Carbon Capture and Sequestration (CCS).

Global hydrogen production exceeds 70 million metric tons per year, emitting more than 830 million tonnes of CO_2 (Vine, 2020). Today, the price of hydrogen made by splitting water ("green hydrogen") is more than twice the price of "grey" hydrogen produced by traditional SMR. However, production costs for green hydrogen are anticipated to decline by 40-70 percent by 2030, with about 0.4 million tonnes/year of green hydrogen capacity and 2.7 million tonnes/year of blue hydrogen capacity added by 2026 (Platts-S&P Global, 2020).

Geothermal energy could be strategic for reducing the current high cost of clean hydrogen. Baseload geothermal energy could alternate between commercial power or heat generation and hydrogen production. When it is more advantageous to sell power to the grid, hydrogen production processes can be readily curtailed to allow geothermal plants to sell power. Geothermal capacity could also power other industries, serve consumers, and provide jobs (Elders, 2016; Shnell et al., 2016; Elders et al., 2018; Van Horn et al., 2016). Hydrogen storage can be long-term - months longer than battery storage. Mitsubishi is planning the world's largest hydrogen energy storage facility inside Utah salt domes with a capacity equivalent to 1GW – enough to serve 150,000 households with no seasonal variation.

California's Salton Sea Geothermal Field and Mexico's Cerro Prieto, two of the world's largest and hottest geothermal fields, may be ideally located for hydrogen production and distribution. In 2019, there were over 400 MW_e of operating geothermal plants in California's Imperial

Valley, which can accommodate more, and there is a growing market for hydrogen in California and elsewhere

How can geothermal power contribute? Very pure hydrogen production by electrolysis is much more efficient at high temperatures. An integrated CLG geothermal hydrogen production system could produce electrical energy for electrolysis and provide cost-effective thermal energy needed to achieve high-temperature production. Additionally, because hydrogen must be compressed for transport, CLG can precisely create and maintain high pressures for compression.

Prospects for using geothermal energy for hydrogen production are doubly attractive since the use of fossil fuels may be avoided as feedstock and as the energy source. Two types of CLG processes are feasible:

- Down-hole reaction methods (DHR) using the components installed in the well itself as reaction chambers, thus applying geothermal heat efficiently to improve production methods and reduce costs, and

- Transporting higher temperature geothermal heat to the surface to reduce the heat and power needed from surface sources, thereby reducing costs and the environmental footprint.

CLG can take advantage of higher down-bore temperatures and pressures to improve the efficiency of several hydrogen production methods. GreenFire Energy has designed down-hole apparatus, systems, processes, and methods to reduce the costs of clean hydrogen production, storage, and delivery by adapting the following hydrogen production methods:

- Alkaline electrolysis method,
- Solid oxide electrolysis cell method,
- Proton exchange membrane method,
- Variations in the above processes that reduce the electrical energy required for electrolysis and/or control flow rates and circulation of various fluids and electrolytes,
- Partial oxidation method,
- Copper chloride method,
- Copper chloride method combined with a hybrid process capturing, storing, and recycling exothermic hydrogen production heat that can be used simultaneously or applied in stages to power endothermic hydrogen production at higher temperature and pressure,
- Steam reformation method,
- Auto-thermal reformation method,
- Liquefaction method, and
- Co-production methods using geothermal brine as a working fluid to generate surface thermal or electrical power.

In addition to lowering GHG emissions, the use of down-hole CLG for hydrogen production should be safer than surface hydrogen production and is expected to be more profitable.

4. Potential Lithium and Mineral Extraction Processes Using Closed-Loop Geothermal

The Department of the Interior classifies lithium as one of 35 minerals critical to U.S. national security and economy. Today, more than 95 percent of the world's lithium supply is sold as lithium carbonate, mostly from brines, and as lithium hydroxide, which is produced by mining. Geothermal brines can provide significant supplies of lithium and other minerals, as well as producing electric power.

In 2017, global lithium demand was about 214 kilotons (kt) of lithium carbonate equivalent (LCE), of which 87 kt LCE was for batteries. In 2025, demand is expected to rise to 670 kt LCE, with 509 kt LCE for batteries (Azevedo et al., 2018). Lithium demand is driven by growing markets for electric vehicles (EVs), utility-size storage batteries, electrification, electronics, tools, equipment, and specific compounds for lubricants and pharmaceuticals. However, concerns about lithium sources, international supply chains, price volatility, and politically restricted availability are being voiced by mining and refining companies, automotive OEMs, battery manufacturers, commodity investors, and politicians.

Four companies dominated global lithium production in 2017, producing about 450 kt, well above demand. Nevertheless, prices were volatile, rising from an average of $5,000/t in 2016 to $19,500/t in 2017, possibly because supplies come from only eight countries; China, Chile, and Australia produce about 85 percent. Because of lower production costs, brine processing is the most prevalent method, but hard rock production of lithium hydroxide is growing, mostly in China (Azevedo et al., 2018).

Cost is not the only advantage of lithium production from brine. A recent study by Jade Cove Partners (Grant, A., 2019) enumerated other benefits:

- Either lithium carbonate or lithium hydroxide can be produced,
- Efficiency – up to 90% of the lithium is extracted vs. 40% via evaporation ponds,
- Speed - lithium is extracted in hours, instead of days,
- Purity – the lithium is pure and highly concentrated for easy processing,
- No need for expensive, large footprint and complicated evaporation ponds,
    - Reduces water consumption to 1/50th,
    - Minimal footprint,
    - Extraction rate and efficiency are not affected by rain or wind speed.

The major components for conventional processes for direct lithium extraction from aqueous resources are shown in Figure 9.

In 2019, there were nine lithium projects in western U.S. sedimentary basins, including those in the Salton Sea KGRA. See Figure 10 (Grant, 2020). By itself, California has all the elements to build an integrated supply chain from "brines to batteries."

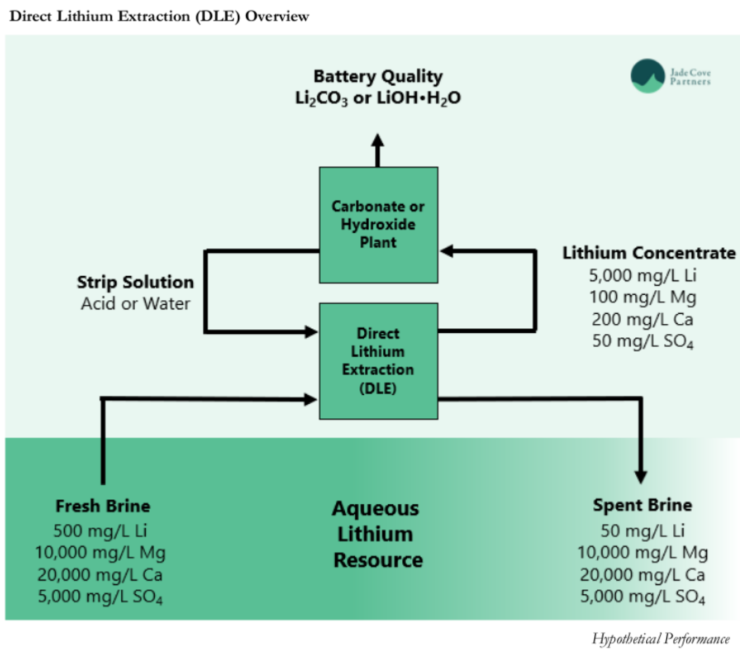

Figure 9: Advantages of Direct Lithium Extraction from Aqueous Solutions (Jade Cove Partners, Grant, 2019).

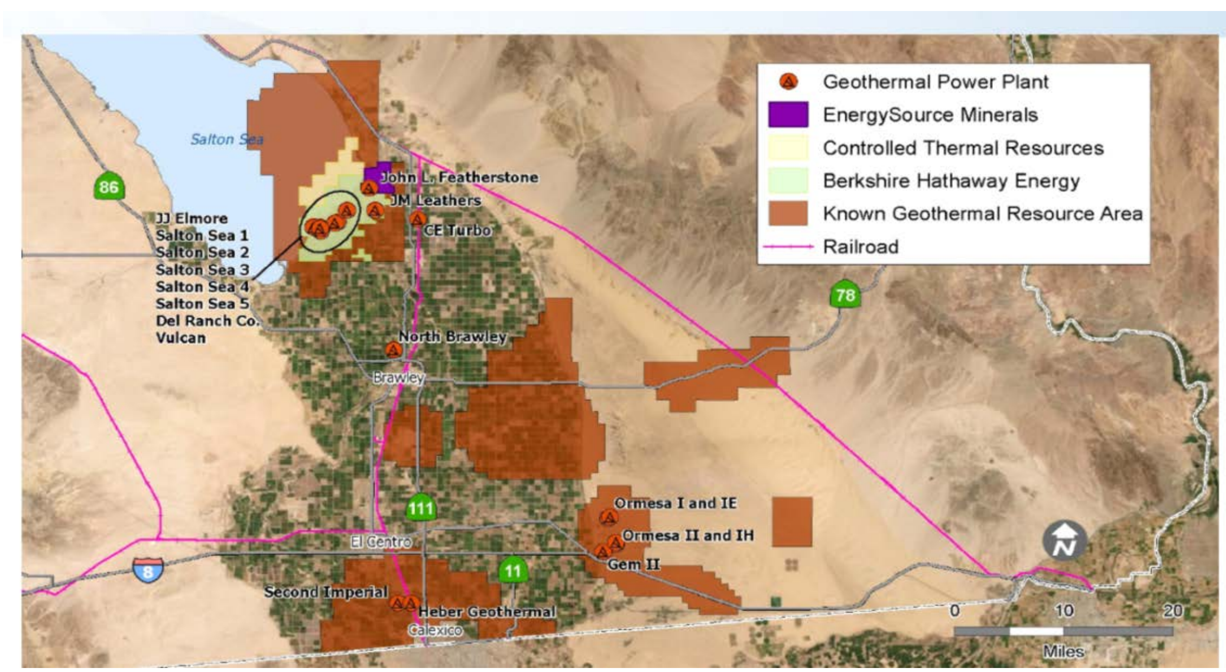

Figure 10: Lithium in the Salton Sea Area – CEC presentation. (Stanford Geothermal Workshop, February 2020).

Recognizing the importance of the Salton Sea area, the CEC conducted a February 2020 symposium to outline California's Lithium Recovery Initiative (CEC et al., 2020). In April, the CEC awarded $9.34 million for projects to test and develop processes to improve lithium recovery. If successful, these could reduce the costs of associated geothermal power by up to 35 percent.

Full utilization of the Salton Sea KGRA for lithium production can simultaneously accomplish other important goals, such as power to desalinate and replenish water evaporating from the Salton Sea, and to mitigate the growing threat of toxic dust (Wilson, 2019). The same capacity can provide drinking water for an arid region, produce hydrogen, reduce GHG emissions, and send flexible power to the grid (Elders et al., 2018; Elders et al., 2019; Shnell et al., 2018).

CLG technology offers a fundamentally different approach to simultaneous power generation and lithium extraction. CLG DHX circulates a working fluid at different flow rates to optimize power generation. Meanwhile, mineralized brine annular flow inside the casing is co-produced at rates selected to co-optimize the efficiency of lithium extraction. Because the brine well flow transfers heat to the working fluid in the DHX, the two respective fluid flow rates are thermodynamically connected and constrained. When compared to systems with a single flow of brine, "two-flow" flexibility makes it easier to optimize the balance between power production and lithium extraction.

As described in section 2.3.2, a DHX design was successfully demonstrated at GreenFire's CLG project at Coso, California, which produced brine to the surface, while alternatively circulating sCO_2 and water as working fluids within a closed loop. However, brines with high Total Dissolved Solids (TDS) as found in the Salton Sea KGRA present challenges not experienced at Coso, where no mineral extraction was considered. Potential issues using a DHX inside conventional geothermal wells relate to (1) chemistry changes associated with the produced brine as it expands, typically flashing and rising to the surface, (2) concentration of silicate and other compounds, and (3) corrosion issues (DiPippo, 2020). In principle, these problems are partially offset by less scaling at the surface and reduced need for water treatment. If implemented, CLG technologies that co-produce power and lithium could optimize performance by enabling independent control of each flow within prescribed limits. Specific well designs would be engineered to account for the wide differences in brine temperature, pressure, and composition characterizing geothermal resources.

5. Conclusions

Closed-loop geothermal (CLG) systems can make significant contributions toward satisfying global energy and environmental needs. Overall:

- Advanced technologies are essential to supply clean energy and reduce greenhouse gases.
- Electricity is the world's most versatile form of energy.
- Reliable, renewable, climate-resilient, and environmentally preferred geothermal energy provides clean, continuous heat and electric power.
- Innovative, closed-loop geothermal systems can access previously unavailable, abundant high energy resources and deliver secure, sustainable carbon-free energy at competitive costs.

CLG technologies are in their early commercialization stages. Applications accessing permeable layer geothermal resources can incorporate down-hole heat exchangers (DHX), apply different concentric pipe-in-pipe architectures, or use single or multi-lateral wellbore configurations to connect inlet and outlet wells in sealed U-Loop systems. CLG energy systems can also access the vast, untapped heat in deeper and hotter rocks, greatly expanding available worldwide geothermal resources. In addition to electric power generation from both new and retrofit geothermal and oil & gas wells, promising applications of closed-loop geothermal systems can provide direct heat and cooling, enhance hydrogen production, improve lithium extraction from geothermal brines, and desalinate water, all while significantly reducing global GHG emissions.

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