Progress for Closed-Loop Geothermal Projects in Steam and 2-Phase Dominated Reservoirs

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ABSTRACT

GreenFire Energy Inc. has been developing technology to apply closed-loop geothermal (CLG) technology in steam dominated and high enthalpy two-phase reservoirs (called Steam and 2-Phase Dominated GreenLoop (S2PGL)) for several years. In S2PGL a downhole tube-in-tube heat exchanger circulates large volumes of a variety of working fluids. The working fluid returns to the surface hot through an insulated tube and can be flashed to produce power at an existing power plant, used for the direct power production by an integrated Organic Rankine Cycle power-generating system, or used for district heating. Downhole steam condenses on the surface of the heat exchanger transferring its latent heat of vaporization to the working fluid. The condensed steam produces a flow of geofluid condensate towards the bottom of the well, where it builds up to produce the hydrostatic head required to force the liquid deep back into the reservoir. The effect of the downbore closed-loop heat exchanger is to extract heat, rather than mass, from the resource, thereby conserving water and maintaining pressure in the geothermal resource and ensuring the long-term sustainability of the resource. This technology has the potential to dramatically expand power production from geothermal resources where conventional geothermal technology is challenged and to substantially de-risk new geothermal projects. Technical papers on the modeling of S2PGL and supporting this assertion were presented at the 2021 Geothermal Rising Conference and the 2021 National Geothermal Association of the Philippines Conference.

Notably, within the last year S2PGL has moved from the technical modeling stage to the implementation stage. In this paper the key participants in various projects describe the implementation status of the initial project and related testing projects. In particular, GreenFire was awarded a grant under the BRIDGE (Bringing Rapid Innovation Development to Green

Energy) solicitation program by the California Energy Commission to implement and test GreenFire's Steam Dominated GreenLoop technology at The Geysers, the largest single geothermal location in the world, which also has very substantial steam dominated reservoirs. The Geysers Power Corporation (GPC), a subsidiary of Calpine Corporation, has agreed to host and support this project. Key aspects of the planning and implementation of this project will be shared in this paper. The paper will also report, consistent with confidentiality obligations, on the progress of other S2PGL projects that are being pursued commercially with existing geothermal owner/operators.

1. Introduction

GreenFire Energy Inc. (GreenFire) has been developing technology to apply closed-loop geothermal technology in steam and two-phase dominated reservoirs (Steam and 2-Phase GreenLoop™ or (S2PGL) for several years (Higgins et al., 2021; Amaya et al., 2021). The effect of the downbore closed-loop heat exchanger is to extract heat, rather than mass, from the resource, thereby conserving water and maintaining pressure in the geothermal resource and ensuring the long-term sustainability of the resource.

Notably, however, within the last year S2PGL has moved from the technical modeling stage to the implementation stage. In particular, S2PGL is being implemented at The Geysers KGRA (The Geysers) with funding from the California Energy Commission in a project to prove its commercial feasibility (GreenFire Energy, 2022).

More broadly, S2PGL projects are also being developed at other locations in the USA, Southeast Asia, the Far East and Europe. This paper describes the project at The Geysers in detail and, consistent with confidentiality obligations, an overview of the progress on other commercial S2PGL projects elsewhere with existing geothermal owner/operators.

2. The Concept of Steam and 2-Phase GreenLoop (S2PGL)

While there are variations tailored to particular geothermal wells and in resources, typically in S2PGL a tube-in-tube downbore heat exchanger (DBHX) circulates large volumes of a variety of working fluids in a closed loop. The hot working fluid returns to the surface through an insulated tube with the thermal energy either converted to electrical energy via a heat exchanger coupled with an Organic Rankine Cycle (ORC) power generation unit or used for direct use applications (district heating/cooling). Specifically during operation, downhole steam condenses on the surface of the heat exchanger transferring its latent heat of vaporization to the working fluid. The condensed steam produces a flow of geofluid condensate towards the bottom of the well where, together with other fluid in the wellbore as applicable, it builds up to produce the hydrostatic head required to force the liquid deep back into the reservoir. While various well configurations can be used to implement S2PGL, the following figure from GreenFire's patent awarded in the USA (Higgins et al., 2022) shows the essential features:

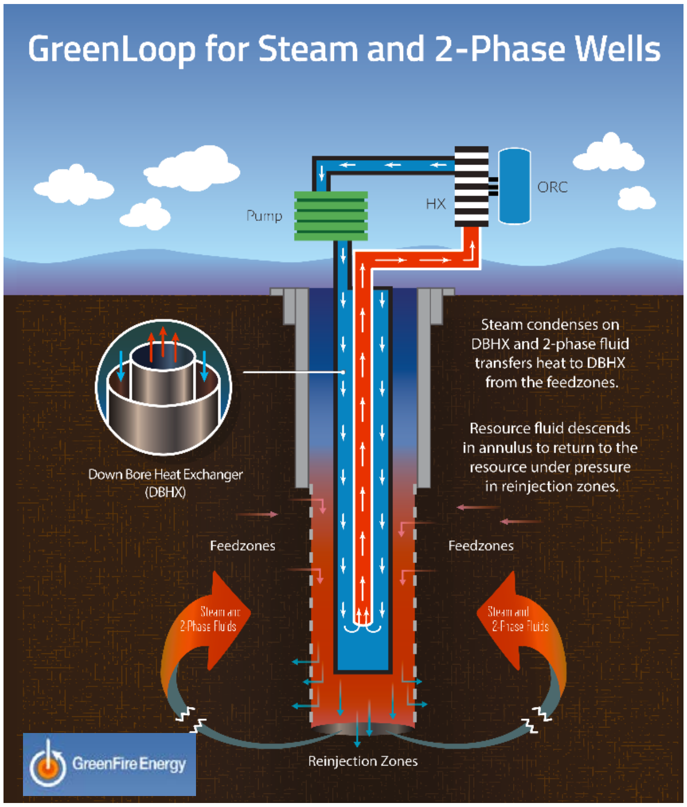

Figure 1: The DBHX is located in a well and hung from the wellhead. Cold and hot fluids flow in the annular region and the center vacuum insulated tube respectively. Steam from the reservoir condenses and flows downwards in the well as depicted by the blue arrows below the DBHX. The condensed fluid is allowed to recycle back into the reservoir to gain heat and supply the DBHX or other wells in the resource.

When applied in the coaxial configuration shown in Figure 1, the S2PGL can be applied in a variety of contexts, including to retrofit idle or unproductive wells, to retrofit producing wells where conventional production systems could deplete the resource of water and pressure and to be used in new wells designed to optimize production on a cost/benefit basis. S2PGL can also be used to de-risk conventional geothermal project development by producing commercially attractive power from unsuccessfully drilled conventional wells. A conventionally drilled well can be unsuccessful for a variety of reasons such as the lack of commercially available permeability, chemistry issues etc. Similarly, S2PGL can also de-risk geothermal sites over time as a geothermal resource changes with reductions of pressure or water as is typical in many steam and 2-phase resources. Therefore, by contemplating the possibility that either up front or over the course of time conventional wells will not be commercially productive, geothermal owners/developers can choose to design their wells such that the S2PGL can be applied right at the time of project initiation.

S2PGL can have different architectures. The most commonly used architecture which is the tube-in tube coaxial heat exchanger is described in this paper. The system uses an insulated tubing (such as vacuum insulated tubing (VIT)) to circulate a working fluid (water is commonly proposed due to simplicity but refrigerants, supercritical CO_2 and ORC fluids can also be used depending on thermosiphon and surface system conditions). Usually, the working fluid is injected into the annular region of the coaxial architecture to enhance the heat transfer process from the resource and returns to the surface through the insulated tubing. The heat gained by the downbore heat exchanger can be used at the surface for different applications including but not limited to: power generation, direct use, and industrial purposes. Therefore, only heat from the resource is extracted through the DBHX and not mass.

S2PGL using a coaxial architecture for a retrofit well application is usually installed to the depth of the primary feedzone. The steam contained in the feedzone is condensed on the outside surface of the DBHX extracting the latent heat of vaporization and transferring it to the DBHX.. The geothermal productivity of the feedzone is controlled by varying the DBHX flow rate and wellhead pressure. Optimization of these conditions allows the system to maximize the power production potential of the well. For more details on the description and analysis of the S2PGL, the authors recommend reviewing Higgins et al. (2021).

3. Steam Dominated GreenLoop (SDGL) Project at The Geysers

The Geysers geothermal field in Northern California USA is one of the oldest and largest developed fields in the world. It is located approximately 121-km (75 miles) north of San Francisco, California, straddles the border between Sonoma County and Lake County and covers a land area of approximately 116 km^2 (45 mi^2). Calpine's Geysers Power Company (GPC) owns and operates thirteen (13) power plants at The Geysers with a net generating capacity of about 725 MW of electricity. Calpine's wellfield consists of three hundred seventy-six (376) production and injection wells. The average well depth is approximately 2590 m (8500 ft), the average reservoir steam temperature is 190°C (374°F), and the average flowing steam pressure is 0.56 MPa-gauge (81 psig). The produced steam is superheated (i.e., “dry”) at average wellhead pressure and temperature conditions (Calpine, 2019) . Since the resource at The Geysers is primarily steam dominated, the technology that is introduced and defined as S2PGL in previous sections is henceforth referred to as SDGL in this section.

In the 1990s GPC took over management of the field and plants from previous owners such as Unocal, Pacific Gas & Electric (PG&E) and the Sacramento Municipal Utilities District (SMUD), inheriting their design and historical operating data. GPC additionally developed their own new projects. GPC and the neighboring Northern California Power Agency (NCPA), which also operates several units in the field, cooperate on large-scale injection improvement projects such as the Southeast Geysers Effluent Pipeline (SEGEP), which collects treated wastewater from nearby communities (Urbank et al., 2021).

The geothermal electric generation facilities at The Geysers have a long history of production with the first power plant, PG&E Unit 1, beginning generation in 1960. As a result, there is substantial published literature documenting the area's geothermal productivity over time, and this literature shows a decline in geothermal production without continued water injection. Sanyal and Enedy presented the cumulative history of production, including the gap between water extraction and water reinjection, leading to a reduction in power potential of the resource (Sanyal and Enedy, 2011).

Various sources of water for injection have been used to successfully slow the rate of depletion. These sources include steam condensate and surface (creek) run-off. By late 1997, a 46 km (29 mile) pipeline from the community of Clear Lake, California began supplying 29,530 m^3/day (7.8 x 10^6 US gallons/day) of treated municipal effluent for injection into the reservoir. This line was lengthened in 2003 to 85 km (53 miles) to connect with alternative sources of municipal effluent. A second pipeline, this one 66 km (41 miles) long, began operating in 2003 to bring in 41,640 m^3/day (11 x 10^6 US gallons/day) of treated effluent from the City of Santa Rosa (Sanyal and Enedy, 2016).

While The Geysers has a long and successful history of steam production and electrical generation, it is now known that for geothermal dry steam fields, it is essential for long-term reservoir management that the mass loss (production less injection) of steam/fluid from the reservoir be minimized in order to preserve steam production flowrates, as well as reservoir and steam production system pressure.

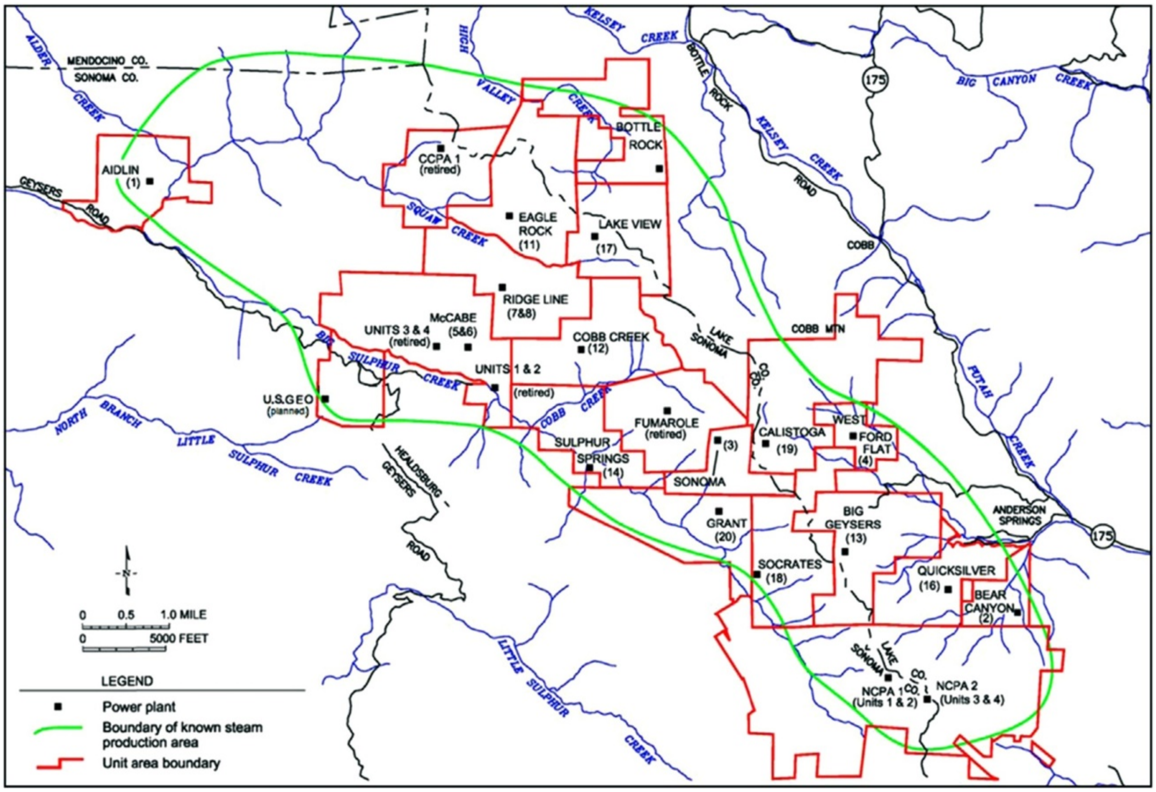

Figure 2: The location of various power plants and unit areas at The Geysers geothermal field. Figure is adapted from Sanyal and Enedy (2016)

3.1 California Energy Commission Support

GreenFire was awarded a $2,705,228 grant by the California Energy Commission (CEC) to advance the development of GreenFire's Steam Dominated GreenLoop (SDGL) system in an existing low-production geothermal well at The Geysers geothermal area in Lake County, California (GreenFire Energy, 2022). The award (EPC-21-015) came from the CEC's Bringing Rapid Innovation Development to Green Energy (BRIDGE) funding opportunity, which competitively selects and awards follow-on funding for the most promising clean energy technologies that have previously received an award from an eligible CEC program or United States federal agency. GreenFire's previous CEC project (GEO-16-004) that retrofitted an existing well and conducted tests with a DBHX at Coso, California were referenced to support award selection.

BRIDGE seeks to 1) help start-up companies minimize the time between when their successful publicly funded project ends and new public funding becomes available; and 2) mobilize more early-stage capital in the clean energy space by providing non-dilutive, matching investments in promising clean energy companies alongside investors and commercial partners. This provides increased support for the most promising clean energy technologies that have already attracted interest from the market as they are developed and continue their path to market adoption.

BRIDGE is part of the CEC's Electric Program Investment Charge (EPIC) program – a public interest research and development program that invests in scientific and technological research to accelerate the transformation of the electricity sector to meet the state's energy and climate goals. The EPIC program invests more than $130 million annually to help:

- Expand the use of renewable energy.
- Build a safe and resilient electricity system.
- Advance electric technologies for buildings, businesses, and transportation.
- Enable a more decentralized electric grid.
- Improve the affordability, health, and comfort of California's communities.
- Support California's local economies and businesses.

Figure 3: The layout of surface equipment along with wellhead modifications that were required for the demonstration project conducted by GreenFire Energy at Coso, California. The project was funded by the California Energy Commission.

3.2 Project Implementation

This project will be implemented in accordance with the BRIDGE Grant Agreement EPC-21-015 executed in March 2021 described above.

The following entities experienced in the geothermal industry will be involved in this project.

GreenFire is the developer and provider of the patented SDGL technology and is the holder of the Grant Agreement with the California Energy Commission (CEC). GreenFire is providing the project equity.

Geysers Power Company, LLC (GPC), a subsidiary of Calpine Corporation, is the owner and operator of thirteen (13) geothermal power plants at The Geysers as well as the associated steam field production and injection facilities supporting the plants. For the project, GPC will provide access to one or more steam production wells at The Geysers for purposes of obtaining well data and testing the SDGL technology. GPC will also provide a variety of support services during the project.

Overall project management will be provided by Manuel Weyman Group, Inc. (MWG), a firm of professionals that have extensive experience within the geothermal power industry and in project management, including at The Geysers. MWG will arrange for engineering services for the design and specification of surface test equipment, instrumentation and controls as well as engineering activities as related to procurement and installation of the surface facilities. MWG will also provide oversight for operations and maintenance of project equipment during the operational phase of the project.

Lawrence Berkeley National Laboratory (LBNL) will provide design review based on previous work done by LBNL for GPC, review and comment on modeling of test well and resource, provide modeling of project and resource performance and sustainability for the test well and in selected steam dominated resources at The Geysers for potential full-scale implementation. LBNL will also assist in design of testing protocols, data collection, and modeling of SDGL at a full-scale application, including a resource impact component.

Vallourec Tubes will design and supply the vacuum insulated tubing (VIT), as it has done for other GreenFire projects, which will be used within the down bore heat exchanger (DBHX) installed inside the test well.

Baker Hughes will advise on and assist with the DBHX installation with local contractors and/or Baker Hughes personnel in addition to software simulations supporting operation of the system.

Geothermal Solutions will provide advice regarding geochemistry matters with respect to the project. This will include advice regarding equipment materials specifications, geothermal chemistry issues anticipated in the modeling and advice regarding any chemistry matters concerning potential full-scale installation of SDGL at selected locations within The Geysers.

The project will be implemented by the completion of eight (8) tasks, as described below.

Task 1: General Project Tasks

General project tasks concern the Grant Agreement and project organization, including the submission of project products such as periodic progress reports and a final project report to the CEC.

Task 2: Well, Reservoir, and Systems Modeling

Well data will be collected and the performance of the well will be modeled. This modeling includes analysis performed by LBNL to enable assessment of the selected project well with respect to suitability for the project. In addition to determining the optimal well for this project, project participants will evaluate whether a full-scale implementation of SDGL technology is commercially viable.

Subtasks include:

- Gathering information from GPC regarding the production well design and performance to allow construction of an accurate model.
- Performance of well surveys such as temperature-pressure-spinner (TPS) logs during different operational flowrates (including static).
- Construction of operational models of the DBHX and surface equipment simulating SDGL operation.
- Proposal of options and alternatives as may be necessary for project implementation.
- Use of GreenFire's thermodynamic models to predict approximate power output.
- Optimize design on selected well(s) using GreenFire's thermodynamic model.
- Create a test plan that will govern all tests to be conducted during the project and that will ensure a full range of data to be generated and measured to assess test results.

Task 3: Well Engineering

Well engineering will incorporate modeling results and well test data to determine the appropriate metallurgy and design of the downhole components, downhole testing equipment, and well head. The results of this task will include engineering analysis, drawings, and engineering specifications.

Subtasks include:

- Design the DBHX's casing considering tensile and pressure loads, heat transfer duty, and potential chemical attack as identified in Task 2.
- Design the vacuum insulated tubing (VIT) and well head.
- Review all drilling and production logs to understand characteristics of the selected well.
- Create an initial design for the SDGL installation (downhole and surface equipment). Perform iterations as necessary to optimize design.

Task 4: Surface Systems Engineering

Surface systems engineering will determine the appropriate equipment to be designed, procured, fabricated, delivered, and erected onsite for the testing program. The deliverables for this task will include process information, drawings, and engineering specifications. The following may be produced as a part of this task:

- Process flow diagram (PFD) with flows and thermodynamic properties.
- Piping and instrumentation diagram (P&ID) with instruments and pipe sizing.
- Pumping requirements and equipment specifications.
- Heat rejection requirements and equipment specifications.
- Requirements, if any, for non-condensable gas handling equipment.

Task 5: Site Work – SDGL Equipment installation

Site work will include receiving the test equipment, securing utilities needed for the testing, installation of the DBHX and wellhead equipment, installation of surface equipment including pump(s), piping, and installation of all instrumentation and control equipment required for operation and data collection.

Subtasks include:

- Mobilization of labor and equipment to prepare the selected production wellpad for construction activities.
- Ensuring through engineering and administrative controls that health, safety, and environmental regulatory requirements are satisfied throughout installation.
- Installation of the SDGL equipment, including the DBHX and all surface equipment, to ensure the safe operation of the SDGL system.
- Installation of the specified surface system for performance measurement, heat rejection, and circulation of closed-loop water at appropriate pressures and temperatures.
- Performance of equipment commissioning and system checkouts to ensure proper operation and safety compliance.
- Performance of quality assurance and quality control (QA/QC) tasks.
- Confirmation of satisfactory operation of all controls, instrumentation and data acquisition and recording equipment.
- Development of operating, health and safety procedures.
- Development of operation and maintenance training materials.

Task 6: Project Operations

Testing will commence after the system is installed and commissioned. The system will be operated according to the test plan for the duration of the project. At the end of testing or for any sustained breaks in operation, safe shutdown and, if appropriate, decommissioning will be performed.

Subtasks include:

- Start-up of the SDGL equipment.
- Operation of the SDGL equipment for a sufficient length of time to meet project objectives. It is anticipated that operation will be for approximately three (3) months but may be of shorter or longer duration as required to fulfill project objectives.
- Maintenance of equipment and periodic calibration of instrumentation as necessary to ensure accurate, reliable data collection and operational safety.
- Monitoring and surveillance of equipment operations to ensure safe operation while complying with all health, safety and environmental permit requirements.
- Safely conduct shutdown and demobilization upon completion of the testing period. Restoration of the well site to pre-project conditions or better.

Task 7: Evaluation of Project Benefits

As a precursor to the final report to the CEC and analysis, operating data will be recorded and analyzed throughout the operation of the project. This data will be directly compared to the modeling results from Task 2 and will be used to predict the financial viability of large SDGL projects using purpose-drilled wells (defined herein as wells that are drilled specifically to extract the maximum potential of the resource using a DBHX).

Subtasks include:

- Collection and consolidation of all flow, temperature, pressure, and other test performance data recorded during operation of the SDGL equipment.
- Comparison of actual performance data to modeled performance.
- Validation of modification of prior modeling as warranted to achieve a confirmed SDGL model.

Task 8: Technology/Knowledge Transfer Activities

In compliance with CEC Grant requirements, detailed plans will be developed to analyze and report the findings to the CEC and the California public.

Subtasks include:

- Development of a Technology Transfer Plan.
- Development of presentation and training materials for CEC’s use.
- Participation in CEC-sponsored symposiums as directed.
- Compilation and submittal of accurate periodic status reports.
- Maintenance of accurate results of tests conducted.

- Compilation of information into a Final Report to the CEC.
- Publicization of results through geothermal industry associations.
- Submittal of press releases to relevant publications.

The SDGL project at The Geysers will aid in obtaining technical data that will help in calibrating the projections for new purpose drilled wells as a part of the larger expansion projects at The Geysers. These projections should couple the performance modeling of the SDGL and the project cost data.

The SDGL modeling process involves various steps. First, it is necessary to evaluate the potential of the feedzones in the geographical area of interest. Usually, this can be achieved by modeling current wellbore performances. Then, the main reservoir and wellbore properties are extracted and input into the SDGL equipment model. During this process, many scenarios of DBHX flow rates and saturation conditions downbore are simulated based on the mass and energy balance of the system considered. Then, the transmissivity of feedzone and reinjection zone at the bottom of the well are analyzed to restrict the operating conditions. Scenarios for temperature, pressure, flow rates, and other conditions over the length of the Downbore Heat Exchanger (DBHX) are then simulated. Additionally, the performance of various working fluids (water, supercritical CO_2, or others) are also simulated along with different surface systems as a part of the optimization routine. Direct use, or power generation scenarios, are also analyzed at this stage. The losses of power due to pumping the working fluid, air cooling, and ORC pumping requirements are also included in the analysis. The modeling procedure has been detailed in Higgins et al. (2021) and Amaya et al. (2021).

For specific well projects, a front-end engineering and design study (FEED study) is elaborated following the sequence described in the following schematic:

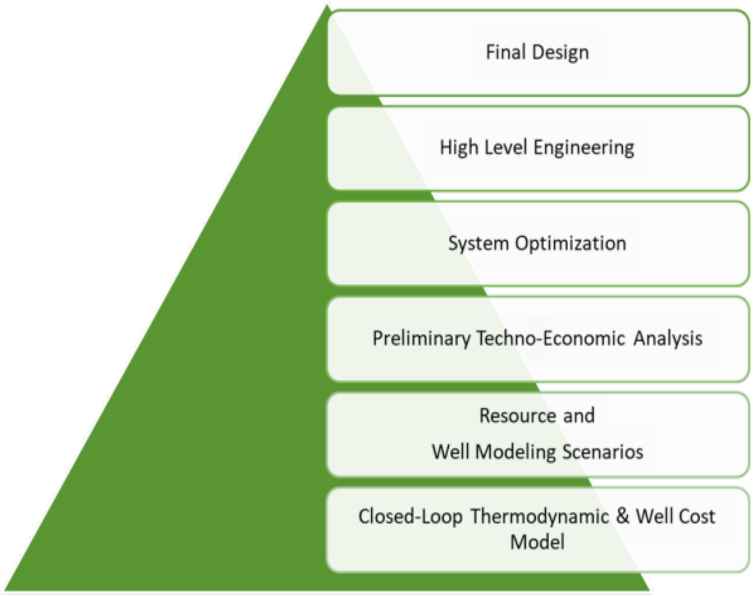

Figure 4: FEED study approach for GreenLoop in Steam and 2-Phase Dominated Reservoirs projects

For the cost modeling, different solutions can be considered. For example, the cost of retrofit projects does not include drilling services cost, as would be needed for new purpose drilling wells. For the scenarios of using existing surface conditions (if the current capacity of the system allows it), the cost of surface power equipment is not included, but for increased capacity scenarios, the price includes the surface system cost.

The Levelized Cost of Electricity (LCOE) for individual purpose drilled wells with SDGL coupled with an ORC system are designed to be cost competitive. The LCOE estimation includes factors like capacity factor, effective discount/debt rate, operation, and maintenance cost, project life asset, etc.

For multiple wells or complete resource projections, the reservoir potential is evaluated using thermodynamic and reservoir models, and then the cost analysis is performed.

4. S2PGL Projects in the Pipeline and the Evaluation of Potential Opportunities Across the World

S2PGL projects are being proposed to geothermal operators and developers worldwide, particularly in countries such as The Philippines, Indonesia, Japan, Taiwan, Italy, Mexico, and the United States. The project proposal usually entails an initial project which involves retrofitting a single or a group of idle/low producing conventional geothermal wells using the technology with the intention of rapidly expanding to purpose drilled wells (also called a field expansion project).

4.1 Key Advantages of S2PGL projects

One of the key advantages of the S2PGL is the ability to control the saturation pressure and the saturation temperature to extract the latent heat of vaporization as a function of the flow rate injected in the closed-loop coaxial system. This means that S2PGL can easily control the downbore heat exchanger performance from the surface to optimize the heat extraction process by choosing or estimating the optimal flow rate. For more details on the flow rate statistical optimization process, the authors recommend reviewing the project results of the Coso KGRA demonstration project (Higgins et al., 2019; Amaya et al., 2019). In general, the gradient of pressure is the guiding force of fluid motion in geothermal systems. The difference between reservoir pressure and wellbore pressure determines the flow rate supplied by the system to the vicinity of the well (near-wellbore region). In the S2PGL, the wellbore pressure is governed by the saturation pressure controlled on the surface, as mentioned before. Then, the optimization of the productivity of the well would be an operational variable function of the amount of working fluid that can be injected economically into the coaxial system (considering that higher flow would require higher parasitic pumping power required due to friction losses). Thus, there is an optimization process that is involved. The diameters of the well and downbore heat exchanger are additional variables that need to be considered in the performance analysis/design of the coaxial systems. For new purpose drilled wells, the geometry can be optimized to minimize friction losses and parasitic pumping power in the system. For retrofit well projects, the geometry optimization is limited to the coaxial system. However, in both cases the same variables are considered in the optimization process.

Another important variable that needs to be integrated into the analysis of alternatives is the surface system requirements (pressure, temperature, and flow) to complete the optimization process. Scalability is another economic factor that needs to be considered for an optimal resource project design. A group of optimally designed purpose drilled wells will be most economical.

For particular reservoirs that have scaling issues (like anhydrate and calcite mineralizing issues), S2PGL can help avoid the deposition of specific minerals by facilitating changes in the operational strategy of the well. The operational strategy consists of deciding the safety flow rate and avoiding the saturation temperature and pressure conditions that are close to the mineral deposition conditions. For more details on this topic, the authors recommend reviewing Amaya et al. (2021).

For the analysis of alternatives and design selection, it is important to emphasize some of the cost-saving items of using S2PGL compared to conventional technology. Some of the items to analyze are implicit in the reinjection process and in the chemical treatment process. For example, S2PGL avoids the cost of designing/drilling reinjection wells, reinjection surface pipelines, reinjection pumps, the operation and maintenance of reinjection wells and lines, chemical water treatment (acid or mechanical cleaning) of production and reinjection wells, and Non-Condensable Gas (NCG) separation stream using surface processes for production wells. All of these activities are not required for S2PGL compared to conventional geothermal systems.

Finally, for the long-term production sustainability, S2PGL has significant advantages over conventional geothermal systems (Higgins et al. (2021)) since the reinjection of water takes place below the production feedzones (at the same temperature of pressure separation). This increases the effective recharge to the system and keeps the pressure and mass constant in the reservoir.

4.2 Economic Considerations

Once the performance of the S2PGL system is computed, the economic analysis is performed to analyze the commercial feasibility of the technology in a particular resource. The capital costs involved are analyzed based on the project type (field expansion or retrofit). The capital costs are computed by considering the tangible and intangible well component costs.

The tangible component costs include the cost of the casing and cementing of the appropriate sections depending on the design of the S2PGL system recommended for the resource. The cost of preparing the wellhead along with the cost of the DBHX assembly are also considered as tangible component costs.

The intangible components, on the other hand, include various different activities and services such as site preparation and restoration, transportation, supervision, communications, drill bit costs, mud logging, drilling fluids, wire line logging, insulated tubing and casing (dual string) running services, etc. depending on the resources available at the field site. Depending on the weight of the DBHX assembly, either a rig or a crane installation is proposed. If a rig is used, the mobilization costs incurred are added to the intangible components. The total cost per wellbore is then calculated by summing the total intangible costs with the total tangible costs.

Depending on the scale of the project, the total cost per wellbore can be optimized. For example, when electricity production is considered, larger projects which require a number of purpose drilled wells could be designed such that the outlet stream from the DBHX, which contains hot fluids, could be connected to a single power plant unit leading to optimized and lower costs per well. Drilling campaigns also lead to reduced inefficiencies and, at times, eliminate factors such as Invisible Lost Time (ILT) and Non-Productive Time (NPT), thereby reducing total costs per well (Van Oort et al. 2021). The Levelized Cost of Electricity/Heat (LCOE or LCOH) is then computed for the entire project by assuming the desired project lifetime with a capacity factor. A suitable discount rate along with an operational and maintenance cost is applied depending on the nature of the project and the location considered for deployment. For certain projects, renewable energy tax credits/energy credits, and subsidies are also incorporated into the economic analysis performed for the S2PGL.

In addition, when planning to expand the conventional geothermal operations, S2PGL can be used to effectively de-risk the project as a whole by enabling power generation where the drilling for conventional geothermal wells has been unsuccessful from its inception. The lack of sufficient permeability, wellbore issues, and low reservoir pressure due to excessive extraction in the past are some of the many reasons why a well drilled for conventional production can be non-productive or idle. Similarly, S2PGL can also de-risk geothermal fields previously using conventional geothermal technology as the reservoir will often experience reductions in pressure or water over time.

4.3 Key Technologies to enable the Techno-Economic Success of S2PGL at scale

Energy service companies, such as Baker Hughes, provide key technologies that will enable economic success of S2PGL in both retrofit, field expansion and greenfield opportunities; the scope of which ranges from cost effective well construction systems, to rotating equipment and power generating turbomachinery. Depending on the operating temperature of the well construction hardware required, the technology needs can be deployed from that used in the oil and gas industry in lower enthalpy 2-phase applications. However, in higher temperature 2-phase or steam-dominated applications where S2PGL is anticipated, such energy service companies can provide bespoke geothermal well construction technology to enable accurate, cost effective and predictable results of the systems energy output.

In the development of field expansion and greenfield opportunities, the targeted economic returns for deployment of S2PGL that enable a competitive return on investment and payback period can be achieved for many resources with traditional drilling technology. However, such returns will be enhanced and available for a broader range of resources with the use of recent advances in drilling technology that have targeted granite formations common to hot dry rock applications and have also demonstrated significant cost reductions in drilling. A primary example of this is at the ST1 Geothermal project in Finland (Cardoe et al. (2021)). Also critical for the longevity of well integrity is cementing technology that has been developed for geothermal systems and conditions. While there are numerous examples of casing failures from the results of inadequate cementing technology (Ingason et al. (2014)), recently developed products built upon those referenced in Doherty et al. (2010) have been demonstrated to perform well in high temperature geothermal reservoirs with high volumes of in-situ CO_2 concentrations.

While drilling and completion technology represent only two examples of hardware that exist or are in further development, there is the consideration of how these cross-functional technologies can be integrated together to synergize and further improve the technoeconomic feasibility of S2PGL as both a well retrofitting solution and bespoke deployment for new wells. Additionally, the systematic integration of the subsurface technology with the topside machinery is in process to drive further efficiencies in S2PGL applications. Targeted aspirations are thematically pursued to broaden the operational envelope for power generation out of lower enthalpy resources, therefore expanding the already vast applicability of S2PGL.

Equally critical for success is new software, advanced reservoir engineering capabilities, and other forms of machine learning based digital tools that can accurately model system performance before capital expenditure. These are applicable for the retrofitting of wells, field expansions and greenfield projects. The key value realized with new digital technology coming online specifically is the ability to derisk projects upfront and accurately customize an economic model for deployment of closed-loop geothermal technology, including S2PGL.

While the system architecture of S2PGL has been developed for use in geothermal applications, multiple studies and demonstrations (Mehmood et al. (2019), Cheng et al. (2019)) have proven that existing oil and gas assets in high temperature reservoirs can be suitable for retrofitting to geothermal energy producers. This offers numerous benefits to the asset owners or operators in that a vast majority of these wells are listed for plug and abandonment procedures and essentially exist as fully depreciated liabilities on both their balance sheets and also from an environmental safety standpoint. In retrofitting applicable wells to geothermal with S2PGL, the cost of plugging a well is mitigated and revenue is able to be generated from the asset via heat extraction. Furthermore, wells that were once used for producing fossil fuels can be transformed into a green energy producer. O&G operators are able to use S2PGL to achieve goals for emission reductions and energy transition.

The retrofitting of oil and gas wells to geothermal is a relatively new frontier for both energy technology providers, like Baker Hughes, as well as oil and gas operators and key challenges have been identified and are being addressed. There are key considerations that must be evaluated around both well diameters, which tend to be smaller in oil and gas wells compared to geothermal wells, and the available heat output from the wells that can be extracted with scalable and attractive economics to the operator. However, as noted by Cheng et al. (2019) there are between 20-30 million abandoned oil and gas wells globally and therefore if an even insignificant percentage of wells are suitable for retrofitting to geothermal with S2PGL, the potential scale is incredible.

4.4 Applications of the S2PGL in projects

S2PGL technology can be applied for various use cases as described below:

- Power generation: The efficiency of conventional geothermal conversion systems using flash and condensing turbines is usually less than 12% (Zarrouk and Moon, 2014). Efficiencies of binary systems are generally higher, but they are directly proportional to the temperature of the resource. ORC efficiency in geothermal systems is usually less than 20% (Quoilin et al. (2013)).

- Direct use: District heating/cooling and hot springs are good examples of using S2PGL as a direct heat application. From a cost analysis point of view, the difference between using the S2PGL for direct use instead of for power generation is that one does not need to apply the percentage heat to electricity conversion factor, and the initial capital cost of the project is less since power generation equipment will not be included. However, for cooling and heating applications, district heating facilities are required. However, a cost competitive LCOH can be obtained if in some special cases the geothermal operator is already connected to a district heating network. In other cases, operators can be located in places where the price of energy is high or locations where a large amount of existing oil and gas wells are in place. This provides an advantage to the operators as new wells are not needed to be drilled. In all these cases, the LCOH analysis needs to be performed with these considerations.
- Industrial applications include: Enhancing efficiencies of hydrogen production (optimizing hydrogen methods or supplying green power to the electrolysis units); Optimizing lithium extraction (by efficiently controlling the two streams of production, one of them dedicated to power production and the other co-production stream dedicated to the mineral production separately); and Optimizing oil and gas heat recovery using green loop technologies.

5. Conclusions

Steam and 2-Phase GreenLoop (S2PGL) technology has great potential for use in many existing geothermal resources, whether in retrofitting wells or in field expansion projects done in resources which can experience depletion of water or pressure extracted using conventional techniques that challenge the long term sustainability of a geothermal project. In addition, S2PGL can be applied in greenfield contexts to vastly expand the number and type of geothermal resources that can be economically productive and sustainable over the long term while de-risking conventional geothermal projects both in the initial drilling stages or over the long term as geothermal resources change over time.

GreenFire’s project at The Geysers, as funded by the California Energy Commission, hosted by Geysers Power Company, and further supported by Baker Hughes, Vallourec Tubes, Manuel Weyman Group, Lawrence Berkeley National Labs, and various other suppliers is designed to demonstrate the commercial viability of this new technology in the world’s largest single operating geothermal resource for application at full scale. The key results of this work will be published in a formal report to the California Energy Commission and otherwise made available to the geothermal community.

Simultaneous with the project at The Geysers, commercial projects are in development worldwide to further demonstrate that S2PGL is practical in various other geothermal resources and with the design of such other projects tailored to such other resources, existing surface systems and preferences and the long-term sustainability goals the owners and operators of such other resources.

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