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Heat Extraction Processes Using Unconventional Geothermal Technologies (GreenLoop) Applied in Different Reservoir Types

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ABSTRACT

GreenFire Energy has been heavily involved in developing unconventional heat extraction technologies from different resource types which include both geothermal and oil and gas resources. Over recent years with significant advancements in various technologies, GreenFire has been engaged to model its technology and/or implement its GreenLoop technology in various geothermal resources across the world. While these initiatives usually commence with proof of concept retrofit projects, the established strategy involves widespread implementation of the GreenLoop technology wherever feasible from a techno-economic perspective within the reservoir.

To meet the set techno-economic goals it is essential to diagnose wells and understand reservoir characteristics. It is commonly acknowledged that resources can be grouped into four categories: steam, two-phase, liquid, and impermeable reservoirs (hot dry rock), all based on properties such as enthalpy and permeability. In addition, geothermal wells can also be classified as low, medium, and high enthalpy systems. Unconventional technology architecture and operating conditions can then be simulated by analyzing key parameters such as reservoir pressure, feedzone transmissivity, inflow characteristics, etc. to ensure optimal heat extraction in each case.

This paper describes the resource and GreenLoop technology characteristics that are most appropriate for commercial-scale heat extraction.

1. INTRODUCTION

GreenFire Energy Inc. (GFE) has been focused on a mission to unlock the potential of existing underperforming assets using efficient, sustainable and unconventional heat extraction technologies for years (Chandrasekar et al., 2023a). GreenFire's GreenLoop® Down Bore Heat Exchanger (DBHX) was first field tested in the Coso Known Geothermal Resource Area (KGRA) in the year 2019. More recently, the DBHX is currently being implemented in The Geysers geothermal field in California, USA (Scherer et al., 2022; Chandrasekar et al., 2023b) and in the Mahanagdong field in The Philippines (USTDA, 2023). In addition, an Advanced Closed Loop (ACL) laboratory was constructed as a part of the Wells2Watts Consortium in Oklahoma City, USA (Klenner et al., 2023). A key element to note is that the DBHX system is being tailored and applied to a wide range of assets/resources with varying thermal properties. Specifically, the near wellbore environment adjoining the DBHX assembly would vary significantly from one resource type to another. For example, The Geysers is a steam dominated resource (Sanyal, 2000) as compared to Mahanagdong which is a two-phase dominated system (StaAna et al., 2002).

In general, irrespective of the reservoir type, it has been found that geothermal energy production often declines with time primarily due to the combined effects of thermal depletion and pressure drawdown (Aydin et al., 2020). This phenomenon leads to idling or abandonment of geothermal wells. Other causes for idling of geothermal wells could include a lack of connectivity to the resource (edge-field wells) and well failure or obstruction (that could be caused by excessive scaling and corrosion problems) as described by ThinkGeoEnergy (2019). Abandonment of wells prematurely translates to lost potential energy generation, representing a significant financial blow for geothermal operators who invest heavily in exploration and development. Besides, there are numerous producing wells around the world that experience flow impedance as a result of localized effects in the near wellbore region. Reasons for this behavior could be formation damage over time, reduction in permeability, or other types of skin effects (Stacey et al., 2011). Hence, it is pivotal to develop unconventional production enhancement technologies that can help optimize the extraction of heat from geothermal reservoirs in a sustainable fashion and increase or maximize the lifetime of power plants.

In this paper, we briefly review some of the unconventional technologies that have been employed in different types of geothermal fields and probabilistically represent the power production that could be expected from the DBHX in steam dominated reservoirs.

2. STRATEGIES FOR UNCONVENTIONAL HEAT EXTRACTION FROM RESERVOIRS

Around the globe, numerous identified geothermal reservoirs are already contributing to clean energy production. Yet the potential stretches far beyond, with untapped resources waiting to be responsibly developed. Most of the known geothermal reservoirs are located along the Ring of Fire, particularly along the west coast of the Americas, Japan, Indonesia, The Philippines, and New Zealand.

There are several classifications of geothermal systems, understanding the type of geothermal system is of utmost importance as directly affects the techno-economics of project development. Temperature based classification of reservoirs have been developed for several years (Muffler and Cataldi, 1978; Sanyal, 2005). A drawback to using only temperature as a basis for classification is that the actual condition of the fluid at the wellhead is not accounted for. Enthalpy based classifications have been represented by Kaya et al. (2011) and Diaz et al. (2016). Exergy based classifications have also be proposed by authors such as Lee (2001). However, a drawback is that the analysis tends to overestimate the utilization efficiency of the power plant (Zarrouk and Moon, 2015). In this study, we limit ourselves to two broad classifications, i.e. dry steam (vapor dominated) reservoirs and liquid dominated reservoirs.

Vapor dominated reservoirs are known for their advective/counterflow heat transfer characteristics. The steam that has a low density travels upwards through the system to the surface and the condensates along with cold ground water flow downwards under gravity to recharge the reservoir. These fields have experienced severe pressure drawdown issues (Zarrouk and Mclean, 2019) which could potentially result in the fields running out of immobile water and drying out eventually.

Reinjection strategies have been deployed to help maintain the reservoir pressure in these fields; however, the fields still continue to show a periodic decline in pressure. This is because only about 46% of the water used for production was actually reinjected back into the resource on an average across 5 vapor dominated fields across the globe (Kamila et al., 2021). Besides, reinjection wells could pose a range of issues from scaling and solid deposition (primarily silica scaling) to a higher risk of seismic events. One solution to mitigate all these issues was described in Higgins et al. (2021). The resource water is not extracted at all and just the heat is extracted through the DBHX technology (only the non-condensable gases (NCG's) could be vented from the wing valve at the wellhead). An important aspect here is that the large scale counterflow behavior observed in the vapor dominated reservoirs is re-created in the near wellbore region as the steam from the feedzone(s) condense around the DBHX and drop down to the bottom of the wellbore to get reinjected back into the reservoir. The thermal hydrological mechanical and chemical (THMC) model built and described in Chandrasekar et al. (2023b) for a well in the Southeast Geysers area showed that the risk of silica scaling is very low as the saturation temperature required for the system to function is always higher than the temperatures at which amorphous silica scaling occurred.

On the other hand, liquid dominated reservoirs contain hot water that is found deep in the reservoir at a pressure and temperature that could allow it to flow to the surface either naturally or artificially. These systems are the most commonly found geothermal reservoirs. Within these systems it is commonplace to find non self-discharging wells in several countries including Indonesia, Philippines, Costa Rica, Iceland, Iran, Mexico, Kenya and New Zealand (Mubarok and Zarrouk, 2017). Its poor ability to discharge naturally can be due to several factors including the following –

- Interzonal communication (multi feedzone wells) potentially leading to cold fluid downflow from shallow zones
- Water levels in the wells are quite deep (reservoir pressure is less than the hydrostatic head of the column of water in the wellbore)
- Slow temperature recovery after well testing
- Relatively lower permeability
- Pressure and temperature decline in the reservoir

For example, the productive reservoir in the Mak-Ban geothermal field in The Philippines has been found to include both "shallow" and "deep" reservoirs that are separated by a low permeability formation (Sunio et al., 2015). On an individual well by well basis it was found that the downflow temperatures were quite hot (in the range of 207°C to 250°C), although lower than the typical reservoir temperatures of about 280°C to 320°C. It is also likely that the mass flow rate of the downflowing brines will increase as the mass withdrawal from the deeper reservoir continues with time. The typically high transmissivities/permeabilities encountered in geothermal wells means that small pressure differences from buoyancy effects or from non-static reservoir profiles may cause substantial flow changes in the wellbore and the near wellbore region leading to highly convective environments even when the well is in the shut-in condition (Grant et al., 1983). Besides downflow processes, it is also possible for wells to exhibit strong cross flow characteristics when the pore pressures are not hydrostatically balanced. Such characteristics do not favor heat extraction using conventional technologies (which rely on wells being typically "upflowing") and therefore there is a need to develop and deploy new technologies for efficient heat extraction.

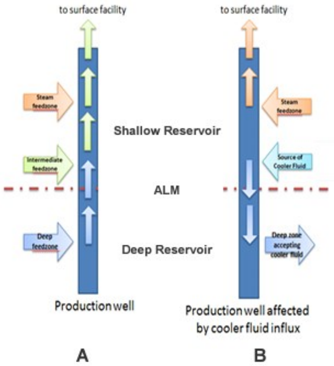


Figure 1: Pictorial representation of a normal production well in the Mak-Ban geothermal field (left-A) compared to the conditions after a downflow starts (right-B). Adapted from Sunio et al. (2015).

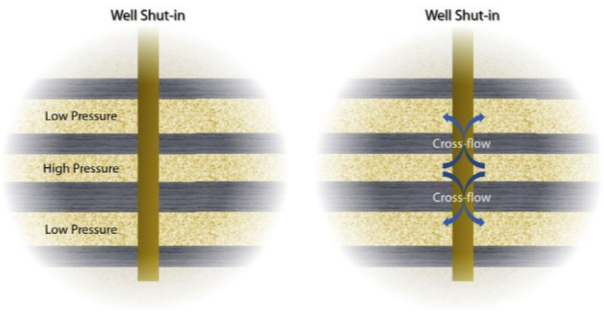


Figure 2: Sample representation of interwell cross flow occurring between layers of higher pressure and lower pressure. Adapted from Jalali et al. (2016).

Techniques such as air compression, well-to-well injection, nitrogen injection, airlifting etc. could be explored. The method that is the most suitable for a specific well will depend on the initial wellbore conditions. These methods look to reduce the density of the water column in the wellbore so that the fluid could heat up and rise to the surface. Due to this the hydrostatic pressure decreases and the reservoir pressure will be higher than the hydrostatic pressure leading to the upflow of geothermal brines. However, it is important to note that each of these methods have their own caveats. There is a possibility of the casing cracking in the case of air compression due to the sudden thermal shock from the flowing fluids during well discharge (especially in high temperature liquid dominated wells). For the well-to-well injection to be effective it is necessary to establish hydraulic communication between the two wells. When the wells are in the same pad it is likely that the method could yield favorable results.

Wells that are shown to exhibit strong cross flows and downflows can also be superior use cases for the DBHX (GreenLoop in liquid dominated systems). It is also important to note that unlike vapor dominated reservoirs, liquid dominated systems typically have larger flow rates and therefore efficient subsurface heat exchange can be possible with favorable near wellbore flows. In addition, for wells with carbonate scaling problems it is favorable to use the DBHX as the temperature of operation (the saturation temperature) is typically lower than the temperature at which the scaling occurs (since calcium carbonate exhibits an inverse solubility as a function of temperature) as described in Chandrasekar et al. (2023).

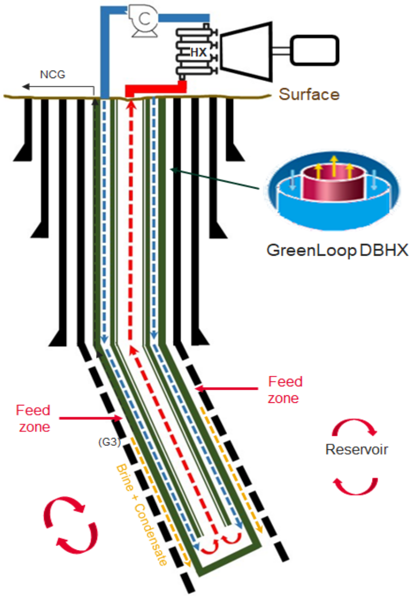


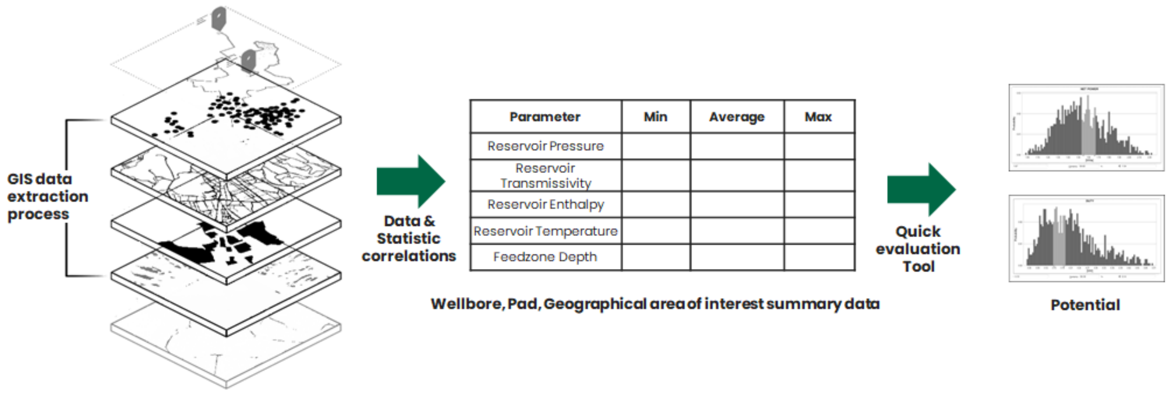
Figure 3: GreenLoop DBHX in liquid dominated systems. The working fluid (water in this case) is injected through the annulus of the DBHX (indicated through the blue dashed lines) and as it gains temperature it flows back up through the center insulated tubing. The methodology relies on interzonal communication between the feedzones of the wellbore (such as downflow processes) or cross flow within a zone(s). The system could be coupled with a pump and a heat exchanger at the surface where the water exchanges heat with an organic working fluid to generator power through the expander.

For the efficient operation of the DBHX in a well (in case the near wellbore characteristics are not favorable) it is also possible to artificially create an environment that could enable a supreme convective environment. Stimulation techniques that are applicable in relatively higher temperatures could potentially be an attractive option to consider. Casing perforation, thermal fracturing, acidizing, hydraulic fracturing, acoustic stimulation, electric stimulation and carbon dioxide stimulation are some examples of possible techniques that could be applied (Noorollahi et al., 2022).

Electric submersible pumps (ESP's) or line shaft pumps can also be considered for wells that are within the temperature rating of the pumps (typically about 250°C as per Baker Hughes, 2024). However, it is important to note that when the wells exhibit severe corrosion or scaling issues with the reservoir brines, it may be important to important to couple the ESP with other technologies (which could include technologies that could lower the near wellbore operating temperatures within the range of pump operations).

3. STATISTICAL EVALUATION OF THE GREENLOOP SYSTEM IN VAPOR DOMINATED RESERVOIRS

In this section a "fast" DBHX estimation framework developed by GFE was employed to run numerous cases with varying properties such as length of DBHX, near wellbore feedzone transmissivity, reservoir pressure, reservoir enthalpy, reservoir temperature, and roughness of casing/tubes. A Monte Carlo analysis was conducted to explore the possible outcomes for power generation considering a wide range of values for each variable of interest through about 1000 simulations. The distribution of net power from the system along with the parasitic pumping power have been represented with the peak of the distribution indicating the most likely power outputs, while the spread highlights the range of possible outcomes and their corresponding probabilities. This analysis can be coupled if needed with a geographical prospection analysis in order to get a better understanding of the potential of a resource/region as a whole as done by GFE in the past. It is important to note that all the analysis shown consider the DBHX (working fluid – water) coupled with an ORC system at the surface.



Parameter	Min	Average	Max
Reservoir Pressure			
Reservoir Transmissivity			
Reservoir Enthalpy			
Reservoir Temperature			
Feedzone Depth			

Figure 4: Overview of the various steps involved in the probabilistic estimation of the GreenLoop potential in vapor dominated resources. Geographical information systems can be employed for extracting and analyzing the spread of key reservoir and wellbore data over regions, which could then act as inputs for the statistical framework that provides ballpark estimates of the heat extraction potential on a per well basis.

The limits of the base case analysis of vapor dominated systems were chosen through extensive literature review. Ingebritsen and Sorey et al. (1988) modeled three types of vapor dominated systems for simulation times that varied between 10,000 to 40,000 years. Limited evidence was found for vapor dominated zone pressures in excess of about 30-40 bars (with about 30.6 bars being the pressure of maximum enthalpy of saturated steam). Therefore, the higher end or the maximum limit considered for the study was chosen to be about 30 bars. Pressures in excess of 60 bars and 100 bars were reported in Travale, Tuscany (Allis, 2000) and in the bottle rock area of The Geysers, but these extreme values were not considered in the analysis. For the lower end of the spectrum, the reservoir pressure reported by Sanyal (2000) of about 15 bars in the year 2000 at The Geysers field was employed for the analysis. The limits of DBHX length were chosen based on the well depths described by Raharjo et al. (2016), Ingebritsen and Sorey et al. (1988), and Truesdell (1991). For example, Truesdell (1991) suggests that the bottom of the vapor dominated reservoir in the Larderello geothermal field is at around 2500 m.

The table below represents the minimum, average and maximum value of each of the parameters (variables) that were inputs for the analysis of retrofitting a vapor dominated well with the GreenLoop DBHX for the base case.

Table 1: Parameters that were varied in the statistical analysis to understand the distribution of power produced from the DBHX in vapor dominated systems (base case)

Parameter	Units	Minimum	Average	Maximum
Reservoir Pressure	bar(a)	15	21	30
Transmissivity	m^3	4E-13	4E-12	1.25E-11
Reservoir Enthalpy	kJ/kg	1900	2850	2950

Reservoir Temperature	℃	198	232	283
Roughness of tube/casing	m	1E-5	5.5E-6	1E-6
DBHX Length	m	1200	1700	2500

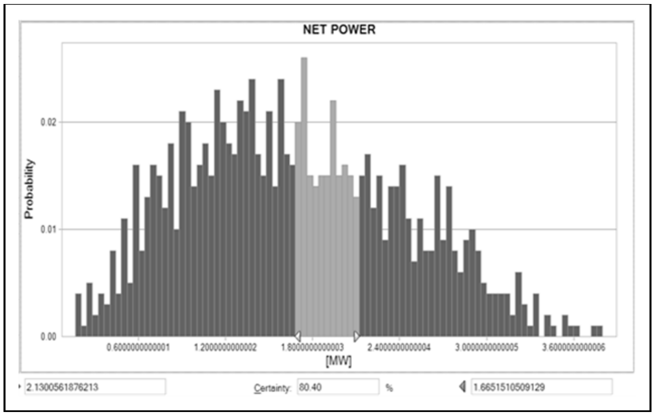


Figure 5: Net Power estimate of the GreenLoop system in vapor dominated systems (base case) represented through the Monte Carlo analysis indicating a potential in between 1.67 and 2.13 MWe per retrofit well with a certainty of about 80.4%

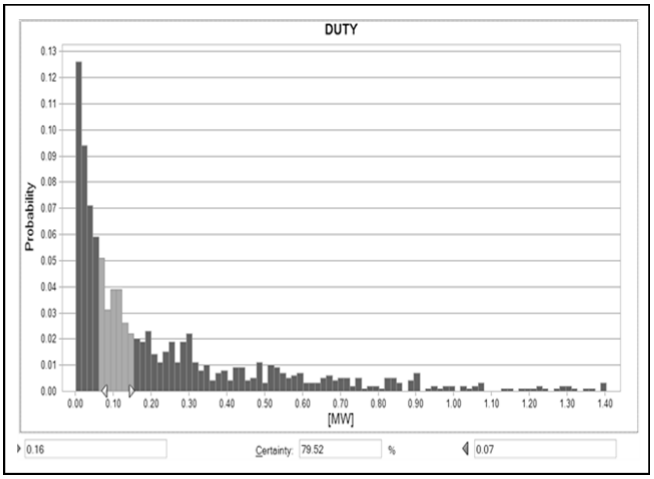


Figure 6: Parasitic pumping power estimates of the GreenLoop system in vapor dominated systems (base case) represented through the Monte Carlo analysis indicating a potential in between 0.07 and 0.16 MWe with a certainty of about 80%

It is important to mention that the above mentioned base case analysis of vapor dominated systems resulted in a gross power in the range of 1.7 to 2.3 MWe.

A more specific case was also conducted for a location using the above mentioned geographical prospection analysis and a summary of the limits are illustrated in the table below.

Table 2: Parameters that were varied in the statistical analysis to understand the distribution of power produced from the DBHX in vapor dominated systems (specific case)

Parameter	Units	Minimum	Average	Maximum
Reservoir Pressure	bar(a)	20	22	24

Transmissivity	m^3	2E-13	4E-12	1E-11
Reservoir Enthalpy	kJ/kg	2650	2850	2950
Reservoir Temperature	°C	212	234	275
Roughness	m	1E-5	5.5E-6	1E-6
DBHX Length	m	1300	1500	2000

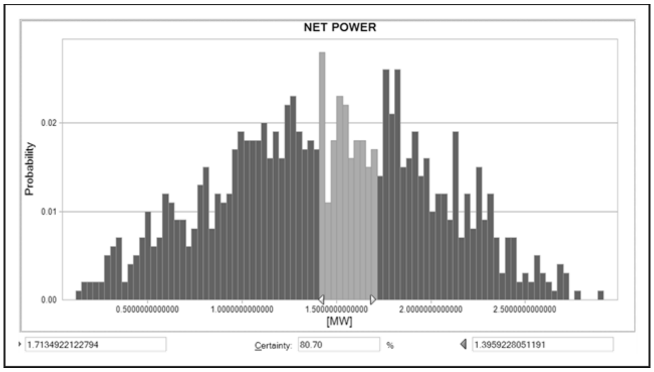


Figure 7: Net Power estimate of the GreenLoop system in vapor dominated systems (specific case) represented through the Monte Carlo analysis indicating a potential in between 1.4 and 1.71 MWe per retrofit well with a certainty of about 81%

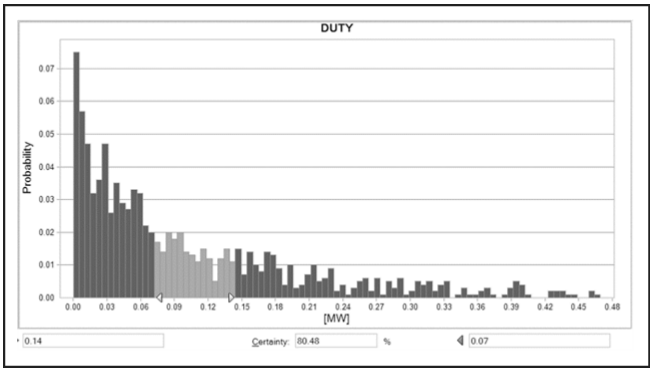


Figure 8: Parasitic pumping power estimates of the GreenLoop system in vapor dominated systems (specific case) represented through the Monte Carlo analysis indicating a potential in between 0.07 and 0.14 MWe with a certainty of about 80%

It is important to mention that the above mentioned specific case analysis of vapor dominated systems resulted in a gross power in the range of 1.5 to 1.85 MWe.

4. CONCLUSIONS

Heat extraction using unconventional geothermal technologies were discussed for vapor dominated and liquid dominated geothermal systems. A statistical analysis was performed for the GreenLoop DBHX system in vapor dominated systems considering a base case and a specific case (which was a result of a geographical prospection analysis of a specific location/site). Gross power estimates were in the range of 1.7 to 2.3 MWe for the base case and 1.5 to 1.85 MWe for the specific case. The statistical tool developed in this paper can be coupled with geographical information systems to provide an overview of the GreenLoop DBHX potential for specific geographic sites/areas of interest. More precise studies of DBHX evaluation for specific wells would require numerical modeling tools. However, this framework can be used for a “fast” analysis to prioritize projects and have an overview of the GreenLoop system in reservoirs.

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