

## Innovative Closed-Loop Geothermal Well Designs Using Water and Super Critical Carbon Dioxide as Working Fluids

Azadeh Riahi, Piotr Moncarz, Walter Kolbe, Branko Damjanac

[ariahi@itascacg.com](mailto:ariahi@itascacg.com), Itasca Consulting Group, Berkeley, California

[moncarz@geothermicsolution.com](mailto:moncarz@geothermicsolution.com), Geothermic Solution LLC, Palo Alto, California

[wkolbe@geothermicsolution.com](mailto:wkolbe@geothermicsolution.com), Geothermic Solution LLC, Palo Alto, California

[branko@itascacg.com](mailto:branko@itascacg.com), Itasca Consulting Group, Inc., Minneapolis, Minnesota

**Keywords:** closed-loop geothermal well, coaxial design, downhole coaxial heat exchanger, heat extraction, thermal power.

### ABSTRACT

This paper investigates the expected performance of closed-loop geothermal systems. In the past, it has been argued that the rate of thermal conduction through rock masses is not large enough to compensate for the thermal depletion around closed-loop geothermal wells, and that such systems, therefore, cannot maintain heat extraction rate required for long-term production. Recently, however because of new technological advances, there is a renewed interest in closed-loop geothermal designs which can exploit the vast energy resources of hot formations unsuitable for conventional hydrothermal geothermal systems. A series of sensitivity studies with respect to injection temperature and flow rate are carried out for GSL design with water as the working fluid. The results in each case are compared to results presented for the ECO<sub>2</sub> technology under identical conditions (Oldenburg et al., 2016). The generated thermal power for both closed-loop geothermal designs are also presented.

### 1. INTRODUCTION

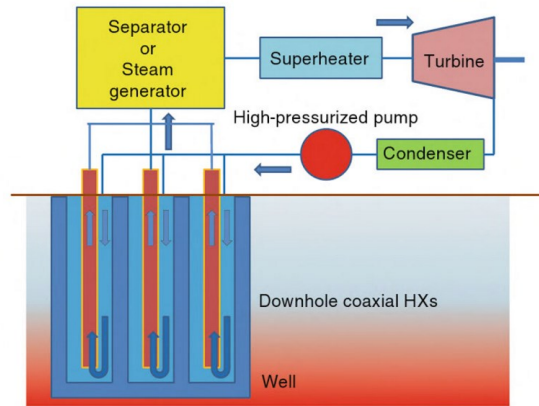
Geothermal heat is an abundant resource of green and sustainable energy. Due to its ubiquity, geothermal energy could become an important element of national energy security, as well as an energy supply in installations demanding an out-of-grid energy source with minimal carbon footprint. Also, it can provide a 24-hours a day, year-round baseload power, independent of weather, time of the year or climate. Conventionally, geothermal energy is extracted from geological systems that have high temperatures, high permeability, and an abundance of in-situ water (hydrothermal systems). However, the vast majority of geothermal resources have very low permeability and water content, and run into a water deficit in a relatively short time. Re-injection of water into the formation to replenish the extracted water is a solution only in areas where inexpensive water is in abundance. It is expected that the injected water diffuses in the rock formation in a manner that is preferred for heat extraction, i.e., cold water circulates through the fractures within a large volume of the rock mass, and then is fully recovered. In order to achieve economical flow rates during heat extraction from such low permeability or low water content reservoirs, an engineered approach is required. Such systems are often known as enhanced or engineered geothermal systems (EGS). In EGS, injected cold water circulates through a pre-existing fracture network that has been stimulated to open the fractures and increase the permeability and fracture connectivity within the reservoir. The success of those simulations has often been doubted as to their effectiveness in increasing the energy harvesting efficiency. Because the injected fluid flows through the rock pores, fissures, and fractures, such systems are viewed as open-loop systems. This paper investigates the performance of the closed-loop geothermal systems. These systems circulate a fluid to the depths and through the rock mass with high temperatures and back to the surface through continuous and closed pipes/wells. There is no direct contact between the working fluid and rock formation. An advantage of the closed-loop system (over all the other mentioned systems, including EGS) is its predictable and steady performance with a negligible environmental impact as it neither demands/consumes precious water, nor extracts ground water/steam. Consequently, it does not bring any minerals to the surface, nor requires reservoir preparation through processes such as hydraulic fracturing, shear stimulation or acidization, thus eliminating the risk of induced seismic events or the perceived risk of polluting the host geology through leakage of the working fluid.

Because heat exchange in the closed-loop systems is taking place only at the contact surface between the wall of the well and the circulating fluid, concerns were raised over the potential of such systems to continuously “harvest” a sufficient amount of heat and to raise and maintain the temperature of the working fluid to a level necessary for economical use of the heat energy over the project life cycle of approximately 30 years. In the past, it has been argued that the rate of thermal conduction through rock masses is not high enough to compensate for the thermal depletion around closed-loop geothermal wells, and that such systems, therefore, cannot meet the sustained heat extraction rate required for long-term production (e.g., Nalla et al., 2005). Recently, however, with major advancement and reduction in the costs of well technology, there is a renewed interest in closed-loop geothermal heat extraction, because, similar to EGS, they can exploit the vast resources of hot but low permeability or low water content formations.

Various designs have been proposed for closed-loop geothermal systems, including co-axial, U-shaped, and multiple string wells. The concept of coaxial geothermal wells was first examined by Horne (1980). Geothermic Solution LLC (GSL), Morita et al. (2005), Ehara

et al., (2005) and Yokimine et al. (2011) have proposed using a co-axial closed-loop system with water as the working fluid (Figure 1). In the co-axial design, pressurized working fluid is injected through the outer tube and the heated water is extracted through the inner tube of the well. These publications have all proposed using water as the working fluid. Also, they have emphasized the use of a well-insulated inner pipe to secure the thermal output of the heat exchanger. In the case of GSL, discussed in this paper, the design involves a well with a vertical and a horizontal section. Ehara et al. (2005), Morita and Tago (1995) and Morito et al. (2005) have named their system the Downhole Coaxial Heat Exchanger System, or DCHE. Morita and Tago (1995) have detailed information on the structure of insulated pipe, a flow diagram of power generation, and economic feasibility. Similar concepts of closed-loop systems have been proposed and discussed by others (Heller et al., 2014), and named differently, such as systems based on the Geyser principal.

Another closed-loop design, advocated by GreenFire Energy (2016), includes a U-shaped design in which water is injected at an injection well and is extracted at a production well. The descending and ascending wells are connected through a horizontal section. Multiple string wells are proposed by Hasan et al. (2012) and Hasan (2016) for another recent closed-loop design introduced by InnerGeo. In the multiple string design, both production and injection tubing are within the same well. The wellbore is divided into a liquid and a gas section. The bottom part of the well is filled with a liquid (e.g., water), while the upper portion is filled with a gas (e.g., nitrogen). Different variations of design (with respect to the length of the production and injection strings) have been proposed. In one design, a long string is used for production while short string is used for injection, while the injection rate is the same as the production rate.



**Figure 1: Conceptual design of a geothermal power plant with closed-loop coaxial wells (Yokimine et al., 2011).**

This paper presents the results of performance simulation of the GSL well for a period of 30 years using a numerical modeling approach carried out by *FLAC3D*, a commercial software developed by Itasca (2015). The model considers heat transfer by (a) conduction through the surrounding rock, (b) advection by fluid circulating in the well, and (c) convective heat transfer (i.e., heat exchange between the surface of the pipe and the moving fluid).

The results of this study are compared to the results presented for another closed-loop design technology, ECO2G (GreenFire, 2016; Oldenburg et al., 2016; Higgins et al., 2016), which circulates supercritical carbon dioxide ( $\text{SCO}_2$ ) instead of water. ECO2G technology is based on a closed-loop design with a U-shaped well geometry that consists of a vertical injection well, a horizontal section, and a vertical production well. It has been argued that due to its unique properties,  $\text{SCO}_2$  produces substantially more electric power than water.

A series of sensitivity studies with respect to injection temperature and flow rate are carried out. The results in each case are compared to the results presented for the ECO2G technology under identical conditions (Oldenburg et al., 2016). The generated thermal power for both the closed-loop designs (GSL and ECO2G) are presented and compared. Most importantly, the results of this study shows that closed-loop systems such as those investigated in this paper can deliver a relatively steady power over a period of thirty years. In the cases presented and studied in this paper, the average thermal power output varies between 3MW to 5MW. This study also suggests that water is an excellent working fluid to extract heat, and its performance in terms of generated thermal power will be comparable to that of  $\text{SCO}_2$ . However, it is noted that  $\text{SCO}_2$  may have some advantages due to its expansion upon heating, which under certain conditions creates a thermosiphon.

This paper is limited to the efficiency and stability of the heat extraction from the hot geological strata, and does not address the surface conversion and use of the heat. The results of this study suggest that the range of generated power for different closed-loop systems is close and comparable. Also, the predictability of the closed-loop system performance over time, in contrast to the EGS system, is a major advantage. Therefore, closed-loop technology could be a promising contributor to geothermal power production.

## 2. NUMERICAL MODELING

This paper summarizes the results of a numerical parametric study of heat production from the method proposed by GSL for heat extraction from a co-axial single geothermic well (“heat harvester”). The cold water is injected in the annulus and hot water is extracted from the inner tube. By preserving above-boiling pressure at every point in the closed-loop system the water is extracted in a liquid

phase at the outlet. Also, it is assumed that, through secured inner tube wall insulation, the inner and outer tubes are completely thermally insulated and no heat exchange takes place between the fluids moving through them.

Modeling has been conducted using *FLAC3D*, numerical software developed by Itasca (2015). *FLAC3D* is a full three-dimensional (3D) numerical code based on the finite difference method. The advection, conduction and convective heat transfer are considered in the analysis.

Heat advection is the transport of heat by a fluid due to the bulk motion of fluid. The partial differential equation of advection is as follows:

$$\frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T = S, \quad (1)$$

where  $T$  is temperature,  $S$  is heat source and  $\vec{V}$  is the velocity vector. The problem of injection into a geothermal well is approximated by one-dimensional advection.

The convective heat transfer, or heat exchange between the fluid and the casing, is represented as follows:

$$q_t = hA(T_w - T_b), \quad (2)$$

where  $q_t$  is the heat flux,  $A$  is the surface where the exchange occurs,  $T_w$  is the temperature of the moving fluid,  $T_b$  is the temperature of surrounding rock, and  $h$  is the convective heat transfer coefficient.

Heat conduction is represented by Fourier's law, which states that the rate of heat transfer through a material is proportional to the negative gradient in the temperature:  $\vec{q} = -k \nabla T$ , where  $\vec{q}$  is the local heat flux,  $k$  is the thermal conductivity, and  $\nabla T$  is the temperature gradient. In the analysis, it is assumed that fluid flow within the well is in steady-state condition. Heat advection is modeled using a one-dimensional finite difference scheme, while heat conduction in rock is solved using a 3D finite difference grid.

The approach adopted in this paper is similar to that presented by Oldenburg et al., (2016), who solve 1D flow in the pipe using the explicit numerical scheme. However, a significant difference between the two approaches is that this work neglects any heat transfer due to convection by fluid flow in the rock mass. It is noted that in a reservoir, natural convection may occur depending on the permeability, and we compare cases in which the permeability and porosity are so low that heat transfer by convection in the rock mass can be negligible. In the case of the zero-permeability reservoir presented by Oldenburg et al. (2016), the reservoir is not discretized, and instead they assume that heat transfer is by conduction as calculated using Ramey's (1962) semi-analytical solution. The semi-analytical solution for heat transfer is used along the vertical injection and production sections of the well in order to simplify the calculation. However, in our approach, conduction through the reservoir is solved numerically using a 3D grid.

Another important difference between the numerical solution presented in this paper and that presented by Oldenburg et al. (2016) stems from the nature of working fluid. The results presented in this paper are based on a design in which liquid water is used as the working fluid. Liquid water is nearly incompressible, and thus it was assumed that toward the end of the injection string (horizontal section), water remains a single-phase liquid and the flow rate is constant, thus potential phase change are not considered in this paper.

Oldenburg et al., (2016) consider single-phase conditions in the pipe as well; however, super-critical CO<sub>2</sub> can undergo phase and significant density changes upon expansion. This results in changes in velocity and density of CO<sub>2</sub> along the pipe, which needs to be solved considering the momentum equation of CO<sub>2</sub> pipe flow, including temporal momentum change rate, spatial momentum gradient, friction loss at the pipe wall, gravity, and pressure gradient.

Finally, it is noted that when dealing with super-critical CO<sub>2</sub> as the working fluid, all forms of energy (potentially due to compression of gas, thermal, kinetic, and gravitational potential) are taken into account in output energy gain (MW), while in our approach, the output energy is coming only from the thermal component.

### 3. RESULTS

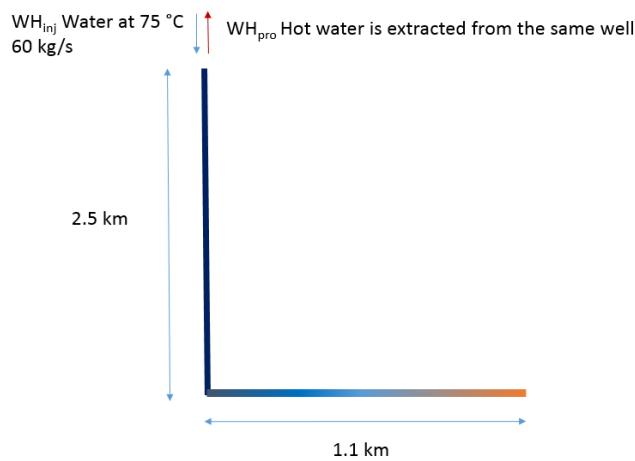
In this modeling study, we investigate the performance of GSL well design with water as the working fluid and the proposed ECO2G technology (GreenFire, 2016; Oldenburg et al., 2016; Higgins et al., 2016), which circulates supercritical carbon dioxide (SCO<sub>2</sub>). In order to carry out a comparative study, we don't consider a typical GSL design, but have chosen the in-situ and operational parameters identical to those presented for the ECO2 technology (Oldenburg et al., 2016).

The GSL well design involves a co-axial design composed of vertical and horizontal sections of a well. The well cross-section is an annulus with inner and outer pipe diameters of 5 and 9.625 inches, respectively. The inner pipe has a thickness of 0.5 inches; the outer pipe has a thickness of 0.797 inches. The inner and outer diameters of the well and the geometry of cross-section are presented in Table 1.

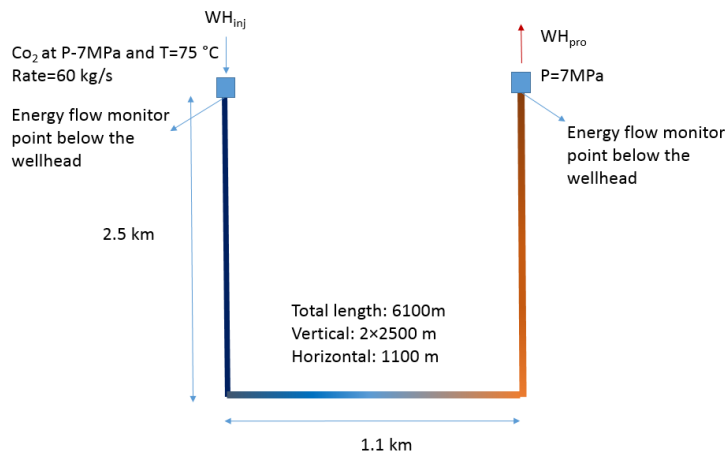
**Table 1. Properties for the ECO2G well design (Oldenburg et al., 2016)**

	Parameter	Value	Unit
<b>Horizontal Well (Lateral)</b>	Length	1100	m
	Diameter	0.168 (6.61 inch)	m
	Tube I.D.	0.154 (6.06 inch)	m
	Material	Steel	-
	Roughness Factor	$4.57 \times 10^{-5}$	m
<b>Vertical sections of well</b>	Length	2500	m
	Diameter	0.168 (6.61 inch)	m
	Tube I.D.	0.154 (6.06 inch)	m
	Material	Steel	-
	Roughness factor	$4.57 \times 10^{-5}$	m

In this study, the GSL well is composed of a 2.5 km vertical section and a 1.1 km horizontal section (Figure 2a), which makes the well length comparable to those presented by Oldenburg et al. (2016). The design presented and investigated by Oldenburg et al. (2016) involve a wide U-shaped configuration with two vertical sections of 2.5 km, and a 1.1 km horizontal portion to increase contact with the high-temperature reservoir as shown in Figure 2b.



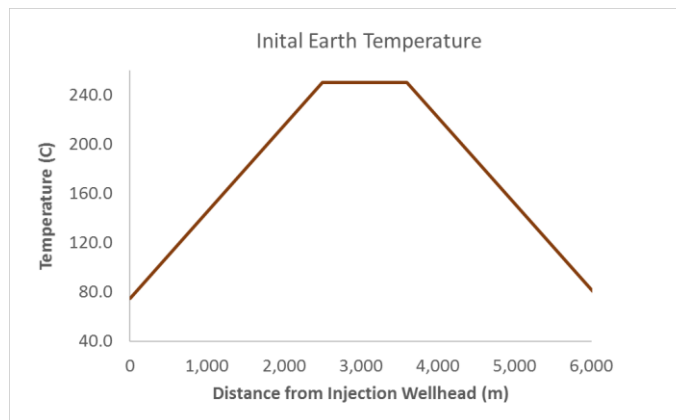
(a)



(b)

**Figure 2: Sketch of closed-loop geothermal systems for (a) GSL design and (b) ECO2 design.  $WH_{inj}$ =wellhead of injection leg,  $WB_{inj}$ =well bottom of injection leg,  $WB_{pro}$ =well bottom of production leg,  $WH_{pro}$ =wellhead of production leg.**

The fluid injection temperature is 75°C. The geological thermal gradient is 0.07°C/m. The earth initial temperature for the considered well configuration and the assumed depth is shown in Figure 3.



**Figure 3: Earth initial temperature adjacent to vertical and horizontal sections of the well.**

Similar to Oldenburg et al. (2016), a thermal conductivity of 4.0 W/m-K is used. It is assumed that the injection rate in the base model is 60 kg/s. Heat production for a period of 30 years is analyzed.

### 3.1. Comparing GSL and ECO2G Design for Base-Case Conditions

In this study, the ECO2 design is compared to two base cases. The first design is a co-axial well with a vertical and horizontal extension, which is what is proposed by GSL. The second design is slightly varied in that the cross-section is preserved to be co-axial and identical to the base case, but the well configuration is a U-shaped configuration. This is only a conceptual model used to study how much gain in power would be achieved if the length of the well was extended similar to what was used in the ECO2 design. The well geometries for both designs are shown in Figure 2. The working fluid in the case of the ECO2 model is  $\text{SCO}_2$ , and the fluid is water in the two GSL designs studied in this section. The injection rate in all models is 60 kg/s. Material properties are outlined in Table 2 **Error! Reference source not found.**

**Table 2. Rock and water thermal and mechanical properties**

Rock grain density (kg/m <sup>3</sup> )	Rock grain specific heat (J/kg°C)	Thermal conductivity (W/m°C)	Water density (kg/m <sup>3</sup> )	Water specific heat (J/kg°C)
2700	1000	4	992	4179

**Error! Reference source not found.** shows the generated power for a period of 30 years for the ECO2G and GSL designs (including the design in which the GSL cross-section is preserved, but the well is U-shaped so that hot water is extracted through a production well). As expected, during the first five years of production, power drops relatively quickly, but after five years, the average produced power decreases relatively slowly. On average, ECO2G and GSL designs produced power between 2MW and 3 MW<sup>1</sup>. It can be concluded that water gains more energy than  $\text{SCO}_2$  because it starts out with a smaller temperature. Although the initial injection temperatures in both cases are the same,  $\text{SCO}_2$  will heat to approximately 110°C upon injection, so there is greater heat extraction by the water in the pipe, as will be shown in the next section.

Overall, the Figure 4 graphs show that the GLS design with water as the working fluid and with the harvester length and rock conditions matching those used by ECO2G can generate an average thermal power of 3MW over a period of 30 years. In the GSL design, the produced power at the outlet is in the form of thermal energy, carried by a highly pressurized water with a temperature well above 100°C, which would change to a gaseous phase if the pressure was removed. In the ECO2G design, the generated power at the outlet is a combination of thermal and mechanical energy, in which the mechanical part is due to the significant expansion of  $\text{SCO}_2$  and its conversion from a supercritical state to a high-pressure gaseous phase at the outlet. The overall efficiency of both designs depends to a great extent on the efficiency of the turbines and heat exchanger.

<sup>1</sup> GSL's typical design involves a significantly longer heat harvester that provides more surface area than the comparison model.

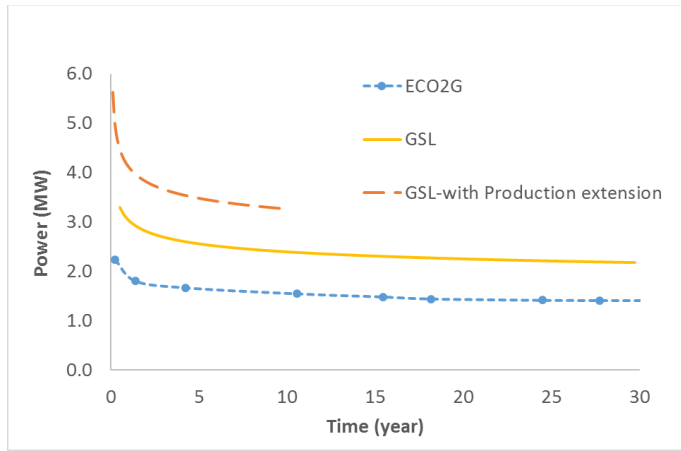
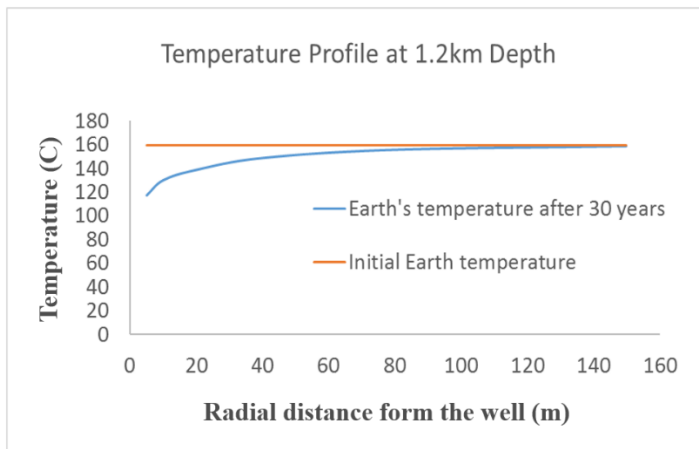
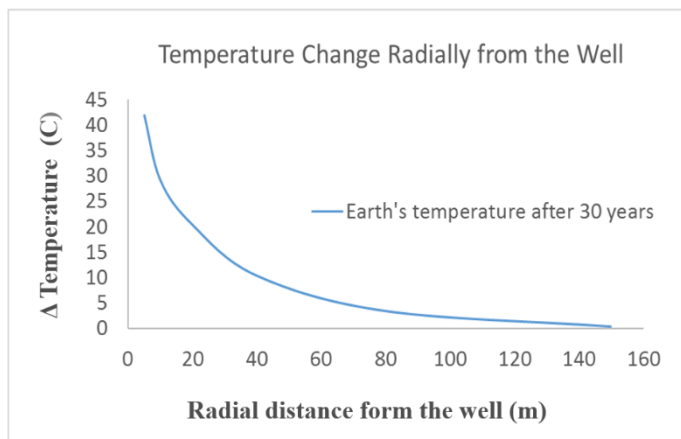


Figure 4: Comparison of generated thermal power for GSL and ECO2G designs.

Figure 5 shows the effect of the well on the temperature of surrounding rock after 30 years. The initial temperature at this depth was 160°C. This figure shows that as a result of heat extraction, the temperature around the well has decreased. This effect can be seen up to a distance of approximately 140 m, while the impact decreases rapidly after 60 m (Figure 4b).



(a)



(b)

Figure 5: (a) Temperature and (b) temperature change at a depth of 1.2 km after 30 years showing the effect of the well at different distances from the well center.

### 3.2. Sensitivity Studies of the Effect of Injection Temperature

The second parametric study presented in this paper involves the effect of injection temperature. In this study, two cases are investigated with temperatures of injected water of 75°C and 40°C. Actually, for generated thermal power, the absolute value of temperature is not essential. Instead, the difference between the injection temperature and the rock initial temperature is the important parameter. However, the total electric power, which is not considered in this work, depends on absolute values because the efficiency of the above-ground system depends on the produced temperature.

Figure 6 shows power for the two considered models. It suggests that for the GSL design, the scenario with an injection temperature of 40°C had resulted in approximately 0.6 MW higher generated power compared to the case with an injection temperature of 75°C. The purple line shows the difference in generated power between the two cases for the GSL design and indicates that if the injection temperature could be decreased by approximately half, then the produced power increases by approximately 20%. The ECO2G well is more sensitive to variations of temperature, which is due to the effects of temperature on thermosiphon mechanics.

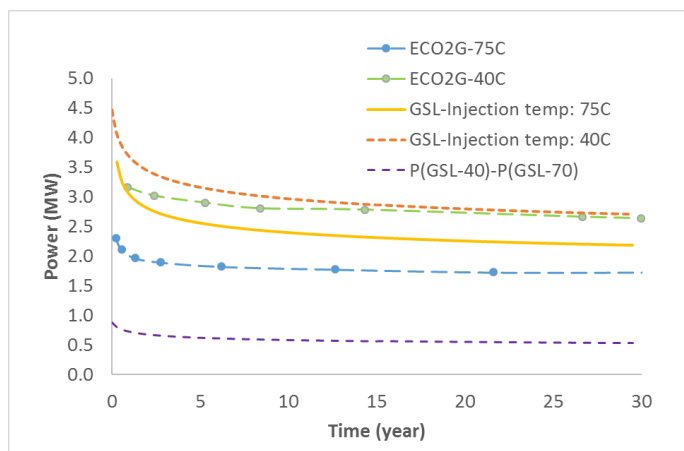


Figure 6: Effect of injection temperature: comparison of generated thermal power for GSL and ECO2G designs.

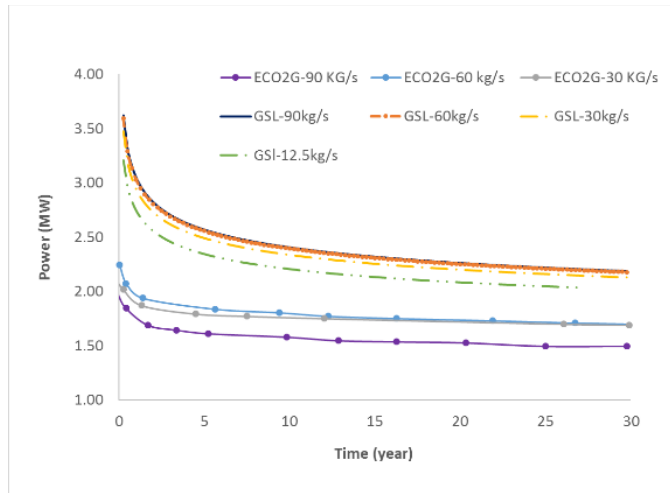
### 3.3. Sensitivity Studies on the Effect of Injection Rate

The next parametric study is with respect to the injection or flow rate. Figure 7 shows the effect of injection rate on the production in the considered closed-loop systems. Figure 7 shows that the response of GSL well design to injection rate is monotonic, i.e., an increase in the rate results in higher predicted power. However, that is not the case for the ECO2G design with supercritical CO<sub>2</sub> as the working fluid. In this case, the produced power increased when the injection rate increased from 30 kg/s to 60 kg/s, but then decreased when the rate increased to 90 kg/s.

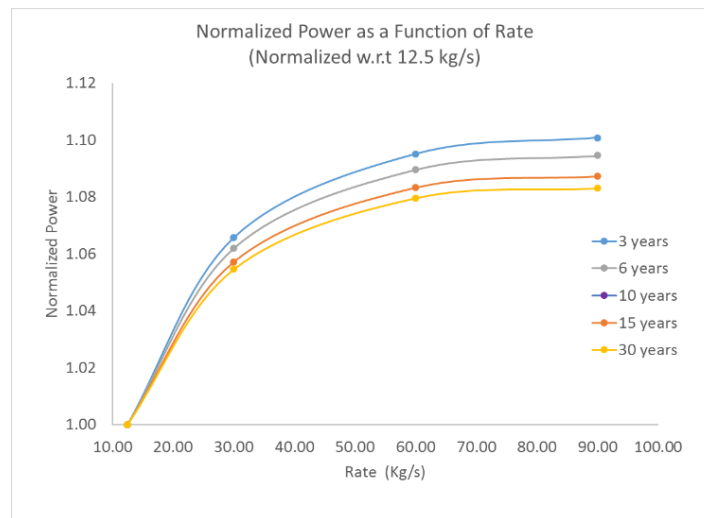
For the GSL design with water as the working fluid, an increase in the injection rate will result in the fluid passing through the well quicker. Thus, in the case of water as the working fluid, changes in flow rate only affect the exposure time. Lower exposure time means lower produced temperature. However, compared to a base case of 12.5 kg/s, the decrease in produced temperature is less than the increase in the rate, resulting in an overall trend of an increase in power with an increase in the injection rate. This trend is nonlinear, and as the rate increases, sensitivity of produced power to the rate decreases, as shown in Figure 8.

The response of the ECO2G is more complicated. The change in flow rate affects (a) initial temperature of fluid, (b) fluid velocity and thus exposure time, and (c) density. As the injection rate increases, initially SCO<sub>2</sub> heats up more, leading to a higher initial temperature. Judging from Figure 5b of Oldenburg et al. (2016), it could be interpreted that injecting SCO<sub>2</sub> with a temperature of 75°C at a rate of 90 kg/s has resulted in an initial temperature of slightly above 120°C. Injecting SCO<sub>2</sub> with a temperature of 75°C at a rate of 60 kg/s has resulted in an initial temperature of approximately 110°C. Finally, injecting SCO<sub>2</sub> with a temperature of 75°C at a rate of 30 kg/s has resulted in an initial temperature of approximately 85°C just below the wellhead. Therefore, although the injection temperature is equal for different rates, the initial temperature below the well head is significantly different for different rates. In addition, differences in rate and temperature result in differences in thermosiphon effect. A higher temperature means that SCO<sub>2</sub> tends to expand more during flow in the pipe, leading to changes in velocity. These effects lead to a non-monotonic response for SCO<sub>2</sub> with respect to rate. For example, in the cases studied here, the 60 kg/s case results in more produced power than either the 30 kg/s or 90 kg/s cases.

Figure 8 shows the normalized power versus normalized rate for different time instances. Normalization is performed with respect to the base case of 12.5 kg/s, i.e., normalized rate = rate/12.5 kg/s and normalized power = power/power(12.5 kg/s). The purpose of normalization is to show how much improvement in generated power can be gained when the rate increases from 12.5 kg/s. This figure shows that if the rate is increased from 12.5 kg/s to 30 kg/s, approximately a 6% gain in power will be achieved. If the rate increases from 12.5 kg/s to 60 kg/s, approximately an 8.5% gain in power will be achieved, and if it increases to 90 kg/s, approximately a 9% gain in power will be achieved. Considering the cost associated with an increased flow rate, an optimum rate needs to be found.



**Figure 7: Effect of injection rate: comparison of generated thermal power for GSL and ECO2G designs.**



**Figure 8: Effect of injection rate: normalized power vs. normalized rate for GSL design. (Base case is the model with a rate of 12.5 kg/s.)**

#### 4. CONCLUSIONS

In the past years, there has been a renewed interest in the closed-loop geothermal systems. This paper investigates a closed-loop design with a horizontal extension and with water as the working fluid. Through numerical modeling, it has been shown that the design proposed by GSL, operating in an assumed modest geothermal environment, produces average thermal power of 3 MW over 30 years. This value is valid for typical reservoirs and operational properties used by Greenfire energy in their study (Oldenburg et al., 2016). The injection rate is 60 kg/s; the reservoir temperature at the injection point of the model is 75°C and the geothermal gradient is 0.07°C/m. The temperature of injected water is 75°C. It has been shown that the difference between the injection temperature and reservoir temperature plays a significant role in generated power. Our analysis shows that with the decrease of injection temperature from 75°C to 40°C, the generated power increases by 20%. One of the other operational parameters that could be controlled is the injection rate. It is shown that the injection rate has a less significant effect on thermal power. For example, increasing the rate from 12.5 kg/s to 90 kg/s (approximately 7.2 times), will result in only a 9% increase in the produced power. Again, it is noted that the overall efficiency must be evaluated by considering the above-ground facilities, including the heat exchangers and turbines, as the efficiency of the heat exchanger will be higher when the difference between the ambient and the produced temperature is greater. Turbine efficiency is higher when the flow rate is higher.

In summary, the results from our analysis and analysis by others show that closed-loop geothermal wells can generate a reliable power supply with a very steady rate over a period of 30 years. The average value that a well can generate depends on its length, cross-

sectional area, temperature of injected fluid and reservoir temperature. The system performance can be predicted using approaches such as the one presented in this paper.

In recent years, studies suggested an improved efficiency of closed-loop systems through EGS-like fluid circulation through rock fractures (Wang et al., 2009, 2010). In this approach, a single coaxial well, similar to that used in closed-loop systems are used. However, to enhance the thermal recovery capacity, geothermal fluid is circulated through reservoir fractures. It is shown that flow through fractures greatly affects thermal output. GSL has been working on developing a Hybrid Closed Loop/Enhanced Geothermal System with the initial results indicating the potential for a significant increase in the heat harvesting capacity. In order to convert the harvested heat into electric power, the clear need for a maximum attainable production fluid temperature will drive future closed-loop developments in the direction of such hybrid systems. Also, future installations will aim at increasingly higher host rock temperatures and lateral lengths of the portion of the harvester located at the maximum temperature strata. Thus, the power output will be maximized by optimizing the mass flow rate and the production temperature of the fluid. Those principally engineering challenges position the closed-loop systems as a very real, practical technology for renewable energy generation.

## REFERENCES

- Ehara S., K. Morita, K. Fukuoka, T. Kuroda, K. Sakemi, Y. Fujimitsu, and J. Nishijima. Development of a new Heating and Cooling System with Downhole Coaxial Heat Exchanger (DCHE) and Ground-Surface Heat Pumps, 2005 World Sustainable Building Conference, Tokyo, 27-29 September (2005)
- GreenFire Energy Inc. "<http://www.greenfireenergy.com/>" (2016)
- Horne, R.N. "Design Considerations of a Down-hole Coaxial Geothermal Heat Exchanger," *Geothermal Resources Council Transactions*, 4, 569 (1980).
- Hasan A.R. and C. S. Kabir, *Fluid flow and Heat Transfer in Wellbores*, ISBN 978-1555630942. Richardson, Texas: Society of Petroleum Engineers. (2002)
- Hasan A.R., Poster Presentations, *An Efficient Closed-Loop Geothermal Energy Extraction System*, SMU Geothermal conference, April (2016)
- Heller K., Teodoriu C., G. Falcone, *A New Deep Geothermal Concept Based on Geyser Principle*, *Proceedings*, 39<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, (2014)
- Higgins B., C.M. Oldenburg, M.P. Muir, L. Pan and A. D. Eastman, Process Modeling of a Closed-Loop SCO<sub>2</sub> geothermal Power Cycle, *The 5th International Supercritical CO<sub>2</sub> Power Cycles Symposium*. March 29 - 31, San Antonio, Texas. (2016)
- Itasca Consulting Group, Inc. *FLAC3D – Fast Lagrangian Analysis of Continua in 3-Dimensions*, Ver. 5.0. Minneapolis: Itasca. (2015)
- Kyoto University. Successful demonstration of the world's first New Geothermal Power System carried out in Kokonoe, Oita Prefecture Online Publication, Nov 2016, [http://www.kyoto-u.ac.jp/en/research/events\\_news/department/kougaku/news/2016/161021\\_1.html](http://www.kyoto-u.ac.jp/en/research/events_news/department/kougaku/news/2016/161021_1.html). (2016)
- Nalla, G., G.M. Shook, G.L. Mines and K.K. Bloomfield. Parametric sensitivity study of operating and design variables in wellbore heat exchangers, *Geothermics*, 34(3), pp.330-346 (2005)
- Oldenburg, C. M., L. Pan, M.P. Muir, A.D. Eastman and B.S. Higgins, Numerical Simulation of Critical Factors Controlling Heat Extraction from Geothermal Systems Using a Closed-Loop Heat Exchange Method, *Proceedings*, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24, SGP-TR-209 (2016)
- Ramey Jr, H.J. Wellbore Heat Transmission, *Journal of Petroleum Technology*, pp 427-435, 14, 04, (1962)
- Morita K., M. Tago and S. Ehara. Case Study on Small-scale Power generation with Downhole Coaxial Heat Exchanger, *Proceedings*, World Geothermal Congress, Antalya, Turkey, 24-29 April (2005)
- Morita K. and M. Tago. Development of the Donwhole Coaxial heat Exchanger System: Potential for Fully Utilizing Geothermal Resources, Geothermal Resource Council (GRC) Bulletin, March (1995)
- Yokomine T., M. Miura and C.O. Tawara. The New Era of Geothermal Energy Utilization with Aid of Nuclear Reactor Technology Zero-Carbon Energy Kyoto 2011, part of the series Green Energy and Technology pp 213-223 (2011)
- Wang Z., M. McClure and R. Horn. Modeling Studies of Single Well EGS Configurations, Geothermal Resource Council (GRC) Transactions, Vol. 33, (2009).
- Wang Z., M. McClure and R. Horn. Modeling Study of Single-well EGS Configurations, *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia, (2010)