Reuse of Abandoned Oil and Gas Wells for Geothermal Energy Production

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ABSTRACT

This paper presents an investigation on the suitability of abandoned wells in California for Enhanced Geothermal Systems (EGS) and low temperature deep Borehole Heat Exchanger (BHE) applications. The study identifies three counties characterized by high numbers of abandoned wells, medium to high crustal heat flows (75-100 mW/m^2), and suitable sedimentary geology: Santa Clara, Monterey, and Santa Barbara. Thermal gradients range between 4 and 7.3 ˚C /100 m and enable access to the bottom hole temperatures between 40-73 ˚C for an average 1,000 m deep well. These rock temperatures are sufficient for low-temperature direct use EGS such as district heating, greenhouse heating, and aquaculture. Abandoned wells reuse mitigation of drilling costs and the documented lithology both reduce the risk associated with EGS. However, hydraulic fracturing of loosely to moderately consolidated sedimentary rock in transitional stress regimes remains one limitation to the EGS conversion of these abandoned wells. The feasibility of deep BHE applications within abandoned oil and gas wells is demonstrated here by a mathematical model. Predictions show that outlet fluid temperatures >40 ˚C can be achieved for 1,000 m deep wells in regions with temperature gradients >7 ˚C /100 m.

Keywords: Geothermal, abandoned well, hydraulic fracturing, BHE, heat flow, California

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1. INTRODUCTION

The objective of this paper is to investigate the prospect of using abandoned oil and gas wells in the state of California for harvesting geothermal energy. According to well data documented and maintained by the California Department of Conservation, Division of Oil and Gas and Geothermal Resources (DOGGR) there are approximately 147,127 wells currently indicated as abandoned, plugged, buried, and/or inactive. Santa Barbara County alone hosts 5,184 of these unused wells (DOGGR 2016). Most of the wells were plugged due to a decline of oil and gas productivity, while other wells were exploratory. In both cases, the existing wells provide valuable subsurface information such as lithology, temperature, and formation porosity. Augustine et al. (2006) showed that wells drilled to 5 km in 2003 cost ca. 5 million dollars each. Considering that drilling costs account for 42%-95% of total Enhanced Geothermal System (EGS) power plant costs (Tester et al. 1994), the pre-drilled and extendable abandoned wells may prove extremely valuable.

Geothermal heat has been traditionally extracted at locations characterized by hydrogeological anomalies, but recent advances in engineering have enabled development of alternative approaches such as are EGS and borehole heat exchangers (BHE). Both EGS and BHE technologies harvest Earth’s heat without the location constraints of hydrothermal systems. Enhanced Geothermal Systems (EGS) produce electrical energy by enhancing in-situ permeability and harvesting heat from hot rock geo-reservoirs. Crustal heat is mined by the injection and permeation of cold fluid through hot rock. Heat is transferred from rock to fluid and ultimately recovered through a production well. The connection between injection and production wells is engineered either by hydraulic fracturing of continuous rock mass or by hydro-shearing of existing fractures in the rock (Tester et al. 2006; Economides 2000). The most important factors which influence the viability of an EGS are fluid flow rate and temperature. Flow rates and temperatures of existing EGS range from 15 to 430 l/s and 40 to 250 ^{o}C, where higher flow rates and temperatures support power generation and lower values support direct hot water use (Li and Lior 2014). EGS flow rates can be increased via georeservoir permeability stimulation, but temperatures can only be increased by drilling deeper in to the Earth’s crust. Crustal temperature depends on crustal heat flow, where temperatures increase with the presence of insulating rock layers and magma chambers. Different from EGS, BHEs harvest geothermal energy without allowing working fluid to contact soil or rock. Instead, BHEs use various closed loop configurations for circulating working fluid through pipes buried in the subsurface, while exchanging thermal energy with the soil. Shallow BHEs extend 50-200 m into the earth and are usually coupled with Ground Source Heat Pumps (GSHP) to exploit the subsurface as a thermal source/sink during winter/summer for residential and commercial heating and cooling (Lund and Boyd 2016). Deep BHEs invoke the same principles as shallow BHEs but they reach depths of 1000 to 3000 m where rock temperatures can exceed 85 ˚C and raw produced fluid temperatures range from 20-55 ˚C (Spinska-Silwa et al. 2015). Like EGS, the production fluid temperature of a deep BHE strongly depends on crustal heat flow. Different from EGS, the efficiency of deep BHEs depend on heat exchanger configuration and the host rock thermal properties (Dijkshoorn et al. 2013) instead of hydraulic properties such as porosity and permeability. In fact, heat exchanger insulation design/cost may determine deep BHE project feasibility (Śliwa and Kotyza, 2000; Dijkshoorn et al. 2013). Table 1 lists some existing deep BHEs in Germany and Switzerland. These examples make use of a coaxial tube configuration consisting of two concentric tubes: one carrying fluid down and the other carrying fluid backup through the center. This deep BHE configuration has been investigated and proven viable in various locations around Europe (Śliwa, Rosen and Jezuit 2014).

Table 1. Existing Deep BHE sites

Site, Country	Peaking method	EWT[1] ºC	Depth (m)	Flow rate (l/s)
Aachen, Germany *(Dijkshoorn et al 2013)*	Heat pump	25-55	2,500	2.77
Prenzlau, Germany *(Schnieder et al. 1996)*	Heat pump and Gas/oil boiler	-	2,786	6
Weissbad, Switzer. *(Kohl et al 2000)*	Heat pump	15	1,200	2.9
Weggis, Switzer. *(Kohl et al 2002)*	Heat pump	40	2,300	0.8-1.75

[1]Entering Water Temperature (outlet temp from abandoned well heat exchanger)

EGS and deep BHE geothermal energy extraction technologies couple well with specific recreational and industrial applications. In many countries 40 ˚C geothermal water sources are used to heat recreational pools and residential houses, while industrial uses for 40 to 70 ˚C water include aquaculture, greenhouse heating, water desalination and district heating (Bai et al. 2010). Although an effective district heating system requires fluid temperature of 40 ˚C (Lund and

Lineau 1997), lower water temperatures (ca. 23 ˚C) combined with locally installed heat pumps is a viable alternative (Kulcar et al. 2008; Østergaard and Lund 2011). Several examples of geothermal based district heating can be found in Iceland, France, Poland, Hungary, Turkey, and the USA. To illustrate the range of BHE capacity, a district heating system in Idaho, USA heats 4000 homes while another system in Reykjavik, Iceland provides heat to 35000 homes using an 85 ˚C source and 1850 l/s (Lund and Lienau 1997).

The economic viability of EGS and deep BHEs depends on a variety of factors including prospecting technologies, drilling technologies, reservoir technologies, energy costs in the region, resource longevity, etc. (Tester et al. 2000). The reuse of abandoned wells removes prospecting and drilling risks, but the remaining factors still require focused research. For example, fracture network stimulation in a sedimentary reservoir requires different procedures compared to a similar network design in an igneous reservoir due to differences in fluid migration, pore pressures, and cementation/crystallization (Economides, 2000). While the economic viability of EGS remains a research topic, deep BHEs stem from well-established shallow BHE technologies (Lund and Boyd, 2015). Without a dependence on uncertain fracture networks, the economic viability of deep BHEs depends almost entirely on comparable regional energy prices (Śliwa and Kotyza, 2003). The same study concluded that plugging an abandoned well may, in some cases, be more expensive than refurbishing it for thermal extraction. Further, a deep coaxial BHE configuration doubles as a “maintained” plug for abandoned wells, since the efficiency of the deep coaxial BHE depends on the continuity of the cement in the casing-rock annulus. This requirement reduces the chance for oil/gas migration to the surface or into aquifers. Another study performed on the reuse of abandoned oil wells in Carpathians, Poland concluded that the benefits were ubiquitous with the only downside being the challenging optimization of design parameters (Śliwa, Rosen and Jezuit 2014). Another economic benefit of retrofitting abandoned oil and gas wells is the large number of identified drilled wells. While one single deep BHE well may not be sufficient to harvest energy equivalent of the relatively larger scale EGS reservoirs, thousands of BHE wells may have comparable scale.

This paper focuses on the reuse of abandoned oil and gas wells situated in predominantly sandstone and shale rock formations at depths of 900 to 2000 m. Based on the available data for crustal heat flow with depth, many of the existing wells may be deepened to produce electricity by exploiting >100 ˚C rock. Alternatively, it is possible to directly use lower temperature fluids

(20-40 ˚C) for recreational, industrial, agricultural and residential applications. The aim of this study is to investigate the feasibility of EGS and deep BHE installations in abandoned wells throughout California. Since deep BHE installations are well studied in other countries, a physics based model was constructed for the range of well depths and crustal thermal gradients that were encountered in Santa Barbara, Santa Clara, and Monterey. The goal of the deep BHE model is to estimate the necessary abandoned well depths and thermal gradients associated with 40 ˚C production fluid temperatures.

2. CALIFORNIA ABANDONED WELLS CHARACTERISTICS

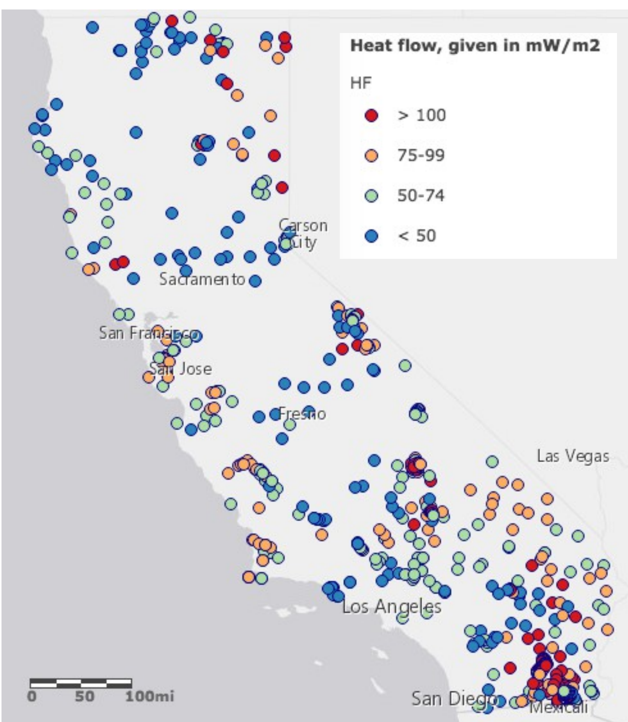
An abandoned well is defined as a well with permanently discontinued use (NPC 2011). Well-plugging is a common practice which mitigates the hazards associated with unplugged abandoned wells, such as ground water contamination, ground water comingling, loss of aquifer pressure head, and uncontrolled gas migration (NDSU 2011). Specific plugging guidelines depend on formation consolidation magnitude, water table level, and oil presence. Newer plugging regulations call for a combination of sand, clay, and neat cement grouts to be shoveled into the well to create an impermeable plug in the well. California plugging regulations require a 15 m long cement plug at the surface, cement plugs extending 30 m above oil bearing strata, and cement extending 15 m above and below water bearing strata (State of California 2007). Older wells (1850s spud dates) may have been plugged with brush, wood, rocks, paper, etc. according to loose regulations (Ide et al. 2006). Old or new, the cement plugs can be easily removed by setting up a special drill rig that breaks up and removes the well cement/debris (pers. comm., J. Trusche 2016).

2.1 Crustal heat flow

Crustal heat flow of California is well documented by numerous studies as shown in Figure 1 (DeAngelo et al. 2013). The highest crustal heat flows are associated with geothermal anomalies south in Imperial County (Salton Sea, >100 mW/m^2, Combs 1971; Lachenbruch 1980), up north in Sonoma (Geysers, ~300 mW/m^2, Walters 1991), and central east California in Inyo County (Coso, >100 mW/m^2). Heat sources for the Geysers, Coso and the Salton Sea geothermal power plants are magma chambers located at approximately 8 km depth (Nakamura 1980; Walters 1991). Generally, the horizontal extent of the geothermal anomalies is <5 km (Nakamura 1980), so well temperatures in the observed regions are governed by crustal heat flow unless they drill into an anomaly. Figure 1 shows moderately high crustal heat flows along the coast in Santa

Clara, South Monterey, and North Santa Barbara Counties (avg=84 mW/m^2, Walters 1991). Inland, Lachenbruch et al. (1985) reported scattered locations of heat flows >100 mW/m^2 in San Bernardino County.

Many of Imperial County's abandoned wells are focused on geothermal exploration south of the Salton Sea largely due to the exceptionally high subsurface thermal gradients and the presence of hydrothermal anomalies. Sass et al. (1984) reported thermal gradients ranging from 5.5-8.2 ˚C/100 m for shallow depths (<300 m). One abandoned well report shows a fluctuating thermal gradient reaching as high as 18.2 ˚C/100 m and a bottom hole temperature of 220 ˚C at 2440 m (DOGGR, 2016). Similar to Imperial County, both the Geysers and Coso geothermal fields also exhibit temperatures greater than 200 ˚C. However, the low number of abandoned oil and gas wells in the proximity of the Geysers, Coso, and Imperial county removes them from the interest of this paper, but it should be noted that any abandoned well (geothermal or oil/gas) in these areas may be equally viable for well reuse given the bottom hole temperature remains >40 ˚C.



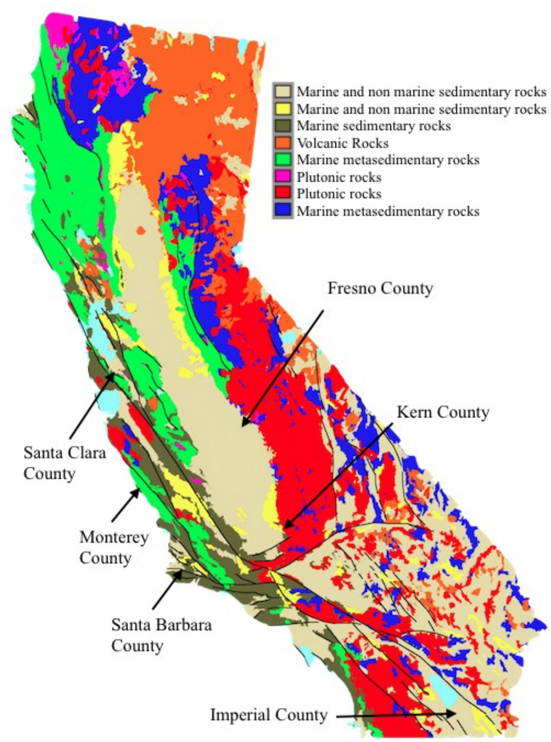


Figure 1. Crustal heat flow map of California (created using publically available data and arcgis.com) (DeAngelo et al. 2013) (left) and California Geology and counties of interest (created using publically available geological map of California) (CGS 2016) (right)

Santa Clara (and neighboring counties San Mateo and Santa Cruz), South Monterey, and North Santa Barbara are coastal regions characterized by medium to high heat flows and countless abandoned oil and gas wells (Table 2). Sass et al. (1971; 1994) measured several shallow less than 300 m deep thermal gradients in Sunnyvale, Santa Clara and reported an average thermal gradient of 5.8 ˚C/100 m. The thermal gradient may even reach higher values due to insulating lithological sequences, but assuming the thermal gradient stays constant at 5.8 ˚C/100 m, a 1,220 m deep well in Santa Clara county should encounter 70 ˚C rock. Further deepening of the well's depth by 1,000 m promises 130 ˚C rock. South in Monterey County, thermal gradients reported by the SAFOD down hole observatory reach 4 ˚C/100 m with a bottom hole temperature of 93 ˚C at 2,130 m (Williams et al. 2004). Further south, in the north region of Santa Barbara county, thermal gradients were reported as 4.9 ˚C/100 m with a bottom hole temperature of 60 ˚C at 1,220 m depth as shown in Figure 2 (Williams 1995). A rare temperature survey performed on an abandoned well in Santa Barbara reported a high thermal gradient of 7.3 ˚C/100 m with a bottom hole temperature of 55 ˚C at 670 m depth (DOGGR 2016). Although the available temperature surveys are subject to error given the variety of methods used, abandoned wells in any of the coastal counties may provide access to crustal temperatures ranging from 48 to 93 ˚C without further well deepening. Methods of deepening the existing wells by 1000 m have a good chance of reaching rock temperatures, which can be candidates for electrical energy production.

Table 2. Comparison of abandoned well characteristics in California counties

County	# Unused Wells[4]	Max well depth/ (average) (m) [4]	Temp Gradient (˚C /100m)	Heat Flow[5] (mW/m^2)	Rock type at 2 km (deepest well)[4]	Rock type at max depth (deepest well)[4]
Santa Clara	5,184	2,000/(550)	5.8 (avg)[1]	75-99	Sandstone poor cons.	Sandstone poor cons.

Monterey	2,627	2,900/(700)	4.0[2]	75-99	Chert well cons. or granodiorite	Sandstone mod. cons or granodiorite
Santa Barbara	6,496	3,900/(770)	4.9[3] - 7.3[4]	75-99	Claystone mod. cons.	Shale well cons.
Kern	81,000	6,600/(720)	2.0[7] - 3.6[4]	50-75	Shale mod. cons.	Sandstone mod cons.
Fresno	8,435	4,900/(1,120)	2.5[7]	50-75	Siltstone poor to mod. cons.	Igneous volcanic poor cons.
Los Angeles	2,380	4,250/(1,800)	2.7[4] - 5.5[6]	50-75	Shale well cons.	Sandstone well cons.
Ventura	8,364	5,000/(1,580)	2.2[4] - 3.5[6]	50-75	Sandstone and shale poor to mod. cons.	Sandstone well cons.

[1]Sass et al. 1994; [2]Williams et al. 2004; [3]Williams 1995; [4]DOGGR 2016; [5]DeAngelo et al. 2013; [6]Higgins 1981; [7]Darton 1920

The previously mentioned counties were characterized by medium to high crustal heat flows, but other California counties still host vast numbers of abandoned wells and low-medium heat flows (50 to 75 mW/m^2) as shown in Table 2. Such counties include Kern, Ventura, Fresno, and Los Angeles. A temperature survey on an abandoned well in Kern County measured a promising temperature gradient of 3.6 ˚C/100 m (DOGGR 2016). Another temperature survey on an abandoned well in Ventura County reported a gradient of 2.2 ˚C/100 m but a high bottom hole temp of 49 ˚C at 960 m (DOGGR 2016), possibly due to insulating rock layers. However, Higgins 1981 reported average gradients between 3.0 to 3.5 ˚C/100 m in the Ventura Basin. Los Angeles temperature gradients might be as low as 2.7 ˚C/100 m above 300 m, followed by a negative temperature gradient due to the presence of fluid (DOGGR 2016). In some isolated cases in the Palos Verdes basin of Los Angeles county, subsurface temperature gradients might reach favorable values of 5.5 °C/100 m (Higgins 1981). Perhaps the reuse of wells in the Palos Verdes basin of Los Angeles county counties is less viable, but the abandoned wells may be candidates for well deepening if the local geology is conducive to geothermal fluid circulation and the surface industrial application is justified for the area.

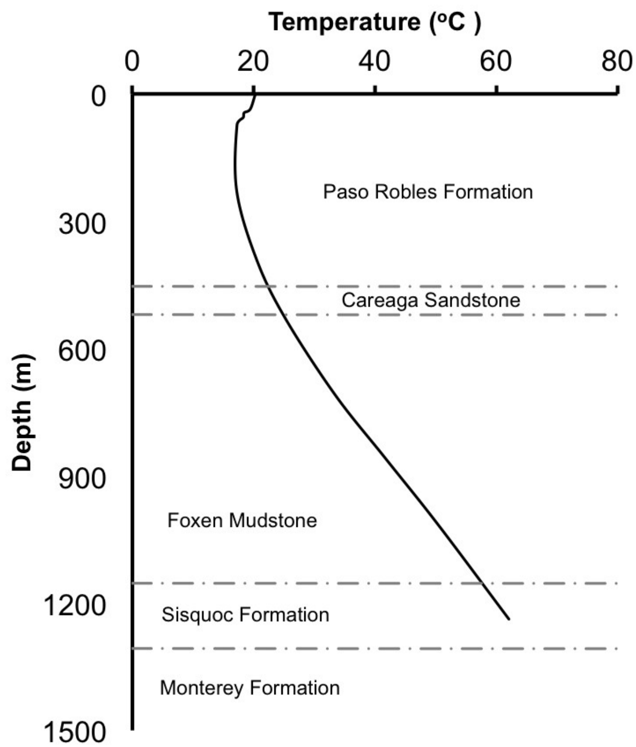


Figure 2. Thermal gradient and lithology for a well located in Santa Maria (North Santa Barbara County) (Williams 1994) (sized for single column)

2.2 Geology

Another important characteristic of EGS is the geology of the geo-reservoir. Rock permeability must be low enough to maintain working fluid pressure (i.e. avoid fluid loss), but it also must be high enough for the working fluid to migrate through the rock quickly enough to maintain required flow rates (Tester et al. 2006). Existing pilot EGS sites target igneous rock formations, such as granite, where fluid circulation through hot crystalline rock mass relies on stimulated permeability by means of hydraulic fracturing or shear displacement of the existing fracture network. Although sandstone and other sedimentary rocks cannot support the same type of fracture network due to higher permeability, some studies have demonstrated the capacity of sandstone to support high flow rates and minimal fluid loss. For example, sandstone's natural primary porosity was combined with stimulated secondary porosity to establish a geothermal reservoir (Legarth et al. 2005; Bolcher et al. 2009; and Zimmerman et al. 2010). Zimmerman et al. (2010) employed a gel proppant stimulation in a 1250 m deep sandstone formation characterized by 8-10% porosity, 150 ˚C and 16.5 mD permeability underlain by a low permeability igneous rock layer. The study concluded that the sustainability of the sandstone fractures was key to the success of the sandstone reservoir. Additional evidence pointing toward the suitability of sandstone for EGS is the occurrence of natural hydrothermal anomalies in sandstone formations and granitic plutons alike (Loucks and Milliken 1981). Therefore, EGS may be suitable in formations comprised of sandstone layers characterized by lower porosities and lower permeability "caps" to control fluid migration.

Most of the abandoned wells in California target oil and gas rich sandstones and shales. Thus, these wells tend to drill through and into marine sedimentary rocks. The geology of Santa Clara County varies from moderately consolidated to loosely consolidated marine and non-marine sedimentary rocks (Figure 1, CGS 2016). Mud logs for abandoned wells show lithology (including San Jose) comprised of mostly silty and sandy shales down to 1,000 m (DOGGR 2016). One well closer to the coast shows 460 m of shale covering a 90 m thick layer of "Costa Sandstone" at 850 m depth. Indirect neutron porosity measurements estimate true formation porosity around 10-25% at these depths (DOGGR 2016). South of Santa Clara, the geology of Monterey is similar but comprised of more frequent alternating sequences of sandstone, shale, and siltstone. CGS (2016) reports the geology as loosely to moderately consolidated alluviums. These sandstone layers range from 15 to 60 m thick with porosity values hovering around 10 to 15% (DOGGR 2016). One unique feature of the Monterey County geology is the presence of a granodiorite floor around 700 m depth for wells further than 5 km from the San Andreas fault (DOGGR 2016). South of Monterey County in Santa Barbara, the geology is reported as the same coastal alluvial deposits with low to moderate consolidation (Figure 1). Various wells in the region report mostly alternating 15 to 60 m thick layers of clay and shale. However, a notable geological shift to sandstone occurs at about 850 m depth as shown in Figure 2 (DOGGR 2016). Although many mud log records do not report rock types beyond 1,000 m depth, the alternating sequences of sedimentary rock described above can be assumed to continue until basement, which exists at depths between 4,000 and 10,000 m (Higgins 1981). Table 2 shows the rock formations encountered at 2,000 m depth and at the max depth reached for the deepest well in each county.

The geology of inland oil fields in regions characterized by lower heat flows is similar to coastal California geology (Figure 1). The majority of wells comprising the Ventura oil and gas field drill into moderately consolidated marine sedimentary rocks from the Pliocene period. For example, a representative well might hit oil-bearing shale at 2000 m followed by hard sandstone at 2050 m followed by shale with streaks of sand at 2057 m. Around 2285 m the wells hit variations of hard shale containing oil, gas, or sand (DOGGR 2016). Fresno County wells reach unconsolidated or semi-consolidated non-marine alluvium deposits. The Southern Fresno and Kern County wells describe alternating claystone, blue shale, siltstone, and poorly sorted sandstone down to 1370 m (DOGGR 2016). Wells logged for density show porosity hovering around 15% between 1370 and 2130 m (DOGGR 2016). A well near the middle of Fresno County offers lithology to a depth of 3000 m. On the way down clay confines 30 to 60 m thick layers of very fine grained sands. At 3000 m a granitic floor marks a geologic transition. A similar geology is observed in the Palos Verdes basin of Los Angeles County where 1,500 to 4,000 m of Cenozoic marine sediments overlie crystalline basement (Higgins 1981).

Finally, the geology of Imperial County shares a similar geology to Fresno County: marine and non-marine unconsolidated/semi consolidated alluvial sedimentary deposits comprising part of the Palm Springs Formation (CGS 2016). Mud logs show alternating lithology of 15 to 30 m thick layers of sandstone and claystone. Formation porosity was measured at 15% around 1250 m depth (DOGGR 2016). The aforementioned well was drilled in 1978, but due to an apparent lack of water productivity the well was plugged and abandoned in 1987. An active liquid dominated geothermal well field (East Mesa) in Southeast Imperial County accesses 120 to 150 ˚C fluids in sandstone covered by shale caprock (DOGGR 2016). Some wells nearby this field access high temperatures and great depths (96 ˚C at 2,040 m, DOGGR, 2016) but were plugged, presumably because they produced little or no fluid. Sass et al. (1984) measured shallow porosities in the area ranging from 15 to 40%.

To conclude, the coastal and inland lithology of California may prove suitable for EGS, especially the geological setting in Monterey. Monterey’s low porosity sandstone formation underlain by a shallow granodiorite basement in combination with a medium to high heat flow might enable a similar EGS configuration to that of Zimmerman et al. (2010). The Zimmerman et al. (2010) project used hydraulic fractures extending from a crystalline basement up into the overlying sandstone formation to deliver water to the sandstone formation where the water permeated the sandstone before reaching a production well. Other counties also sit on crystalline basements, but these basements range from 4,000 to 10,000 m depth (Higgins 1981) and need to be further evaluated.

2.3 Stress regimes

The development of EGS involves the stimulation of formation porosity by means of hydraulic fracturing or hydroshearing. Since fracture propagation is governed by in-situ stress direction and magnitudes, the crustal stress state is reported here for each of the regions of interest to illustrate in-situ EGS suitability. The general stress setting is strike-slip, demonstrated by the proximity of these counties to the San Andreas Fault. However, local stresses may be rotated due to the weak shear strength of the fault and historically active stresses in the region (Zoback et al. 1987). The conclusions suggest a normal/strike-slip stress regime, both of which encourage vertically oriented fracture planes. SAFOD provides insight into the stress state at great depths in Monterey and other regions along the San Andreas Fault. Borehole breakouts and drilling induced tensile fractures were used to constrain a transitional strike-slip to reverse faulting regime (Hickman and Zoback 2004). This conclusion suggests the possibility of compressional horizontal confinement stresses being larger than the compressional vertical confinement stress, which may yield horizontal fracture plane orientations. Hardebeck and Hauksson (2001) used earthquake focal mechanisms to estimate the stress orientation of Southern California. Findings show that Los Angeles follows a similar transitional regime of strike-slip to reverse, while down south in Imperial County the regime follows a transitional normal to strike-slip faulting pattern.

3. PERMEABILITY STIMULATION OF SEDIMENTARY ROCK FORMATIONS

The implementation of an EGS system in abandoned oil and gas wells in California depends strongly on the hydraulic fracturing processes within loosely to moderately consolidated sedimentary rock. The Geothermal Reservoir Well Stimulation Program in the USA showed that Hydraulic Proppant Fracturing (HPF) can be applied to sedimentary formations (Cambpell et al. 1981; Entingh 2000). Specific to California’s sandstone geology, the sandstone siltstone rock matrix of the East Mesa geothermal site experienced an apparent increase of permeability following HPF treatment, which corresponded to a doubled production flow rate (Campell et al.

1981: Entingh 2000). One of the East Mesa HPF treatments was performed at 1500 m depth and successfully corrected permeability impairment near the wellbore. Although East Mesa is a hydrothermal system, the HPF treatment is of specific relevance to the current study due to the common geology, abandoned well depth (1500 m), and management of near wellbore damage.

Despite reported successful sandstone HPF treatments, Legarth et al. 2005 outlines difficulties encountered in the poorly cemented Rotliegend sandstone. Particularly, the unforeseen mechanical and chemical processes occurred during the fracture closure. Zimmerman et al. 2011, however, details the successful permeability enhancement of the same Rotliegend sandstone by application of a revised gel-proppant treatment. The treatment involved the injection of resin coated high strength proppant in high viscosity cross-linked gel. Both studies indicate the importance of better understanding the fracture stimulation design, fracture propagation associated with flow rates, treatment duration, and fluid dynamic viscosity.

The prediction of fracture propagation and the applicability of the Linear Elastic Fracture Mechanics (LEFM) to the loosely to moderately consolidated sandstone is still not well understood. Khodaverdian and McElfresh (2000) experimentally observed both the pore pressure increase and the development of high shear stress within the process zone at the fracture tip due to the plasticity of loosely consolidated sandstone. The observations by Khodaverdian and McElfresh (2000) pointed toward a shear failure within the plastic zone unexplained by LEFM and largely controlled by pore pressure increase in the process zone ahead of the fracture tip. Bohloli and De Pater (2006) demonstrated that the viscosity of the injected fluid has as much control over the geometry and extent of fractures in loosely consolidated rock, as the injected fluid pressure. Despite these challenges, advances in numerical modeling (Zhai and Sharma 2005) coupled with decades of directional drilling and hydraulic fracturing of sandstones (Monus et al. 1992) provide a strong foundation for the development of EGS in loosely to moderately consolidated sandstone formations.

4. LOW TEMPERATURE HEAT EXTRACTION BY DEEP BHE FEASIBILITY STUDY

The feasibility of reusing abandoned oil and gas wells as deep BHEs is investigated by mathematically modeling fluid flow through a coaxial deep BHE configuration. Convective and conductive heat transfer are modeled between the incompressible fluid and the surrounding rock matrix. An envelope of desirable crustal temperature gradients, well depths, and flow rates is determined by parameterizing the deep BHE model according to well and heat flow characteristics observed in Santa Barbara, Santa Clara, and Monterey, California, USA.

4.2 Methodology

The numerical solutions to the equations for fluid flow and heat transport are solved using the finite element method in COMSOL Multiphysics software. The governing equations for the model include Navier-Stokes for fluid flow through the BHE and conservation of energy for convective and conductive heat transfer. The fluid is assumed incompressible ($\nabla \cdot u = 0$¿ and the inertial forces are assumed to be much smaller than viscous forces. Thus, the Navier-Stokes equation is reduced to:

$$0 = -\nabla p + \nabla \cdot \left(\mu \left(\nabla u + (\nabla u)^{T} \right) \right) \tag{1}$$

where p is the fluid pressure (Pa), u is the fluid velocity (m s^{-1}), and μ is the fluid dynamic viscosity (Pa·s). For convective and conductive heat transfer, the conservation of energy equation can be written as:

$$\rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_c \tag{2}$$

where ρ is the water density (kg m^{-3}), C_p is the water specific heat capacity (J kg^{-1}K^{-1}), T is the temperature (K), Q_c is a heat source (crustal heat flow) (W m^{-2}), and k is the thermal conductivity of rock or water (W(mK)$^{-1}$). The term on the left-hand side of Eq. 2 describes the heat convection associated with the fluid flow. The current study investigates long-term industrial applications for deep BHEs. Therefore, the equations are solved for the steady-state since BHE production temperatures fall with time and ultimately plateau (Aachen, Germany - Dijkshoorn et al., 2013).

This study uses the Coefficient of Performance (COP) as a metric for comparing parameter combinations.

$$COP = \frac{Q_r}{W_p} \tag{3}$$

$$Q = C_p \rho q \left(T_{out} - T_{¿} \right) \tag{4}$$

where Q_r is the thermal heat extracted from the reservoir (W), C_p is the heat capacity of water (J kg^{-1}K^{-1}), ρ is the density of water (kg m^{-3}), q is the fluid flow rate through the BHE, T_{out} and $T_{¿}$ are the inlet and outlet fluid temperatures of the coaxial BHE (K), and W_p is the work consumed by the electrical water pump (W):

$$W_p = \frac{q \rho g h_f}{\eta} \tag{5}$$

where g is the acceleration due to gravity (m s^{-2}), η is the pump efficiency (0.8), and h_f is the headloss due to friction (m) as defined by the Darcy-Weisbach equation:

$$h_f = f_D \frac{L V^2}{D 2 g} \tag{6}$$

where L is the length of the heat exchanger (m), V is the velocity of the fluid, D is the hydraulic radius of the pipe (m), and f_D is the friction factor defined by using the Reynolds number (Re):

$$\Re = \frac{\rho V D}{\mu} \tag{7}$$

and relative pipe roughness, ε / D, (ε is 0.025 for steel) with the Moody diagram.

The heat transfer across the inner and outer well casings was computed using a pair thin layer resistive layer boundary condition:

$$q_2 = \frac{T_1 - T_2}{d_s / k_s} \tag{8}$$

where T_1 is the temperature on the inside of the layer and T_2 is the temperature on the outside of the layer, d_s is the thickness of the thin layer (m), k_s is the thermal conductivity of the thin layer (W(mK)$^{-1}$), and q_2 is the heat flux vector on the outside of the layer (W m^{-2}). q_1 is simply the opposite of q_2 .

Well and reservoir model domain geometry and mesh are shown in Figure 3. The domains are discretized in 2D and the final solution is axisymmetric. The modeled well depths are 1000, 3000 and 5000 m, which match well depths encountered in Santa Barbara, Santa Clara, and Monterey county. The 200 m width of the domain was determined by convergence study shown in Figure 4 to provide a sufficient buffer between the boundary conditions and the well domain. Beyond 200 m domain width, the steady state outlet temperature remains is unaffected. The coaxial BHE configuration dimensions follow the dimensions of existing abandoned wells of interest: 180 mm and 120 mm outer and inner diameters, respectively. Figure 3 shows the FEM discretization of the domains, where the element size ranges from 7.5 mm in the well to 20 m at the boundary of the domain.

Model boundary and initial conditions are shown in Figure 3. The edge of the model follows a variable-with-depth temperature boundary condition (Dirichlet) to simulate crustal temperature gradient. Values for the edge boundary conditions were parameterized to 4.5 and 7.0 ˚C/100m, which match the range observed in Santa Barbara, Santa Clara, and Monterey. The bottom of the domain was constrained by a constant heat flux of 75 mWm^{-2} (Nuemann) boundary condition, which follows crustal heat flow estimates gathered by several geological surveys (DeAngelo et al. 2013) for the counties of interest. The inlet mass flow rate of the coaxial heat exchanger was parameterized to 1, 4.4, and 10 kg/s, which aligns with the heating demand of a single commercial building (Dijkshoorn et al. 2013). For the outlet of the coaxial heat exchanger, a constant pressure boundary condition of 0 Pa was used. The boundary condition of the fluid flow domain (well casing) is no-slip (velocity of fluid at wall is 0 m/s).

In summary, a total of 18 parameter combinations are used for this study. Specifically, well depths of 1000, 3000, 5000 m, mass flow rates of 1, 4.4, 10 kg s^{-1}, and edge temperature gradients of 4.5 and 7.0 ˚C/100m.

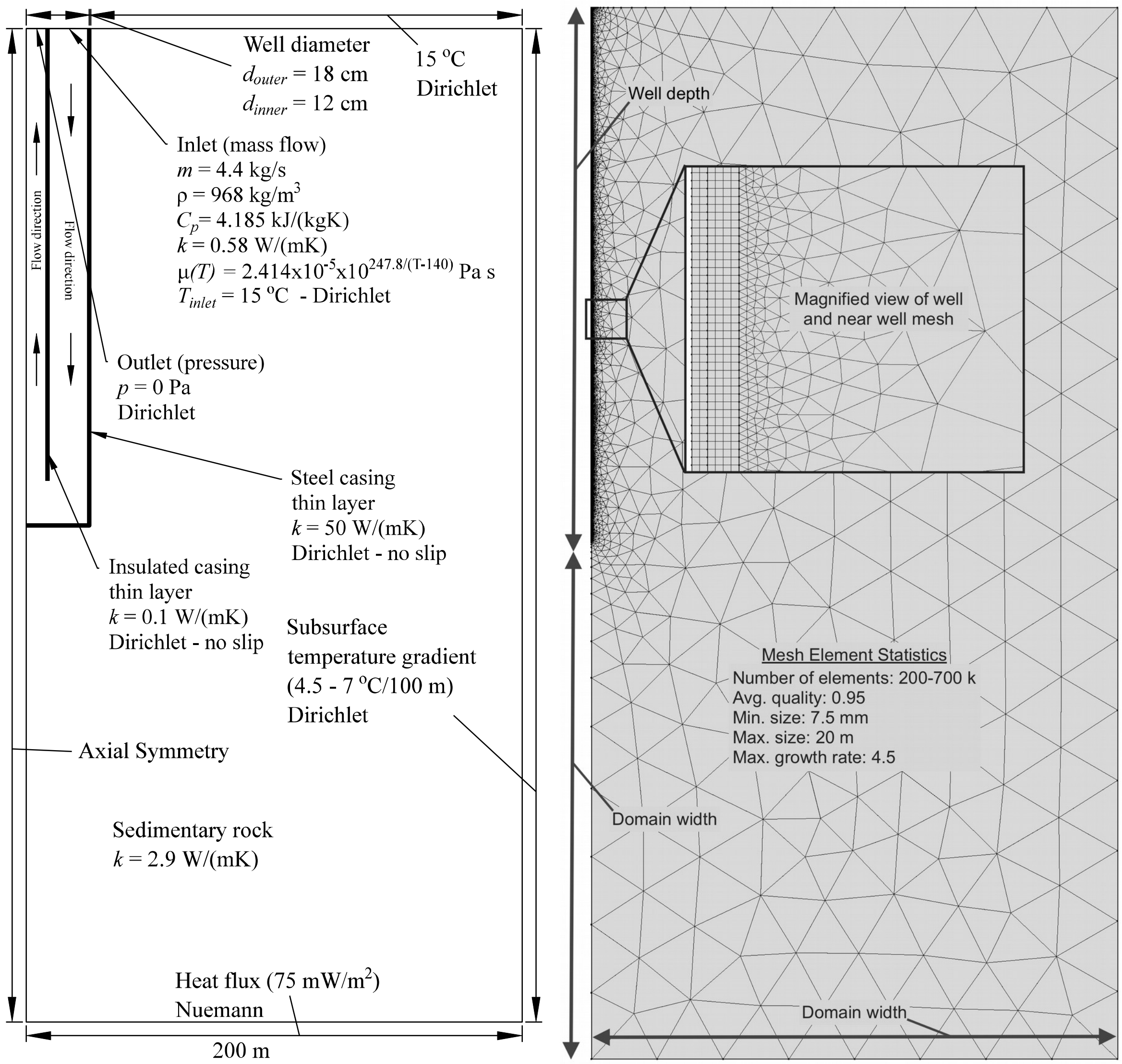


Figure 3. Model geometry and details (not to scale) (left) and domain discretization (right)

Model parameters are also reported in Figure 3. Effective thermal conductivity, k, was used to represent the sedimentary rock surrounding abandoned wells in California. Saturated sandstoneswith average quartz content and porosities ca. 10 to 15% exhibit effective k as high as 4.5 W(mK)$^{-1}$ while unsaturated shales exhibit lower effective k closer to 1.25 W(mK)$^{-1}$ (Robertson 1988). For these reasons an average effective k of 2.9 W(mK)$^{-1}$ is used to represent the semi saturated sandstones encountered in the counties of interest. The model uses a thermal conductivity of 0.1 W(mK)$^{-1}$ for the insulating inner pipe, which matches the installed

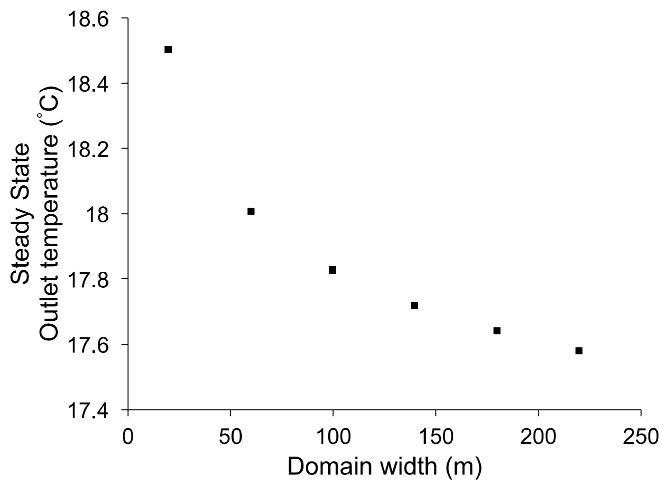


Figure 4. Domain width convergence study

conductivity of the double-walled vacuumed insulating pipe the deep BHE of Weggis Switzerland (Kohl et al. 2002).

4.3 Results

This feasibility study estimates the production temperatures and flow rates for abandoned wells converted to deep BHEs in Santa Barbara, Santa Clara, and Monterey counties. Various depths (1000 to 5000 m), temperature gradients (4.5 to 7.0 ˚C /100 m), and flow rates (1 to 10 l/s) result in a wide range of fluid temperature increases between 1.2 and 130 ˚C. Figure 5 shows how lower flow rates (1 l/s) are necessary to achieve fluid temperature increases >10 ˚C in 1000 m deep wells. However, in deeper wells (ca. 3000 m) the temperature gradient plays a larger role in increasing the outlet fluid temperature beyond the target for direct use. An increased subsurface gradient from 4.5 to 7 ˚C/100 m increased the production temperature by 36.5 % for 4.4 l/s flow rate in a 3000 m deep well. Flow rate also plays a key role, a change of flow rate from 1 to 10 l/s decreases the production fluid temperature by 40.7 % for a 3000 m deep well characterized by 7 ˚C/100 m. Figure 5 also shows how the impacts of subsurface temperature gradient and flow rate become greater as well depth increases. Ultimately, the target well depth, flow rate, and subsurface temperature gradients range from 1250 m with 1 l/s flow rate and 7 °C/100 m to 5000 m with a flow rate of 10 l/s and 4.5 °C/100 m.

The COPs for the analyzed combinations of fluid flow rates, well depths and subsurface temperature gradients are shown in Figure 6. It is observed that COP increases with well depth and decreases with increasing flow rate. The COP for the flow rate of 4.4 l/s increases by ca. 425% with well depth between 1000 and 5000 m and decreases for a 3000 m deep well by ca. 50% as flow rate increases from 4.4 to 10 l/s. Although the general trend follows an increasing COP with increasing well depth, at low flowrates and high well depths the COP starts to decline. This decline is caused by the low Reynolds number which corresponds to a higher friction factor (f_D) from the Moody diagram leading to increased head loss due to friction (h, Eq. 6) and the work necessary to pump the fluid (W_p , Eq.5), yielding a lower COP (Eq. 3)

A similar analysis was run by Śliwa et al. 2015, however that analysis focused on well coaxial configurations. Table 3 shows the comparison of two similar simulations. Despite differing insulation thermal conductivity and flow rates, the similarity of the results validates the methods used in both studies.

Table 3. Deep BHE simulation comparison

	Śliwa et al. 2015	Present study
Well depth (m)	2316	1600
Bottom hole temp (ºC)	73.5	72
Flow rate (l/s)	2.5	4.4
Inlet temperature (ºC)	11.6	15
Insulating thermal conductivity ($Wm^{-1}K^{-1}$)	0.26	0.1
Outlet temperature (ºC)	23	ca. 25
Well diameter (outer, inner mm)	120, 70	180, 120

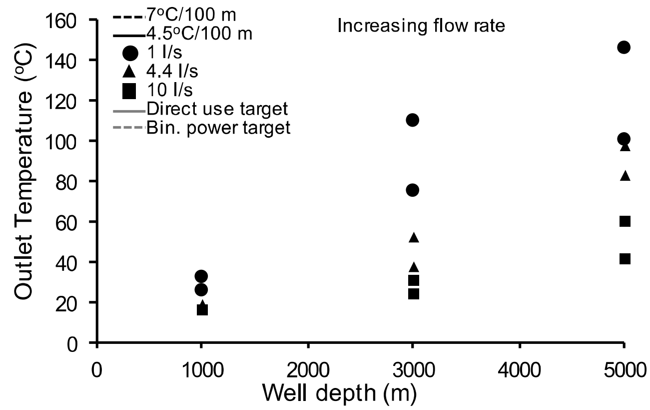


Figure 5. Steady-state coaxial BHE outlet fluid temperature for various flow rates, well depths, and subsurface temperature gradients

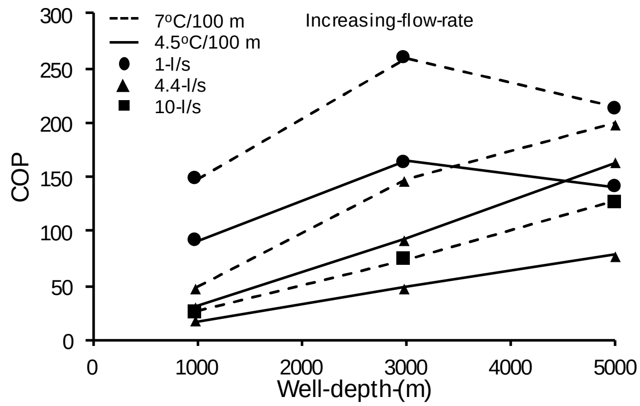


Figure 6. COP for various flow rates, well depths, and subsurface temperature gradients

5. CONCLUSIONS

The vast number of abandoned wells in California presents an opportunity for the development of low cost renewable geothermal energy. This paper identified counties within California characterized by a high number of abandoned oil and gas wells, medium to high crustal heat flows, and sedimentary geology suitable for the extraction and direct use of geothermal energy via sedimentary EGS and deep BHE. These counties include Santa Clara, Monterey, and Santa Barbara, and they may benefit from a local investigation of abandoned wells to better understand their suitability for a low temperature direct use. For example, district heating requires a close proximity to users, while industrial applications such as greenhouses or aquaculture need to be located at the abandoned well site.

In general, the abandoned wells located in Santa Clara, Monterey, and Santa Barbara counties tap into low to moderately consolidated sandstone rock layers at depths of 900 to 2000 m confined by shale layers with similar consolidation characteristics. Bottom hole temperatures depend strongly on crustal heat flow and well depth, but in general temperatures range from 40 to 70 ˚C with some wells reaching up to 90 ˚C. These depths and temperatures are suitable for direct use low temperature EGS such as district heating or greenhouse heating. The paper identified other counties characterized by high numbers of abandoned wells and suitable sedimentary geology, but low crustal heat flow. These counties include Fresno, Kern, Ventura, and Los Angeles. The abandoned wells within these counties exhibit temperature gradients as low as 2.2 ˚C/100 m and may require deepening of several hundred meters to reach usable temperatures.

Although the bottom well temperatures in Santa Clara, Monterey, and Santa Barbara are already suitable for EGS, one of the challenging issues is the prediction of hydraulic fractures in loosely to moderately consolidated sedimentary rock for various stress regimes. In some cases, it may be desirable to identify regions characterized by reverse faulting regimes depending on the proposed abandoned well reuse. A single well EGS may benefit greater from a reverse faulting regime that would enable several individually stimulated horizontal fracture zones stacked vertically. This configuration allows operators to pump water into one zone, and produce hot water from another zone, all within the same well. In other cases, the normal or strike-slip regime may suit a double well system better since the control of water migration is easier with vertical fractures and vertical wells. However, directional drilling enables regime controlled well configurations (i.e. within a strike-slip faulting regime, a well could be directionally drilled to enable a single well EGS). Despite the versatile nature of EGS, experimental and numerical research still needs to be conducted to better understand the mechanics of hydraulic fracturing in the specific rock types found in the aforementioned California counties. Further, models should incorporate transitional stress regimes for better predicting the path of hydraulic fractures.

Deep coaxial BHE is a feasible low cost, low-risk alternative to EGS. Results of a mathematical model conclude that target outlet temperatures >40 ˚C are easily achievable for counties with high temperature gradients (7 ˚C /100 m). A 180 mm diameter coaxial BHE yields >40 ˚C production temperatures for well depths >1250 m and flow rates between 1.0 to 4.4 l/s (it should be noted that 40 ˚C can also be achieved with 10.0 l/s and a 4000 m deep well). The results of the deep BHE simulation also indicate that flow rate negatively impacts the COP while well depth improves the COP for moderate to high flow rates. Findings show that despite high production temperatures at low flow rates, the COP is larger for moderate flow rates (4.4 l/s) and great depths (5000 m). Flow rates between 0.8 and 6.0 l/s are currently used in deep BHEs for district heating in various buildings throughout Europe.

The study found that deep BHE is suitable for counties with high and low heat flows. Santa Barbara is characterized by high temperature gradients and high numbers of deep abandoned wells. These depths and temperatures could support a variety of industrial low-temperature applications such as greenhouses, water desalination, and general space heating. In counties characterized by lower temperature gradients (<4.5 ˚C /100 m), 40 ˚C water temperatures can only be achieved with well depths of 3000 to 5000 m. Fortunately, the counties characterized by lower temperature gradients (Kern, Fresno, Los Angeles, Ventura) also host substantial numbers of abandoned wells deeper than 3000 m, making them suitable for deep coaxial BHE investigations. It is worth noting that lower production temperatures (<40 ˚C) associated with shallower wells (<1000 m) and lower temperature gradients (<4.5 ˚C /100 m) can also be coupled with a heat pump to deliver viable fluid temperatures for general space heating. Although the addition of a heat pump would reduce efficiency, a solar power coupling could offset the energy costs and pair well with unique direct geothermal uses such as greenhouse-water desalination (Goosen et al. 2010) or a reverse osmosis desalination configuration (Houcine et al. 1999; Kamal 1997). Furthermore, less desirable geological conditions might produce exceptional heat production if the thermal loading is cyclic instead of steady. For example, Kohl et al. 2002 observed 40 ˚C production temperatures from a 2133 m deep 3.0 ˚C/100 m BHE in Weggis, Switzerland.

In conclusion, abandoned oil/gas wells in California may provide a starting point for well deepening, but in other cases the abandoned wells may only require unplugging and re-casing to isolate sandstone formations of interest (EGS) or increase casing contact with surrounding rock (deep coaxial BHE). In all cases, a mitigation of drilling costs corresponds to a reduced EGS project cost of 42%-95% (Tester et al., 1994).

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