What Are the Challenges in Developing Enhanced Geothermal Systems (EGS)? Observations from 64 EGS Sites

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ABSTRACT

Since the 1970s, numerous projects have experimented with methods to enhance permeability at both existing and new geothermal sites. While the accomplishments and findings of these Enhanced Geothermal Systems (EGS) are at the center of publications on these sites, there is less discourse on what has gone wrong. Understanding the obstacles facing EGS projects can help EGS developers avoid potential mistakes in the future and focus research efforts on the most prevalent development issues. This paper compiles and describes challenges experienced in EGS projects, based on observations from 64 EGS sites. We found that six sites ceased operations temporarily or shut down due to seismicity or seismicity concerns. Drilling and plant operation issues, such as holes and cracks in wellbore casing, stuck drill strings, and well collapses, have increased costs, delayed or terminated at least 24 EGS projects. At least 18 sites faced challenges in reservoir creation and circulation, such as insufficient connectivity between the injection and production wells or water loss. Inability to raise financing either initially or in later project phases has been a major block for many EGS projects. While EGS sites often encounter difficulties, this review shows that at least 29 of the projects, including in-field and green field, continue to operate and generate electricity at an increased rate due to stimulation operations.

1. INTRODUCTION

For the purposes of this paper, we define an EGS according to Williams et al. (2011), as "the portion of a geothermal resource for which a measurable increase in production over its natural state is or can be attained through mechanical, thermal, and/or chemical stimulation of the reservoir rock" (Breede et al., 2013). We have collected information regarding 64 sites at different phases of execution, from planning to operating. A map of these sites is shown in Figure 1 and a complete list is tabulated in the appendix.

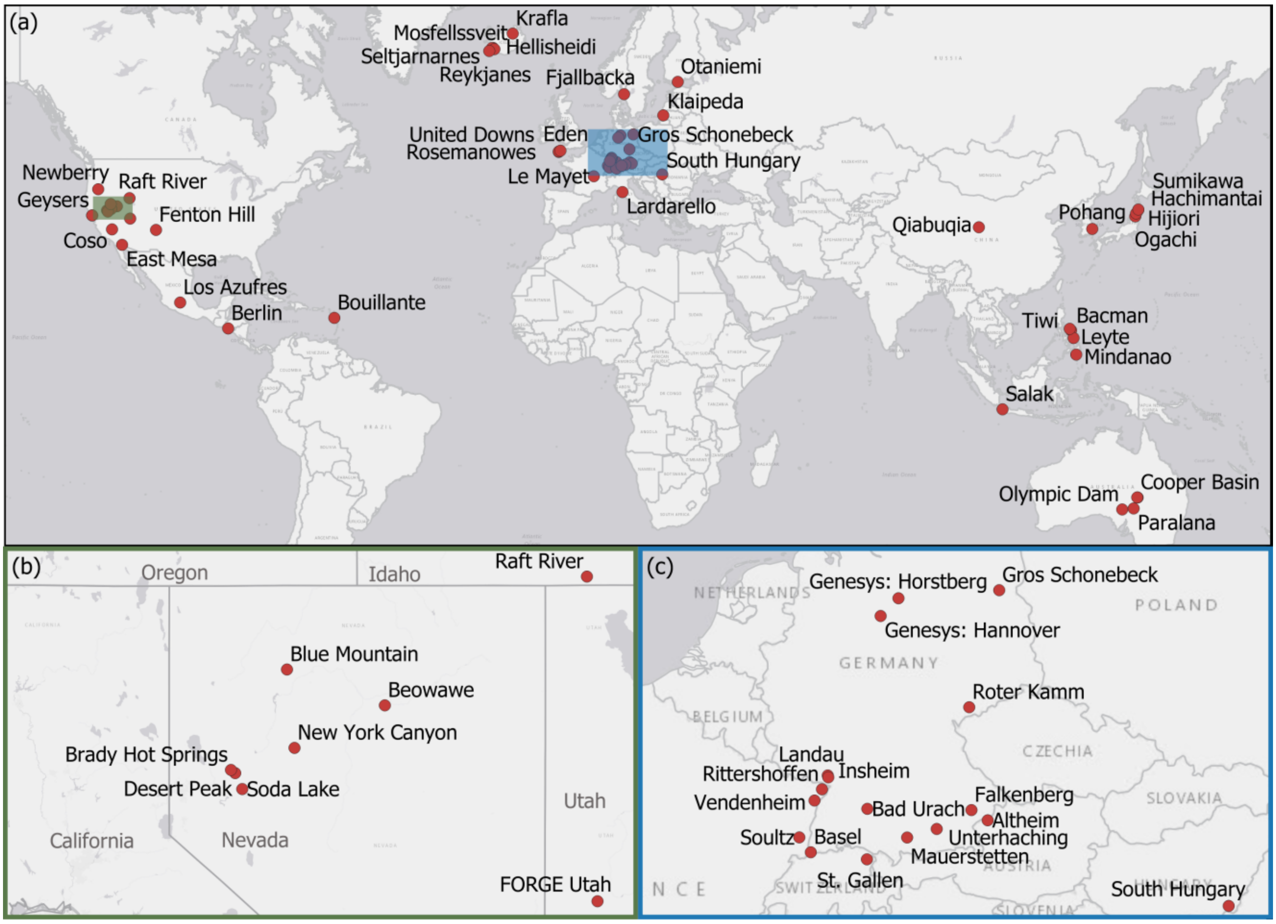


Figure 1: (a) Map of the 64 sites discussed in this paper. Two zones with high concentrations of EGS sites are highlighted with green and blue rectangles and zoom-ins around these areas are shown in subfigures b and c, respectfully.

This paper is a compilation of past and ongoing EGS projects based on previous compilations as well as individual papers. Reviewed previous global compilations include those by:

- Tester et al. (2006), who studied 17 sites,
- Sandrine (2007), who studied 17 chemical stimulation sites,
- Breede et al. (2013), who studied 31 sites,
- Sigfússon et al. (2015), who studied 32 sites, and
- Lu (2018), who studied 18 sites.

Excellent more localized reviews included in this compilation are the review by Entingh (2000) of the ten DOE Geothermal Reservoir Well Stimulation Program experiments, the review by Axelsson and Thórhallsson (2006) of well stimulation experiences in Iceland, and the review by Bendall et al. (2014) of three Australian EGS projects. Further insights regarding past EGS sites can be gained from the above-mentioned reviews.

This review adds to the literature by collecting information from a total of 64 sites in a single paper. Besides those reviewed in other compilations, information regarding 7 new sites, such as Qiabuqia in China and Vendenheim in France, is added. While some reviews mainly focus on "greenfield" sites using hydraulic stimulations methods, this review includes both greenfield and infield projects that used various types of stimulation methods. This review does not provide descriptions or of the EGS projects. Instead, this paper compiles and describes only the challenges experienced in EGS projects. Understanding the challenges can help those planning EGS projects better prepare for obstacles, and help innovators identify areas for technological improvement.

This paper is divided into five sections, each discussing a set of different challenges faced by EGS projects:

1. Induced seismicity,
2. Drilling and plant operations,
3. Reservoir creation and circulation,
4. Geophysics, characterization and geomechanical modeling, and
5. Regulations and finances.

2. INDUCED SEISMICITY AND PUBLIC CONCERN

At several sites across the world a causal link has been established between stimulation activities at EGS sites and increased seismicity (e.g., Baisch and Vörös 2010; Cladouhos et al. 2010; Evans et al. 2012; Majer et al. 2007). In sparsely populated areas, induced seismicity can have no impact on an EGS project as there are no nearby structures to be damaged or populations to feel the earthquake vibrations. In fact, microseismic events are beneficial for reservoir development and can help identify where reservoir stimulation has occurred (see Section 5.2), thus helping in targeting production wells (e.g., Cladouhos et al. 2013). At sites where the local population did feel induced seismicity, however, the seismicity has often posed a challenge for the EGS project. This section reviews two sites where seismicity caused damage and were shut down, three sites where induced seismicity did not cause damage but nevertheless necessitated resources for addressing public concern and seismic risk, and one site where fear of possible induced seismicity impacted the project before stimulation operations even began.

Earthquakes have caused damage to buildings at the Pohang site in South Korea and Basel site in Switzerland. Most recently, in November, 2017, a 5.4 M_w (moment-magnitude) earthquake occurred at Pohang (Lee, Ellsworth, et al., 2019; Lee, Yeo, et al., 2019; Zingg et al., 2019). Kim et al. (2018) calculated the epicenter of the earthquake as adjacent to one of the site's stimulated wells. The earthquake caused structural damage of US$52M (Kim et al., 2018) and is the only event we have seen that also caused harm to people, injuring 90 people (Kim et al., 2018). Prior to the Pohang earthquake, the most notable earthquake induced by EGS operations was a 3.4 M_L (local-magnitude) event in the Basel EGS site in December, 2006 (Kraft et al., 2009; Mukuhira et al., 2013). The site was in an industrial zone in Basel and the earthquake was felt by the local population. The earthquake led to mainly non-structural damage in buildings, such as plaster cracks on walls, and a total of US$7 M in claims paid by the operator's insurance company (Kraft et al., 2009). The events even led to criminal prosecution of the operator director, though he was soon after acquitted as it was found that he did not act carelessly or deliberately damage buildings (Associated Press, 2009).

Induced seismicity was clearly the dominant reason for the closures of the above EGS sites. Three other EGS sites were also impacted by more minor induced seismicity. In St. Gallen, Switzerland, an injection test followed by an acid treatment was performed after drilling the first well. At that point, an over-pressured natural gas zone that was intersected in the subsurface caused an unwanted increase of well pressure (a "gas kick") and a well control situation (Moeck et al., 2015). A day later a 3.5 M_L earthquake occurred (Breede et al., 2013; Moeck et al., 2015). Remarkably, the project continued with a production test following this event, and retained solidarity from the public according to Moeck et al. (2015), possibly due to initial public engagement prior to the project. The project eventually ended mainly due to low flow rates, high volumes of natural gas, and low temperature measured in the production test (Moeck et al., 2015). Yet, the risk of induced seismicity that might occur during further necessary stimulation of the underproductive well was still a secondary reason for the site closing (Moeck et al., 2015).

Induced earthquakes occur during both circulation and stimulation. During circulation at the Landau project in Germany (Groos et al., 2013), two induced earthquakes with magnitudes of 2.7 M_L and 2.4 M_L that occurred in 2009 were felt by the local population and led to the suspension of the project (Vasterling et al., 2017). In response, the plant was only allowed to restart after purchasing €50 million of annual liability insurance (Breede et al., 2013; DiPippo, 2012) and the production rate of the plant was decreased to 55 liters/s (Vasterling et al., 2017). While the Landau earthquakes occurred during circulation, two induced earthquakes with local magnitudes of 2.2 and 2.4 occurred during reservoir stimulation in 2010 at the Insheim project in Germany (Groos et al., 2013). Seismicity was addressed by drilling a leg to the injection well and spreading the fluid flow between these two well bores (Breede et al., 2013). However, this did not completely solve the seismicity problem, and an additional 2.0 magnitude earthquake was felt following this solution implementation (Breede et al., 2013). At Soultz in France, earthquakes with magnitudes of 2.4 M_w and later

2.9 M_w occurred in 2002 and 2003, respectively, in proximity to reservoir stimulation operations (Majer et al., 2007). The felt earthquakes led to concerns from the local community around the site, followed by public meetings and an investigation, even though no damage was caused. According to Majer et al. (2007), the public concerns led to some curtailment of stimulation activities at the site.

At the Engineered Geothermal System Demonstration Project at the Northern California Power Agency (NCPA Geysers EGS), induced seismicity was an issue even before stimulation processes started (Breede et al., 2013). A New York Times article from 2009 (Glanz, 2009) criticized the project for planning to fracture rocks even though such stimulations led to earthquakes three years prior in Basel. According to the project operator (Cladouhos et al. 2010; AltaRock Energy 2013), the negative public opinion against the project delayed the project and impacted its success.

3. DRILLING AND PLANT OPERATIONS

In this paper, 24 sites out of 64 EGS sites (37%) have suffered from drilling, well completion, and well integrity obstacles. Though many of these issues are not theoretical showstoppers for EGS deployment, the prevalence of operational issues has led to substantial increases in the cost of EGS projects. Sections 3.1 through 3.9 identify operational problems that occur during the drilling, completion and initial injectivity assessment phase, such as breaking equipment, lack of water, and bad weather. Sections 3.10 and 3.11 discuss operational issues during circulation and plant operation.

3.1 Well integrity

This section documents six sites with well integrity problems. A successful stimulation was performed at the well Rossi 21-19 in 1983 at the Beowawe Nevada site, increasing the injectivity 2.3 fold (Entingh, 2000). Yet, the project's success could not be measured with a production test. After the packer placed in the wellbore for stimulation was removed and surface equipment prepared, the well was kicked off using nitrogen lift. Once the nitrogen was shut off, the well stopped flowing (“died”). Using a temperature log, it was found that cold inflow from an upper section of the wellbore was quenching the well and preventing it from flowing on its own. This upper section was previously perforated and found impermeable, and it was thought it would not cause problems (Morris et al. 1984). A similar problem occurred at the Newberry, Oregon site in the United States in 2012, where much of the stimulation fluid was escaping at two shallow leaks in the casing near the casing shoe, leading to an unsuccessful initial stimulation stage (Cladouhos et al., 2015). Leaking also occurred at Reykjanes, Iceland in 2017, when flow testing following the thermal stimulation was delayed by over a year due to leaking from damaged casing (Friðleifsson et al., 2019).

EGS projects often do not have the funding to drill new wells and therefore often resort to using preexisting "wells of opportunity." At Raft River, Idaho, an existent well, RRG-9, was chosen to perform stimulation experiments in order to save the cost of drilling a new well. The original plan was to deepen the well. Yet, the project failed in doing so due to the well condition, and instead needed to drill a sidetrack (Bradford et al., 2013). The well was eventually successfully recompleted, but at higher cost than originally planned.

Well integrity issues may also develop during the stimulation phase. During a stimulation in Sumikawa, Japan, in 1989, several wells were thermally stimulated by injection of cold water into the reservoir. Following the stimulation, two out of the three stimulated production wells showed improved productivity. One well, SA-2, decreased in productivity. It was suspected that this may be due to a casing break caused by the heating and cooling cycles (Kitao et al., 1990). At Desert Peak in the United States, a chemical stimulation experiment showed little improvement in injectivity. Upon investigating the matter, it was found that the bottom 208 ft of the wellbore, including an outflow zone, had caved in and filled the well with debris (Chabora et al., 2012). Chabora and Zemach (Chabora & Zemach, 2013) assessed that the chemical stimulation may have caused the wellbore instability. During a hydraulic well stimulation in Seltjarnarnes in Iceland, the well collapsed three times around the feed zones. It was determined that the collapse was due to material from around the feed zones entering the well (Tulinius et al., 1996). Each time the well collapsed, the project would be slightly delayed, as the injection needed to be stopped in order to run a log that would determine the blockage depth and then the blockage would need to be cleaned out (Tulinius et al., 1996).

3.2 Lost/stuck equipment downhole

Eight sites were delayed or terminated due to stuck equipment in the wellbore. As part of the Habanero project in Cooper Basin, Australia, the Habanero-1 well was drilled in 2003, followed by Habanero-2, which was completed in 2004. Pressure communication was observed between the two wells, and artesian flow of up to 25 kg/s was measured in Habanero-2. Circulation testing was planned between the two wells, but lost equipment downhole gradually prevented flow in Habanero-2, stalling the project (Tester et al., 2006).

Savina-1 was another one of the wells that were part of the Cooper Basin project. Drilling of the well began in 2009 and continued until a depth of 3700 m when an over-pressured fracture caused “differential sticking” of the drill string (Budd & Gerner, 2015), meaning the drill string could not be moved from its location due to the pressure differentials, and later cuttings and filter cake which accumulated around the string. Even though the well had high potential in terms of temperature at that depth, it was necessary to plug the well at 2640 m (Budd & Gerner, 2015). At the NCPA Geysers EGS site, in 2009, a drill string also became differentially stuck when it encountered a fractured zone, necessitating the drilling of a side track. A mud rotor and directional drilling equipment were also in the well at the time and the equipment could not be recovered (“fished”) due to various other complications in the bottomhole setup (AltaRock Energy, 2013). Drilling pipes have also become stuck at the Soultz and Basel sites (Tester et al., 2006). At the Bad Urach project in Germany in 1992, a drill string ruptured while reaming the bottom of the Urach-3 well. While attempting to fish the drill string, the drilling line on the rig suddenly broke. This led to further complex fishing operations that were only partly successful (Tenzer et al. 1999). At Soda Lake, Nevada in the United States, delays from a fishing job as well as cold weather led to forgoing a well test prior to stimulation (Ohren et al., 2011).

An EGS project at Coso, California, partially funded by the U.S. Department of Energy, targeted stimulation of well 46A-19RD, the hottest well ever drilled at Coso with maximum measured temperature of 327°C, but which was impermeable. To perform the stimulation, however, it was necessary to remove the slotted liner from the well. The drilling crew tried to pull the liner for a month, but did not succeed, and thus the project was terminated (Rose, 2012).

3.3 Breaking equipment

Torn off drill rods in the borehole led, among other reasons, to the stop of the Bad Urach project (Breede et al., 2013). At the Rittershoffen project in France, during one of the production tests, the downhole pressure gauge stopped working, and therefore the downhole pressure buildup data could not be monitored and analyzed (Baujard et al., 2017). At Fenton Hill, a long term production test needed to be shut down due to the injection pumps failing (Tester et al., 2006). Malfunctions in the stimulation pumps interrupted a stimulation at Newberry (Petty et al., 2013) and Seltjarnarnes in Iceland (Tulinius et al., 1996) and led to delays.

3.3.1 Breaking equipment for zonal isolation

Specifically, there have been multiple instances of breaking equipment used for zonal isolation, most commonly packers. At Fenton Hill, only 6 out of 11 packer operations were successful, while the rest of the time the packers either ruptured, leaked, or dropped down hole (Hammel, 1982). Similarly, packer failures have led to unsuccessful mini-frac diagnosis tests at Bad Urach, Solutz and Coso (Davatzes & Hickman, 2006; Klee & Hegemann, 1995). Recently, in 2018, a five-stage stimulation was performed in Otaniemi, Finland. During the stimulation, it was suspected (Kwiatek et al., 2019) that the frac port controlling the second stage malfunctioned, such that the third stage was also stimulated during the second stimulation phase.

3.4 Equipment rated to correct pressure

At Jolokia, Australia, the well head was planned based on an estimated fracture gradient. During the stimulation in 2008, the stimulation pressure reached the 69 MPa limit of the wellhead unit (Hogarth et al., 2016). The stimulation was unsuccessful. According to Budd and Gerner (Budd & Gerner, 2015), it is possible that higher pressures may have been able to better enhance permeability and the equipment pressure limitation was the cause of the unsuccessful stimulation. Similarly, at Newberry, the pressures necessary to improve the well injectivity were higher than initially predicted (Cladouhos et al. 2015). It was necessary to limit the injection pressure due to the technical limits of the pumps, well head, and surface piping, impacting the success of the stimulation (Cladouhos et al. 2015). At Salak in Indonesia, the injection pressure during a thermal-hydraulic stimulation was also limited due to the operating limit of the wellhead unit (Yoshioka et al., 2019).

3.5 Equipment designed for deviated wellbores

At the Rittershoffen project in France, many logs were taken of the two geothermal wells to aid in subsurface characterization. Yet, according to Albert et al. (2015), most of the logging tools could not go through the open section of GRT-2 since it is significantly deviated.

3.6 Lack of water

The New York Canyon Stimulation project in the United States performed exploration and obtained permits for drilling. The area had an oversubscription of water rights and despite extended efforts, the lack of water that was needed for drilling and stimulation led to project termination in 2012 (Raemy, 2012). At the Bouillante project in the island of Guadeloupe, no fresh water was available so it was necessary to use sea water treated with scale inhibitor (Correïa et al., 2000).

3.7 Overpressure

Overpressure caused many issues in the Australian projects. During drilling in the Cooper Basin Habanero project, kicks (unwanted increases in well pressure) and mud losses occurred when the mud pressure was different from that in the over-pressured fault (Holl & Barton, 2015). Discovering that the fault zone was overpressured, the Habanero project needed to change to a 10,000 psi (69 MPa) blow-out preventer (Hogarth & Holl, 2017). In a different project in Australia, at Paralana, in 2009, the deviated section of the wellbore was unable to be cased due to over-pressure and consequent well breakouts, setting back the project (Reid et al. 2012).

3.8 Weather conditions causing delays

Weather conditions adversely impacted operations at Paralana, with rain and flooding occurring during different phases of the well construction and testing, increasing the cost of well construction, causing delays, and at times restricting access to the site (Budd & Gerner, 2015). Cold weather at Soda Lake led to forgoing a well test prior to stimulation (Ohren et al., 2011).

3.9 Performing two types of injectivity improvement operations without testing in-between

In the Soda Lake project, two consecutive actions that may have improved the permeability were performed: the upper section of Well 41B-33 that was once cased was perforated and then a deflagration was performed at that perforated zone. Because there was no flow test in-between these actions, it was unclear whether productivity improvement in the well was due to natural permeability of the newly perforated upper section or due to the deflagration (Ohren et al., 2011).

3.10 Fluid - casing chemical reactions

At Habanero, Australia, after a successful circulation test between the wells Habanero-1 and Habanero-3, in April 2009, there was a “sudden and violent” release of geothermal brine from Habanero-3, which continued to flow uncontrolled for 28 days (Geodynamics Limited, 2015). After a two-year investigation, it was concluded that the well failed due to stress corrosion cracking (Budd & Gerner, 2015). Specifically, “highly caustic fluids were remnant in the annulus between production and intermediate casings due to difficulties encountered while mixing slurry for cementation” in combination with high production temperatures caused the catastrophic well failure (Budd & Gerner, 2015).

At the Genesys site in Hannover, Germany, fresh water was used for stimulation. Six months after the stimulation, a production experiment was initiated at the site. As the water rose to the surface, it cooled down and halite (salt) precipitated and led to the clogging of the tubing, suspending the project (Breede et al., 2013; Hesshaus et al., 2013). Scale was also an issue in Hijiori, Japan. Following thermal breakthrough in Hijiori, production fluid temperature decreased, and calcium carbonate precipitated and deposited scale in pipelines (Yanagisawa, 2015).

At the Northwest Geysers, there were corrosion problems. The Northwest Geysers area has elevated chloride concentrations, which causes many corrosion related issues. The EGS demonstration project increased the depth and recompleted two abandoned wells as an injector-producer pair (Garcia et al., 2015). The injection well was stimulated via injection of cold water into the subsurface to cause thermal cracking. The results showed increased permeability and successful circulation between the two wells from December 2012 to February, 2013. Circulation was stopped due to near-surface corrosion of the well casing, which caused a steam leak. The producer well was shut in until a corrosion-resistant liner could be installed (Garcia et al., 2015).

At the NCPA Geysers project, serpentine rock interacted with drilling water, causing borehole collapses (Cladouhos et al., 2010; AltaRock Energy 2013). At the same project, the cement type was inappropriate and set too quickly, resulting in the drill string being cemented in the hole (AltaRock Energy, 2013). These examples show the importance of evaluating water-rock-pipe-surface equipment interactions given a full range of potential production temperatures and fluid chemistries.

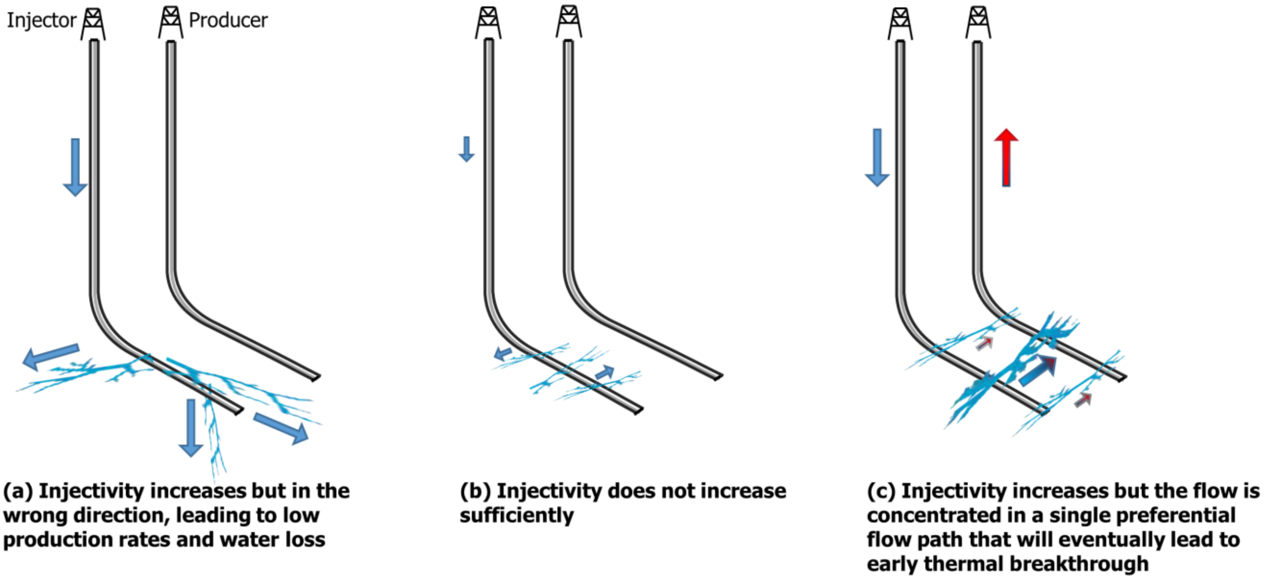
3.11 Radioactivity

Rocks contain naturally radioactive elements. High temperature geothermal fluids can lead to leaching of these elements into the geothermal fluid, which is then pumped to the surface facilities (Breede et al., 2013). Cuenot et al (2015) write that low levels of radioactivity have been found at Soultz. The relatively higher levels of radiation were found on the reinjection line, where the cold fluid led to the precipitation of sulfates and sulfides which trap radionuclides (Cuenot et al., 2015). To comply with the French National Agency for Nuclear Safety, Soultz operators had to set up radiation protection procedures, especially for personnel working on tasks that require contact with possibly radioactive material, such as cleaning filters and heat exchangers or dismantling pipes (Cuenot et al., 2015).

4. RESERVOIR CREATION AND CIRCULATION

The main goal of an EGS is to create a low-impedance connection between the injector and the producer that will allow for high flow rates, minimal thermal drawdown, and minimal water loss. The creation of an EGS reservoir that meets those targets is a delicate manner, which involves balancing competing concepts. For example, a strong connection between an injector and a producer can be ensured by placing the wells closer to each other. Yet, if the wells are too close, there is a high risk of faster thermal breakthrough. Injecting at high pressures can increase flow rates but may also increase water loss. A successful stimulation may decrease the reservoir impedance, but if the stimulation is not spread across multiple zones, preferential pathways may form, which will then lead to faster thermal breakthrough. Balancing these tasks has proven challenging at many EGS sites.

The first five sections below highlight three main challenges in reservoir creation and circulation that are illustrated in Figure 2. Section 4.1 describes sites where there was minimal connectivity between the injection and production wells, a scenario illustrated in Figure 2(a). Section 4.2 describes a common byproduct of having no connectivity between wells, which is that injected water is lost to different zones around the reservoir. Sections 4.3 and 4.4 list sites where there was insufficient injectivity improvement (Figure 2(b)). Section 4.5 discusses sites that experienced thermal short circuiting, a phenomena visualized in Figure 2(c).



(a) Injectivity increases but in the wrong direction, leading to low production rates and water loss

(b) Injectivity does not increase sufficiently

(c) Injectivity increases but the flow is concentrated in a single preferential flow path that will eventually lead to early thermal breakthrough

Figure 2. Illustration of three common challenges when creating an EGS reservoir.

4.1 No connectivity between the injection and production zone

At the Horstberg site in Germany, a single well concept was tested, where an inclined well was stimulated at its bottom. Vertical fractures forming as a result of the stimulation were expected to connect to a more porous zone above the bottom of the well. Even though the stimulation did create an extended fracture, there was still insufficient communication established between the injection and production zones (Tester et al., 2006).

This issue of connectivity was notably present in the initial stages of EGS projects at Fenton Hill, Rosemanowes, and Hijiori where production wells were drilled prior to stimulating the injection well and analyzing the location of the stimulated zones (Tester et al., 2006). These projects then needed to perform additional costly drilling to target the zones that were actually stimulated.

4.2 Water loss

Water loss occurs when fluid injected into the EGS is not recovered at the production well, instead escaping from the injection well into different directions away from the production well (Figure 2(a)). At least five sites have experienced water loss, including Ogachi, Hijori, Fjällbacka, Falkenberg, and Rosemanowes. Water loss at the Ogachi site was a dominant reason for termination of the project. An injection well was stimulated at the site and then a production well was drilled into the stimulated zone area, at a distance of 80m at depth from the injection well (Kaieda et al., 2005). Even though the wells were close, during the first circulation test, water recovery was only 3%, meaning 97% of the water was lost to the outside reservoir. After multiple stimulations and circulation tests, the maximum achievable water recovery rate was 32% (Kaieda et al., 2005). Similarly, at Fjällbacka, Sweden, the distance between the injection and production wells was 100 m and the fluid recovery rate was only 50% (Wallroth et al., 1999). At Hijiori, various circulation test configurations led to water recovery rates between 45% and 70% (McLing, 2017; Tester et al., 2006). During one of the circulation tests at Rosemanowes, loss of circulating fluid was estimated to be 70% (Parker, 1999). At Falkenberg, the water loss was considerable, reaching 60% to 100% (Dalgleish et al., 2007). These water loss percentages can be compared to a water loss rate of 7%-11.7% at Fenton Hill (D.W. Brown, 1994), which has set the standard for reasonable water loss rates.

4.3 Insufficient injectivity improvement for commercial operation

Sometimes stimulations can lead to substantial increase in injectivity. However, wells with initial low injectivities may not reach commercial levels even after several factors of injectivity improvement. At the Bradys Hot Springs EGS project, well 15-12 ST1 had an initial injectivity of 0.047 gpm/psi. After wellbore stimulation, a long-term injection test was conducted, and the injectivity was measured as 1.4 gpm/psi. Even though this is a significant 30-fold increase in injectivity, it did not meet the goal of an injectivity of 10 gpm/psi for a commercial well at the Bradys field (Drakos & Akerley, 2017).

4.4 Negligible increase in injectivity for unclear reasons

At Jolokia, despite an extended stimulation at high pressure, the flow rate only reached a maximum of 7 l/s at 69 MPa well head pressure, an injectivity of approximately 0.011 gpm/psi (Hogarth et al., 2016). Such situations have also occurred during chemical stimulations. Even though chemical stimulations have been shown to be successful in many geothermal fields throughout the world, acidizing treatments led to no increase in productivity at the Geysers, Baca, and Fenton Hill geothermal fields (Sandrine et al., 2007).

4.5 Thermal short circuiting

Thermal short circuiting occurs when a preferential high permeability path forms between the injector and producer, as illustrated in Figure 2(c). Injected fluid flows mainly through this path, cooling down the rock around the path, and eventually leading to production of cold temperature fluid. In addition, short circuiting decreases residence time and area for heat transfer. This is what most likely occurred in at least four EGS projects. During the first phase of the Fenton Hill project, a circulation test was conducted between wells EE-1 and GT-2 for 75 days. The production temperature decreased from 175°C at the beginning of the test to 85°C at its end, possibly because the reservoir may have consisted of a single 300 ft (100 m) vertical joint and therefore did not access sufficient hot surface area (Brown et al., 2012). At Rosemanowes in England, during a period of a long term flow test, temperatures decreased from 80.5°C to 70.5°C, which has been attributed to a formation of a short circuit (Tester et al., 2006). Similarly, during a long term flow test in the Hijiori project in Japan, the production temperature cooled from an initial 163°C to about 100°C (Tester et al., 2006). At Bacman in the Philippines, ten wells were chemically stimulated with acid. After the stimulation of injector well PN-2RD, its injectivity increased by 367% and the operator was able to inject 187 kg/s of water into it. The connectivity, however, to nearby production wells was too direct and eventually led to a reduction in production temperatures. Therefore, the injection rate was reduced down to 70 kg/s (Buning et al., 1995).

4.6 Reservoir consisting of a single large fault structure instead of multiple zones

Having a single fault structure instead of multiple zones is linked to the possibility of thermal short circuiting. When most of the flow goes through a single structure, the surface area available for heat exchange is limited, which may lead to thermal short circuiting if flow rates are too high. At Soultz, a single zone in well GPK-3 controls 70% of the flowrate in the well (Albert et al., 2015). Similarly, the Habanero reservoir in Australia was deemed to be a single pre-existing fault, where most of the injected fluid during circulation would flow between the wells along the fault (Geodynamics Limited, 2015). This went against a previous hypothesis at the site that fractures would be stimulated at multiple depths in the granite rock. This finding resulted in significantly lower estimated values of potentially recoverable thermal energy (Geodynamics Limited, 2015).

4.7 Interplay of water loss and pressure-dependent permeability

Several sites, most notably Rosemanowes and Fenton Hill, experienced pressure-dependent permeability. At both of these sites, Tester et al (2006) observed that under high injection pressures during circulation, fractures in the subsurface would open and the injectivity of the reservoir would increase. At Rosemanowes, the high pressures led to continued fracture growth and higher water loss. As soon as pressures were lowered, though, the fractures would close and the flow rate would decrease substantially (Tester et al., 2006). The pressure dependence of the permeability meant that energy consuming injection pumps needed to be run continuously, significantly lowering the energy efficiency potential of the site (Tester et al., 2006).

4.8 Sustainability of stimulated permeability

Related to the issue of the pressure dependence of permeability is the question of whether stimulated fractures retain their permeability once high-pressure injection is completed. Following a set of hydraulic stimulations in 2002 at Bad Urach, flow tests showed an increase of transmissivity by a factor of 2.9 (Stober, 2011). During a pumping test in 2003, however, the transmissivity returned close to its original levels, indicating that the permeability improvement was not permanent (Stober, 2011). On the other hand, in other areas, the opposite effect has occurred: where continual circulation increased the permeability over time. For example, at Hijiori, during a year-long circulation test, the pressure required for fluid injection dropped from 84 to 70 bar, indicating increased injectivity (Tester et al., 2006). A similar phenomena of circulation increasing reservoir size has also been noted at Soultz (Doughty et al., 2018; Tester et al., 2006).

4.9 Stimulation with proppant and gel

Proppant has been used at nine EGS sites at least, including: East Mesa, Raft River, Baca, Le Mayet, Fenton Hill, Groß Schönebeck, Hachimantai, Bad Urach, and Rosemanowes, mostly leading to positive results (Entingh, 2000; Niitsuma, 1989; Stober, 2011; Tester et al., 2006). At Rosemanowes, lowering the production pressures increased the system impedance, as joint apertures were assessed to be closing at lower pressures (see Section 4.7). To keep the joints open, proppant was injected into the formation using a high viscosity gel. The proppant worked better than planned, significantly reducing the impedance as well as water loss. The proppant, however, exacerbated the thermal short circuiting (Tester et al., 2006). At Raft River, following well stimulation with proppant, during a flowback period, the well produced substantial quantities of proppant. It was necessary to wait ten days for the flow of proppant to diminish and be able to continue downhole operations (Verity, 1980). At Le Mayet, sand and gel were injected during a stimulation test, but after 300 kg of sand were injected, the sand plugged up the wellbore and later needed to be cleaned out (Cornet, 1987).

4.10 Temperature loss to rock surrounding the wellbore

During a 55 days flow test at Fenton Hill, the surface temperatures dropped. The hypothesis was that the low flow rates resulted in heat loss to zones around the wellbore (Tester et al., 2006).

4.11 Explosive stimulations risk creating near-wellbore damage

Los Alamos National Laboratory conducted an explosive stimulation in a well in the Geysers, California in the United States in 1981, detonating 5000 kg of explosives at 1697 m depth in a well owned by Unocal. Instead of increasing permeability, the explosives led to a 35% reduction in steam flow rate, attributed by researchers to blockage of steam entry zones by rubble (Entingh, 2000).

5. GEOPHYSICS, CHARACTERIZATION AND GEOMECHANICAL MODELING

Many troubles in the process of creating a reservoir may be due to an incorrect understanding of the subsurface, including both the characterization of subsurface properties as well as prediction of subsurface response to stimulation activities. Subsurface characterization has been challenging due to issues in both collecting as well as analyzing geophysical and well data, as discussed in sections 5.1 through 5.4. Issues with theoretical understanding of fracture propagation in response to stimulation in the presence of pre-existing natural faults, has led to non-ideal planning of EGS stimulation, as discussed in section 5.5.

5.1 Issues with borehole data acquisition and interpretation

At Habanero, Australia, the quality of image logs were poor due the presence of barite mud in the wellbore which decreases the imaging capability of the acoustic borehole imaging tool (Bendall et al., 2014). An acoustic borehole imaging tool was also used to detect fractures at Jolokia, Australia. A "mud excluder" was used during the logging operation to address the issue of the image quality, but the solution did not work and the image quality remained poor (Hogarth et al., 2016). Also at Jolokia, it was found that the data quality from a cross-dipole full waveform sonic log degraded with depth. Hogarth et al. (2016) associated this phenomena with the "gradual thermal degradation of the wireline cable." At Groß Schönebeck in Germany, there have been issues with data transfer to surface from some of the well tools (Breede et al., 2013).

There have also been challenges in well log interpretation. Image logs record fractures along the wellbore, yet it was observed at the Habanero site that many of the fractures identified in the image logs, even if they have high slip likelihood, were not hydraulically conductive (Bendall et al., 2014; Hogarth & Holl, 2017). A similar observation was made at Soultz, where the well intersected thousands of natural fractures, but only few of them showed evidence of permeability during drilling from mud loss measurements (Jean, 2015).

A number of EGS projects (e.g., Newberry, Raft River) have deployed fiber optic cable in boreholes to continuously monitor temperature changes throughout the stimulation process using distributed temperature sensing (DTS). Such monitoring can provide insights into where injected fluids are entering the formation, thus pinpointing zones where stimulation has occurred. However, if the fiber breaks or if it degrades over time due to the elevated temperature conditions, this information can be lost (Cladouhos et al., 2016).

One of the most important attributes of an EGS reservoir is its temperature. It is important to estimate the subsurface temperature while drilling in order to be able to determine when the temperature is sufficient for stopping to drill. It may be difficult, however, to determine the true bottom-hole temperature during drilling. Mud circulation during drilling decreases the temperature inside the wellbore, and it may take several days or longer for the wellbore to return to the subsurface in-situ temperature conditions. At the FORGE project in the United States, an initial observation well was drilled and different types of temperature data were collected during intermissions in drilling. Allis et al. (2018) report that the task of estimating the natural (undisturbed) bottom hole temperature while drilling was challenging.

5.2 Microseismic monitoring

The success and location of a stimulation is often assessed via monitoring the acoustic emissions from microearthquakes. The microseismicity, however, may be an inaccurate proxy for enhanced permeability. At the Paralana, Australia, EGS site, it was found that the cloud of seismicity extended further than the area that had its permeability enhanced (Riffault et al., 2018). In addition, in scenarios where a well had been previously stimulated, the microseismicity may also not be accurate. During the restimulation of Habanero-1 in Australia, the immediate vicinity of the injection well showed no microseismic events, possibly due to the Kaiser effect, where seismicity only begins near the outer rim of the zones of past seismic activity (Baisch et al., 2009). At Soultz, well GPK4 was drilled into a subsurface zone where many microseismic events were detected, indicating that the zone was stimulation. Even so, the well did not show good connectivity to other wells even after stimulation (Tester et al., 2006).

Microseismicity can be impacted by noise. At Desert Peak, several of the monitoring geophones were initially placed on the surface, but surface noise was observed in the measurements (Chabora et al., 2012), leading to a recommendation by Chabora et al. (Chabora et al., 2012) to place the geophones in boreholes. In addition, at Desert Peak, Chabora et al. (Chabora et al., 2012) recommended to improve microseismicity analysis algorithms to better filter false triggers and better identify small events that are less than 0 moment magnitude.

5.3 Injectivity tests may not reflect final productivity in high temperature wells

The success of a stimulation is often measured via an injectivity test at the end of stimulation. Injectivity improvement, however, may not have a one-to-one relationship with productivity improvement. At Reykjanes, it was observed that high injectivity wells have a productivity that is higher than the measured injectivity following stimulation, while wells with the lowest injectivity have even lower productivity during the production tests (Axelsson & Thórhallsson, 2009).

5.4 Incorrect subsurface models

In predicting reservoir response to stimulation, both a numerical model (discussed in section 5.5) and the subsurface parameters (discussed here) are necessary. Incorrect assessments of subsurface parameters have affected many sites. At Fenton Hill, an unexpected change in the stress field led to the stimulated zone not connecting the injector and producer (Tester et al., 2006). Similarly, at Rosemanowes, shallow stress measurements at 300m test wells did not correspond to stress measurements at the reservoir creation depth (Tester et al., 2006). The unexpected presence of natural faults at Rosemanowes, and most probably other sites, led to water loss and propagation of the stimulated zone in unexpected directions (Tester et al., 2006). At both Jolokia and Newberry, as mentioned in section 3.4, incorrect characterization of the stress state and prediction of the pressure at which stimulation would occur led to equipment that was not rated for sufficiently high pressure (Budd & Gerner, 2015; T. T. Cladouhos et al., 2016).

5.5 Prediction of stimulation behavior

In an EGS context, the task of a numerical simulator is to predict the fracture development in response to different stimulation operations and subsurface characteristics. Throughout the history of EGS experiences, there have been sites where the predicted stimulated zone did not match the actual stimulated zone, which negatively impacted the success and predictability of the projects. This discrepancy is sometimes attributed to incorrect geomechanical modeling of fracture propagation in the presence of natural fractures. Tester et al. (2006) suggest that incorrect prediction of the direction of reservoir growth at Rosemanowes was due, amongst other reasons, to incorrect prediction of the dominant mode of fracturing (tensile vs. shear vs. mixed) in geothermal reservoirs with pre-existing natural fractures. The topic of different modes of hydraulic stimulation is discussed in McClure and Horne (2014) regarding several EGS sites and by Norbeck et al. (2018) regarding Fenton Hill.

Often, only a single simulation of the reservoir response to stimulation is performed, and this may lead to false confidence in future stimulation results. At Klaipėda, Lithuania, it was predicted that a project to enhance permeability in a wellbore via radial jet drilling would lead to a 57% increase in injection rate compared to the unstimulated well. The stimulation resulted in an increase of 14%. It was found in later analysis that model predictions were highly sensitive to several parameters, such as the lateral inclination of the jet, where each sensitive parameter could change the injectivity by over 10% if it varied slightly (Nair et al., 2017).

5.6 Drilling long wellbore sections without a substantial increase in temperature

Enhanced geothermal systems are both a technical and economic venture. The technical decisions need to be cost effective. At Soultz, wells were drilled to five km depth. The initial temperature gradient for the first 1000 m is 110°C/km, then the 1000-3500 m section has a thermal gradient of 5°C/km, and the bottom of the well has a gradient of 30°C/km (Albert et al., 2015). Therefore, it was necessary to drill approximately 3300 m (from 1700 m to 5000 m) for an increase in temperature from 140°C to 200°C. According to Genter et al. (2015), it may have been more economic to target a well at lower temperature and shallower depth, also because those zones had more initial natural permeability. Prior subsurface prediction, if possible, of the temperature gradient per depth may perhaps be able to alleviate this issue in the future.

6. REGULATIONS AND FINANCES

Regulatory and financial issues have stymied EGS projects. EGS projects are still high risk ventures and thus the financial challenges can be substantial. In addition, regulatory processes have delayed or terminated EGS projects. Sections 6.1 through 6.3 detail regulatory issues. Sections 6.4 through 6.6 detail financial issues.

6.1 Regulatory permission to exceed certain pressures

Regulatory agreements specified at Newberry that the stimulation pressures cannot exceed 210 bar (3000 psi) and this limited the stimulation success (Cladouhos et al., 2015).

6.2 Slow and complicated permitting process

As part of the DEEPEGS project, two geothermal demonstration sites were planned in France. Even though exploration licenses for those two sites were secured, many challenges in obtaining the drilling licenses for those sites led to the cancellation of the demonstrations at those locations. Bogason et al. (2019) attributed the licensing troubles to lack of staff experienced with geothermal projects at the regulatory body.

6.3 Standard geothermal permitting restrictions

Site selection for an EGS may be influenced, like any other geothermal development, not only be technical consideration, but also by ease or possibility of permitting. At the South Hungary EGS Demonstration, the site selection was influenced among other considerations by permitting restrictions on drilling near archeological sites, natural features, and water resources, as well as production rights in the different areas (Garrison et al., 2016).

6.4 Lack of financing and economic uncertainties

In the end, most abandoned projects also failed due to financial constraints. A notable situation where this has occurred is at the Paralana site. The site demonstrated a successful stimulation, and needed to raise an additional $5 million in equity to receive a $13 million grant awarded by the Australian Renewable Energy Agency (ARENA) as well as qualify for a $24.5 million Renewable Energy Development Program (REDP) grant, but did not succeed in raising the $5 million necessary (Francisco Rojas, 2014). This was also attributed to the Global Financial Crisis (GFC) which reduced the availability of risk capital (Budd & Gerner, 2015). Other finance-related issues were brought up by Budd and Gerner (2015) in relation to the faltering of Australian EGS projects: a decrease in power demand in Australia, increase in the cost of rigs due to the demand from other markets such as the US shale market, and uncertainties relating to governmental programs benefitting renewable energy, including a carbon tax.

6.5 High cost of drilling

The cost of drilling and stimulation can reach to over 50% of an EGS project (Yost et al. 2015). Tester et al. (2006) listed the cost of drilling as one of three major issues remaining at the end of the Fenton Hill project as a barrier to EGS commercialization. At Habanero, the well failure of H03 and the difficult drilling environment led the project operator Geodynamics to invest in designing a well that would eliminate well integrity issues (Geodynamics Limited, 2015). The drilling of H04 was successful, but came at a cost of AUD50.5M (USD34.4M) (Budd & Gerner, 2015). According to Geodynamics (Geodynamics Limited, 2015), however, lessons learned from the drilling would reduce the expected cost of a future well to approximately AUD16.5M (USD11.25M).

6.6 Need for transmission lines

Constructing an EGS in a remote area is beneficial for addressing concerns of induced seismicity, but could be problematic if there are no nearby transmission lines. Construction of transmission lines would greatly increase the project expense. Both the Paralana and Cooper Basin projects in Australia would have necessitated large transmission line construction (Ward, 2010).

DISCUSSION AND CONCLUSION

This paper has discussed the challenges faced by EGS projects worldwide, split into five subtopics: induced seismicity, drilling and plants operations, reservoir creation and circulation, geophysics and characterization, and regulations and finances. This review found 24 sites that have had drilling and plant operation issues, six sites that were affected by induced seismicity, and 18 sites that were challenged by reservoir creation. These counts are shown in Figure 3. The count only covers instances of challenges found in the process of writing this paper, and thus represents a minimum count. Despite all these potential roadblocks, this review also found that many of the stimulation experiments were successful, and 29 sites are still active and improved today due to EGS technology, see the Appendix. Future interesting work could discuss individual items brought up in this review in a more comprehensive manner. As examples: what sites attempted multi-zone isolation and what were the results? What operational problems are still an issue given current technological and procedural advances?

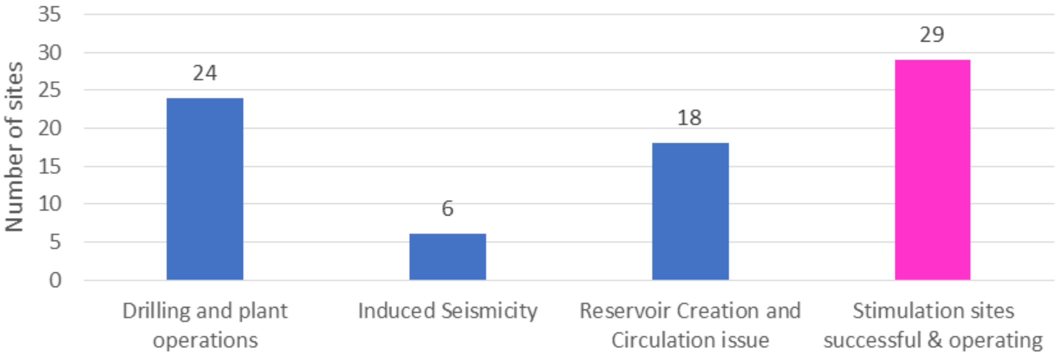


Figure 3: Bar chart of the number of sites that have faced challenges of different types in creating an EGS, as well as the number of sites that were successful and are operating.

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APPENDIX

Table with the name, location, starting year, and stimulation type of the EGS sites, as well as an indication of whether the project was successful and still operating. The stimulation type acronyms are as follows: H: Hydraulic, C: Chemical, T: Thermal, E: Explosive, Cyc: cyclic pressure loading and J: Jetting. References for the different sites are in the right column. Some additional sites of interest that are not listed in this table are prospective sites for the DESTRESS project, such as the Mezöbereny site in Hungary, see Huenges et al. (2018). In addition, some past prospective EGS projects from Australia, such as Hunter Valley, are also not listed, see Ward (2010).

	Name	Location	Year Start	Type	Stimulation successful and EGS part of the field still operating?	Reference
1	Mosfellssveit	Iceland	1970	TH	Yes	(Tomasson & Thorsteinsson, 1978)
2	Fenton Hill	New Mexico, USA	1973	HC	No	(Donald W. Brown et al., 2012)
3	Bad Urach	Germany	1977	H	No	(Stober, 2011)
4	Falkenberg	Germany	1977	H	No – shallow research facility	(Dalgleish et al., 2007)
5	Rosemanowes	UK	1977	HE	No – below 100°C research facility	(Batchelor, 1987; Tester et al., 2006)
6	Le Mayet	France	1978	H	No – shallow research facility	(Cornet, 1987; Cornet & Morin, 1997)
7	East Mesa	California, USA	1980	H	Stimulation was commercially successful. Unclear if specific stimulated wells are in operation today.	(Entingh, 2000)
8	Krafla	Iceland	1980	T	Yes	(Axelsson & Thórhallsson, 2009)
9	Baca	New Mexico, USA	1981	H	No	(Entingh, 2000)
10	Geysers Unocal	California, USA	1981	E	No	(Entingh, 2000)
11	Beowawe	Nevada, USA	1983	H	Stimulation successful, but well had integrity issues. Unknown if fixed.	(Entingh, 2000)
12	Fjällbacka	Sweden	1984	HC	No – shallow research facility	(Wallroth et al., 1999)
13	Hijiori	Japan	1985	H	No	(Matsunaga et al., 2005)
14	Soultz	France	1986	HC	Yes	(Genter et al., 2010)
15	Altheim	Austria	1989	C	Yes	(Pernecker, 1999)
16	Hachimantai	Japan	1989	H	No – shallow research facility	(Niitsuma, 1989)
17	Ogachi	Japan	1989	H	No	(Ito, 2003)
18	Sumikawa	Japan	1989	T	Yes	(Kitao et al., 1990)
19	Bacman	Philippines	1993	C	Yes	(Buning et al., 1995)
20	Seltjarnarnes	Iceland	1994	H	Yes	(Tulinius et al., 1996)
21	Mindanao	Philippines	1995	C	Yes	(Buñing et al., 1997)
22	Bouillante	France	1996	T	Stimulation increased injectivity. Unknown if stimulated well was then connected to plant.	(Correïa et al., 2000; Sanjuan et al., 2010)
23	Leyte	Philippines	1996	C	Yes	(Malate et al., 1997)
24	Groß Schönebeck	Germany	2000	HC	Yes – three binary units totaling ~1MW installed. Not clear if still operating.	(Zimmermann et al., 2010)
25	Tiwi	Philippines	2000	C	Yes	(Ontoy et al., 2003)
26	Berlin	El Salvador	2001	C	Yes	(Barrios et al., 2002; Monterrosa, 2002)
27	Cooper Basin: Habanero	Australia	2002	H	No	(Geodynamics Limited, 2015)
28	Cooper Basin: Jolokia 1	Australia	2002	H	No	(Geodynamics Limited, 2015)
29	Coso	California, USA	2002	HC	Yes - 1993 chemical stimulations and hydraulic stimulation of 34A-9 No - 2005 34-9RD2 intended stimulation	(Evanoff et al., 1995; Rose, 2012; Rose et al., 2005)
30	Hellisheidi	Iceland	2003	T	Yes	(Bjornsson, 2004)
31	Genesys: Horstberg	Germany	2003	H	No	(Torsten Tischner et al., 2010)
32	Landau	Germany	2003	H	Yes	(Schindler et al., 2010)

33	Unterhaching	Germany	2004	C	Yes	(Sigfússon & Uihlein, 2015)
34	Salak	Indonesia	2004	CTHCyc	Perhaps – 2004 chemical stimulation increased injectivity. Unknown if stimulated well was then connected to plant. Yes – 2008 thermal, hydraulic and cyclic pressure loading stimulation. Yes – 2012 hydraulic.	(Pasikki & Gilmore, 2006; Yoshioka et al., 2015, 2019)
35	Olympic Dam	Australia	2005	H	No	(Bendall et al., 2014; Meyer et al., 2010)
36	Paralana	Australia	2005	HC	No	(Albaric et al., 2014; Peter Reid, Mathieu Messeiller, 2012)
37	Los Azufres	Mexico	2005	C	Yes	(Armenta et al., 2006)
38	Basel	Switzerland	2006	H	No	(Häring et al., 2008)
39	Lardarello	Italy	2006	HC	No – 1983 hydraulic Yes – 2006 chemical	(Cataldi & Calamai, 1983; Sandrine et al., 2007)
40	Insheim	Germany	2007	H	Yes	(Küperkoch et al., 2018)
41	Desert Peak	Nevada, USA	2008	HC	Stimulation was successful, but do not know if well was put in regular operation.	(Chabora et al., 2012)
42	Brady Hot Springs	Nevada, USA	2008	H	No	(Drakos & Akerley, 2017)
43	Southeast Geysers	California, USA	2008	H	No	(AltaRock Energy, 2013)
44	Genesys: Hannover	Germany	2009	H	No	(T. Tischner et al., 2013)
45	St. Gallen	Switzerland	2009	HC	No	(Moeck et al., 2015)
46	New York Canyon	Nevada, USA	2009	H	No	(Raemy, 2012)
47	Northwest Geysers	California, USA	2009	T	Stimulation successful, but well had integrity issues. Unknown if fixed.	(Garcia et al., 2015)
48	Newberry	Oregon, USA	2010	H	No	(T. T. Cladouhos et al., 2016)
49	Mauerstetten	Germany	2011	HC	No	(Mraz et al., 2018; Tamaskovics et al., n.d.)
50	Soda Lake	Nevada, USA	2011	E	Stimulation was successful, but not known if well was put in regular operation.	(Ohren et al., 2011)
51	Raft River	Idaho, USA	2012	HT	No – 1979 Yes – 2012	(Bradford et al., 2015; Campbell et al., 1981)
52	Blue Mountain	Nevada, USA	2012	H	Yes	(Petty, 2016)
53	Rittershoffen	France	2013	THC	Yes	(Baujard et al., 2017)
54	Klaipėda	Lithuania	2015	J	Slight improvement. Unclear if stimulated well is operational.	(Nair et al., 2017)
55	Otaniemi	Finland	2016	H	Successful stimulation of first well. Drilling of second well in progress.	(Ader et al., 2019; Kwiatek et al., 2019)
56	South Hungary EGS Demo	Hungary	2016	H	Status unclear. Project was awarded up to EUR 39.3M from the EU NER program.	(Garrison et al., 2016; NER300, 2018; Sigfússon & Uihlein, 2015)
57	Pohang	South Korea	2016	H	No	(Kim et al., 2018)
58	FORGE Utah	Utah, USA	2016	H	In progress	(Moore et al., 2019)
59	Reykjanes	Iceland	2017	T	Unclear – Pre 2006 In progress - 2017	(Axelsson & Thórhallsson, 2009; Friðleifsson et al., 2019)
60	Roter Kamm	Schneeberg, Germany	2018	H	In progress	(Hlousek et al., 2015; Wagner et al., 2015)
61	United Downs	Redruth, UK	2018	H	In progress	(Bridgland 2011; Ledingham et al. 2019)
62	Eden	St Austell, UK	2018	H	In progress	(Project, 2019; Sigfússon & Uihlein, 2015)
63	Qiabuqia	China	2018	TH	In progress	(Lei et al., 2019)
64	Vendenheim	France	2019	?	In progress – DeepEGS demo	(Bogason et al., 2019)

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