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A Systematic Review of Enhanced Geothermal System

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ABSTRACT

Enhanced geothermal systems (EGS) refer to methods of harvesting energy from Earth's crust by passing fluid through a zone of enhanced permeability in rock at depth. The enhancements come from 1) drilling to sufficient depths that high temperatures are reached; 2) creating enough permeability that fluid can be flushed at significant rates through the hot rock deep in the crust, the objective being to transfer the thermal energy to the fluid without excessive loss of fluid into the rock; and 3) extracting the energy from the fluid to produce useful effects, either in terms of electricity generation or heating operations. This paper reviews the Imaging and Characterization methods for EGS, EGS Creation and Production, Potential Technologies for EGS and Also more objective approach to the pros and cons of 'conventional' EGS systems.

1. INTRODUCTION

Geothermal energy is a clean renewable energy source with an average capacity factor of approximately 74.5%. With the application of the latest generation technology, the capacity factor of a geothermal plant at an ideal site can reach 90% [Edenhofer O et al. 2011] and thus has the characteristics of base load power. According to theoretical calculations, the energy reserves in the upper 10 km of the earth's crust are approximately 1.3 × 1027 J [J.w. Lund 2007]. Enhanced geothermal systems (EGS) refer to methods of reaping energy from Earth's crust by passing fluid through a zone of enhanced permeability in rock at depth. The enhancements come from: 1) drilling to sufficient depths that high temperatures are reached. 2) creating enough permeability that fluid can be flushed at significant rates through the hot rock deep in the crust, the objective being to transfer the thermal energy to the fluid without excessive loss of fluid into the rock. 3) extracting the energy from the fluid to produce useful effects, either in terms of electricity generation or heating operations. As seen in Fig. 1[P.Olasolo et al. 2015], an EGS plant comprises complex above- ground and underground facilities. The above-ground powerplant accounts for a significant proportion of the overall cost of a commercial EGS plant, and is an important factor in determining whether it is financially viable in the last analysis.

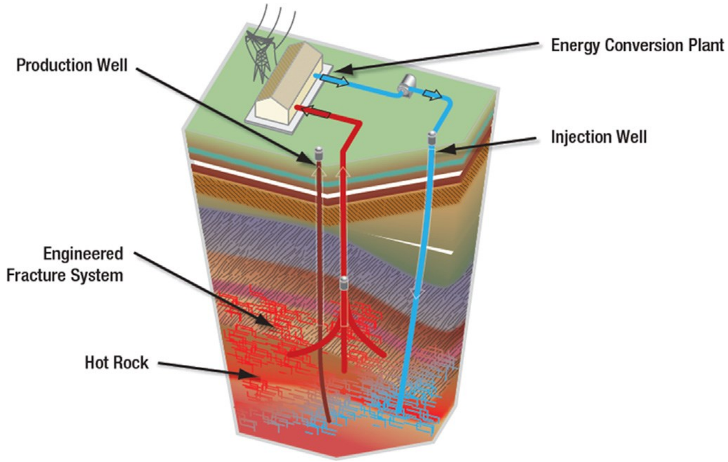

Figure 1: A Basic Layout of EGS type Geothermal Plant

The U.S., conventional geothermal power supplies 2.5 GWe at present, and the electric power generation potential from additional identified resources is estimated at about 9 GWe [Williams, et al.,2008]. Where available, conventional geothermal resources provide an attractive base-load power source that can be economically competitive without subsidies. EGS refers to a spectrum of perspective, with enhancement of conventional geothermal production at one extreme. Conventional geothermal extraction depends on naturally occurring waters bringing heat from Earth's interior to the surface. The necessary hydrothermal conditions are relatively rare, however, occurring predominantly in volcanic regions with abundant groundwater.

EGS activities can range from enhancing conventional geothermal systems, in which extra fluid is flushed through a hydrothermal system in addition to the naturally available groundwater and perhaps with stimulation to create additional permeability, all the way to hot dry-rock (HDR) in which there would be no natural geothermal potential without artificial pumping of fluids at depth [Augustine et. 2011] [R. Jeanloz ,H. Stone et al 2013]. This spectrum of activities greatly increases the amount of thermal energy that is accessible, with the potential generating capacity from all EGS approaches estimated by (Williams, et al.2008) to exceed 500 GWe for the U.S., which represents nearly half the current capacity from all domestic sources [AEO2013]. There is now precedent of encounter in various aspects of EGS, providing a path for identifying the technical issues that need to be addressed for EGS approaches to add value beyond present U.S. Conventional Geothermal Resources. The major technical issues are:

- The ability to design and execute stimulation methods that optimize permeability and water exposure to hot rock.
- The ability to identify well sites where the subsurface features will allow rates of water circulation across hot rock sufficient to produce economically valuable rates of water or steam production.
- The ability to design, drill and operate wells in increasingly difficult geological media for wells at the hot dry rock end of the spectrum of EGS.

DOE, through the Geothermal Technologies Office (GTO) within the Office of Energy Efficiency and Renewable Energy, requested this study, identifying a focus on:

1. Assessment of technologies and approaches for subsurface imaging and characterization so as to be able to validate EGS opportunities.
2. Assessment of approaches toward creating sites for EGS, including science and engineering to enhance permeability and increase the recovery factor.

2. IMAGING AND CHARACTERIZATION METHODS FOR EGS

DOE has broad interests in characterizing the subsurface, and is therefore engaged with a variety of technologies for imaging and monitoring regions within Earth's crust [Snieder, et al. 2007] The needs of EGS are sufficiently distinct, however, that it is worth identifying promising opportunities for characterizing:

1) Regions being considered for future stimulation and production.

2) The spatial extent and characteristics of a stimulated volume;

3) The spatial-temporal evolution of the region from which heat is being extracted.

Stimulation by hydrofracturing, for instance, is expected to create vertical fractures due to the principal normal stress performing vertically at the depths, that being contemplated for EGS. Due to this reason, the reflection seismology is majorly used in oil and gas exploration as it gives the highest resolution over the greatest distances, to be performed at depth, in order to have near-normal incidence relative to the vertical fractures.

There is an arrangement between range and resolution of features that can be imaged in the subsurface, with Figure 2.1 showing typical values for high frequency seismic (kHz-MHz) and electromagnetic (MHz-GHz) methods. In detail, the values depend on material properties such as seismic-wave velocities and dielectric constant, the latter being especially sensitivity to the presence of moisture, as it is main factor in use of ground-penetrating radar (GPR). Nevertheless, resolution of meters or less generally requires imaging at distances less than tens to hundreds of meters, which implies getting sources and sensors near the region of interest.

2.1 Ambient Field Sensing Imaging

The only means of achieving near-normal incidence for vertical fractures at depth is to reposed sources and sensors in the subsurface. This is possible through conventional drilling, and may in the future be significantly enhanced by micro-drilling approaches. A major development in seismology is to dispense with sources. In particular, the ambient seismic field (background seismic noise) present in the crust can be used as a form of seismic "daylight" that illuminates the subsurface [Snieder and Wapenaar et. 2010] [Snieder and Larose et.2010].

Shear-wave polarization can be used to determine fracture orientations at depth, and that cross-correlation of ambient seismic and electromagnetic fields can additionally provide a basis for characterizing subsurface permeability and fluid flow through poro-elastic effects [Snieder and Wapenaar et. 2010]. A recent example of monitoring daily changes in an oil field at several hundred meters depth through ambient seismic noise [deRidder and Biondi et. 2013].

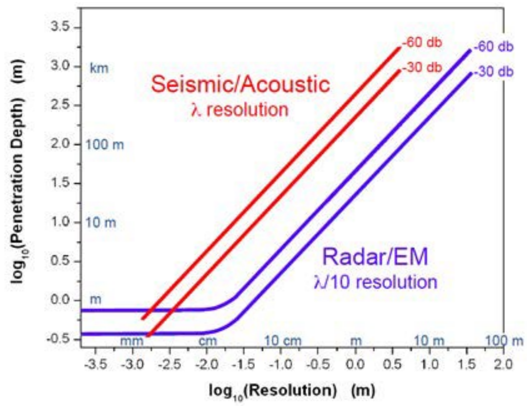

Figure 2: Calculated distances (penetration depth or range) over which Calculated distances (penetration depth or range) over which high-frequency seismic (acoustic) and electromagnetic (Radar/EM) wave based imaging can achieve a given resolution for return signals 3-6 orders of magnitude smaller than transmitted (-30 and -60 db).

2.2 Non-Linear Elastic Response

[Johnson, et al., 1987] [Johnson and Shankland,1989] [Guyer and Johnson, 1999][Pasqualini, et al., 2007]Nonlinear elasticity of rock has been studied in the laboratory for more than 25 years, and shown to provide highly sensitive information about the presence, nature and spatial distribution of fractures, grain boundaries and other structural defects . Nonlinear elasticity potentially offers unique Advantages for subsurface imaging relevant to EGS. Firstly, the nonlinear response of rock – deviations of observed strain from being directly proportional to the stress applied to a volume of rock – is highly sensitive to the presence of fractures under low effective stress (i.e., when fluid pressure inside the fractures closely matches the normal stresses due to overburden).

The condition of low effective stress is of interest for:

i) Identifying subsurface regions susceptible to stimulation for EGS;

ii) Quantifying the degree (success) and spatial extent of stimulation;

iii) Monitoring the temporal evolution of a stimulated zone at depth.

Secondly, the imaged: that is, dimensions of meters to perhaps hundreds of meters instead of crack widths of milli-meters to meters, is not individual fractures but the complete zone that is (incipiently) fractured. Therefore, the need for spatial resolution is far less demanding than required for the usual linear-elastic imaging of structures Figure 2.

The basic idea is that fractures can be opened and closed by externally imposed stresses, assuming a condition of low effective stress. The elastic response of a fractured volume differs greatly (non-linearly), depending on whether the cracks are in the process of opening up or are clamped shut (e.g., shear waves with polarization in the plane of the cracks being scattered or not, respectively). Therefore, regions of a rock insonified with a mix of low-frequency waves (that open and close fractures, where present) and high-frequency pulses (that scatter off opening cracks) can in principle be used to reveal the presence of fractured zones.

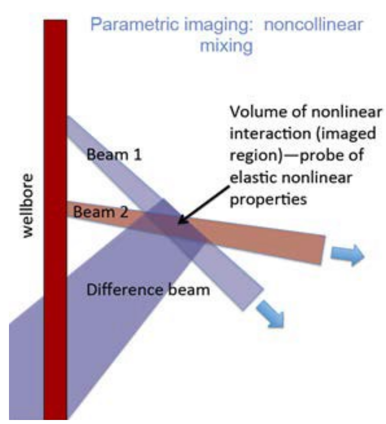

Figure 3: Schematic of nonlinear elastic imaging as applied to the subsurface, using arrays of transducers in a borehole to send two beams (low frequency forcing beam plus high-frequency probe beam) in order to insonify and image a region of

interest, as revealed by the difference (and/or sum) beam that emerges from the volume of nonlinear interaction (courtesy of P.A. Johnson).

One implementation that might be applied to the subsurface, shows that a crack insonified by a low-frequency wave is effective in scattering a high-frequency probe beam so as to produce an image of the crack (Figure 3); not surprisingly, the crack was nearly impossible to resolve by standard (linear-elastic) methods. If scaled up from laboratory to field distances, nonlinear elasticity could offer an important advance in subsurface imaging relevant to EGS.

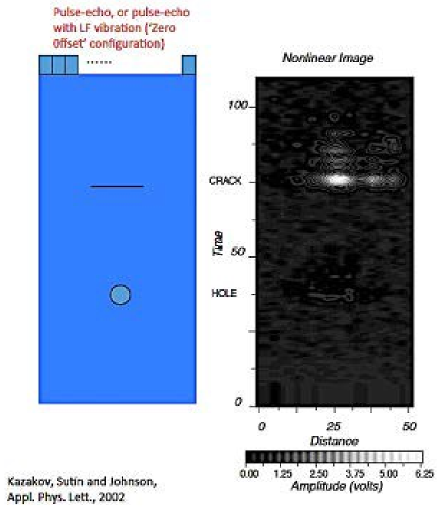

Figure 4 : Laboratory demonstration of nonlinear elastic imaging of a crack in a steel plate that also contains a hole.

[Ulrich, et al., 2008] Time-reversal imaging of nonlinear elastic response is established as a means of non-destructive evaluation of materials at the laboratory scale. It is now necessary to validate this method at field scales of tens to hundreds of meters in order to ascertain the useful ranges and sensitivities of the method for application to EGS. There will be practical considerations concerning the equipment and configurations to be used in addition to characterizing the quality of the signal that can be obtained. For instance, driving low-frequency insonification from the surface using Vibrioses or equivalent technology may be preferable than employing downhole transducers (Figure 3). It will also be necessary to establish the best frequency ranges.

2.3 Drilling

[T. U. Clausthal et, 2011] Drilling plays many roles for EGS, from exploration and characterization of likely sites to development and production of a field. We move on to discussing drilling technologies because drilling is crucial to characterizing the subsurface, whether it can be by directly sampling the rock at depth or by granting access to other instrumentation (such as the electromagnetic and seismic sensors mentioned above and the tracer experiments discussed below). Numerous difficulties encountered while drilling for EGS are also encountered when drilling for hydrocarbons. As a result, EGS can benefit from innovations created for the considerably bigger hydrocarbon business.

2.3.1 Conventional Holes

With a strong bit pressed against rock, shear force is applied during drilling, which causes tensile and shear failure behind and around the sliding contact. Because the shear strength is substantially lower than the uniaxial compressive strength, this is crucial for hard rock (e.g., 200 MPa versus 5 MPa for granites). Historically, drilling for conventional geothermal has been among the most difficult drilling tasks due to the hardness of the rock and the size of the holes that must be made. PDC bits, or polycrystalline diamond compacts, were created 30 years ago for geothermal drilling but are now commonly utilized in other industries (oil and gas). (Schlumberger, 2012) There have been modest improvements in the relevant conventional drilling technology with PDC, and they are becoming more widely used than conventional roller cone bits. Schlumberger reports a 1/3 increase in average run lengths for its newest bits for high-temperature hard rock drilling.

2.3.2 Microholes

Both the hydrocarbon industry and EGS for exploration and seismic sensing are interested in developing technology for quick drilling of small holes because noise levels are much lower even at depths of a few hundred feet than at the surface and EGS requires monitoring microcosms that indicate fracturing. The use of generated seismicity as a mapping tool and real or imagined potential hazards are additional reasons to improve EGS system monitoring. An array of geophones is positioned inside a distribution of holes to perform tomographic monitoring. (Lu et al., 2013) Another driver for small holes has been gas control for coal mine safety

As described by (Majer, 2013), the target is for boreholes that

(a) can be drilled at 100 to 200 ft/hr to minimize cost,

(b) extend to depths of at least 5000 ft at these high drilling rates;

(c) have minimum waste, which maximizes speed while minimizing permitting issues;

(d) have small rig footprint, for rapid deployment as well as minimizing permitting issues;

(e) have minimum formation damage to borehole walls and surrounding rock to improve monitoring;

(f) have a small diameter that allows better seismic coupling of instrumentation to the rock.

2.3.3 Resonant drilling

Fluid is necessary in rotary drilling to transport the drilled material out of the way of the bit. Simple solutions like air and water can be used to flush media for sonic drilling. The turbulent flow created at the drilling interface by a sonic drill bit's vertical oscillation forces loose drilled material to one side. In contrast to rotary drilling, the actual number of flushing media needed is little. Sonic (termed resonant, because a drill pipe is oscillated at its lowest resonant frequency) drilling is being developed for comparatively shallow wells, generally in soft or unconsolidated material. It may be useful for drilling the shallow wells (to 500 ft) needed in larger numbers for emplacement of seismic sensors

2.3.4 Fluid injection drilling

Abrasive jet cutting was proposed early on for drilling (Kolle, 1999). H2O or CO2 can be used as the fluid. Use of a CO2 slurry mix, nozzle and high-pressure slurry pump has been demonstrated in the lab to have high penetration rates in basalt. If a larger bore is required, rotation of the nozzle(s) can be provided with a small down hole hydraulic or electric motor. The pump accelerates and pressurizes the slurry. A nozzle can be focused to concentrate the slurry stream on the periphery of the drill hole, reducing the work required, as demonstrated in the 1960s (Maurer, 1980) Abrasive jet drilling has not succeeded in drilling deep holes because of the difficulty of handling and delivering the amounts of abrasives required at depth, the need to balance the high-pressure of the jet with the pressure of fluid in the hole, and difficulties in steering. Wear on the nozzles by the abrasive could be reduced with the use of toughened materials discussed above (e.g., diamond-based materials). (Lu et al., 2013) Work continues on developing hybrid technologies that involve abrasive jets and impact drilling but field tests in EGS-relevant environments apparently have not been reported.

2.3.5 High-speed dual string drilling

(Able, 2013) This method produces pulverized stone with sub-millimetre particles, in contrast to the large broken up rock typically produced from slow grinding. The lower weight on the bit produces less wear. Both diamonds impregnated bits and PDC have been used. The first high-speed dual string system will be tested in the field this year.

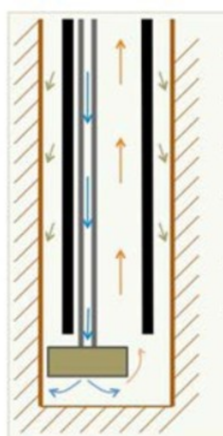

Figure 5 : Schematic of a high-speed dual string drilling (Able, 2013)

3 EGS CREATION AND PRODUCTION

3.1Heat Transfer Features of EGS

Two primary determinants of the possible success of a geothermal system, from conventional hydrothermal to hot dry rock (HDR), are the recovery factors for thermal energy and the possible lifetime of a given producing region. Both features require understanding the coupling of heat transfer to the water and the change of the thermal energy in the rock. An essential aspect of geothermal energy extraction is that the temperature of the hot rock gradually drops to approximate the temperature of the injected water when energy is collected from the rock by contacting it with flowing (colder) water. The only way for the rock to recover thermally in the absence of significant permeability is by heat conduction, which is a somewhat sluggish process. Due to heat transfer principles, the rock has been locally cooled over a distance of (4rt)1/2 = (4 5 yr 30 m2/year)1/2 25 m within t = 5 years of contact with cool water (where r is the rock's thermal diffusivity).

3.2 Water

For geothermal plants operating in water-stressed areas, fresh water withdrawal and consumption is a crucial and delicate issue. Geothermal systems use water when, in addition to other purposes typical of construction projects, drilling wells and applying hydraulic pressure on the rock to fracture it. The majority of water consumption, however, occurs during ordinary operations when water is needed as feed water to replace losses from the hydrothermal reservoir and to cool surface heat exchangers. Enhanced geothermal systems (EGS) also need a water source to first fill the reservoir in cases of hot, dry rock or in places where natural hydrothermal waters run out. Additionally, it has been discovered through experience that natural hydrothermal systems gradually lose water over time, and even those in "hard" rock frequently have channels that drain water out of the system.

Some geothermal systems, such as The Geysers in northern California, generate hot, dry steam directly from the ground, which powers a turbine. Although in such systems the steam can also be condensed and returned to the reservoir, the exhaust is vented to the atmosphere. One method involves feeding hot water that has reached the surface into a tank under low pressure. This causes the water to flash into steam, which can power a turbine or heat exchanger. One type of flash system involves heating an organic fluid in a closed loop so that it vaporizes at a lower temperature, powers the turbine, and then returns through a condenser (Figure In order to compensate for water lost underground, these systems require cooling water for the condenser. Additionally, some systems use dry cooling, which involves chilling them with air.

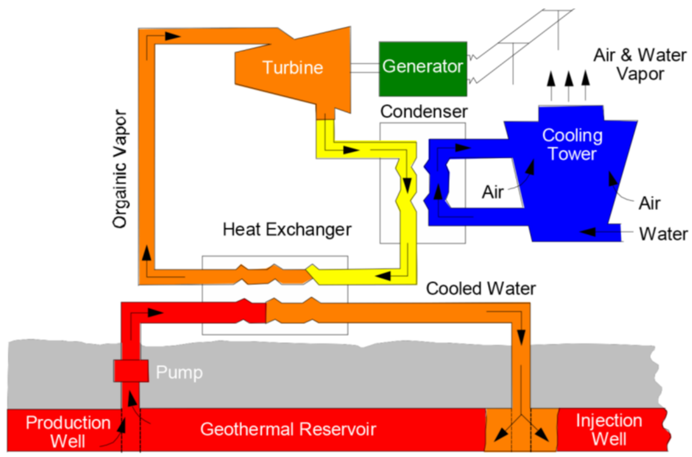

Figure 6: Geothermal system with binary cooling (T. Reilly et, al. 2008)

3.3 Corrosion and Scaling

Conventional geothermal systems have significant problems with corrosion or scaling of transfer piping, and this will be an issue for EGS systems as well. Both gases contained in the steam and other chemicals that are dissolved in the brine have the potential to induce corrosion and scaling. Gases mixing with the steam at the Geysers fields, such as hydrogen chloride and hydrogen sulphide, contribute significantly to corrosion. Brines are a mixture of dissolved substances, including orthosilicate ions, chloride ions, sulphates or sulphides (depending on the redox state of the brine), cations of calcium, magnesium, sodium, iron, and many other metals. The relative amounts of these dissolved substances are determined by the pH of the brine.

3.4 Induced Seismicity

(National Research Council, 2012; Ellsworth, 2013) One consequence of geothermal production is the generation of earthquakes. Induced seismicity is a relatively well-documented phenomenon associated with changing fluid pressures at depth, for instance due to impounding water behind a dam or injecting fluids into the crust, and it has on more than one occasion caused significant public concern with EGS and other geothermal Projects. (Julian et al., 2010) Small earthquakes are also caused by hydro-fracturing, as may be used for EGS stimulation, in fact, micro-earthquakes provide important information about the spatial distribution of stimulated zones at depth, so could have been discussed above as part of subsurface characterization Micro seismicity (numbers and locations of events) can be monitored over thousands of meters, but we advocate more detailed measurements coupling estimates of spatial-temporally varying permeability and stress-state based on coupling tracer and electromagnetic with seismic methods.

4.POTENTIAL GAME-CHANGING TECHNOLOGIES

EGS presents significant opportunities for increasing the contribution of geothermal energy to the production of U.S. electricity by a factor of a few over the following few years, and by a great deal more if this initial success is properly leveraged over succeeding years. The current state of key technical choke points includes characterization of subsurface flow in order to forecast and manage heat recovery factors and well-pair lifetimes. Both for subsurface characterization and production, there have been significant technological advances, and in many situations, the next crucial step is to develop and evaluate these capabilities at field scale. Many of the technical challenges addressed by EGS research are of broad interest to industry, academia and government. Notably, imaging and characterization of the subsurface and of subsurface flow – including through rapid access as potentially made feasible by micro drilling and related technologies – is important.

Technologies

1) Drilling

2) Subsurface Flow

Drilling: Drilling innovations have a big impact on EGS. Drilling continues to be a significant expense in the exploration, development, and production of EGS, on the one hand. On the other hand, there are significant prospects for drilling advancements to support EGS, which could be achieved even with field-scale deployments of current technologies.

Subsurface Flow: The spatial heterogeneity of the flow channels and how the flow at depth changes over time are two features of subsurface flow that need to be defined. However, this is not a novel interpretation of the data, therefore it needs to be confirmed, and additional aspects that might influence recovery factors need to be researched.

5. OBJECTIVE APPROACH FOR PROS AND CONS OF CONVENTIONAL EGS

Conventional Enhanced Geothermal Systems (EGS) involve drilling into hot, dry rock and injecting water to create a geothermal reservoir. This process can be used to produce electricity through the use of a steam turbine, or for direct use applications such as heating and cooling.

Pros of conventional EGS include:

- High energy potential: EGS have the potential to produce large amounts of electricity, making them a viable alternative to fossil fuels.
- Renewable energy source: EGS is a renewable energy source that does not produce greenhouse gases or other pollutants.
- Flexibility: EGS can be used in a variety of settings, including urban and rural areas, making it a versatile energy source.
- Durable: Once an EGS is established, it can produce energy for decades.

Cons of conventional EGS include:

- High cost: The initial costs of drilling and building an EGS can be high, making it less economically viable in some areas.
- Environmental concerns: Drilling and building an EGS can have a negative impact on the environment, including potential seismic activity.
- Limited availability: EGS is only available in certain regions that have the necessary geothermal resources.
- Technical challenges: There are still technical challenges that need to be overcome in order to make EGS more efficient and cost-effective.
- The high cost of drilling and creating the geothermal reservoir compared to traditional geothermal can be a deterrent for some.

It's important to note that conventional EGS systems are still in the early stages of development and ongoing research is being conducted to further improve the technology and reduce costs.

6.CONCLUSION

Numerous publications offer striking statistics regarding the potential of EGS, but there is still much to be done to harness this power. However, based on this examination of EGS initiatives worldwide It turns out that EGS is still a work in progress. Any EGS initiative has high financial risks because success is not assured, and in certain situations, this might result in the project being abandoned. (Jung, 2013) The problem is that of handling each particular EGS system in such a way that economic flow rates at the right temperature and over a sufficient time span can be obtained. It is commonly accepted that for an EGS doublet system to be of commercial size, assuming a depth greater than 3 km and a temperature greater than 150°C, the system should operate at flow rates between 50 and 100 l/s and produce an electric power of 3 to 10 MWe over a life of at least 25 years. It is critical for EGS to ensure that relevant technologies are applied, having minimal risk of seismicity, and permitting the exploration of geothermal resource in a safe and environmentally friendly manner.

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