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A Techno-Economic Concept of EGS Power Generation in Pakistan

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ABSTRACT

This is a techno-economic study probing the feasibility of power generation through Enhanced Geothermal System (EGS) in Pakistan. The concept surrounds around providing the preliminary answers on the usefulness and workability of a geothermal power plant in the country. Operational parameters, relevant technologies and associated risks are also addressed along with economics of the proposal. A site is selected, and preliminary data is retrieved from industrial sources as the starting point. Considering the data available, establishing correlation with other similar geothermal sites, a design of a 1.5 MW geothermal power plant is proposed.

1. INTRODUCTION

Geothermal energy is a relatively greener and more sustainable form of energy compared to energy from traditional energy sources including hydrocarbons, which can be used for range of purposes including power generation. It is a cleaner source of energy and have average capacity factor of 74.5 that can be increased up to 90% in the ideal conditions (Lu, 2018). Many countries in the world such as the USA, Turkey, Iran, China etc. have put efforts in geothermal assisted plants in an attempt to advance their energy capacities. No considerable work has been done in Pakistan so far when it comes to geothermal energy. International energy agency estimates 30% increase in consumption of electricity by 2040. It is the time now that Pakistan, like other countries leading in geothermal energy, explore new means of energy providing higher sustainability and lower environmental impacts (Halfhide *et al.*, 2009).

Pakistan's energy demands are increasing and currently facing a shortfall of almost 4554MW (April 2017). Pakistan is in a desperate need of increasing power generation options. Geothermal power generation plant can be one of such options. Studies have revealed that Pakistan is potent geothermally and Pakistan's geothermal energy is being wasted for nothing. At the same time, Pakistan is one of the gifted countries rich in both, conventional and renewable energy resources. Despite huge energy resources, Pakistan falls under energy deficient countries due to energy management crisis. Geothermal energy is, yet, unexplored resources for power generation. Pakistan counter energy shortage by harnessing nonconventional energy resources, i.e., geothermal energy. A good number of the hot springs and mud volcanoes are located within the seismic belt. The country has practical geothermal energy manifestations (Younas *et al.*, 2016).

The objective of this current study is to provide a comprehensive review of literatures of how electricity is being produced globally by utilizing geothermal energy resources. The study serves these sub-objectives: (1) to identify the depth, geology and temperature suitable for a proposed Enhanced Geothermal System (EGS) for power generation in Pakistan; (2) review and selection of type of power plant suitable for the prevailing conditions; (3) techno-economical comparison of proposed geothermal power plant with conventional power generation method. Study on technical feasibility of installing a geothermal power system at an appropriate location will help determining the availability, adequacy, and effectiveness of geothermal resource and its utilization. It will be a step towards the sustainable and environmentally friendly energy production to assist countering the energy crisis of the country. The proposed setting may serve as the initiative for further prospects and research. Furthermore, the economic analyses will help determine the extent of economic self-sufficiency and impact on economic growth. The study undergoes different stages which includes feasibility model, site selection, technical analysis, design of plant, economic analysis, sensitivity analysis, and techno-economic comparison (Valasai *et al.*, 2017).

2. BACKGROUND

2.1 Geothermal Systems

A geothermal system comprises of three elements: (1) permeable rock, (2) heat source, and (3) fluid to carry heat to the surface. Essentially, the only fundamental requirement is a heat source as permeability may artificially be created in the rock mass and fluid flow can be induced. Two types of geothermal systems are suitable for power generation: (1) hydrothermal systems wherein fluids peculates through pores or fractures in rock mass in vicinity of high heat contents and (2) hot rock systems wherein fluids flow is induced in artificially in rock mass with permeability artificially created for heat transfer. Hot rocks at depths greater than 3 km generally possess low porosity and permeability, thus, requiring fluid flow be induced (Hammons, 2004).

Enhanced Geothermal Systems (EGS) is a way to convert enormous resources contained in the earth's crust into electricity on a large scale. Conventionally, generating electricity on large scale from geothermal energy has been tied up with tapping large hydrothermal reserves. It involved extracting hot fluid from a reservoir, so that the heat contained may be converted to electricity (Gokcen *et al.*, 2004).

Enhanced Geothermal System (EGS) technology follows the principle of increasing the naturally low hydraulic communication of the geothermal reservoir by fracture stimulation techniques. The permeability of the host rock is enhanced so as to improve the circulation of the geothermal brine. This allows transmission among preexisting fracture network for an effective extraction of the geothermal fluid (Ehara *et al.*, 2000). The hydraulic stimulation involves injection of fluid with high pressure and flow rate, thus increasing the pore pressure and promoting the shearing of naturally occurring fractures (Zhang *et al.*, 2018). After halting the injection, the occurred shearing is irreversible, and fractures do not restore to their close position resulting in an enhanced permeability (Bakhsh *et al.*, 2017). Mechanical effect of improve permeability may take place in near-field or at some distance from the well (Esposito and Augustine, 2011; Tomasini-Montenegro *et al.*, 2017).

2.2 Geothermal Resources and The Geology

A 'geothermal play' is a model of how numerous geological factors constitute a recoverable geothermal resource in certain geological setting. Like the concept for hydrocarbon plays, geological factors provide the essentials of a geothermal play including the reservoir, heat recharge source, the regional caprock, the timely relationship of the above three ingredients, and the play fairway. In petroleum geology, a play type represents a stratigraphy or structural geology established by source rock, reservoir rock and trap. Equivalent in geothermal systems, a play type is comprised by heat source and the geological factors for heat transport and storage capacity (Batini, Brogi and Lazzarotto, 2003). Geothermal plays are classified at the system scale into two groups: (1) convection heat transfer geothermal plays, and (2) conduction heat transfer geothermal plays (Hammons, 2004). Convection-dominated geothermal plays are further divided into volcanic type and plutonic type under magmatic class and as extensional domains under non-magmatic class (Freymark *et al.*, 2015). Conduction dominated system, on the other hand are of two types, i.e., Igneous geothermal plays– basement type and Intracratonic basins and orogenic belts (Vernoux *et al.*, 1995).

EGS is suitable for a wide variety of geologic settings i.e. volcanic, metamorphic, magmatic and sedimentary environments. All these geologic settings differ in characteristics like temperature, stress field, structural features, lithological variability, porosity and permeability, extent and types of natural fractures, brine chemistry (Arshad, Nakagawa, Bakhsh, *et al.*, 2016). These characteristics help deciding the appropriate method of stimulation (Calcagno *et al.*, 2008).

2.3 Micro Seismicity

Induced seismicity can be defined as the earth quakes by anthropogenic activities. It has been observed with activities such as extraction of hydrocarbons, deep mining activities, large water dams and geothermal activities (Lin and Wu, 2018). Particularly in geothermal projects, seismicity can be induced during stimulation phase or during the operation of a geothermal field (injection and production of fluids) (Piccolo *et al.*, 2018). Induced seismicity can be due impoundment of lakes, mining activities, injection or production at hydrocarbon reservoirs, disposal of waste water and geothermal applications etc. (Lacirignola and Blanc, 2013). Thousands of seismic activities arise due to geothermal applications each year. But in most cases their magnitudes are below local magnitude i.e. 2 and in some 2.5. while at other sites seismic activities were too low to be detected (Christopher, Armstead and Tester, 1987).

2.4 Crustal Heat

The heat content of crust can provide a large portion of the global energy needs for a very long time. But the mantle and cores of the earth contains probably 3000 to 4000 times that of the crustal heat. As in near future it is not possible to penetrate down to the Moho, boundary between the 'rigid' crust and the more plastic mantle but it would be realistic to estimate the crustal heat resource base in terms of penetration ability. No doubt, deep heat will have high temperature, and will have attractions for the application of high efficiency power generation. But problems of accessibility, challenging difficulties of chemistry and handling of fluids will reduce its attraction. Present drilling capabilities are up to depth of 10 km for vertical wells and 6 km for deviated wells (Li *et al.*, 2018).

In some parts of the crust abnormally high temperatures are found at shallow depths. Such places often occur at or tectonic plate boundaries, rift or subduction zones having high seismic activity, where hydrothermal fields or volcanoes sometimes occur. To estimate the crustal heat resources of earth some assumptions are made: (1) all the land areas of earth are non-thermal i.e. having temperature gradients not more than 25-degree Celsius and (2) all the abnormally hot areas are ignored (Bakhsh *et al.*, 2016). Crust heat is represented quantitatively in two ways i.e. specific crustal heat or per sq. km of land area per degree Celsius of average crustal cooling (Christopher, Armstead and Tester, 1987).

Crustal heat producing elements has been estimated near the Sudbury Neutrino Observatory, Ontario, Canada. Sampled heat production from this region is consistent with composition i.e. felsic rocks have higher amount of heat production than heat from mafic rocks. Average heat production from the region is higher than the estimated average heat from Archean crust (0.6-0.7μWm^{-3}). Granophyre samples possess highest heat comparable with granite (3 $\mu W\ m^{-3}$). Norite have heat near to archean crust i.e. .89 $\mu W\ m^{-3}$. For this region was divided into two geological provinces superior and southern. Both provinces showed higher heat production. In superior province consistent high heat is produced in the presence of granite and felsic gneisses. In southern province greywacke samples showed very high heat production (Phaneuf and Mareschal, 2014). In southern Tuscan geothermal areas including Lardere-Travale and Monte Amiata, young granite plutons are primary source of heat (Ebigbo *et al.*, 2016).

2.5 Well-field Design

Geothermal well field design is a complex step in establishing the Enhanced geothermal power plant. In order to make the precise decision regarding the location and amount of well required, extensive study and testing is required. The scientific tools now allow for better characterization of geothermal resources before the expensive well drilling. A better and reliable characterization of drilling sites is possible by defining the subsurface field, thus, increasing the chances of a successful well discovery and field development. The physical as well as the chemical properties of the geofluid during production phase are of prime importance during the feasibility study of a geothermal power project. In order to develop a successful well field pattern, a comprehensive exploration program is a definite requirement consisting of literature survey, geological survey, airborne survey, hydrological survey, geophysical survey, and geochemical survey (Xie and Min, 2016). Hydraulic proppant fracturing, water fracturing, hybrid fracturing, chemical injection (Luo *et al.*, 2018), and thermal fracturing are some commonly practiced crack activation techniques used for EGS (Reinicke *et al.*, 2010).

2.6 Geothermal Power Plants

Power plants, no matter if fueled by hydrocarbons, nuclear power, or geothermal energy, share one common feature: converting heat to electricity. Geothermal energy (heat from the Earth) is accessed by drilling deep wells similar to drilling for oil (Lee, 2017). The amount of energy produced by a geothermal power plant depends on factors such as the characteristics of geothermal resource (i.e., temperature, permeability, and amount of fluid), the available technology, and economic factors. Due to the high up-front cost of development, however, plant size is mainly dictated by the geothermal resource, location with respect to infrastructure, and power demand. In general, power plants are sized to fully utilize the proven resource (Hillesheim and Mosey, 2013).

Geothermal power plants and traditional power-generating stations have many components in common including turbines, transformers, generators, and other standard equipment. Geothermal power plants use steam produced from hot water reservoirs located a few miles or more below the Earth's surface to generate electricity. The steam rotates a turbine and, in turn, activates a generator. Geothermal power plants fall under three types: dry steam, flash steam, and binary cycle (Hillesheim and Mosey, 2013).

Dry steam power plants are among the very first type of commercial geothermal power plant. Dry steam power plants recover heat from resources of steam in underground setting. Flash steam power plants, on the other hand, are among the most common ones and use reservoirs of water with temperatures above 182 degrees of Celsius. Flash plants are installed with a steam separator to separate brine from steam (i.e., flash), and the steam is then directed to the turbine. Single-flash and double or triple flash systems are further classes of flash power plants. Closest in working principle to conventional plants are the binary cycle geothermal power plants wherein in the working fluid has a closed cycle. The working fluid is selected as per thermodynamic properties. It collects heat from the geofluid, evaporates, expands through a prime mover, condenses, and is directed back to the evaporator through a feed pump. Binary plants are able to generate electricity at temperatures around 74 °C, depending on climate and availability of cooling water (Hillesheim and Mosey, 2013).

2.7 Impacts of Geothermal Power Generation on Environment

Although, among all other sources of electricity, geothermal energy produces electricity with minimal environmental impact, tut environmental effects cannot be excluded during geothermal power generation considerations (Nakagawa, Bakhsh and Arshad, 2016). The overall impacts are much lower than conventional hydrocarbon and nuclear power plants (Arshad, Nakagawa, Jahan Bakhsh, *et al.*, 2016). Additionally, on an equivalent energy output basis, geothermal power production has lower impacts compared to other renewables such as solar, wind, and biomass. This is because a geothermal source is underground, and energy conversion equipment at the surface is relatively compact, resulting in smaller footprint overall. EGS power plants with closed loop circulation have added benefits of minimal greenhouse gas and other emissions providing additional environmental benefits (MIT, 2006).

In the last 40–50 years, Geothermal development have revealed that it is not totally free from adverse environmental impacts. These impacts raise an increasing concern, and may now be limiting developments to an extent (Cakin *et al.*, 2012). These impacts greatly differ with site characteristics, reservoir properties, and power plant (Ahmad and Rashid, 2010). Geothermal energy can make a significant contribution, in near future, towards reducing the emission of greenhouse gases (Bakis, 2008). The impacts may occur as air pollution, noise pollution, water pollution, land and water use, land subsidence, thermal pollution, aesthetics, and other catastrophic events such as seismic events. About thermal pollution, geothermal power plants reject a lot more heat than other type plants per unit of electricity generated (DiPippo, 1991).

2.8 Economics of Geothermal Power Generation

Geothermal energy, which is either used for direct heating or transformed into electricity is not only extremely capital intensive but also technology dependent industry. The required capital investment may be characterized in three phases: (1) feasibility, exploration and drilling of test as well as production wells, (2) energy conversion facilities and infrastructure, and (3) future re-drilling and well stimulation as discounted value. Estimates of California Energy Commission (CEC) in 2006 on capital cost reflected that capital reimbursement and interests together totaled to 65% of the net cost of the plant. The rest included fuel, parasitic pumping loads, labor and access charges, and variable costs. By way of contrast, the capital costs of combined cycle natural gas plants are estimated to represent only about 22% of the levelized cost of energy produced, with fuel accounting for up to 75% of the delivered cost of energy (Hillesheim and Mosey, 2013).

The delivered cost of electricity is taken as criterion for power generation technology or a plant. The levelized cost of energy or Levelized Electricity Cost (LEC) is used for comparison of the cost of power from competitor technologies such as hydro power, fuel oil, and Biomass and wind power generation plant (Dunnington *et al.*, 2016). The LEC is calculated from the present value of plant building and plant operation over the span of its projected economic life. Costs are levelized in real currency or adjusted to be free from the impact of inflation (Tomasini-Montenegro *et al.*, 2017). Power generation facility is subjected to multiple fixed and variable costs. A thorough comparison of power generation requires same units of quantities, costs capitalized for fixed assets and levelized for operation (Zhu *et al.*, 2017). Different power generation technologies vary in terms of attributes as well as delivered cost of energy (Herzog, Tester and Frank, 1997). Table shows the characteristics of energy technologies provided by the EIA.

Table 1: Energy Technology Characteristics

Technology	Overnight Cost, $/KW	Total overnight (w/variable O&M) costs, $/KW	Variable Costs, $/MWh	Fixed Costs, $/MWh	2001 Heat rate, Btu/KWh	2010 Heat rate, Btu/KWh
Conventional Pulverized Coal	1,046	1,119	3.38	23.41	9,386	9,087
Integrated Coal Gasification	1,250	1,338	0.8	32.67	7,869	6,968
Conventional Gas/Oil CC	435	456	0.52	15.61	7,618	7,000
Advanced Gas/Oil CC	546	590	0.52	14.46	6,870	6,350
Conventional Gas Turbine	323	339	0.1	6.45	11,380	10,600
Advanced Gas Turbine	451	474	0.1	9.16	9,020	8,000
Fuel Oil	1,810	2,091	2.08	14.98	5,744	5,361
Advanced Nuclear	1,772	2,144	0.42	57.23	10,400	10,400
Biomass	1,536	1,725	2.9	44.95	8,911	8,911
MSW Landfill Gas	1,336	1,429	0.01	96.31	13,648	13,648
Geothermal	1,663	1,746	0	70.07	32,173	32,173
Wind	918	962	0	25.54	N.A.	N.A.
Solar Thermal	2,157	2,539	0	47.87	N.A.	N.A.
Solar PV	3,317	3,831	0	9.85	N.A.	N.A.

2.9 EGS Status in Pakistan

Pakistan is a developing country subjected to dramatic increase in energy demand due to modern development and population explosion. The country's demand is rising at about 11% on annual basis, whereas the production is falling behind the demand. Like majority countries, Pakistan depends on fossil fuels to fulfil most of its energy requirement. The search for new or nonconventional resources and development of new hydropower projects are very slow. Despite crisis as well as countering efforts over the last decade, the country has not been successful substantiating head-way to reduce dependence on foreign oil. As of now, Pakistan has 20 GW installed electricity generating capacity. 66% of this capacity is reserved by thermal plants (oil, gas, and coal) with hydropower contributing 32% and nuclear plants only 2%. As of now, Pakistan is facing a shortfall of 5,000MW with drastic increase every year (Younas *et al.*, 2016).

Pakistan is located on the seismic belt propitious with geothermal potential. Initial investigation reveal Pakistan's Geothermal manifestations in the form of mud volcanoes, hot springs, and geysers (Shuja, 1986). The Arabian plate to the south, the Indian plate to the north and the Eurasian plate in the east constitute the tectonic framework of the Middle. Collision and subduction of the Arabian plate under the Eurasian plate caused self-crustal melting, resulting the Chagai volcanic arc. In the north, the Indian plate subducted underneath the Eurasian plate leading to continent-to-continent collision, forming the Himalayas, and initiating geothermal activity facilitated by fault systems (Kessides, 2013).

Hot springs have been discovered in the few of the Northern areas. Another zone with indicated geothermal potential extends from NE to SE in the form of a narrow belt next to the Indus basin margin, all the way down to Karachi. Dadu District of the Sindh province is yet another huge geothermal manifestation. A select number of geothermal zones include Himalayan collision zone, Chagai volcanic arc, Indus basin margin, Hamun-e-Mushkhel graben, and Mekran coastal and central zone (Ahmad and Rashid, 2010).

3. PROPOSED PLANT

The biggest hurdle in carrying out such a study is the availability of the required data and relevant experimentation. With only scarce availability of the input parameters and total absence of experimentation, the study is merely a preliminary desk study. The required data has been provided for in one of the following three ways:

1. Acquiring whatever the data is available. Using all necessary means some of the data relating to rock mass characteristics including temperatures and structural setting has been acquired. This data has been requested to be kept classified for its source and location, but it does serve the purpose of reasonable estimates for different parameters. None of the site or prospect location had completed set of the data. Stratigraphic data at such depths as 3 km was available for only limited sties. One of such sites was selected as prospect site and averaged out temperature gradient were assumed to be valid for this site as well. Some of the data related to costs, energy statistics, and plant parameters was readily available.

2. Some of the data was borrowed from literature review of other EGS power plants around the world based on similarities among subject and referenced project. Given the initial data from the first step, some basic characteristics of the subject site were drawn and compared with existing projects to find a project with similar or closely relevant geological characteristics. Based on depth and output temperatures Soultz-sous-Forêts EGS power plant in France was selected as reference project to borrow unknown parameter values. Although, stratigraphy of the subject site and the reference site is not quite similar. Number of wells, flow rate, capacity, and similar operating parameters have been borrowed from the reference project.

3. Some of the parameters that were still unknown even after first two steps of data collection. Such parameters were assumed as per globally accepted values. For example, output of a small EGS power plant.

Once the data was arranged, the required parameters were either calculated or estimated. EGS plant and wellfield components and techniques for executing various operations were selected based on literature review and assumed site characteristics. An economic comparison and sensitivity analyses has been added in the end to add more meaning to designed power plant.

3.1 Host Rock Temperatures

Thermal gradient data was available from the petroleum sites in northern areas of Pakistan for about 20 different sites. This data was averaged out to figure out the final gradient of the site. Figure 1 is a plot of averaged out temperature vs the depth of the host rock. In an effort to find reasonably suitable temperature and convenient geological setting, at the thermal gradient from figure 1, the depth of the geothermal play was assumed to be around 5,000 m. a simple equation may be used to extract the temperature at assumed depth.

$$y = 0.0531x + 89.22$$

where,
y = Temperature at ‘x’ length in Fahrenheit, x = depth in meters

Using this equation and extrapolation, at required depth of 5,000 m, the temperature of the host rock turns out to be about 266.26 °F or 130.14 °C**.**

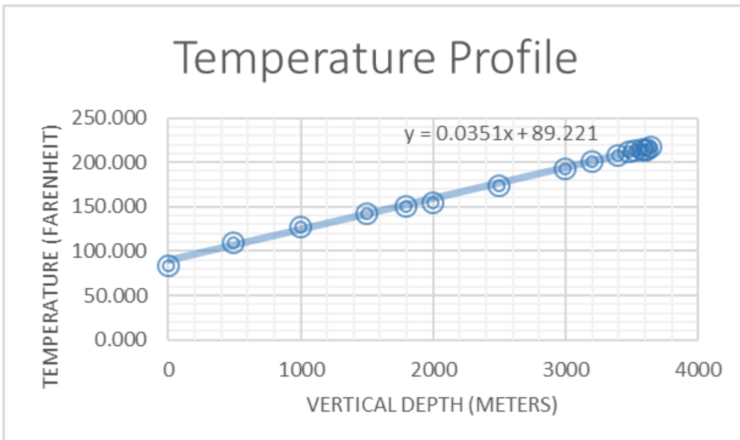

Figure 1: Temperature Profile

3.2 Geological Setting and Stimulation Technique

Geological data assumptions from another deep exploration borehole site dictates a favorable geological play. The geological play features, i.e., sedimentary environments, temperatures, stress field, structural geology, porosity and permeability, framework of natural fractures, and brine chemistry, were assumed to be favored by hydraulic fracturing as crack and flow stimulation technique.

3.3 Well Field and Plant Design

For the fact that the proposed EGS power plant is assumed to be operating at similar depth and temperature conditions as Soultz-sous-Forêts EGS power plant in France, some of the well field design and plant operating parameters were conveniently borrowed from the said project. Available temperatures at the assumed geological setting leads to the proposed plant to be a binary type power plant based on the Organic Rankine Cycle turbine. Some other design parameters including well field geometry, well bore design, drilling technique, and well casing didn’t have sufficient ground to be selected based on the available or assumed data. Table 2 shows the operating parameters of Soultz-sous-Forêts and proposed EGS power plants.

Table 2: Comparions of Operating Parameters of Soultz-sous-Forêts and proposed EGS power plants.

Parameters	Soultz-sous-Forêts	Proposed Plant
Power Plant Type		Binary Power Plant
Plant Capacity	2 x 1.5 MW electrical power (1.5 MW capacity currently installed)	1.5 MW
Working Cycle	ORC	ORC
Vertical Depth	5,000 m	5,000 m
Reservoir	EGS/ HDR/ petrothermal	EGS/ HDR/ petrothermal
Working Fluid	--	Water
Source Temperature\	> 180 °C	130oC
Discharge Temperature	--	100oC
Flow Rate	2 x 35 l/s	35 l/s

4. ECONOMIC CONSIDERATIONS

As noted in the text, applications involving geothermal energy are associated with high capital cost and relatively lower O&M (operation and maintenance) costs. For power generation, about 50% of total costs are reserved by the extraction and reinjection of the heat carrier fluid, roughly varies from $500 to $4000 per kW generated. Plant construction mounts to 40%, generally falls within $1500 to $1700 per kW generated. The remaining 10% accounts for other expenses. Therefore, the net cost ranges from $2000/kW to $6000/kW. O&M costs contribute anywhere between 10 to 20% of the net cost of power generation, i.e., range of 3 to 12 cents/kW h. Production cost per kW h from fossil fuels and nuclear is about 6 cents and the same varies from 3 to 9 cents for hydropower. Geothermal power plants do offer the option of smaller and more economical units than hydropower stations (Yunus and Kanoglu, 1999).

5. CONCLUSION

As other sources of power generation in Pakistan lack in providing the required amount of energy, geothermal power generation can assist fulfilling the needs of electricity generation in Pakistan. Geothermal energy has a very huge installation costs, but geothermal power plants comes with a very low running cost as compared to other power generation methods. It can provide cheap electricity. Geothermal power plants are environment friendly and sustainable form of energy and so may be utilized without much harm.

EGS power plant is a considerable option for a country like Pakistan. This study provides a detailed insights of geothermal electricity generation in Pakistan using the available field data. It can be used as a preliminary step, but definitely, a more detailed analysis or a feasibility study is required to install a geothermal power plant. All the aspects of a borehole must be studied before using that borehole using the fracturing data and other aspects which were missing in this study. Test plants and sites must be setup before further studies, and in future, actual field data is suggested to be used for plant feasibility study.

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