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Review Article

Geothermal Energy

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Geothermal energy as a source of heat and power generation has unique attractive features of environmental consideration and is economically viable as well. The general nature and distribution of geothermal sources along with exploration and conceptual aspects of power generation and the economics are discussed here. The global as well as Indian scene is discussed briefly. The novel aspects which would lead to expansion of geothermal energy utilization beyond restricted favorable sites are briefly reviewed.

Keywords: Geothermal Energy; Renewable Power; CHP; EGS-Engineered Geothermal System; Binary Cycle Power Plant

Introduction

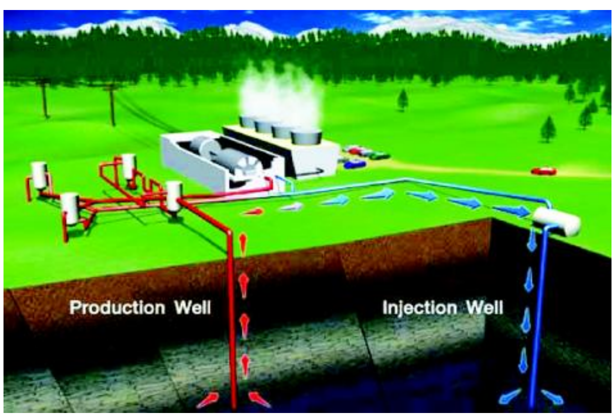

Fig. 1: A production well setup in a geothermal power plant

Sources of Heat

The Earth is the only planet which has a hot interior among all planets in the solar system; and in that sense is "alive" with volcanoes and is far from thermal equilibrium. The temperature at the centre of the Earth is around 6000ºC. About 20% of the heat is from the gravitational accretion of the matters which coalesced and crashed to the centre. The remaining 80% of the heat is of radioactive origin. The long half-life radioactive elements namely thorium, uranium 238, potassium and uranium 235 decay and contribute radioactive heat in that order. The half-life of these elements are 14, 4.5, 1.25 and 0.7 billion years, respectively. This fact ensures that the source of heat is *perennial* on human scale and the source is certainly *sustainable* in a general sense.

Thermal Gradients

There is a thermal gradient from the centre to the surface. The internal architect of the Earth is shown in Fig. 2. In the crustal part, the average temperature gradient is 22ºC/km. The heat flux on the average near the surface is 55 mW/m^2. Thus, there is a kind of dynamic equilibrium. The heat generated by the radioactive decay is conducted out and dissipated.

Two properties of rocks are important in the production of geothermal energy. They are specific heat and thermal conductivity. The specific heat for the rocks is in the range of 700 to 1000 Joules/kg/ºC. For comparison, the specific heat of water is 4800 Joules/kg/ºC. For rough and ready calculations,

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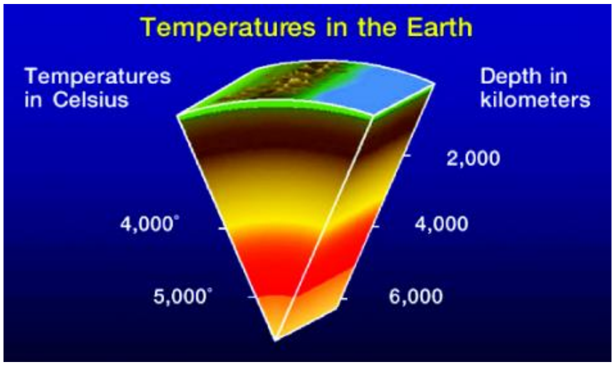

Fig. 2: Earth's interior

specific heat of a typical rock is 1000 Joules/kg/^{o}C, which is a good number and easy to remember and use. The other property is thermal conductivity. The range for thermal conductivities of the rocks is 1.7 to 7W/m/^{o}C, the measure of heat flux across a rock sample with 1m^2 cross-sectional area, with 1^{o}C/m temperature gradient; 2.5 W/m/^{o}C is a good working value for the rock. For comparison, the thermal conductivity of copper is 400W/m/^{o}C, steel is 15W/m/^{o}C, while that of wood, is of the order 1W/m/^{o}C.

Theoretical Geothermal Energy Available

We are now already equipped to obtain the good overall picture of the heat content and fluxes. The heat flux on the continents is $K*A*(dT/dZ)$, where K is thermal conductivity, A is the area and dT/dZ the temperature gradient. With area of the land as 148 million km^2, we obtain 9 TW as the total heat flux through land. The world today consumes electric energy at the rate of 2.4 terra Watts (TW) and India consumes 0.12 TW. The total energy consumption rate of the world is 18 TW (heat) and that of India 0.7 TW (heat). If we restrict ourselves to land area, then around 9 TW is the heat flux of geothermal origin. Due to ever increasing population and exploding per capita consumption, the energy requirement already exceeds the heat flux from the ground. So, even if we can utilize all the energy by geothermal source on the land; we cannot meet the present day energy demand.

The energy is available as heat and in final analysis running some kind of heat engine to extract useful work is the way to exploit it. This limits the efficiencies to Carnot engine efficiency. We know that in practice at the most 50% of this efficiency is realized. Thus, to have actual efficiency of say 15%, we must aim at temperature of 150^{o}C plus. With the temperature gradient of even 35^{o}C, /km, the desired temperature is present at a depth of 3500 m. For a plant delivering 1 MW power, we need to capture 5MW flux for conversion with 20% efficiency. With flux of the order of 0.06W/m^2, that will require an area of around 100km^2. Thus, the geothermal energy cannot be practically exploited at any random place on the Earth.

Geological Prerequisites for Geothermal Site

On the geological time scale, the continents move around as plates. The plate tectonics is driven by the convection caused by temperature gradients and leads to movement of continents. In addition, the magma now and then pierces through the thinner sections of the crust as volcanoes. Further, there are ridges along which the plates are pulled apart and fresh hot magma erupts along these mid-continental ridges. There are certain hot spots in the mantle where temperature is very high. When the wandering plate moves over the hot spot, it gives rise to lava flows forming a trap. The Deccan Trap is an example from India. Around 65 million years ago, the Indian plate moved over a hot spot situated in the Indian Ocean leading to eruption of Deccan Trap as hot lava flows. These geological realities give rise to heterogeneities in the temperatures and temperature gradients.

Mid-continental ridges, active volcano belts and hot spots are suggested as the natural places to look for favourable conditions to exploit the geothermal energy as energy source. The crust of the Earth does not consist of monolithic blocks. There are layered sedimentary formations, intrusions of igneous rocks and so on. The rocks on the large length scales are plastic and undergo deformations under stress. They are also fragile and are faulted and fractured. Once we cover them with surface water and ice flows of rivers and glaciers, the picture is more or less complete.

The geysers, which are periodic eruptions of steam and hot water in the form of natural fountains, have all the elements required for the ideal geothermal site:(1) Very hot environment at relatively shallow level (around 2000 m) provided by the magma, (2) Seepage of telluric water through fractures and faults to that level, reservoir of porous rock and or fractures and vugs and finally (3). A system of faults and fractures providing a path up to the surface through which the hot fluids flow up to the surface.

Here, the water flowing from the surface flows down and comes in contact with the hot rock and exchanges heat and converts into steam. The steam then builds up pressure in the reservoir and once the pressure crosses the threshold, the fluids erupt as a jet on the surface carrying heat with it. That results in pressure drop in the reservoir and the jet cannot be sustained any further. The cycle repeats.

Thus, for a geothermal site, in addition to hot magma as a heat source relatively near the surface, an aquifer with very good support of water from the surface is required. By drilling a well, a controlled system for bringing out the hot fluids is provided. Depending on the temperature, pressure and quality of the produced steam, different methods are adopted for generating electricity. A typical geological setting is depicted in Fig. 3.

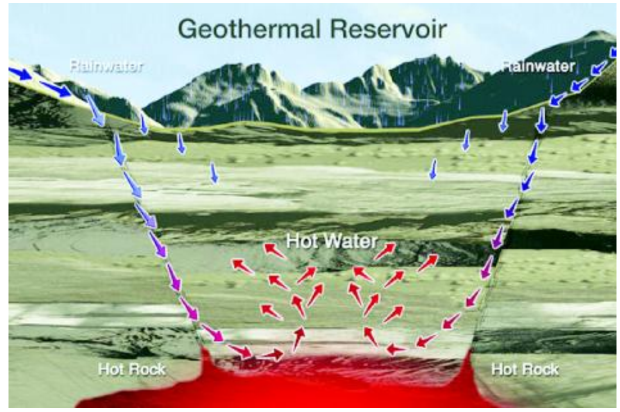

Fig. 3: Geothermal reservoir

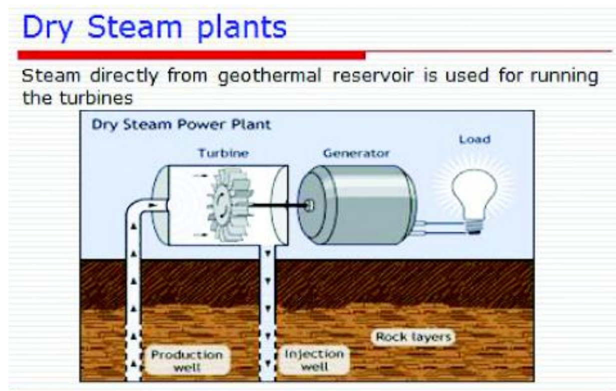

Fig. 4: Dry steam geothermal plant

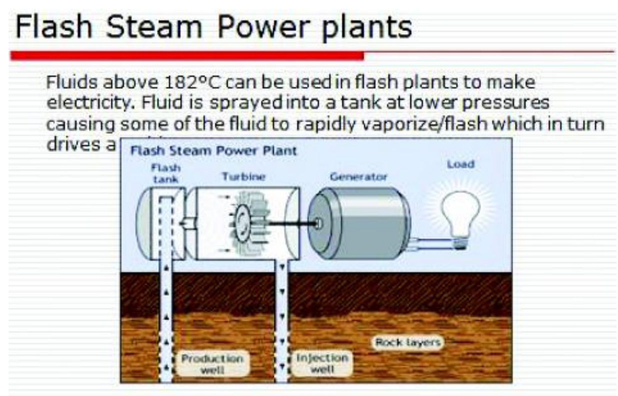

Fig. 5: Flash steam geothermal power plant

Geothermal Project: Surface/subsurface Installations

Having located a geothermal site, a well is drilled up to the reservoir and the reservoir fluid is produced on the surface. If the produced fluid is dry steam, then a steam turbine is run to produce electricity. If the reservoir does not have prolific water support, then the condensed water is injected back into reservoir through an injection well. The schematic is depicted in Fig. 4.

If the produced fluid is hot with temperature above 180^{o}C and at a high pressure, then the fluid can be flashed at lower pressure causing the liquid to evaporate fast. The produced steam is then fed to run the turbine to produce electricity. The condensed water then is injected into the reservoir through an injector. The schematic is depicted in Fig. 5.

When the produced fluid is moderately hot (below 180^{0}C), then a different scheme is adopted, called as the binary cycle power plant. The heat is exchanged with an organic fluid with lower boiling point. Thus, with exchanged heat the organic fluid vaporized, a turbine is run on this vapour to produce electricity. The condensed organic fluid is then again fed to the heat exchanger. The water produced from

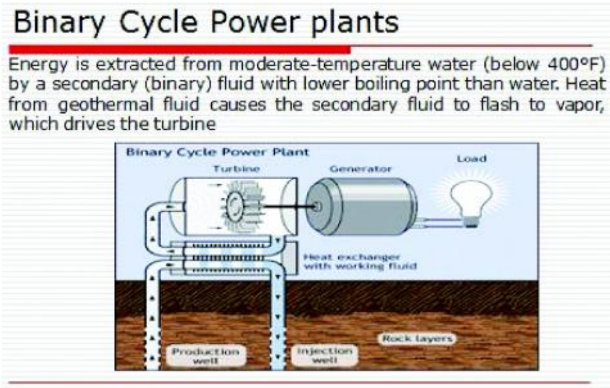

Fig. 6: Binary cycle geothermal power plant

the reservoir after exchanging the heat is then injected back into the reservoir. The schematic is depicted in Fig. 6.

There are situations where it is possible to dovetail the binary cycle with dry steam or the flash steam power plant to extract more work out of the condensed water if it is hot enough to run the binary cycle plant. This is an example of a hybrid plant.

In any case, if it is possible to utilize the low quality heat for space heating or crop drying or any other agricultural or industrial applications, the overall efficiency of the geothermal heat utilization is very high. Such opportunity if available, then it is a combined heat and power plant (CHP plant).

It is also possible that temperature of the produced water is around 100^0C or less. In that case, there is no possibility of power generation. It is still possible depending on the location to find an application for utilizing heat as space heating or some other agricultural or industrial application.

Global Scene

Currently, 24 countries have exploited geothermal energy for power generation and 72 countries use the geothermal heat directly for other applications. Historically, hot water springs have been always used as a source of heat energy for space heating, bathing, and cooking. The world has an installed capacity of around 11,000 MW. This is about 0.5% of the total installed capacity. In addition, 28,000 MW of geothermal energy is exploited for direct heat application. Iceland is a leader in direct heat applications. The space heating is a necessity in Iceland all round the year; 93% of space heating is from geothermal energy. Reykjavik, the capital of Iceland has the world's biggest district heating system in the world based on geothermal energy. Earlier, Reykjavik was known as the most polluted city in the world since coal was used for space heating. However, today with changeover to geothermal heating, it is the world's cleanest city!

So far, the utilization of geothermal energy is mainly restricted to areas along the circum-Pacific "Ring of Fire," spreading centres, continental rift zones and other hot spots. Fig. 7 shows the "Ring of Fire" and other known hot zones.

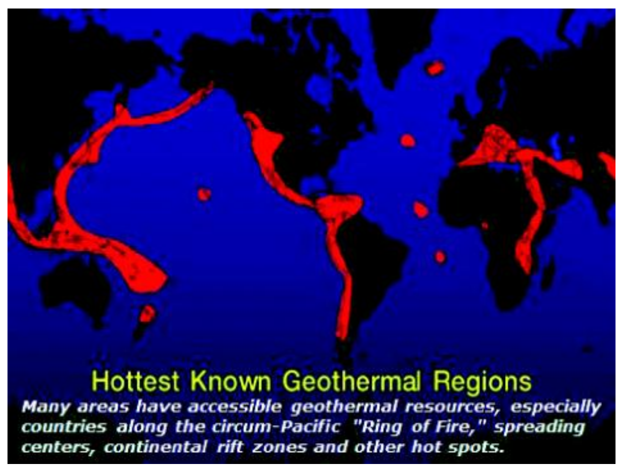

Fig. 7: Ring of Fire

Fig. 8, shows the location of existing geothermal power plants in the world.

As expected, we see a total overlap in the ring of fire and the locations of geothermal power plants. Thus, it is a location-specific niche energy source. We also note that a reservoir with sufficient capacity and sustaining high production rate is also a necessary condition. In fact, it is the productivity of the well which determines and limits the power generation potential, given the geothermal reservoir. Depending on ambient temperature and fluid temperature (say, about 150°C) for a closed loop binary cycle, geothermal power plant water production capacity is required to be in the range of 100 to 140 m^3/h or 2400 to 3500 m^3/day for 1 MW electricity generation. These are very high capacities requiring thick and very permeable water-bearing zone. For water temperature of 100ºC, the required production rates are in the range of 300 to 400 m^3/h.

Exploration for Geothermal Field

The exploration for geothermal site starts from satellite pictures and field geological surveys to isolate the promising areas. Geysers, hot water streams, leakage of steam along fractures, active volcanoes and craters of extinguished volcanoes are the preliminary signs of a possible site. After identifying the area of interest, the geology of the region is studied. Seismic, electromagnetic and geochemical surveys are conducted. Based on these studies, shallow and deep exploration drilling is undertaken mainly to collect the cores of the subsurface rocks and to measure the subsurface temperatures. Based on these studies, if a good prospect is located, an exploratory testing well is drilled targeting the reservoir. The reservoir is then tested for fluid production extensively to determine the extent of the reservoir laterally and thickness as well as the productivity of the well. With the help of these data, the size of the plant is decided and the power plant is designed and installed. The injection well is then drilled to inject back the fluids.

Economic Considerations

About 50% of the cost of the plant is incurred in drilling. Exploration is very expensive. Even in known areas with high temperature gradients over extensive zones, exploration risk is high. In contrast to hydrocarbon exploration, the rewards are not very high. One MW electric power plant is just equivalent to 40 barrels of oil per day. The evacuation of power is also an issue. Unless the site is situated near the market for low quality heat and an electric grid in which power can be fed, the economics may not be favourable. The project with additional financial burden of a transmission line may not be viable. Comparatively, direct heat applications require shallower drilling because the required temperatures are not very high.

A pair of wells, depending on the quality of the heat source, can produce around 5 MW power. In extremely favourable circumstances, even a single well dry steam producer can yield 8MW capacity.

Novel Approaches and Concepts

The known areas of geothermal potential in many cases are getting saturated. Therefore, efforts are in progress to expand geothermal potentials in two different directions. The first approach has led to rapid expansion in the relatively low temperature applications through a binary cycle power plant. The other direction is to eliminate the need for high temperature gradients and water reservoir altogether. This would enable the exploitation of geothermal energy practically all over the world at any location!

On drilling deep enough, one is guaranteed to come across high exploitable temperatures. The rock is likely to be a igneous rock such as basalt or granite; or metamorphic. If two wells are drilled and fractured over a long horizontal section, then we can use this pair as injector and producer. The fracture complex connecting the two wells can act as a conduit for fluid as well as a heat exchanger between the rock and fluid. Thus, in a closed loop, this arrangement will fulfill the requirement of a geothermal prospect. The concept is depicted schematically in Fig. 9.

Another variation of this concept is possible in the sedimentary basin. In sedimentary basin, aquifers are very common occurrences. If deeper aquifers are known to occur based on the drilled data of oil

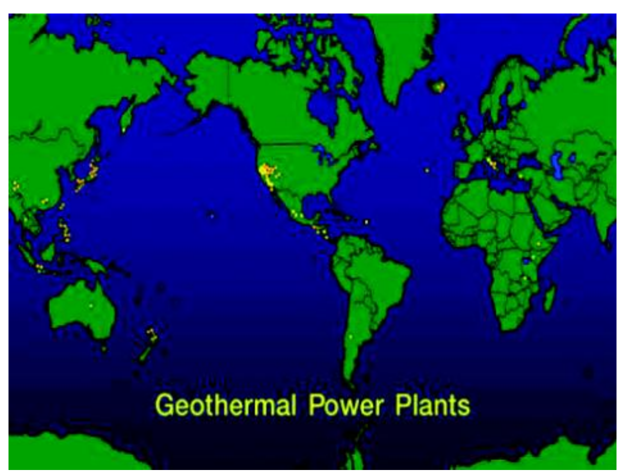

Fig. 8: Locations of geothermal power plants

and gas exploration and production, then utilizing the aquifer as a reservoir and heat exchanger and developing a geothermal prospect in such a location is feasible. The otherwise expensive exploration studies and data are already available with the oil companies. Thus, the first very expensive phase is already accomplished in the oil and gas province. Such concept is under development. It may eliminate the difficult, uncertain and expensive fracturing step from engineered geothermal system (EGS).

Unique Features as Energy Source

Geothermal energy consists of many attractive features. First and foremost, it is a "green " environmentally benign and clean energy source renewable on the human time scale; but unlike other renewable sources such as solar or wind, it is not intermittent and is available round the clock. The land requirement is also minimal. For production of 1000 MW, a geothermal plant has footprint of only 3.5 km^2 versus 32 km^2 and 12 km^2 required for coal-based plant and wind farm, respectively.

Along with land, fresh water is another resource which is getting scarce and has multiple competing demands. Geothermal plant requires just 20 litres of freshwater for 1MWh compared to 1000 litres per MWh required for coal, oil or nuclear plants.

Dissolved greenhouse gases are present in varying proportion in the produced fluid. Greenhouse gases are emitted by the source of auxiliary power for pumps. Existing geothermal plants emit 122kg of CO_2 per 1MWh, which is just a fraction of the emission intensity of fossil fuel-based plant.

Finally, if an appropriate site is available, then geothermal energy is affordable and does not require any subsidy. The major cost is incurred in drilling of two wells. Electric plant construction and drilling of the wells may cost about (€ 2 to 5 million) Rs. 14 to 35 crores per MW. Electricity and breakeven tariff costs (4 to 10 eurocents) Rs. 3 to 7 per unit. The plant load factor is very high. Only normal maintenance of the plant is required. There is no fuel cost and the plant is immune to rising fuel costs. The wells can last for several decades.

The expertise required for exploration and drilling operation is very similar to the upstream oil and gas industry. Hence, it is not a surprise that Chevron, the well-known oil company, is the biggest private producer of geothermal energy.

The Indian Scene

In India, there are several geothermal provinces where hot water streams are present. The provinces are: Tattapani in Chhatisgarh, Puga Valley in Jammu and Kashmir (J&K), Cambay graben in Gujarat, Manikaran in Himachal Pradesh, Surajkund in Jharkhand and Chhumathang in J&K. In India, geothermal energy is a state subject. Various states have floated tenders or called for 'Expression of Interest'. However, lack of background knowledge is the main hurdle. Secondly, though there is no doubt of temperature anomalies, the quality, depth and areal extent are not known. In places such as Puga Valley, the terrain is tough and there may be evacuation problem. As a result, no serious deep exploratory drilling has been undertaken so far at any of the sites. Unless there is more clarity on geology and nature of the prospect, private parties may not come forward. The state governments need to work in partnership with companies coming forward rather than treat it as a proven geothermal field and expect an income out of it.

Apart from these provinces, there is the Himalayan Geothermal belt passing through India, Tibet, China, Myanmar and Thailand replete with more around 1000 hot water springs. Thailand has a 300

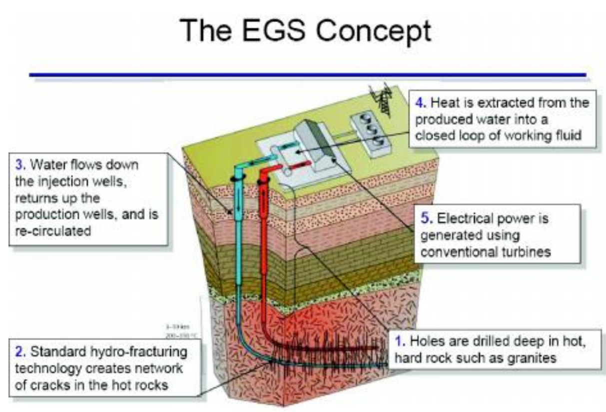

Fig. 9: Engineered geothermal system

kWe plant in tandem with utilization of exhaust heat for crop drying, cold storage and recreational park with bathing pools. Yangbajang in Tibet generates 25 MWe supplying 40% electricity requirement of the city of Lhasa. There are seven more plants near this area producing 1 MWe each.

Inaccessible areas, rough and tough terrain, away from the major metropolitan or industrial centres are some of the reasons why this promising but limited source has not received focused attention so far.

Conclusions

We note that geothermal is a clean and sustainable source of energy. In CHP (combined heat and power) mode, the efficiency is very high. Therefore, countries which require space heating have an added advantage. However, the present day technology allows exploitation of geothermal energy only in geologically suitable zones. Unless new technologies such as EGS succeed in the sedimentary basin, there will be limits to the development of the geothermal energy sector. Globally, renewable energy (excluding conventional hydroelectric power generation) accounts for less than 1% of the total energy consumption and within that geothermal contributes 10%.

For India, exploration in the prospective area is a high-risk venture; yet the rewards are not very high. Hence, concentrating on geothermal energy in the sedimentary basin and keeping track of development elsewhere in EGS is the best strategy.

References

The information, especially the quantitative data and the illustrations are from the following.

References

http://physics.ucsd.edu/do-the-math/2012/01/warm-and-fuzzy-on-geothermal/

http://en.wikipedia.org/wiki/Geothermal_energy

http://geothermal.marin.org/geopresentation/sld001.htm

http://www.indiaenergyportal.org/subthemes_link.php?text=geothermal&themeid=13

http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0114.pdf.