

Geothermal Power—A Giant Energy Source Still to Be Tapped in Brazil

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Abstract

This paper presents the Brazilian geothermal potential for electricity generation. The main areas of hot springs are presented as a guideline for future evaluation of electricity generation from geothermal reservoirs. Locations of wells with the main anomalously high geothermal gradients identified from an inventory of 6200 wells are presented, along with heat flow measurements and their site geology detailed to provide a basis for further development. The availability of water supplies at each potential site is also presented. Data on the geothermal gradient of each site, as well as geothermal flux and thermal conductivity are provided. Economic, logistical and other factors are also considered to show the feasibility of a geothermal power project in Brazil. In addition, the potential of geothermal energy and the different techniques for exploiting geothermal energy are presented to show how the Brazilian potential can be exploited. The report shows that there are 40 potential sites for geothermal power plants in all regions of the country. This report indicates that it is possible, with current technology, to generate geothermal power at depths of no more than 3 km in Brazil. The lack of familiarity with this type of project in the country, coupled with the numerous easily accessible sustainable energy sources in Brazil, presents a challenge for investors considering investing in this emerging form of power generation in the country.

Keywords

Brazil, Geothermal Power, Geothermal Energy in Brazil, Renewable Energy, Energy Transition, Energy, Power

1. Introduction

This article explores the various types of geothermal resources, including low, medium, and high enthalpy resources, and their applications in electricity generation and direct heating. It also discusses the geological conditions necessary for suc-

successful geothermal projects, the environmental impacts associated with geothermal energy production, and the economic advantages of utilizing this energy source compared to fossil fuels. Furthermore, the article highlights the potential for geothermal energy development in Brazil, where existing geothermal resources have primarily been harnessed for direct heating applications. By examining the current state of geothermal energy, its technological advancements, and its future prospects, this article aims to underscore the importance of geothermal energy as a sustainable and viable alternative in Brazil's energy landscape. The main objective of this paper is to present the Brazilian geothermal energy potential with a focus on electricity generation. Most uses of geothermal energy in Brazil are so far restricted to health, tourism and bathing with a few industrial applications for heating. These are not going to be presented in detail here. Main areas of hot springs are presented just as guidance for future assessment for electricity generation purposes out of geothermal reservoirs. The whole Brazilian territory or its largest part is suitable for the use of geothermal air conditioning, beyond geothermal heat pumps. We will just show how it works for those who are not familiar with the subject.

2. Geothermal Energy

Of the world's total energy matrix, only 0.4% is generated from geothermal sources [1]. Geothermal energy is a renewable source of energy that comes from the earth's natural heat. The source of such heat is the earth's core, mantle and crust. At the base of the earth's crust temperatures are between 200°C and 1000°C. And at the earth's core temperatures can be estimated at between 3500°C and 4500°C. (or 5000°C - 6000°C). Heat is transferred from the interior to the surface by conduction. The average geothermal gradient is 25°C - 30°C/km (ratio of temperature increase to depth). Geothermal production pools are at 2 km deep (sometimes > 3 km). The temperature in dry rock at 3 km deep = 90°C - 100°C (for a normal gradient of 25°C - 30°C/km). Geothermal generation of electricity comes from areas with abnormal gradients (>25°C - 30°C/km) [2].

High-temperature geothermal fields are located at the boundaries of tectonic plates in areas of intense island-forming volcanic activity or where the boundaries advance across continents. Tectonic plates are large rigid plates that make up the Earth's crust and float on the mantle, moving relative to each other at a rate of a few centimetres per year. Where plates collide, there is intense seismic activity, faulting and, in many cases, volcanic activity. High levels of fracture and pressure are generated, creating large porosity and high temperatures. Most plate contacts occur under the ocean. In other cases, magmatic intrusions (sometimes with molten rock) reach temperatures of over 1000°C just a few kilometers underground, heating the groundwater. Examples: the "belt of fire" [3] (surrounding the Pacific Ocean (Pacific Plate) with intense volcanism and geothermal activity in New Zealand, Indonesia, the Philippines, Japan, Kamchatka, the Aleutian Islands, Alaska, California, Mexico, Central America and the Andes, Iceland (the largest island on

the edge of the Atlantic Mesocean Ridge), the East African Rift (volcanoes with geothermal resources in Djibouti, Ethiopia and Kenya) [2].

Basically three kinds of geothermal energy resources can be distinguished: low enthalpy resources ($<90^{\circ}\text{C}$) used for ($30^{\circ}\text{C} - 69^{\circ}\text{C}$) thermo-culture, bathing and ($70^{\circ}\text{C} - 140^{\circ}\text{C}$) water and space heating, drying; Medium enthalpy resources ($140^{\circ}\text{C} - 220^{\circ}\text{C}$) used for drying, heat for industrial processing, electricity generation (binary system), and; high enthalpy resources ($>200^{\circ}\text{C}$) used for ($>220^{\circ}\text{C}$) steam thermoelectric, binary electrical generation system, process steam.

High temperature fields are mainly related to volcanoes or magmatic activities used for conventional energy production and for the direct exploitation of thermal energy. Production wells are located between 1.5 - 2.5 km deep. Production temperature is generally between $250^{\circ}\text{C} - 340^{\circ}\text{C}$. Useful electrical energy (on the grid) is generally between 5 and 10 MWe and rarely above 15 MWe per well.

Low temperatures are generally not directly related to volcanoes or magmatic activity. They use direct thermal energy. Hot water with a lower density than the surrounding cold water flows to the surface along fractures and where there is greater permeability (convection). There are four types: 1) Related to the deep circulation of meteoric water along fractures and faults, probably the most common type of hot spring in the world. They occur in most rock types of various ages. Most visible in mountainous regions along faults in valleys. They are more numerous in areas with high regional conductive heat flow (with or without volcanic activity) and less frequent in areas with normal or low heat flow. The main conditioning factor is the pattern by which meteoric water circulates into the terrain. This type of geothermal source is common in areas of recent tectonic activity. Examples: Balkan peninsula and Turkey [2].

The other three types are: 2) In very porous rocks under high hydrostatic pressure. This is the most important geothermal resource not associated with recent volcanic activity. Deep sedimentary basins with rocks of high porosity and permeability, isolated from surface aquifers by an impermeable stratum, cause water to be heated by confinement and regional heat, in many regions of the planet, regardless of the geological age. These basins may have extensive Geothermal reservoirs (hundreds of kilometers). Thermal waters in such basins have temperatures between $50^{\circ}\text{C} - 100^{\circ}\text{C}$ (in wells <3 km deep), varying according to depth and local geothermal gradient. Examples of such areas are under exploration in Paris (Paris basin), Hungary (Pannonian basin) and several areas in China. Geothermal resources of this type rarely manifest themselves on the surface, but are usually detected when prospecting for gas or oil. In Brazil there are some oil drilling that reached these hot water reservoirs and are nowadays used to provide hot water and heating for industrial purposes; 3) In very porous rocks at pressures much higher than the hydrostatic load (*i.e.* geopressurized); 4) In hot dry rock formations (low porosity) – HDR. In general, natural systems have mixed characteristics of these types. Geothermal resources of the types: a) and b) Where there is a large amount of fluid that vaporizes for energy generation are called hydrothermal and are the only commercial geothermal resources for energy generation [4].

Basic conditions for a geothermal project are: lateral or upward heat conduction; network of interconnected fractures shallow enough for economic drilling; the fractures constitute the geothermal reservoir where the hot water and steam is stored; geothermal fluid temperature $> 150^{\circ}\text{C}$ (100°C in some cases); low content of mineral salts and gases in the fluid; Complementary availability (“make-up”) of water for cooling the steam; flow and/or minimum availability of water between 100 and $360\text{ m}^3/\text{h}$ for 1MW; proximity to transmission or load lines [4].

Environmental impacts of Geothermal electricity generation plants can be summarized as follows: 1) Emissions: Flash installations may produce excess steam. On the other hand, there are no gas or liquid emissions in binary plants (current technological trend). Emissions of SO_x , NO_x , CO_x contained in the gases of older single-cycle plants are five times lower than other thermoelectric plants (SHPE, 1997); 122 g/kWh CO_2 (Bertani and Thain, 2002, 85 plants studied in 11 countries); 91 g/kWh CO_2 , 85 H_2S , 750 CH_4 , 599 NH_4 [4], plants USA). In Italy and the USA, plants are obliged to remove H_2S from emissions to the environment. There may be traces of H_2S , NH_4 , Hg, Rd, emissions from low-temperature geothermal plants fraction of high-temperature plants (for electricity generation); 2) Effluents: Geothermal water is recycled, restoring reservoir capacity; 3) Waste: Dissolved salts and minerals (“waste”) contained in the geothermal fluid are re-injected with excess water into the reservoir below the level of the surface aquifers. Some geothermal installations produce sludge or some solid material that is disposed of in specialized sites or is a source of raw materials for industry (zinc, silica, sulfur) as a by-product; 4) Visual Impact: “Nonexistent” at GEOTHERMAL HEAT PUMPS and Lower than all other energy generation facilities from other sources (except sub-oceanic); 5) Sustainability: The Earth’s Heat is generated continuously at the center of the Earth. Even in areas dependent on the existence of a hot water reservoir, the extracted volume can be reinjected, making this energy source sustainable (evidence: Lardarello-1913, Wairakei, NZ-1958, Geysers-1960) [5] (Table 1).

Table 1. Relative intensity of environmental impacts caused by geothermal energy [5].

| IMPACT | PROBABILITY | CONSEQUENCE |
|------------------------------------|-------------|-------------|
| AIR POLLUTION | L | M |
| WATER POLLUTION | M | M |
| SUBSOIL POLLUTION | L | M |
| SUBSIDENCE | L | LM |
| NOISE | H | LM |
| EXPLOSIONS | L | LM |
| ARCHEOLOGICAL AND CULTURAL IMPACTS | LM | MH |
| SOCIO ECONOMICAL PROBLEMS | L | L |
| CHEMICAL OR THERMAL POLLUTION | L | MH |
| WASTE DISPOSAL | L | L |

Legend: L—Low; M—Moderate; H—High.

Reykjavik's geothermal district heating has made the city one of the cleanest in the world. The dense generation of smoke from chimneys and heating [6] has been abolished with the ban on the use of fossil fuels to heat homes. Almost 90% of all homes in the country are nowadays heated by geothermal energy. The rest are heated by a combination of hydroelectric (83%) and geothermal (17%). Reducing CO₂ emissions by replacing fossil fuels with geothermal energy has reduced CO₂ emissions by around 2 million t/year. Total CO₂ emissions in Iceland in 2004 were 2.8 million tons. The reduction has significantly improved Iceland's global emissions position. After 95% of the buildings being heated with geothermal energy. Reykjavic is now one of the cleanest cities in the world [7]. This could occur in other countries or locations (e.g. Santiago-Chile).

It is important to note in **Table 2** that, among the renewable energies, the highest CAPACITY FACTOR for electricity generation is GEOTHERMAL POWER.

Table 2. Costs comparison between Geothermal energy and other renewable sources of energy [8].

| Electricity production and costs from renewable energy | | | | | | | | | |
|--|---------------------------|-------------|-----------------------------|-------------|-----------------|----------------------|------------------------------|-------------------------|---------------------------------------|
| | Energy production in 1998 | | Installed capacity end 1998 | | Capacity factor | Current energy cost | Potential future energy cost | Turnkey investment cost | Increase in inst. Capac. Last 5 years |
| | Twh(e) | % | Gwe | % | % | USCs/KWh | USCs/KWh | US\$/KW | %/year |
| Hydro* | 2000 | 92.00 | 663 | 91.80 | 20 - 70 | 2 - 10 | 2 - 8 | 1000 - 4000 | 2 |
| Biomass | 160 | 5.66 | 40 | 5.53 | 25 - 80 | 5 - 15 | 4 - 10 | 900 - 3000 | 3 |
| Geothermal | 46 | 1.63 | 8 | 1.11 | 45 - 90 | 2 - 10 | 1 - 8 | 800 - 3000 | 4 |
| Wind | 18 | 0.64 | 10 | 1.38 | 20 - 30 | 5 - 13 | 3 - 10 | 1100 - 1700 | 30 |
| Solar photovoltaic | 0.5 | | 0.5 | | 8 - 20 | 25 - 125 | 5 - 25 | 5000 - 10,000 | 30 |
| thermal electricity | 0.05 | | 0.12 | | | | | 3000 - 4000 | |
| | 1 | | 0.4 | | 20 - 35 | 12 - 18 | 4 - 10 | | 5 |
| Tidal | 0.6 | 0.02 | 0.3 | 0.04 | 20 - 30 | 8 - 15 | 8 - 15 | 1700 - 2500 | 0 |
| Total | 2826.1 | | 722.2 | | | | | | |
| Heating production and costs from renewable energy | | | | | | | | | |
| | Energy production in 1998 | | Installed capacity end 1998 | | Capacity factor | Current energy costs | Potential future energy cost | Turnkey investment cost | Increase in inst. Capac. Last 5 years |
| | TWth | | GWth | | % | USCs/KWh | UScents/KWh | US\$/KW | %/year |
| Biomass** | >700 | | >200 | | 25 - 80 | 1 - 5 | 1 - 5 | 250 - 750 | 3 |
| Geothermal | 40 | | 11 | | 20 - 70 | 0.5 - 5 | 0.5 - 5 | 200 - 2000 | 6 |
| Solar heat low temperature | 14 | | 18 | | 8 - 20 | 3 - 20 | 2 - 10 | 500 - 1700 | 8 |

* Large hydro stations produce 2510 TWh (capacity 640 GWe) and small 90TWh (23 GWe). ** The table also shows ethanol under biomass, with operating capacity (end 1998) 18 billion litres, energy production of 420 PJ, current energy cost 8 - 25 US\$/GJ and future potential energy cost of 6 - 10 US\$/GJ.

Studies carried out in Australia corroborate this claim, mainly when considering the need to control emissions of pollutants from fossil fuels (Figure 1).

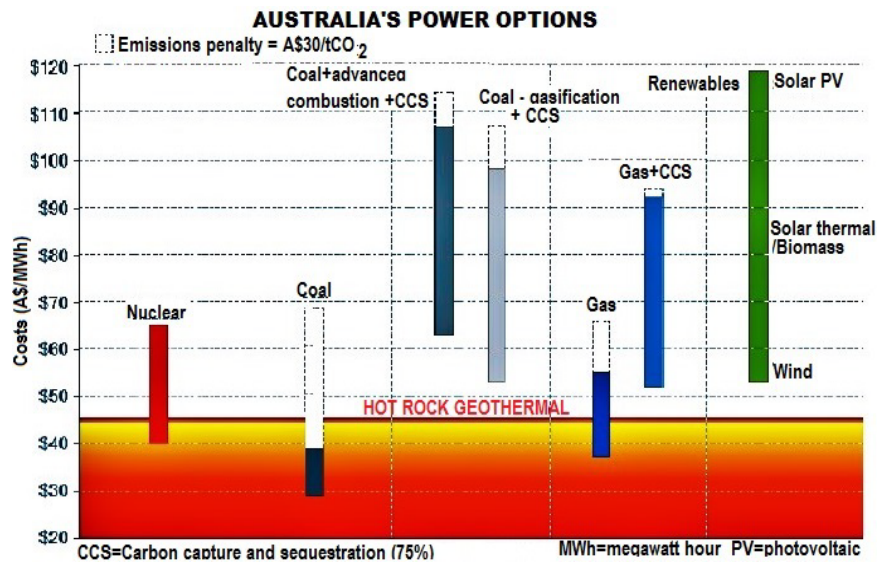


Figure 1. Cost comparison among several energy sources in Australia [8].

Costs expressed in Figure 1 refer to levelized cost of electricity (LCOE). The studies all used levelized cost of electricity (LCOE) estimates to calculate a constant cost for each generation option. The levelized cost is the constant real wholesale price of electricity that recoups owners' and investors' capital, operating, and fuel costs including income taxes and associated cash-flow constraints. The LCOE approach is widely used and easy to understand, but often produces widely varying results mainly because of differences in the assumptions and inputs used in calculations [9]. It is also important to note that where generation produces emissions, a penalty is also applied, increasing once more this cost, represented by the prolongation of the dashed lines. In addition, other renewable energy source, such as wind and solar, although do not emit gases during generation, materials for constructing solar panels and wind turbines may have a high environmental impact.

In summary, of all the forms of renewable energy, geothermal energy has the greatest availability for energy generation, with up to 90% of the time being suitable for this purpose. It is noteworthy that, even in Brazil, where wind and solar power have the highest capacity factors worldwide, they are still lower than the average capacity factor of geothermal power, among other advantages (see Table 3). This constitutes yet another compelling argument for exploring the potential of geothermal energy. Furthermore, it is estimated that the world's reserves of geothermal energy of the HDR (Hot Dry Rock) type (Figure 2) exceed all known world's fossil fuel reserves by approximately 30 times. Nevertheless, Brazilian official authorities and government research companies have thus far neglected to incorporate the extant geothermal resources of the country into their studies of the nation's energy matrix. Fuel reserves by around 30 times. However, Brazilian

official authorities and research government companies do not even consider the existing geothermal resources that have been used in Brazil, in their studies of the energy matrix of the country.

Table 3. Comparison among renewable power sources in Brazil and geothermal power.

| DATA FOR A 30MW POWER PLANT | INVESTMENT COST (R\$ × 10 ⁶)* | LAND USE (×10 ⁴ m ²) | MEAN CAPACITY FACTOR (%) | O & M COSTS (R\$/KW)* | LIFESPAN (YEARS) |
|-----------------------------|---|---|--------------------------|-----------------------|------------------|
| WIND | 102 (3.4/MW [10]). | 74.04 [11] | 40 [10] - 50 [12] | 100 [13] | 20 [13] |
| PHOTOVOLTAIC | 105 - 120 [14] | 60 - 90 [15] | 30 [12] | 39 [13] | 20 [13] |
| HYDRO** | 304.2 (US\$2600/KW [13]) | 30 [16] - 200 [17] | 55 [12] | 50 [13] | 30 [13] |
| GEOTHERMAL*** | US\$75 × 10 ⁶ [18] | 12 - 97 [19] | 78 [20] | US\$110/Kwyear [21] | 35 [22] |

*- Costs are in Brazilian Reais (R\$) and cannot be translated to US\$ except when specific conversion is provided, since the currency varies significantly in very short time. **- Area occupied by hydropower plants are limits between the largest and the smallest hydropower plants in Brazil. ***- US\$ values from international standards and markets are not compatible for comparison with Brazilian values.

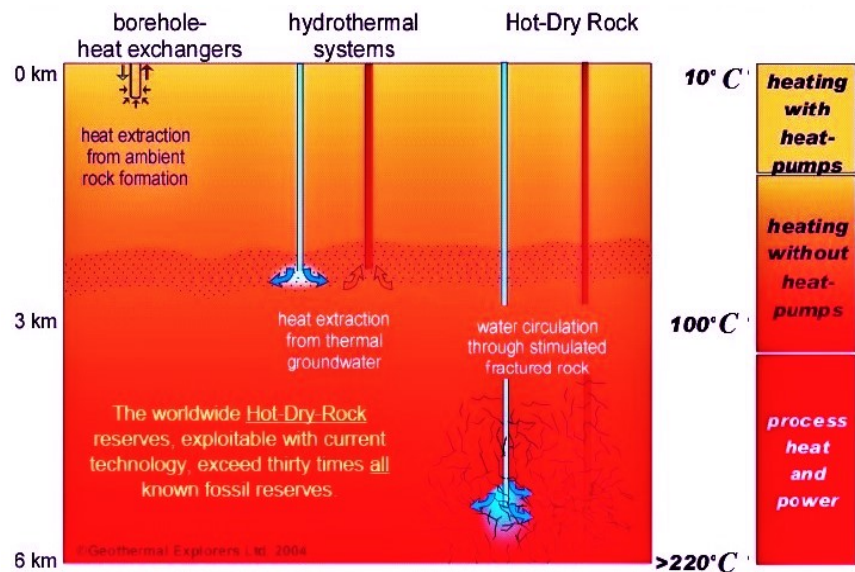


Figure 2. Types of geothermal resources from the Earth's heat. All systems show extraction wells (red) and injection wells (blue) [23].

Figure 3 shows all uses of geothermal energy according to the temperature demand and source temperature. Main reservoirs and typical source depths are presented in **Figure 4**.

Geothermal resources, as shown in **Figure 4**, are an initial view of such resources, based in conservative approaches. Therefore, the depths considered are based in the average Earth's geothermal gradient and exploration of deep wells supported by two drillings, one for fluid injection and the other for steam escape. However even medium enthalpy projects use to work, nowadays, with geothermal gradients around or above 50°C/Km, what points to drillings around 3 km deep, or, at the most, less than 4 km deep. In addition, present projects propose the use

of only one well working like a heat exchanger. The fluid is injected and escape from the same well (Figure 4). Other than that, working with binary cycle, the system may be fully enclosed. One must notice that, although the diagrams show hot fluid flow, this is just a question of depth, temperature and water volume to have steam, instead of hot water.

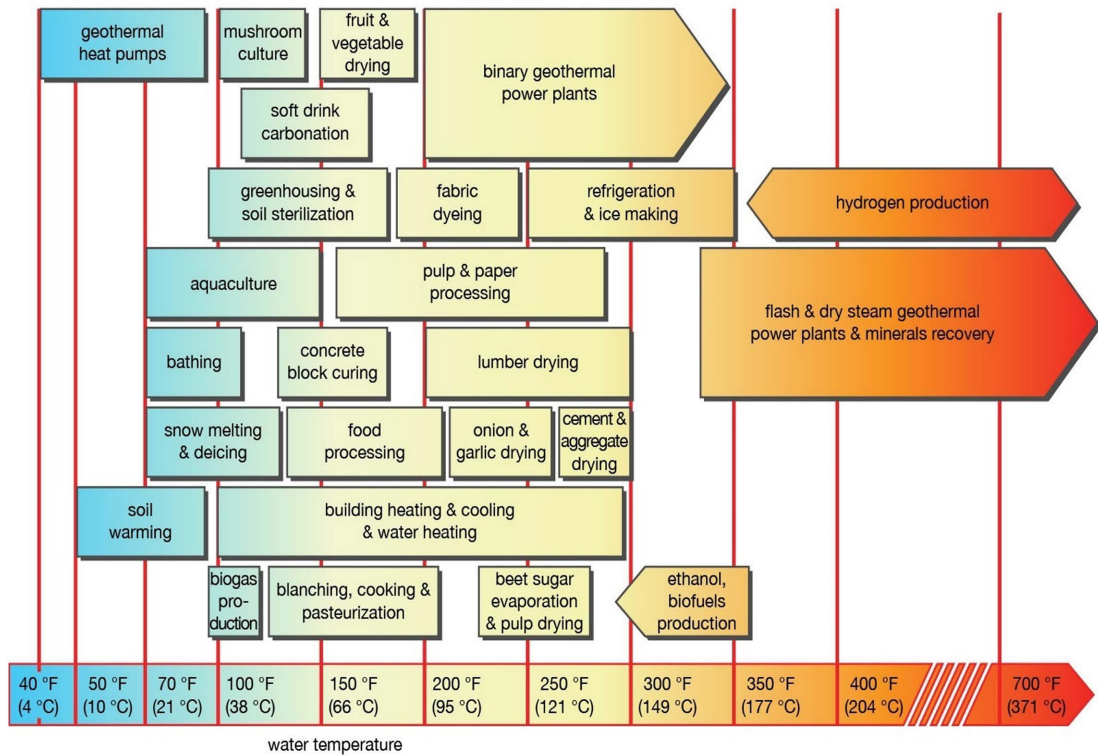


Figure 3. Geothermal energy uses [24].

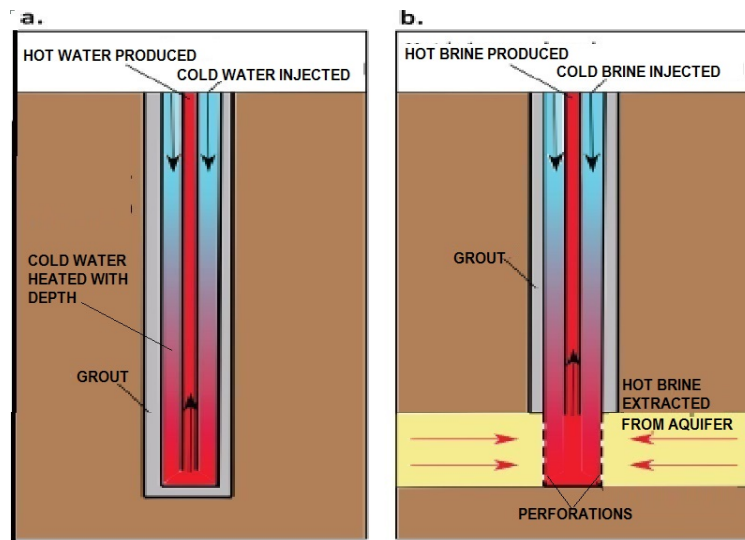


Figure 4. Schematic of different single well extraction methods: (a) is a conventional deep borehole heat exchanger, while (b) shows the open standing column “deep geothermal single well” design [25].

2.1. Technologies for Geothermal Energy Use

Direct Use of Heat

Hydrothermal waters have been used since ancient times for spa purposes all over the world. In Brazil, the resort of CALDAS NOVAS (GO) stands out, receiving the largest influx of visitors in the country for this purpose. The waters are simply extracted and used as showers or in artificial pools (Figure 5). Natural lakes and waterways are also used for this purpose. The simple conduction of hot water through pipelines or the circulation of cold water through deep underground pipelines (less than 500 m) and their extension into enclosed and open spaces for space heating or melting snow on sidewalks and urban roads is used in cold climate countries and is, after bathing, the second largest direct use of geothermal resources. (Figure 6) In natural gas exploration, oil companies also use natural heat from deep wells for gas lift operations. Figure 7 shows a schematic example in use by PETROBRAS in Brazil.

GEOHERMAL ENERGY TECHNOLOGIES FOR ENERGY USE



Figure 5. Caldas Novas (GO), Brazil—hot water park in a SPA hotel.

GEOHERMAL ENERGY TECHNOLOGIES FOR ENERGY USE



Figure 6. Installation of hot water pipelines in parkway for snow melting.

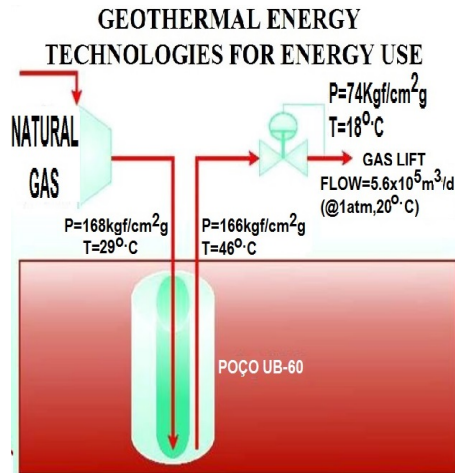


Figure 7. Direct use of geothermal heating for natural gas [1].

1) *Geothermal heat pumps*

Another direct use of heat that is gaining increasing use is by means of heat pumps. They are ordinary heat pumps that use the Earth’s heat instead of atmospheric air to provide space heating and cooling and in most cases hot water. Because they use the Earth’s natural heat, they are among the most efficient and comfortable forms of heating and cooling currently available. ENERGY STAR-labeled geothermal heat pumps consume around 30% less energy than conventional heat pumps. The system can also be used for industrial heating and cooling. Depending on the latitude, the underground temperature varies from 7°C to 21°C. Like a cave, this underground temperature is warmer than the air during the winter and cooler during the summer. They don’t use energy to cool or heat, but only to move air from one place to another. They replace air conditioning equipment and furnaces or heaters (Figure 8). Several arrangements can be used (Figure 9).

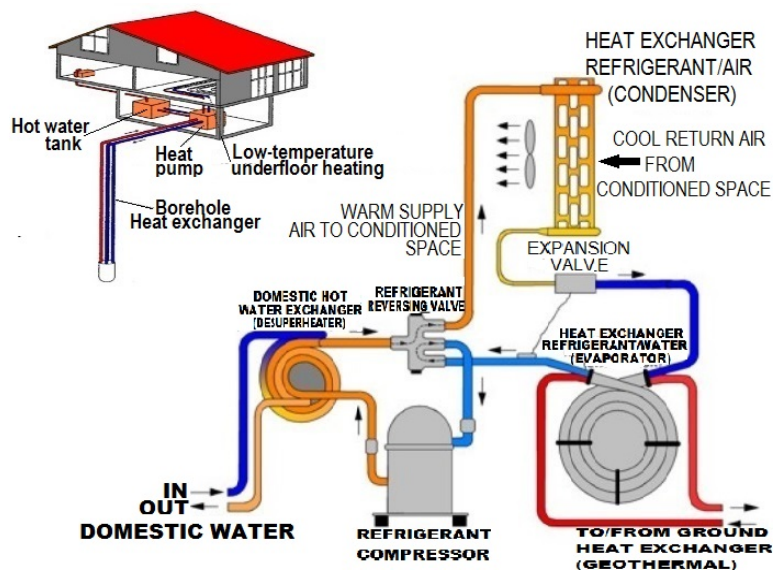


Figure 8. Geothermal air conditioning using a geothermal heat pump [3].

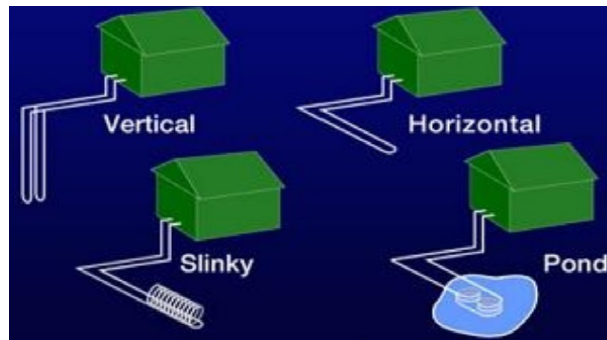


Figure 9. Geothermal heat pumps ground loops [25].

The use of the Earth's geothermal energy, in this case, is based on the fact that from a few meters deep in the ground, the temperature of the ground is stable, regardless of the temperature of the external environment on the surface. In different locations, it has been found that this is generally observed around 10m deep in the ground, and is invariable with the time of year, be it winter or summer and regardless of soil composition. Therefore, even if the surface temperature is around -10°C or 40°C , around 10 m deep it will be invariable. Nevertheless, this stable temperature varies from place to place. Figure 10 illustrates two examples. In this way, although geothermal pumps, in North America, are currently being used as heat pumps, this characteristic of the soil, opens up great possibilities for geothermal pumps be also used to cool the environment, especially in hot countries like Brazil. In the particular case of Brazil, the region with the lowest geothermal gradients and still made up of poorly heat-conducting soils is located precisely in the region of the country where surface temperatures are the highest, making these regions ideal for the use of geothermal pumps as environmental coolers. However, in order to do so, they must have reversed flow (Figure 8). In other words, they cannot work on a single flow as in the case of geothermal heat pumps.

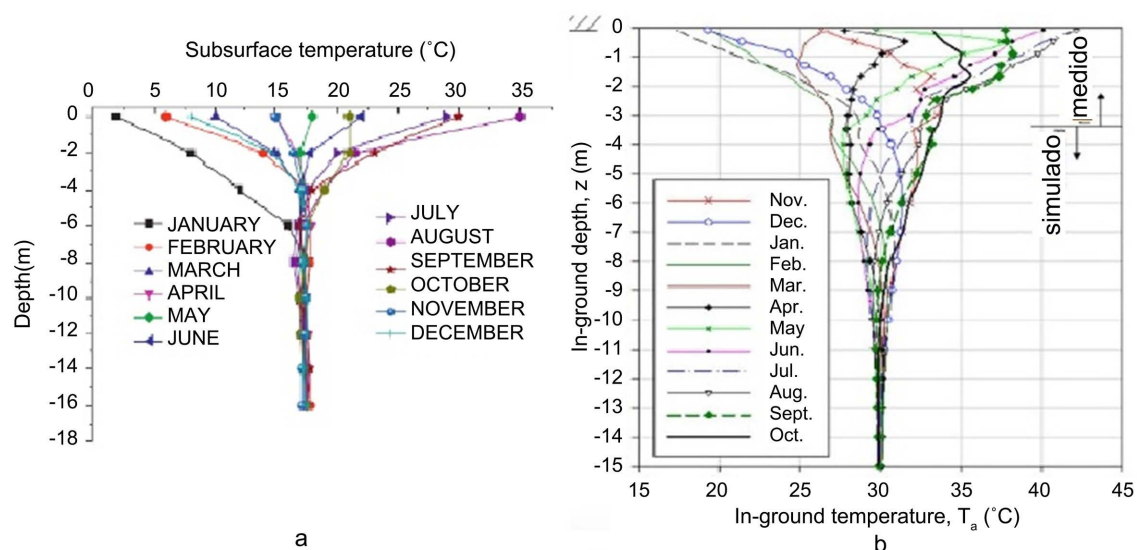


Figure 10. (Monthly ground temperature with depth for (a) Beijin area [26] and for (b) Riyad, Saudi Arabia [27].

Another possibility, as shown in **Figure 9**, is the use of bodies of water as heat exchangers. Water is an excellent heat exchanger. Water mirrors have been used from ancient times to the present day for this purpose, improving the comfort of the environment. The Moors used to do this in the past and today modern buildings also use the same principle to save energy. In addition, many bodies of water, due to their depth and extent, have a thermal zoning according to their depth. In the shallowest part, exchanges with the external environment cause temperature variations in the body of water. However, after a certain depth, there is an “isolation” of this superficial part, by means of a thermocline, moving to a colder deep region with a stable temperature. **Figure 11** illustrates this case. Depending on the purpose for which the geothermal pump is to be used, the heat exchanger pipe can be placed at the top and/or bottom, and the flow in the pump can be reversed, depending on the purpose of the moment, *i.e.* cooling or heating the environment. This solution is particularly interesting for large projects that use large bodies of water. For example, airports. Some have their own dams or supply lakes or draw from nearby bodies of water. These same bodies could serve as heat exchangers, generating geothermal air conditioning for the development.

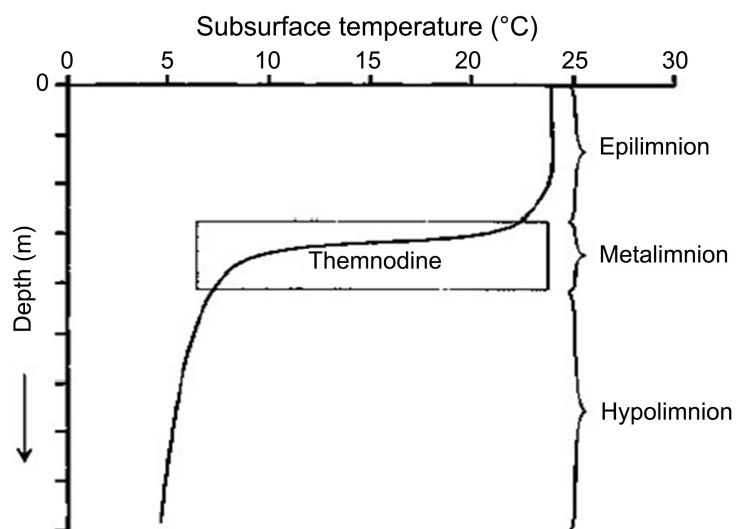


Figure 11. Typical temperature profile from a stratified lake in the temperature zone, showing the division of the water into three layers of different density [28].

In both cases, the internal part of the room to be acclimatized is fitted with conventional air conditioning pipes up to the geothermal pump. From there, PVC pipes with a diameter, length and resistance appropriate to the purpose and requirements of the project are used for the ground or body of water.

2.2. Electricity Generation

Electricity is usually generated by conventional steam turbines. Steam, the temperature of which generally exceeds 150°C, flows directly from the dry steam wells or, after separating the wells with a steam/liquid mixture, into electric generators.

The steam then passes through a condenser where vacuum conditions are maintained by cooling water. The generating units are usually between 20 - 50 MW. Binary-type plants are currently preferred because they can use fluids at lower temperatures than geothermal steam, between 85°C - 170°C. They use a secondary working fluid, usually organic, with a low boiling point and high steam pressure. The fluid passes through the turbine in the same way as geothermal steam in conventional cycles. Binary plants are usually built in modular units of a few MW capacity and interconnected. Kalina is one of the most recent models to use a water-ammonia mixture as the working fluid. This increases the cycle's efficiency compared to other binary cycles. The efficiency of using geothermal energy is substantially increased by co-generation plants where, in addition to producing electricity, hot water can also be used for heating or direct use. However, the use of hot water requires a large consumer market or a specific market in the vicinity of the installation. In Iceland, the co-generation plants in operation are located at distances of 12 to 25 km from consumer cities [2]. One can distinguish four types of geothermal electricity plants: "direct-steam"; "flash steam (vaporization = steam purge)"; "single-flash (vaporization or single purge)"; "double-flash (vaporization or double purge)"; binary and hybrid. Hybrid systems may be a combination of: "direct-steam/binary", "single-flash/binary". "integrated single/double flash" or fossil/geothermal systems. Plant performance is measured by the application of the second law of thermodynamics (Work available). Geothermal plants operate as a series of processes, not a cycle. The thermal efficiency for a cycle does not apply in this case except for binary type plants. Even in this case it only applies to the closed working fluid cycle. The utilization efficiency (η_u) measures how well the plant converts the exergy (or available work) of a resource into useful work (energy).

For a geothermal plant, this is:

$$\eta_u = w/m \cdot e$$

where:

W = net electrical energy supplied to the grid

m = total mass flow of geofluid

e = specific energy of the geofluid under reservoir conditions, given by the formula:

$$e = h(P_1 - T_1) - h(P_o - T_o) - T_o[s(P_1 - T_1) - s(P_o - T_o)]$$

"The specific enthalpy h and entropy s are evaluated at reservoir conditions P_1 e T_1 and at so-called 'dead-state' P_o , T_o . The latter correspond to the local ambient conditions at the plant site. In practice the design wet-bulb temperature may be used for T_o (in absolute degrees) when a wet cooling system is used; the design dry-bulb temperature may be used when an air-cooled condenser is used [29]."

2.2.1. Binary Cycle Plants

Of particular importance for regions with medium enthalpy geothermal fields, binary cycle plants, which use a working fluid, are the most suitable and a current

trend. This allows the deepening of the generator wells to be reduced. As in the case of Brazil, the fields that generate electricity from geothermal energy are probably medium or low enthalpy, with very few cases of high enthalpy, the location of which makes them unexplorable. Therefore, it is justified to present a little more about this system. Under this cycle, the geofluid does not come into contact with the moving parts of the plant, eliminating or minimizing the adverse effect of corrosion. They are advantageous alternatives in the case of low geofluid temperatures ($<150^{\circ}\text{C}$) or when the geofluid has a large amount of dissolved gases with great potential for erosion and deposition in the pipes. This problem is aggravated when the liquid vaporizes in production wells. Most of these plants operate with pumped (non-stream) wells. The geofluid remains in the liquid phase throughout the process. Cooling can be with water or air depending on local conditions. The use of cooling water requires an additional source of water, since the condensate from the geothermal steam is not available as in "DIRECT" or "FLASH" type plants. Due to chemical impurities, wastewater is not suitable for use in the cooling tower. There are several types of working liquids for the closed generation cycle. The choice is based on the thermodynamic suitability of the working fluid for the geofluid (mainly T). In general, hydrocarbons (ISOBUTANE, ISOPENTANE and PROPANE) are used. With the use of mixed working fluids (e.g. ISOBUTANE + ISOPENTANE or WATER + AMMONIA = KALINA) evaporation and condensation take place at varying temperatures, allowing a better fit between the geothermal fluid and the working fluid (evaporation) and between the cooling water and the working fluid (condensation) increasing the efficiency of the heat exchange and the system in general. In addition, if the turbine exhaust still has excess heat, a heat recuperator (economizer) can be used to preheat the working fluid (e.g. Kalina-type plants). Standard, trailer-mounted units can be prefabricated, tested and assembled for delivery to the field installation site. Several units can be interconnected on site to achieve the source's generation potential. The optimum working fluid should give the plant high efficiency of use and safe, economical operation. They are best suited to schemes of 1 - 3 MW/unit [29]. **Figure 12** shows a simplified flow diagram of a binary cycle plant.

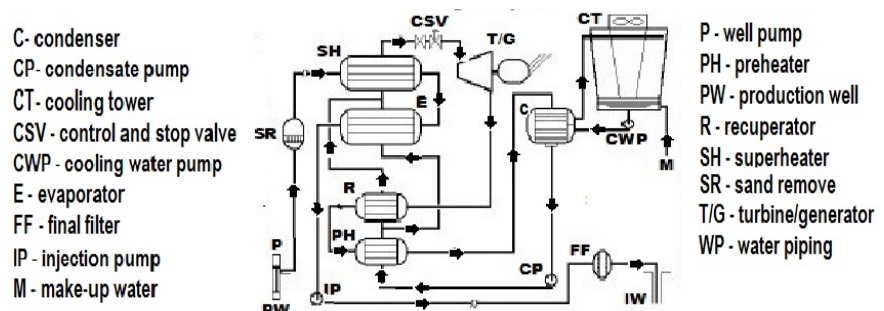


Figure 12. Simplified flow diagram for a Kalina binary geothermal power plant [29].

2.2.2. HDR/EGS

A naturally occurring geothermal system, known as a hydrothermal system, re-

quires three key elements to generate electricity: heat, fluid, and permeability (when water can move freely through the underground rock) [30]. These elements are associated with high enthalpy conventional geothermal power plants. When some of these three elements are not sufficient or lack, the question may be solved by using solutions according to the element that is lacking. In the case of lower enthalpy reservoirs, binary cycle system with a working fluid with a low boiling point and high steam pressure may be used. However if there is not enough water in the geothermal reservoir or if there is not adequate permeability, or both, this may be solved by creating an Enhanced Geothermal System (EGS) associated with a binary cycle plant. In an EGS, fluid is injected deep underground under carefully controlled conditions to circulate throughout the fractured hot rock where it becomes hot as it circulates. With the heat the fluid may vaporize and be extracted through another well, called purge well, and this steam will move a turbine to generate electricity for the grid. If the fluid does not vaporize but is still very hot, this is extracted through the purge well and used as a heat exchanger to vaporize a working fluid with lower boiling point and high steam pressure to move the turbine. There is also the case when permeability and fractures are not enough to allow fluids to circulate and get heated. In this case, techniques already used for decades in the Oil drilling industry are applied to increase and open fractures. Hot Dry Rock (HDR) is a host rock, which is buried deeper and has a higher temperature compared to conventional hydro geothermal systems. HDR geothermal reservoirs are characterized by high geothermal gradient and high heat flow. They lack fluids and permeability conditions and in order to be exploited such reservoirs need the use of an EGS system. Since these terms are usually associated, they may generate confusion in their use. Sometimes they are used interchangeably, but HDR originally referred to the assumption of “dry” conditions in the deep crystalline basement, which has been found to be “wet” or “moist” in reality. HDR are mainly related to widespread igneous rock distribution. These are usually large and homogeneous bodies of rock that reach a few km deep in the crust, allowing them to have a large thermal storage capacity. The evaluation indexes for EGS include heat flow, geothermal gradient, and thermal storage. On the other hand, geophysical methods, such as gravity and magnetic surveys, are used to characterize HDR reservoirs [31].

The use of two deep wells to develop a geothermal field requires significant capital investment. However, if the primary purpose of the fluid is to drive a turbine with steam, the primary goal of the system is to generate steam or heat a fluid that generates steam to drive a turbine and generate electricity. So, why not use a single well as a heat exchanger? This is a question to be considered carefully and without prejudice. The working fluid, with a lower boiling point and higher steam pressure, could be injected in a closed loop pipe to the bottom of the well, where it would evaporate and return to the surface to drive a turbine through an external casing to that pipe. The amount of fluid flow and the rate of injection would be controlled by the amount and pressure of steam generated. Proper design of the pipe, end outlet, and surrounding casing would prevent steam from being purged

through the injection pipe. A closer look at such possibilities is given in **2.2.2.2. Single Well Technologies**. Alternatively, instead of using an existing fracture system, it may be possible to create a large underground cavern at the end of a single deep well, where the fluid would be injected, converted to steam, and returned to the surface.

1) United Downs Deep Geothermal Power

A recent sample of an EGS/HDR project is the United Downs Deep Geothermal Power project in the Carnmenellis Granite, in Cornwall, U.K. This has started to deliver energy in the second half of 2023. It started, and is still considered, a research project, that begun in the early 1980's. With up to date drilling technology it reached 5.27 km deep in one hole and 2.39 km in another, being the first one the purge well, and the second one the injecting well. The project got £24 million to generate 3MW initially and a total of 10 MW including heating. The water is injected at 80°C in the upper part of a fractured fault zone in the granite and purged at the bottom at 190°C (Figure 13).

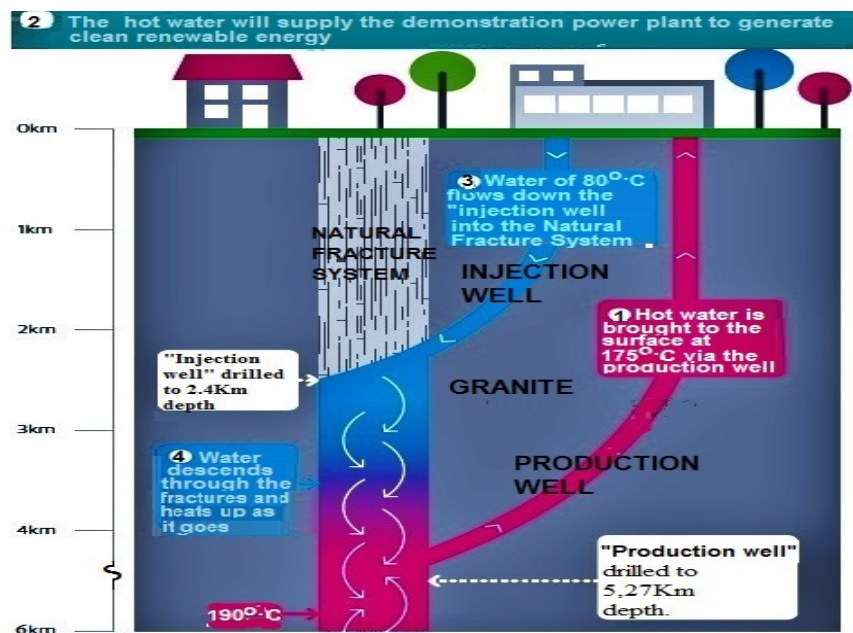


Figure 13. Schematic diagram of United Downs Deep Geothermal Power Project in Cornwall, U.K. (updated) [32].

EGS projects are seen by geothermal energy generating companies as extremely expensive and require the use of high pressures to promote hydraulic fracturing in order to open or create open fractures for the circulation of fluids that will be heated in the fractured medium and generate steam. However if a dry rock, highly open fractured is available to just receive water injection, there will be no need for fracturing.

2) Single Well technologies

The major cost component of a geothermal power plant is the drilling of the wells. This is also the largest risk component of the venture, which keeps many

investors away from this excellent energy source.

Fortunately, it is now possible to reduce the cost of drilling wells by more than half, making this excellent source of power generation even more competitive.

With today's technologies, the flow of water and its availability in the reservoir is no longer a factor limiting a geothermal power project. By combining the use of the binary cycle, which uses a closed-loop working fluid in a single heat-generating well, it is possible to generate geothermal power without the need for dual wells, induced fracturing and water injection.

These technologies allow countries with medium to low enthalpy reservoirs to use their geothermal resources to generate electricity, as is the case in Brazil.

These new technologies are commonly known as ACL (Advanced Closed Loop) or AGS (Advanced Geothermal System). This late designation may have arisen to distinguish it from EGS. The term EGS has been associated with high cost, high pressure, risk of earthquakes, then the use of AGS instead. In AGS, fractures can be created to host a closed loop technology, while in ACL the loop is simply introduced in deep wells.

New technologies are sometimes perceived with restrictions. In discussions with individuals with experience in traditional geothermal energy projects, concerns were expressed about the dissipation of energy from the source to the surface when using a single well to inject and extract fluid due to the injection of "cold" fluid in the same well. However, it should be noted that some technologies propose the use of downhole insulation to reduce or eliminate this possibility.

a) GreennFire binay cycle closed loop technology

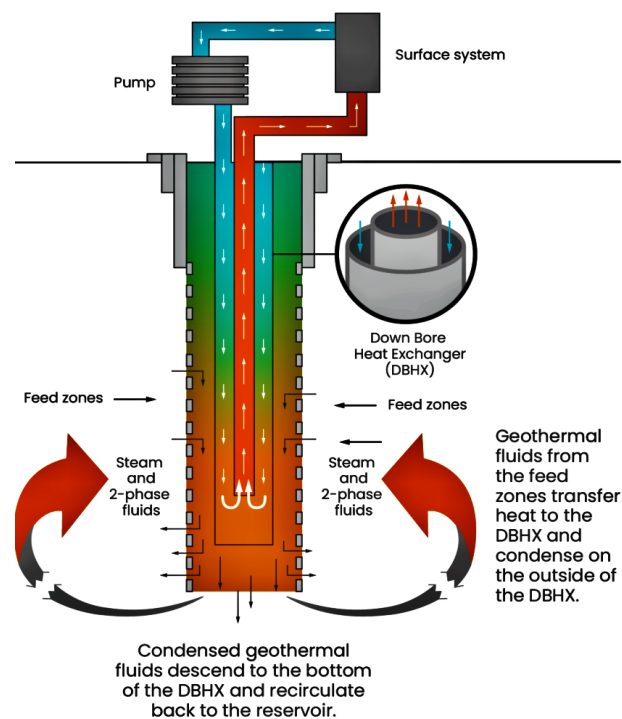


Figure 14. Greenfire single well concept [33].

The concept is to insert an insulated coaxial DBHX (Down Bore Heat Exchanger) in an existing or new well to reach the feed zones of that resource and pick up the latent heat of vaporization when the steam in the resource condenses on the DBHX (Figure 14). The DBHX then brings that heat to the surface by running the working fluid inside insulated tubing [33].

b) Eavor Technology

The company has developed Eavor-Loop™ geothermal technology, a closed-loop system in which working fluid (freshwater) circulates several thousand meters underground and collects heat by thermal conduction, without the need for natural convective hydrothermal resources (Figure 15). A natural thermo-siphon drives this system, so there is no pumping or fracking required, no induced seismicity, and no greenhouse gas emissions with a small surface footprint. It consists of two wells, an injector and a producer, drilled to the target depth. A radiator section is then built by drilling and connecting successive lateral pairs. Eavor's design uses a single drilling location for both vertical wells. Deep down in the earth, the wells turn approximately 20 to 90 degrees and then split into multilaterals to create more surface area for the working fluid to be in contact with the rock, thus increasing heat extraction and overall efficiency [35].

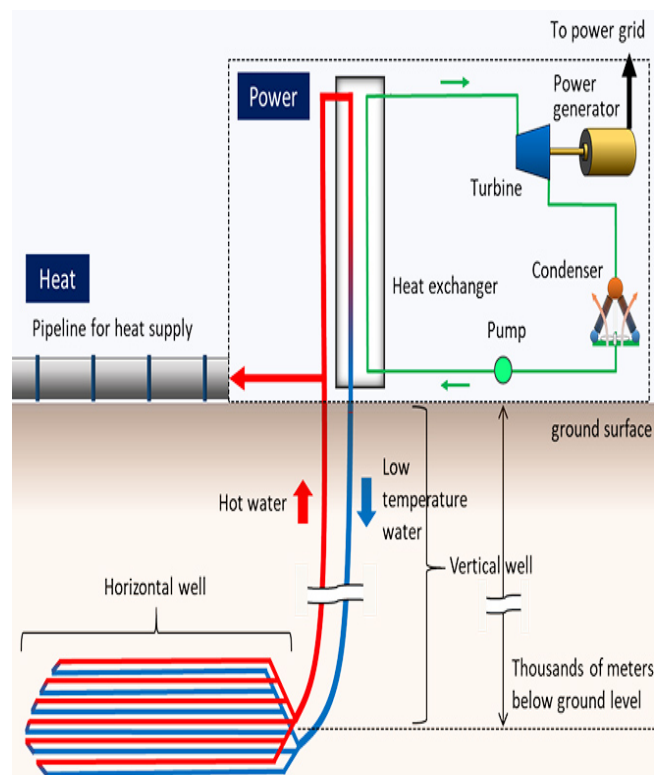


Figure 15. Eavor Chubu Electric Power [34].

c) Sage Geosystems™ closed loop technology

Sage Geosystems™ envisions a closed loop vertical geothermal single-well design (Figure 16), reducing capital cost. In addition to new dry rock locations, it

could be used to recomplete underperforming hydrothermal wells and depleted deep natural gas wells. Cooled fluid is pumped from the surface down the outer ring of a double-walled tube. Heated fluid returns to the surface via the inner tube. This results in no discharge to the air of hydrogen sulfide or steam during operation and no fluid exchange or loss with the subsurface. The proprietary HeatRoot™ technology developed by SAGE grows fractures downward, to promote natural convection (Figure 17) with higher-temperature deeper zones [36].

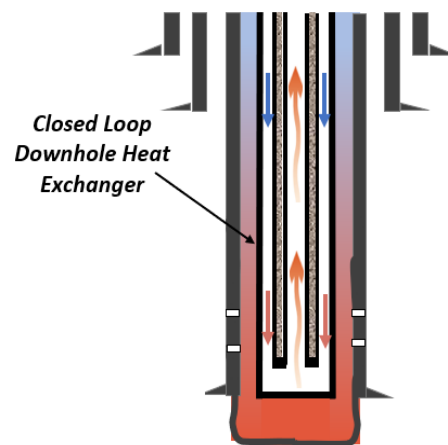


Figure 16. Sage Geosystems single well technology [36].

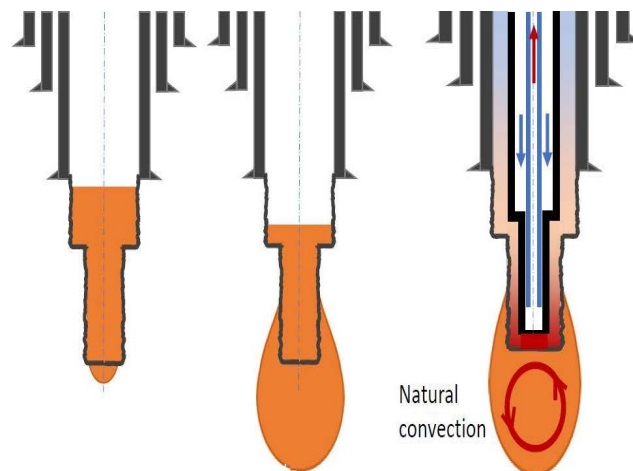


Figure 17. Heat root technology [36].

3. Geothermal Parameters Determination

3.1. Geothermal Gradient

The direct determination of the geothermal gradient is obtained through measurement data using various methods, such as conventional (CVL), stable bottom hole temperature (CBT) and bottom hole temperature (BHT). According to the scale of priorities suggested by Hamza and Muñoz [37], results from these methods can be considered to be of superior quality to those obtained by geochemical methods. However, in some cases, geochemical methods, as (GCL)—Geochemical

and (GCL/AS) Groundwater geochemicals, need to be used. In the conventional method (CVL) the geothermal gradient is determined for selected depth intervals, based on information from the lithological profile of the well in question. In the case of shallow wells with evidence of thermal disturbances, corrections are applied to minimize the effects of climate change and local topography. The stable bottom hole temperature (CBT) method is used in cases where the thermal field is altered by the flow of fluids inside the well. In these cases, the thermal disturbance is practically zero at the bottom of the well. The bottom hole temperature (BHT) method is used for determining thermal gradients in oil wells. Direct data was obtained mainly from PETROBRAS oil wells and water wells. It must be noticed that most water wells were at the most few hundreds meters deep, and rarely exceeded 500 m, with one sample, Fernandópolis (São Paulo State) reaching 2000 m deep. Oil wells were generally between 1000m and 5000m deep. However, the current experience with these wells has demonstrated that they are typically the source of low to medium enthalpy geothermal energy, which is most suitable for heating purposes or other thermal industrial applications, rather than for power generation.

3.2. Energy Generation Potential Calculation

Regarding the energy output potential, Muffler and Cataldi [38], divided geothermal resource evaluation methods into four categories: 1) Thermal flow at the surface; 2) Planar fracturing; 3) Magmatic heat; 4) Volumetric. The surface thermal flux method consists of measuring the ratio of thermal energy lost from the surface by conduction. The planar fracture method [39] [40] involves a model of thermal energy, which is extracted from impermeable rocks through the flow of water along a planar fracture. The calculations are based on thermal conductivity and heat transfer by conduction. It requires the estimation of fracture area, fracture space, initial rock temperature, etc. The magmatic heat method involves calculating the thermal energy of young igneous intrusions and adjacent rocks depending on the temperature, size, age and cooling mechanism. The volumetric method involves calculating the thermal energy contained in a given volume of rock and water. The thermal energy is calculated by the product involving the volume of the reservoir, the temperature and the specific heat of the rock and water. The method widely used in geothermal resource evaluations is the volumetric method [41]-[43] due to its ease of implementation. The potential for generating geothermal energy depends on:

- 1) the ROCK (porosity, specific weight, volume and specific heat of the rock)
- 2) the FLUID (its specific weight, flow rate and specific heat)
- 3) and/or the TEMPERATURES of the rock, fluid and air.

Except for the temperature factor, the other parameters are inherent to the materials:

-SPECIFIC HEAT is the amount of heat needed to raise a unit of mass by 1 °C. E.g. Water = 1 calorie/gram °C = 4.186 joule/gram °C.

-SPECIFIC WEIGHT = DENSITY = mass/volume.

-POROSITY is a characteristic of the medium, the amount of voids in it ($\varphi = (V_v/V_t) \cdot 100$), but not necessarily its interconnectivity. POROSITY \neq PERMEABILITY (free path).

To estimate how much geothermal energy can be generated from a single source, the total Thermal Energy must be estimated:

$$H_{total} = H_R + H_F \quad [38]$$

$$H_{total} = (1 - \varphi) c_R \rho_R V (T_R - T_A) + \varphi c_F \rho_F V (T_R - T_A)$$

where:

H = Thermal energy, J

φ = Porosity, %

c = Specific heat, kJ/kg·°C

ρ = Specific gravity, kg/m³

V = Hot rock volume, m³

T = Temperature, °C

The indices R , F and A are, respectively, **R**ock, **F**luid and **A**tmosphere.

The density of the hot reservoir fluid (ρ_F) is considered as a function of temperature only and computed from the **Kell equation**, [44], for water below 150°C

$$\rho_F = \left[\left(\left(\left((aT + b)T + c \right)T + d \right)T + e \right)T + f \right] / 91 + gT$$

where:

F = water

T = temperature in °C

$a = -2.8054253 \times 10^{-10}$

$b = 1.0556302 \times 10^{-7}$

$c = -4.6170461 \times 10^{-5}$

$d = 0.0079870401$

$e = 16.945176$

$f = 999.83952$

$g = 0.01687985$

Note: 1 KJ = 1 KWsec or 3600 KJ = 1 KWh

For a better understanding, let's take an example of a compact basalt, with a temperature of 50°C, volume of 10Km³ and an external, ambient temperature, of 25°C:

$$H_{total} = (1 - \varphi) c_R \rho_R V (T_R - T_A) + \varphi c_F \rho_F V (T_R - T_A) \quad (1)$$

$\varphi = 0.02(2\%)$

$c_R = 0.88 \times 10^3$ J/kg·K

$\rho_R = 3000$ Kg/m³

$V = 1 \times 10^{10}$ m³(10 Km³)

$T_R = 50^\circ\text{C}$

$T_A = 25^\circ\text{C}$

$c_F = 4.19 \times 10^3$ J/kg·K

$T_F = 120^\circ\text{C}$

$$\rho_F = 943 \text{ kg/m}^3$$

Applying the data to formula (1), we arrive at:

$$H_{total} = 7.25 \times 10^{16} \text{ J (available for exploitation) or 20.15 TWh}$$

3.3. Estimating Local Energy Demand and Water Flow Needs and Depth of Geothermal Wells

Considering a city with a population of 500,000 inhabitants, we can estimate the city's energy consumption of the city based on the average standard of per capita consumption. Assuming a base value of 1 kw/inhab-day, we arrive at a value of 500 MW. If we now take a fluid with a temperature of 120°C, we can define the flow requirement of the source to generate this energy, as follows:

$$Eg = Q \times C_F \times (T_F - T_A)$$

where:

Q = Fluid flow in Kg/sec

Eg = Energy in J/sec

C_F = Fluid specific heat in J/Kg·K

T_F = Fluid temperature in °C

T_A = External environment temperature in °C

then:

$$500 \text{ MW} = 500000000 \text{ J/sec} = Q \times 4.19 \times 10^3 \text{ J/Kg} \cdot \text{K} \times (120 - 25)^\circ\text{C}$$

$$Q = (500000000 \text{ J/sec}) / (4.19 \times 10^3 \text{ J/Kg} \cdot \text{K} \times (120 - 25)^\circ\text{C})$$

$$Q = 1256.12 \text{ kg/sec}$$

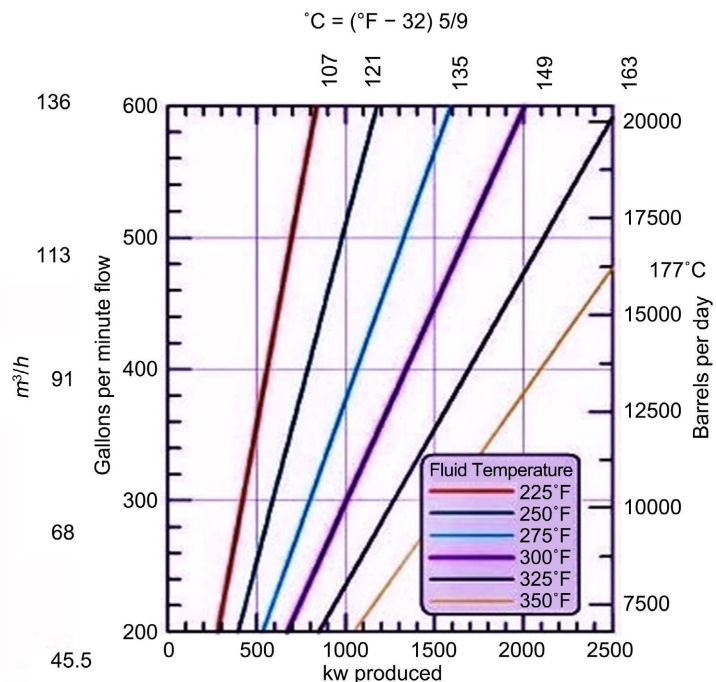


Figure 18. Relationship between energy output, water flow and temperature [45].

On the other hand if one takes as valid for most geothermal regions **Figure 18** and considering an already known fluid flow, estimate may be made for the depth a drilling must reach in order to achieve an aimed production. For example: Consider:

- 1) City with 5000 people = 5000 Kw energy consumption
- 2) Suppose 4 sources of 1250 Kw each
- 3) If water flow = 68 m³/h and 1250 Kw demand for each source, in **Figure 14**, the first line to be reached is 163°C
- 4) If I have an average surface temperature of 25°C, source temperature must be 163 – 25 = 138°C
- 5) If the geothermal gradient of the source is 60°C/Km, drilling depth shall be (138°C/60°C) Km.

The drilling must reach the depth of 2.3 Km.

4. Non-Technical Requirements for Introducing Geothermal Power

The equation is much more complex than just a feasible resource for carrying out a successful energy project. Just to mention a few requirements:

- 1) regulatory framework
- 2) Ownership of rights
- 3) Licensing
- 4) Social and political stability
- 5) The country's credit rating and monetary issues
- 6) PPA (Power Purchase Agreement) structures
- 7) Energy market
- 8) Public-private partnership issues
- 9) Infrastructure
- 10) Environment

If any of these are not at the right stage or in the right position, it will be difficult to put together a complete source of funding, from the initial investment of high-risk capital to debt financing, which will lead to the failure of the project. A comprehensive evaluation of each of these topics may be found in Bloomquist et al [46]. In the case of Brazil, items 4 and 5 of the list vary with time. Therefore these conditions may be considered by the time of decision of investment. On the other hand, the energy market in the country (item 7) favors new investments mainly in renewable and non polluting energy sources, favoring investment in geothermal. In addition a short supply of energy the country is facing right now, asks for new investments in generation. Another positive factor is the infrastructure (item 9). Most potential sites for geothermal exploitation have access to good infrastructure and also a good market. Considering the regulatory framework (item 1), thermal-electric plants are already regulated in Brazil. They must follow the guidelines of the National Environmental Plan (PNMA) whose main concern is the use of fossil fuels. Therefore, for a geothermal power plant, it shall be much easier to

license, since the energy source is water steam from underground and a fluid mixture of water-organic fluid operating in closed circuit. In addition, since there is already use of geothermal sources for heating, with drillings made down to 2 Km depth just for this purpose, the available regulatory framework is sufficient for proceeding to geothermal power projects. The Decree Law No. 7.841 of August 8, 1945, rules any water exploitation for any purposes. Regarding ownership (item 2) of water resources, the 1988 Brazilian Constitution in its article 26. item I includes among State properties all waters, "I - surface or underground waters, flowing, emerging and in deposit, except in this case, in the form of the law, those arising from works of the Union". This means that exploitation is open to anyone in any place, by means of requirement directed to the National Mining Agency (AMN). In the case of a private owner of the land where the geothermal drilling and thermal plant will be installed, the law, attributes to him a small percentage of the State mineral tax for the water exploitation. However, the owner is entitled to a lease of the land for the exploitation. In practice an agreement between the owner and the explorers is a better way to move, or simply buying the land. Oil fields in private land, in Brazil, use to pay a lease to the owner of the land, to exploit oil in his land. PPA structures (item 6) and Public-private partnership (item 8) are already introduced and familiar to the Brazilian energy market. Licensing, Ownership of rights and Environmental issues are questions that deserve a more political and negotiable approach. Most energy investors, nationals and internationals, already acting in Brazil, are familiar with all these questions. Therefore, these items are more a question of bureaucracy and time to deal with them.

Existing Experience in Introducing New Geothermal Power Plants

In contact with potential investors in the energy sector, with a view to setting up a geothermal power plant, the author has been asked about a number of their uncertainties regarding the implementation of a geothermal power generation project. What is noticeable is that there is little hesitation in setting up a wind or solar farm, despite their low capacity factor, *i.e.* the low availability of solar and wind energy generation, given their relative ease of installation. On the other hand, when it comes to setting up a geothermal power generation plant, that has a very high capacity factor, there is enormous hesitation, given the relative complexity of setting up the generator wells. It is therefore necessary to explain the current experience to them, so that they can understand the risks and advantages of the investment. The following is a summary of the relevant points, by way of clarification. These data are based on all existing geothermal power generation plants in the world, as there is no such experience in Brazil:

- 1) Capacity of the initial generation unit: 1 to 3 MW.
- 2) Average capacity of a single producing well: 4 - 10 MWh/h [29]. Rarely over 15 MWh/h [47].
- 3) Average conventional geothermal well water flow rate: 1100 - 3400 l/h [48]

4) Typical complete plants: 20 - 30 MW in 3 MW modules, world average: 38 MW. Expansion does not necessarily depend on new wells [49].

5) Capital cost: conventional – maximum = US\$18 million (3 MW); binary cycle (average enthalpy) – maximum = US\$30 million (3 MW); latest EGS/HDR in United Kingdom = £25 million (3 MW) + 10MW thermal.

6) Commissioning time: 40 months (theoretically) [33] or 5 - 10 years [34].

7) Lifespan = limited by the thermoelectric plant = 35 years [22].

8) LCOE cost (2020): US\$0.009 – 0.027/Kwh decreasing by 4% per year [19].

9) O&M costs (2022):US\$0,0125/Kwh (US\$110/Kwyear) [21].

10) Energy conversion efficiency: 12% average (21% maximum) [50].

11) Generation availability: 24 h/day, 365 d/year (100%).

12) Capacity factor: 60% - 90%, average binary cycle = 78% [20].

13) Potential regions in Brazil for setting up the 1st plant: medium enthalpy binary cycle = West-center and South; high enthalpy = North-East and North.

14) Licensing = for conventional thermoelectric plant + for deep hot water wells.

15) Technical requirements:

- Preliminary selection of the site to be investigated based on existing geological, geophysical and geothermal data;

- In-situ geological, geophysical and geothermal investigation, with selection of drilling points;

- One or two deep wells drilled to more than 2km and, most probably, between 3 and 5km deep, with oil or groundwater technology;

- Installation of hot water or steam injection and/or collection;

- Installation of reservoir and independent closed circuit of working fluid;

- Installation of conventional thermoelectric generation module coupled to the working fluid circuit;

- Steam/working fluid heat exchanger.

16) Investment return rate average: 15%.

17) Payback time: 1 to 7 years [51] depending on energy output.

18) Lowest land use of any renewable energy: 7.5 km²/Twh generated (PV uses 5 times more and wind 10 times) [52].

19) Water consumption for binary cycle plants: 1 m³/Mwh [53] [54].

20) Other aspects to be considered.

- Ownership, association or lease of the area—whichever is most convenient

- Local political and social stability—factor to be analyzed

- Economic stability of the country—factor to be analyzed

- PPA structure—already consolidated in the country

- Energy market—important to complement electricity supply with steam and/or heat and/or hot water, market should increase as there is a lot of pent-up demand. But it depends on the tariff.

- Local infrastructure—preference for the southeast

- Public-private partnerships—if necessary

Note: The world's largest geothermal energy market is the USA, which has the

potential to increase 26-fold by 2050. The similar size of the USA to Brazil, despite the climatic difference and with the exception of the high enthalpy west coast, shows the possibility of introducing and expanding the Brazilian market with the use of geothermal pumps for air conditioning and medium to high enthalpy electricity generation. The main thing missing is entrepreneurship.

5. Use of Geothermal Energy in Brazil

Geothermal energy in Brazil has been used solely for the DIRECT USE OF HEAT. Its use has been mainly for two main purposes BRT—bathing, recreation and tourism and TDB—for therapy, potability and bathing. In addition it has been used for space heating and industrial use, mainly for drying or heating grains (**Figure 19**).

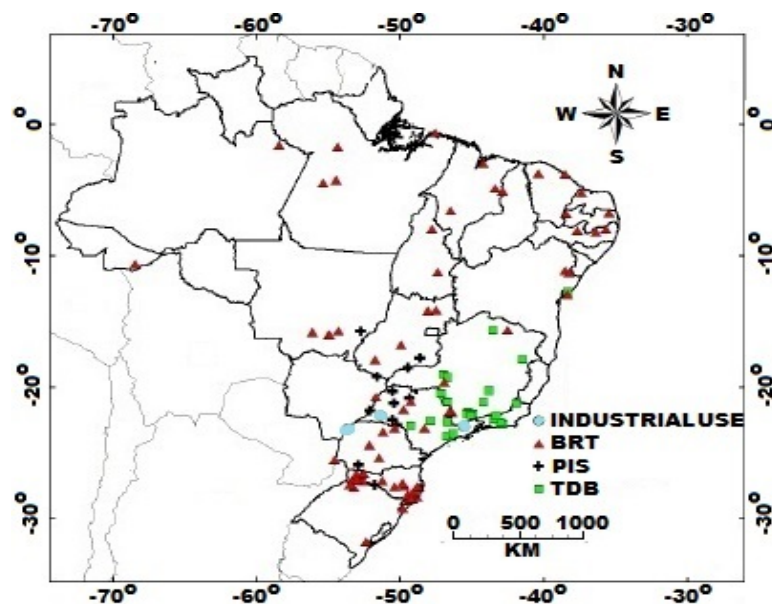


Figure 19. Locations of direct use of geothermal energy for BRT, PIS, TDB and industrial processing (use) in Brazil [56].

Table 4 shows main BRT/TDB destinations in Brazil. The coordinates refer to the main property where the thermal water is used in the region. It also shows the temperature at the surface. In each of these cities, there may be several sources of thermal water at different coordinates and coming from different wells and depths. Some of these places may be accessed regarding generation of electricity. However, further studies are needed to select the proper spot to drill. Four locations show higher temperatures than others, Fernandópolis, Presidente Epitácio and Presidente Prudente in São Paulo Estate and Mossoró in Rio Grande do Norte State. The first three ones are in the center of the Paleozoic sedimentary basin of Paraná in a region of large basalt flows close to pipes of pyroclastic rocks. These basalts are highly fractured and are composed by a series of superposed successive flows. The basin thickness (depth) reaches 8 km. Mossoró is located in Creta-

ceous-Cenozoic sedimentary terrains, in the Potiguar hydrographic basin, where oil fields are exploited. However, high geothermal gradients in this region seem to be related to Oligocene volcanism associated to the Fernando de Noronha lineament [55].

Table 4. BRT and TDB locations in Brazil.

| CITY | ESTATE | MAXIMUM SURFACE TEMPERATURE (°C) | LATITUDE(S) | LONGITUDE(W) |
|---------------------------|---------------------|----------------------------------|-------------|--------------|
| AGUAS DE LINDOIA | São Paulo | 28 | 22°28'21.2" | 46°35'20.2" |
| AGUAS DE SÃO PEDRO | São Paulo | 34 | 22°35'51.1" | 47°52'43.1" |
| AGUAS MORNAS | Santa Catarina | 39 | 27°41'48.7" | 48°49'34.4" |
| ARAXÁ | Minas Gerais | 28 - 30 | 19°38'47.4" | 46°56'58.1" |
| AUGUSTO DE LIMA | Minas Gerais | 32 | 18°02'06.6" | 44°04'24.5" |
| BARRA DO GARÇAS | Mato Grosso | 31 - 43 | 15°52'55.1" | 52°42'45.3" |
| CACHOEIRA DOURADA | Minas Gerais | 30 | 18°31'11.5" | 49°29'54.2" |
| CALDAS NOVAS | Goiás | 37.5 | 17°44'22.1" | 48°37'53.5" |
| CHAPADA DOS VEADEIROS | Goiás | 30 | 14°13'37.9" | 47°55'21.0" |
| CONCEIÇÃO DAS ALAGOAS | Minas Gerais | 36.4 | 20°01'13.3" | 48°09'58.3" |
| FERNANDÓPOLIS | São Paulo | 59 | 20°16'15" | 50°12'27" |
| FOZ DO IGUAÇU | Paraná | 36 | 25°34'03.6" | 54°33'18.2" |
| GRAVATAL | Santa Catarina | 36 | 28°19'27.5" | 49°03'57.7" |
| IRETAMA | Paraná | 42 | 24°17'04.5" | 52°06'05.2" |
| LINS | São Paulo | 36 | 21°41'23.4" | 49°45'35.3" |
| MACHADINHO | Rio Grande Do Sul | 45 | 27°35'17.9" | 51°39'34.7" |
| MARCELINO RAMOS | Rio Grande Do Sul | 34 | 27°30'09.4" | 51°59'12.1" |
| MOSSORÓ | Rio Grande Do Norte | 58 | 05°10'04.2" | 37°21'07.4" |
| NOVA PRATA | Rio Grande Do Sul | 41 | 28°46'30.6" | 51°30'58.5" |
| OLIMPIA | São Paulo | 38 | 20°43'18.5" | 48°55'03.5" |
| PIRATUBA | Santa Catarina | 38 | 27°25'35.0" | 51°47'02.9" |
| POÇOS DE CALDAS | Minas Gerais | 37 | 21°47'15.9" | 46°34'06.6" |
| Presidente Epitácio | São Paulo | 78 | 21°75'23.3" | 52°09'40.3" |
| Presidente Prudente | São Paulo | 63 | 22°12'06.6" | 51°41'37.3" |
| RIO QUENTE | Goiás | 26-47 | 17°46'29.3" | 48°44'53.2" |
| SANTO AMARO DA IMPERATRIZ | Santa Catarina | 39 | 27°43'46.6" | 48°48'38.0" |
| VERÊ | Paraná | 36.5 | 25°45'32.7" | 52°57'03.8" |

The high surface temperatures do not necessarily reflect a high geothermal gradient. Other than that, this is not the only requirement for a potential site for a geothermal power plant. Water flow and steam generation are important addi-

tional factors, that may not be present. However, in a further investigation scenario, these are potential places to be detailed. Many of these places already have an evaluation of geothermal energy output, in terms of thermal energy.

6. Potential Areas for Geothermal Power Generation in Brazil

Since the early 70s, because of the first oil crisis, Brazilian researchers have been looking for alternative sources of energy with good results. Since then the geothermal potential has been accessed and a good abstract of such information is contained in the Brazilian geothermal database, updated in 2022. Considering this source of information, locations were selected with geothermal gradients determined by different available methods in each case, above 58°C/Km. The choice of this cut-off parameter was chosen, considering an average surface temperature of 25°C. Therefore, with this parameter, it may be possible to reach a minimum temperature of 150°C, medium enthalpy resource, down to 3 Km deep, and use a binary cycle system for power generation. However, this will depend on the maintenance of the same geological conditions down to 3 km deep. Therefore, this is just the first approach to select prone areas for further investigations. **Table 5** shows these locations and related information.

Table 5. Location of highest geothermal gradients in Brazil [55]-[57] [59].

| BRAZIL | LOCATION | GEO THERMAL GRADIENT | HEAT FLOW | DETERMINATION |
|------------|----------|----------------------|----------------------|---------------|
| REGION | | (°C/Km) | (mW/m ²) | METHOD (*) |
| NORTH | N-1 | 90.62 | 203.25 | CBT |
| NORTH | N-2 | 97.19 | 213.83 | CBT |
| NORTH-EAST | NE-1 | 67.40 | | |
| NORTH-EAST | NE-2 | 76.23 | | |
| NORTH-EAST | NE-3 | 99.94 | | |
| NORTH-EAST | NE-4 | 86.28 | | |
| NORTH-EAST | NE-5 | 99.84 | | |
| NORTH-EAST | NE-6 | 79.10 | | |
| NORTH-EAST | NE-7 | 82.74 | | |
| NORTH-EAST | NE-8 | ----- | 370 | -?- |
| NORTH-EAST | NE-9 | 58.31 | 128.28 | CBT |
| NORTH-EAST | NE-10 | 72.6 | 159.72 | CBT |
| NORTH-EAST | NE-11 | 58.65 | 129.03 | CBT |
| NORTH-EAST | NE-12 | 62.3 | 158.22 | CBT |
| NORTH-EAST | NE-13 | 60.32 | 143.67 | CBT |
| NORTH-EAST | NE-14 | 115.14 | | |
| NORTH-EAST | NE-15 | 141.68 | | |
| NORTH-EAST | NE-16 | 155.76 | | |

Continued

| | | | | |
|-------------|-------|-----------|--------|---------|
| WEST-CENTER | WC-1 | 59.54 | 139.94 | AQT |
| WEST-CENTER | WC-2 | 81 | 240 | --?-- |
| WEST-CENTER | WC-3 | 63.33 | 146.23 | AQT |
| WEST-CENTER | WC-4 | 71.33 | 164.71 | AQT |
| WEST-CENTER | WC-5 | 63.33 | 161.29 | AQT |
| WEST-CENTER | WC-6 | 71.33 | 181.67 | AQT |
| WEST-CENTER | WC-7 | 63.33 | 124.68 | AQT |
| WEST-CENTER | WC-8 | 62.33 | 122.72 | AQT |
| WEST-CENTER | WC-9 | 70 | 198.93 | AQT |
| WEST-CENTER | WC-10 | 63.33 | 179.97 | AQT |
| WEST-CENTER | WC-11 | 71.67 | 203.67 | AQT |
| WEST-CENTER | WC-12 | 59 | 146.91 | CVL |
| WEST-CENTER | WC-13 | 59.46 | 123.07 | CBT |
| SOUTH-EAST | SE-1 | 62 +1.68. | 167 | CVL |
| SOUTH-EAST | SE-2 | 69+3.6 | 186 | Na-K-Ca |
| SOUTH-EAST | SE-3 | 64+3.4 | 189 | Na-K-Ca |
| SOUTH | S-1 | 60.33 | 85.07 | CGL/AS |

(*) AQT—Aquifer; CBT—Stable bottom hole temperature; CVL—Conventional; CGL/AS—Groundwater geochemicals.

Conventional geothermal power plants are feasible from 150°C according to some authors or above 250°C according to others, depending on the technology adopted. However, geothermal power plants that use a binary cycle are feasible from 99°C. The average geothermal gradient in Brazil is 22.68°C/Km \pm 9.19°C/Km. The minimum and maximum values found to date are 6.8°C/Km and 81°C/Km respectively [57]. In terms of heat flow, the average Brazilian value is 66.37 mW/m² \pm 31.03 mW/m² [57]. Worldwide, the average heat flow values are around 62.805 mW/m² [58]. The same study mentions that geothermal fields for energy generation should have between 10 and 1000 times the average heat flow value [58]. However, present geothermal projects around the world have heat flow in the triple digits and generally around 200 mW/m² or a little more.

Cardoso, Hamza and Alfaro [59], identified more than 20 crustal blocks in South America (Figure 20) where the resource base per unit area, referred to the accessible depth limit of 3 km, are in the range of 10¹³ to 10¹⁴ Joules (between 1 to 10 Gwh). Still, according to the authors, the area extent of the blocks ranges from several tens to hundreds of kilometers. And, among the high temperature resources, they mention the well known sector of magmatic activity in the Altiplano region in Bolivia. This may explain the high geothermal gradients in the North region, 200 Km far from the Altiplano. They also point to occurrence of medium temperature geothermal resources at depths of 3 to 5 km in some sectors of the eastern parts of the continent, mainly in the northeastern and central parts of Bra-

zil. The Goiás geothermal gradients are related to this central source. The authors also mentioned that thickness of sediments are between 2 km and 8 km and upper crust in almost all Brazilian territory, between 12 km and 16 km deep with few small areas up to 20 km thick. Regarding temperatures their article points to temperatures of 1000°C at the base of upper crust. They also mentioned that “*In the eastern parts of the continent, basal temperatures (of hard sediments) in excess of 300°C are found to occur in the northeastern coastal region of Brazil and also along an east west trending belt between the northern part of the state of Mato Grosso and northern parts of the state of Rio de Janeiro in the central part and northwestern portion of the country*”. Theoretically, based on the geothermal gradient, heat flow, the anomalous values found in Brazil and shown in **Table 5**, and related to the resource base identified in South America indicate that the installation of conventional geothermal power projects is possible with boreholes no more than 3km deep. However, there are two other important technical constraints to be identified: availability of a sufficient fluid reservoir and continuity of geological conditions down to this depth. If there is no circulation or sufficient reservoir, even if the other conditions exist, a source and supply of fluid must be made available, using the medium through an EGS/HDR or ACL/AGS system.

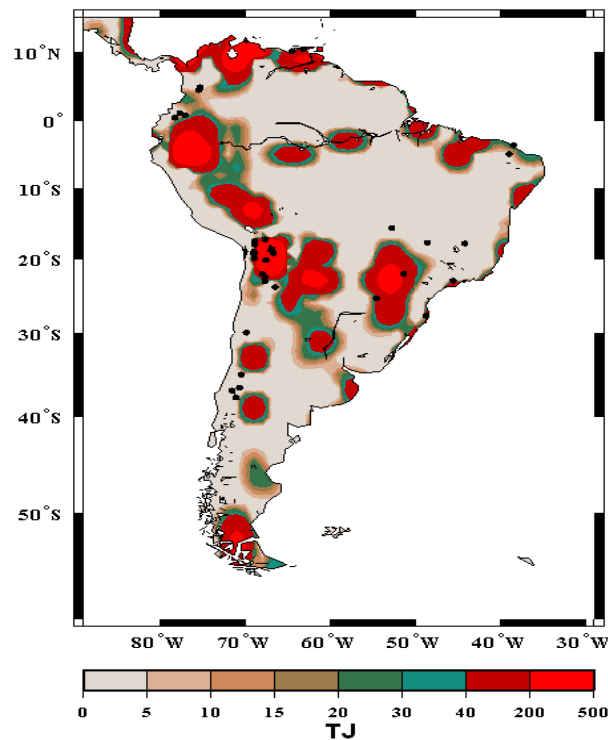


Figure 20. Resource base for the hard sediment layers. Dots indicate geothermal areas. Red colors “arc” trend regions of higher geothermal potential [59].

So far the gradients shown in **Table 5** and the detection of basal temperatures in excess of 300°C, as already mentioned, points to the Northeast region as a possible area for high enthalpy reservoirs at depths of no more than 3 km. Other po-

tential high enthalpy area may be found in the North region. On the other hand, medium enthalpy and possibility of high enthalpy are found in West-central and Southeast regions. These seem to be the most important to generate electricity, although there are other regions with potential for medium and high enthalpy reservoirs.

On the other hand, if the geological conditions, that guarantee the prevalence of the geothermal gradient to the depth that allows the ideal temperature for generating electricity to be reached, do not persist, then the geothermal power generation project could be unfeasible if at least 99°C is not reached for the implementation of a binary cycle system, with a sufficient supply of primary fluid. Theoretical studies to date have sought to obtain this information. Therefore, in order to access the geological possibilities it is needed to take a closer look into the geological framework in more detail.

Geological Framework

In order to access the geology of potential areas, a general understanding of the Brazil geotectonics must be known. **Figure 21** gives a general synoptic view of Brazil's geotectonics.

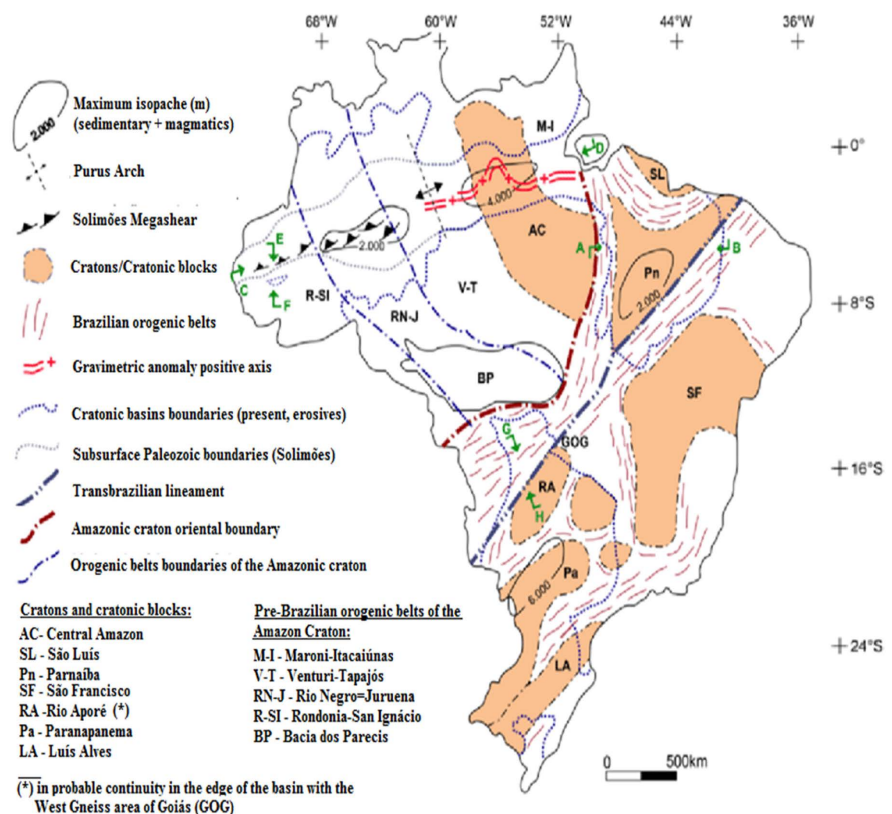


Figure 21. Schematic tectonic framework of Brazil with the main discontinuities, cratonic blocks and orogenic belts of the basement (translated from Portuguese) [60].

Figure 21 depicts the structural elements that underpin all the Paleozoic sedi-

mentary basins, with their boundaries delineated. The basins are more clearly delineated in **Figure 22**.

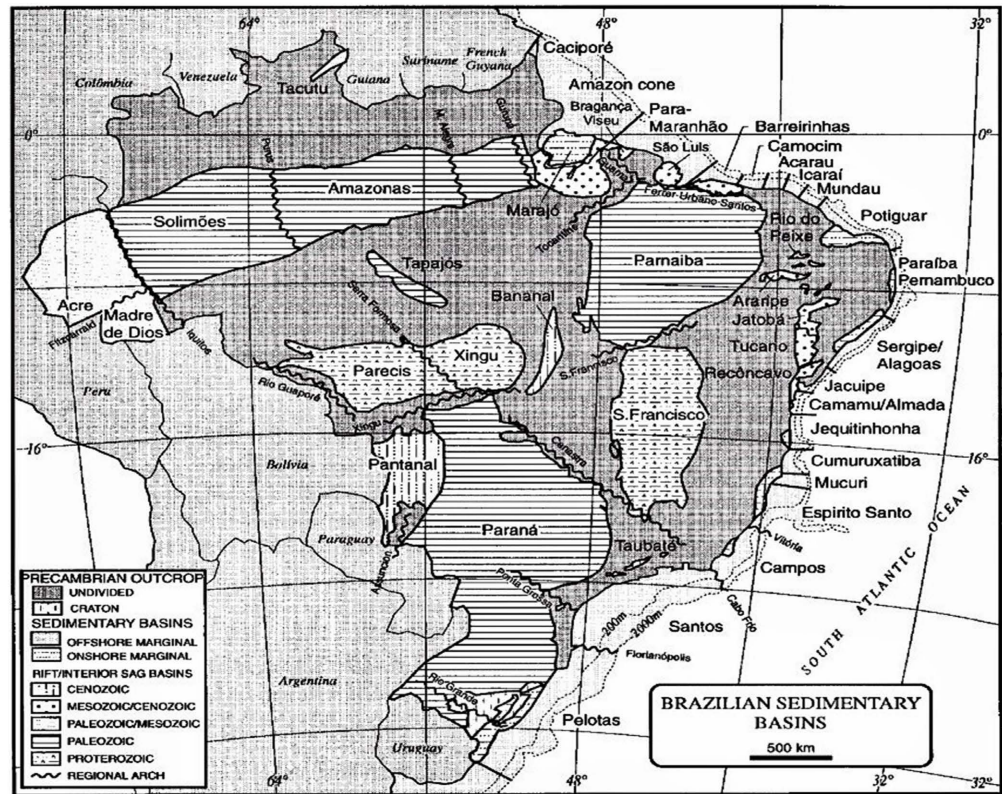


Figure 22. Simplified map of the onshore and offshore Brazilian sedimentary basins and intervening regional arches [61].

Geothermal areas of interest for power generation are located in the northeastern part of the map and between the Parecis and Pantanal basins, in the central western part of the map. These are likely to have high enthalpy geothermal reservoirs located in highly fractured mobile basement belts surrounding some granitic bodies. In the northeastern part, some faults still show some activity and the area also has some occurrences of recent volcanic rocks. In addition, the northeastern region is also affected by continental fractures related to the mesoceanic opening, of E-W trend, developing from the Fernando de Noronha archipelago. The medium to high enthalpy geothermal reservoirs of Goiás are located in the triangle formed by the São Francisco and Canastra arcs with the western boundary of the São Francisco craton, on an undivided Precambrian basement.

It is important to note that although not related to actual volcanism or active continental tectonic margins, the low tectonic activity present may be the cause of the higher geothermal gradient in the northeast region.

7. Conclusion

The text lists unnumbered advantages of geothermal energy over other sustainable

energy sources. Geothermal energy uses fewer resources to produce power, requires less land to produce the same amount of energy as other sources, has a lower environmental impact, lower operating and decommissioning costs and a higher capacity factor. It is also clear that, like other energy sources, it is dependent on the availability of site conditions for its use. However, identifying and proving the availability of the resource is dependent on traditional high cost technologies compared to solar, wind and hydro. However, it is not climate-dependent and does not vary as much as other sources once exploited. On the other hand, prospecting for potential geothermal sites in Brazil, as shown here, shows that although there aren't any traditional, readily identified geothermal fields in Brazil, there is evidence of the possibility of exploiting existing resources using traditional injection and purging wells, as well as new technologies, including binary cycle systems. These resources are present in all Brazilian regions and await further investment for exploitation.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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