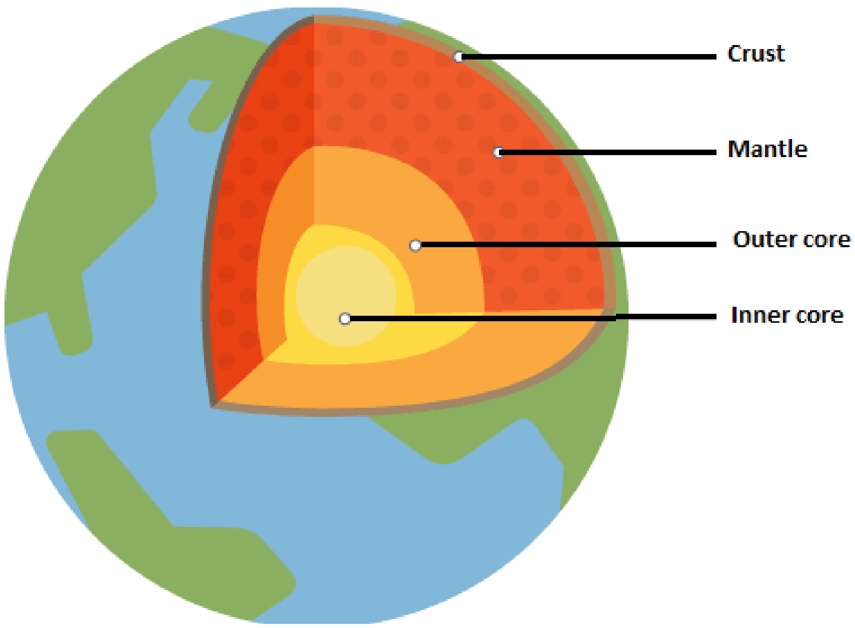
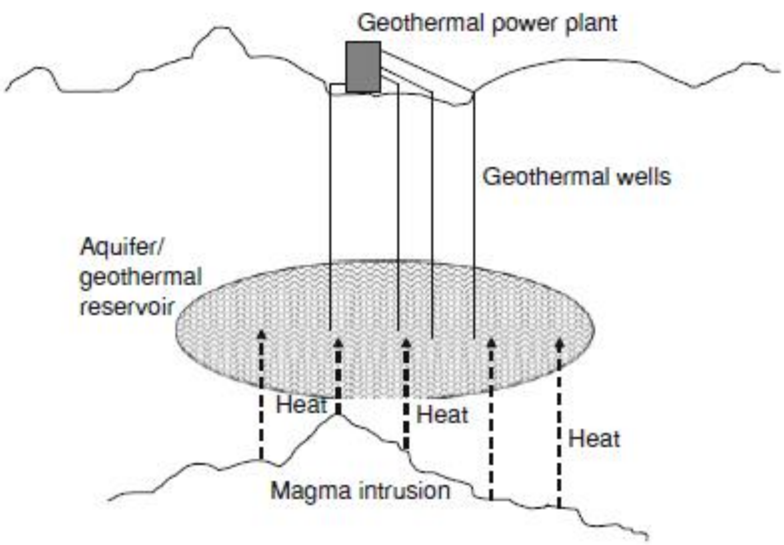
Geothermal Energy

Geothermal energy is the primordial energy (since the beginning of the world or the universe) of the earth, produced in the interior of the earth by nuclear reactions. Approximately 44 TW (44 x 10^{12} W) of heat power is transferred from the interior to the surface of the earth. Of this amount, 30 TW is generated by the radioactive decay of elements in the core of the earth. Given that the average power consumed by the entire earth's population is approximately 16 TW, it follows that geothermal power alone may satisfy the energy requirements of the humans. However, geothermal is thermal power that appears at the surface of the earth at low temperatures, and its conversion to electricity is accomplished with significantly low efficiencies. In addition, a great deal of the geothermal power is dissipated in the oceans, which constitute more than 70% of the surface of the earth. For this reason, geothermal energy may produce small amounts of electricity, but may not be reasonably relied upon to provide a high percentage of the total energy needs of the earth's population.



The core (inner and outer) or central part of the earth is in liquid state at temperatures that are estimated to be between 6000 and 4000 ^{o}C and are maintained at this level from the radioactive decay of nuclear isotopes. The core is surrounded by the cooler layer, the mantle, which consists of the magma, a hot, semi-glassy, viscoplastic material, with temperatures ranging from 3000 to 1500 ^{o}C. The upper layer of the earth is a thin solid layer, the crust, of 8–10 km thickness, which is made up of six major tectonic plates, and several minor plates. The crust of the earth consists of several solid plates that are floating on a pool of magma. The insulating characteristics of the crust help to maintain the lower temperatures at the surface of the earth and to limit the heat transfer from the mantle to the atmosphere and the outer space. However, at the boundaries of the tectonic plates, which are referred to as geological faults, there are significant intrusions of hot magma into the crust layer. Heat from these pockets of hot magma is conducted to local aquifers, often called geothermal reservoirs, where water temperatures may rise to 200 to 300 ^{o}C. Because the local static pressure is significantly high, water at these temperatures is below the corresponding saturation temperature and exists in the liquid state.

Figure on the next page, a schematic diagram that shows how the intrusion of magma close to the earth's surface creates a geothermal field in the local aquifer. Geothermal wells, which are drilled deep into the aquifer zone, bring the geothermal fluid to the surface of the earth and supply a geothermal power plant that produces electric power. Oftentimes, the high pressure in the geothermal reservoir is augmented by the insertion of a downhole pump, which supplies a higher volume of geothermal fluid to the power plant.



In addition, water that has been used in the power plant is often injected back to the aquifer via reinjection wells. Because of the replenishment (fill again) of the water and the very long time associated with the cooling of the earth, geothermal resources are considered renewable energy sources. However, it has been observed that, in a period of a few decades, the pressure, temperature and volumetric flow rate of water produced by a specific geothermal well decline. When this occurs, the well may be shut and another well may be drilled at a different location, in the same aquifer.

Geothermal Resources

The type and quality of the geothermal resources depends on the type of fluid the wells produce and is related to the specific exergy of the geothermal fluid. In general, geothermal resources are classified in the following types:

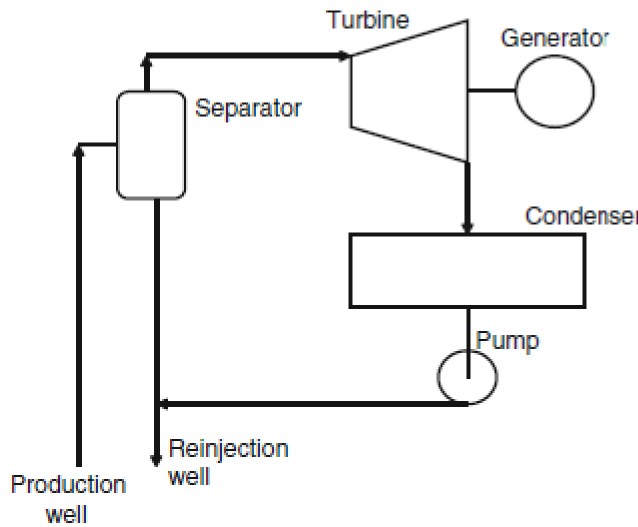
1. Dry steam: The water in these aquifers is at a significantly high temperature, typically in the range 200 to 280 ^{o}C. As the water flows through the porous medium that constitutes the aquifer, its static pressure drops and a great deal of steam is produced inside the aquifer by local flashing. The steam, with a small fraction of droplets is carried in the geothermal well, where the pressure is further reduced and most or all of the droplets evaporate to produce a higher amount of steam. Thus, wells from a dry steam resource supply the power plant with saturated or superheated steam, which may be fed directly to a turbine for the production of power.

2. Liquid water: When the reservoir temperature is lower, liquid hot water at high pressure is produced at the bottom of the well. As the water rises in the well, its static pressure decreases due to the gravitational and frictional losses in the pipe. The temperature of the geothermal fluid is also reduced because of heat losses to the surrounding rock. However, given the insulating properties of the rocks, the rate of temperature reduction is very low. The continuous reduction of pressure in the well may cause the static pressure of the fluid to become lower than the saturation pressure of the fluid at the prevailing temperature. At this level of the well, flashing of the water occurs and some steam is produced. As the fluid moves upwards to the wellhead, more steam is produced by flashing. A mixture of steam and liquid water is directed to the power plant, where additional steam may be produced by flashing. The dryness fraction (quality) of the fluid at the wellhead steam depends to a great extent on the characteristics (pressure and temperature) of the geothermal reservoir as well as on the depth of the well. From the thermodynamic properties of water and steam, one may easily deduce that the specific exergy of the fluid produced by liquid water resources is lower than that of the dry steam type.

3. Geopressured: Temperatures in the geopressured reservoirs are very low, typically in the range 120 to160 ^{o}C, which correspond to low saturation pressures. These reservoirs are typically located at greater depths than the dry steam and liquid water resources and, hence, the reservoir pressures are significantly higher. At all levels in the well, the pressure of the geothermal fluid is significantly higher than the saturation pressure. Thus, flashing does not occur and vapor is not produced. Liquid, hot water is produced and may be directed to the power plant. The exergy of the liquid water is significantly lower than that of steam and, hence, these resources are considered to be of significantly lower quality than the dry steam resources.

4. Hot dry rock: As the name implies, these resources are hot rocks at a significant depth from the earth's surface. Despite the fact that there is no local fluid to be carried to the surface, one may develop an engineering system to harness the thermal energy of the rock by drilling a number of wells, injecting a fluid to the wells, bringing this fluid to the surface and using the thermal energy of this fluid for the production of electric power. The working fluid is not necessarily water and may be another fluid with convenient thermodynamic properties, such as butane, pentane or a refrigerant.

Geothermal Power Plants



Geothermal power plants utilize dry steam for power production. Essentially, the geothermal well produces dry (or almost dry) steam, which may be fed directly to a steam turbine that drives the electric generator. A schematic diagram of a dry steam power plant is depicted in Fig. The steam from the well is fed to the steam dryer or separator where any water droplets that are present are removed. The steam is then directly fed to a turbine, which drives the electric generator, and finally exhausts in the condenser. The condensate, which is almost pure water, is then re-injected to the geothermal reservoir or is used locally as a water source.

Environmental Effects

Geothermal energy is a clean source of energy. The operation of the geothermal power plants causes minimal environmental impact. The main source of atmospheric pollution from geothermal units is the discharge of the non-condensable gases, primarily CO^2. The quantity of CO^2 released to the atmosphere is by far less than that produced by an equivalent fossil fuel plant. Geothermal power plants produce 1000 to 5000 times less CO^2 per kWh produced than fossil fuel plants.

Soil subsidence may become a problem in the vicinity of geothermal power plants: As steam or water is removed from the geothermal aquifers, open cracks shrink and the permeability of the aquifers decreases. The surrounding rocks and soil are displaced to fill all major voids and the soil surface subsides, but not always in a uniform manner. Uneven soil subsidence on the surface may pose problems to structures and buildings. Water re-injection and rainwater seepage mitigates to a large degree the soil subsidence. Since most of the geothermal resources and power plants are located far from the major population centers, soil subsidence does not pose a significant problem to large populations.

Thermal pollution, which is caused by the heat released to the environment as a result of the operation of the cooling system, is another environmental effect. Subsequently the thermal pollution per unit energy produced (kJ/kWh) is higher (about 1.7–2.5 times more) than that of the fossil fuel plants.

Finally, noise, which is always a problem with all power plants, is also an environmental concern for the geothermal units. Ejectors of non-condensable gases, especially steam ejectors, add significantly to the noise pollution. However, since the vast majority of geothermal power plants are isolated and far from population centers, noise pollution is not a significant environmental concern and only affects the wildlife in a way that is similar to the noise effect of wind turbines.