Geothermal Energy Resources, Exploitations and Applications

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Abstract

A geothermal resource is one that is accessible. A geothermal resource constitutes quantity of stored energy between the earth surface and specific depth in the earth's crust underneath a specified area and is measured from local mean temperature. The most common criteria to classify geothermal resources is the enthalpy of geothermal fluids which is the energy carrier. It is the enthalpy that influences or determines the classification of the geothermal resource as low enthalpy, medium enthalpy, or high enthalpy geothermal resource. Geothermal sysems can be classified as convective dominated systems, which include liquid-vapour dominated hydrothermal system, conductive dominated system which include hot rock and hybrid systems which source from convection, conductio and high heat producing source e.g. magma. A geothermal system is made up of three main elements namely, a heat source, a reservoir, and a fluid, which is the carrier of the heat. The heat source can be either a very high-temperature (greater than 600 °C) magmatic intrusion that has reached relatively shallow depths (5 to 10 km) or, as in certain low-temperature systems. Most geothermal resources are near the boundaries of the earth's tectonic plates. The most active geothermal resources are usually found along major tectonic plate boundaries where most volcanoes are located.

Keywords
Geothermal Energy, Resources, hydrothermal

1. Introduction
The word "geothermal" is derived from the Greek word's geo, meaning earth," and *therme,* meaning "heat." Therefore, geothermal energy means heat from the earth(Kabeyi, 2019; M. J. B. Kabeyi & A. O. Olanrewaju, 2022). Geothermal resources are reservoirs of hot water or steam that exist at varying temperatures and depths on the Earth's surface. A geothermal well is drilled is drilled into the earths crit to reach the reservoirs to tap steam and hot water for delivery to the earth's surface for various applications including electricity generation, direct use, and heating and cooling.

2. Geothermal Resource Capacities
The heat that comes from deep within the Earth's crust is known as geothermal energy. Water and/or steam transport geothermal energy to the Earth's surface. The first commercial use of geothermal technology to generate electricity was in 1913, when a geothermal power plant with a capacity of 250 kW was built in Italy (Stober and Bucher, 2013). Recently, geothermal energy met a considerable portion of the electricity needs in countries like Iceland, New Zealand, El Salvador, the Philippines, and Kenya as well as it meets over 90% of Iceland's heating needs. Compared to recent years, capacity expansion was rather slow in 2020 (due partly to disruptions caused by the epidemic), with nearly all new facilities being situated in Turkey (Global Status Report, 2021; Statista, 2021a). In this regard, approximately 0.15 GW of new geothermal power generation capacity went online in 2020, increasing the global total to roughly 14.1 GW(M. J. B. Kabeyi & A. O. Olanrewaju, 2022). The capacity of Turkey was raised by 99 MW, whereas the US, New Zealand, and Italy all saw smaller increases. Overall, the power generated using geothermal energy has increased from 1 GW in 2010 to 14 GW in 2020, with a 14% increase rate. Figure 1 depicts the recent global expansion of geothermal power capacity (International Renewable Energy Agency, 2021). The top ten geothermal power producers by 2020 were the US, Indonesia, the Philippines, Turkey, New Zealand, Mexico, Kenya, Italy, Iceland, and Japan.(Bakken et al., 2012; M. J. B. Kabeyi & O. A. Olanrewaju, 2022)

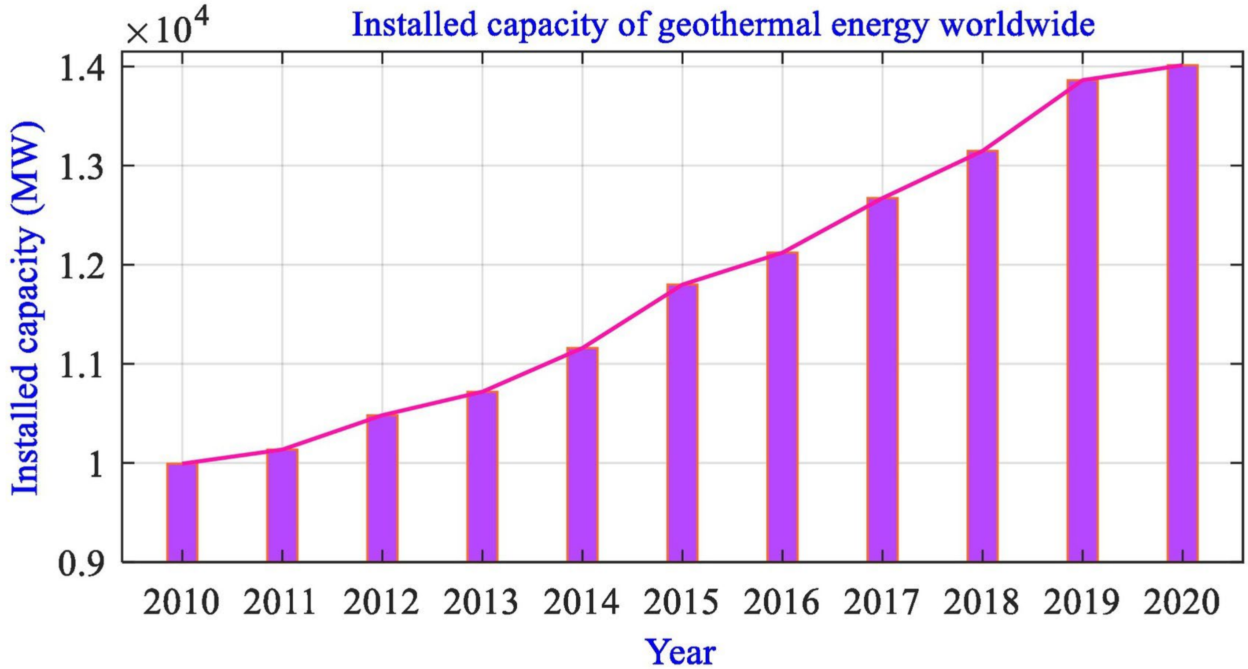

Figure 1. Power generated from geothermal energy during last years

3. The structure of the Erath

The internal structure of Earth is the layers of the Earth, excluding its atmosphere and hydrosphere. The structure consists of an outer silicate solid crust, a highly viscous asthenosphere and solid mantle, a liquid outer core whose flow generates the Earth's magnetic field, and a solid inner core. Scientific understanding of the internal structure of Earth is based on observations of topography and bathymetry, observations of rock in outcrop, samples brought to the surface from greater depths by volcanoes or volcanic activity, analysis of the seismic waves that pass through Earth, measurements of the gravitational and magnetic fields of Earth, and experiments with crystalline solids at pressures and temperatures characteristic of Earth's deep interior (Rudnick & Gao, 2003).

Surrounding the earth's core is the mantle, thought to be partly rock and partly magma. The mantle is about 1,800 miles thick. The outermost layer of the earth, the insulating crust, is not one continuous sheet of rock (Figure 2), like the shell of an egg, but is broken into pieces called plates. These slabs of continents and ocean floor drift apart and push against each other at the rate of about one inch per year in a process called continental drift.Magma (molten rock) may come quite close to the surface where the crust has been thinned, faulted, or fractured by plate tectonics. When this near-surface heat is transferred to water, a usable form of geother- energy is created. Geothermal energy is called a renewable energy source because the water is replenished by rainfall, and the heat is continuously produced by the earth (Kabeyi, 2019; Kabeyi and Oludolapo, 2020).

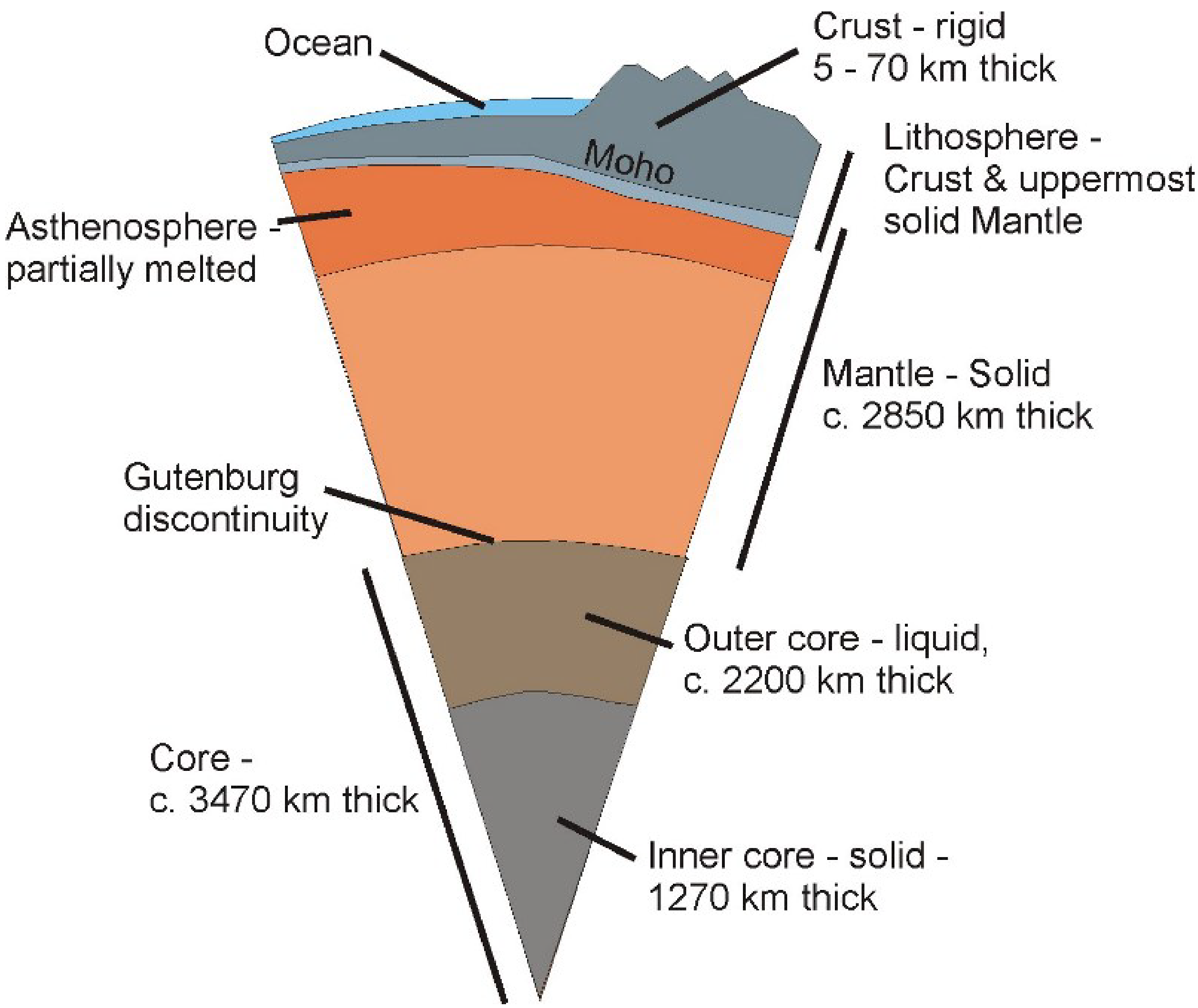

Figure 2. The structure of the Erath

3.1 The crust

This is the outside layer of the earth and is made of solid rock, mostly basalt and granite. There are two types of crust: oceanic and continental. Oceanic crust is denser and thinner and mainly composed of basalt. Continental crust is less dense, thicker, and mainly composed of granite(Rudnick & Gao, 2003).

Earth's crust ranges from 5–70 kilometres (3.1–43.5 mi)[7] in depth and is the outermost layer.[8] The thin parts are the oceanic crust, which underlie the ocean basins (5–10 km) and is mafic-rich[9] (dense iron-magnesium silicate mineral or igneous rock).[10] The thicker crust is the continental crust, which is less dense[11] and is felsic-rich (igneous rocks rich in elements that form feldspar and quartz).[12] The rocks of the crust fall into two major categories – sial (aluminium silicate) and sima (magnesium silicate).[*citation needed*] It is estimated that sima starts about 11 km below the Conrad discontinuity,[13] though the discontinuity is not distinct and can be absent in some continental regions. Earth's lithosphere consists of the crust and the uppermost mantle.[15] The crust-mantle boundary occurs as two physically different phenomena. The Mohorovičić discontinuity is a distinct change of seismic wave velocity. This is caused by a change in the rock's density[16] – Immediately above the Moho, the velocities of primary seismic waves (P wave) are consistent with those through basalt (6.7–7.2 km/s), and below they are similar to those through peridotite or dunite (7.6–8.6 km/s).[17] Second, in oceanic crust, there is a chemical discontinuity between ultramafic cumulates and tectonized harzburgites, which has been observed from deep parts of the oceanic crust that have been obducted onto the continental crust and preserved as ophiolite sequences. Many rocks making up Earth's crust formed less than 100 million years ago; however, the oldest known mineral grains are about 4.4 billion years old, indicating that Earth has had a solid crust for at least 4.4 billion years (Remington et al., 2006).

3.1. The mantle

The mantle lies below the crust and is up to 2900 km thick. It consists of hot, dense, iron and magnesium-rich solid rock. The crust and the upper part of the mantle make up the lithosphere, which is broken into plates, both large and small. To learn more about these plates see the Plate(Rudnick & Gao, 2003) .

Earth's mantle extends to a depth of 2,890 km (1,800 mi), making it the planet's thickest layer [This is 45% of the 6,371 km (3,959 mi) radius, and 83.7% of the volume - 0.6% of the volume is the crust]. The mantle is divided into upper and lower mantle[20] separated by a transition zone.[21] The lowest part of the mantle next to the core-mantle boundary is known as the D″ (D-double-prime) layer.[22] The pressure at the bottom of the mantle is ≈140 GPa (1.4 Matm).[23] The mantle is composed of silicate rocks richer in iron and magnesium than the overlying crust.[24] Although solid, the mantle's extremely hot silicate material can flow over very long timescales.[25] Convection of the mantle propels the motion of the tectonic plates in the crust. The source of heat that drives this motion is the decay of radioactive isotopes in Earth's crust and mantle combined with the initial heat from the planet's formation(Remington et al., 2006).

3.2. The core

The core is the centre of the earth and is made up of two parts: the liquid outer core and solid inner core. The outer core is made of nickel, iron and molten rock. Temperatures here can reach up to 50,000 C(Rudnick & Gao, 2003).

Earth's outer core is a fluid layer about 2,400 km (1,500 mi) in diameter [19% of the Earth's diameter, 15.6% of the volume] and composed of mostly iron and nickel that lies above Earth's solid inner core and below its mantle.[30] Its outer boundary lies 2,890 km (1,800 mi) beneath Earth's surface. The transition between the inner core and outer core is located approximately 5,150 km (3,200 mi) beneath Earth's surface. Earth's inner core is the innermost geologic layer of the planet Earth. It is primarily a solid ball with a radius of about 1,220 km (760 mi), which is about 19% of Earth's radius [0.7% of volume] or 70% of the Moon's radius(Remington et al., 2006).

The inner core was discovered in 1936 by Inge Lehmann and is generally composed primarily of iron and some nickel. Since this layer is able to transmit shear waves (transverse seismic waves), it must be solid. Experimental evidence has at times been inconsistent with current crystal models of the core.[33] Other experimental studies show a discrepancy under high pressure: diamond anvil (static) studies at core pressures yield melting temperatures that are approximately 2000 K below those from shock laser (dynamic) studies. The laser studies create plasma (Figure 3) and the results are suggestive that constraining inner core conditions will depend on whether the inner core is a solid or is a plasma with the density of a solid. This is an area of active research (Remington et al., 2006).

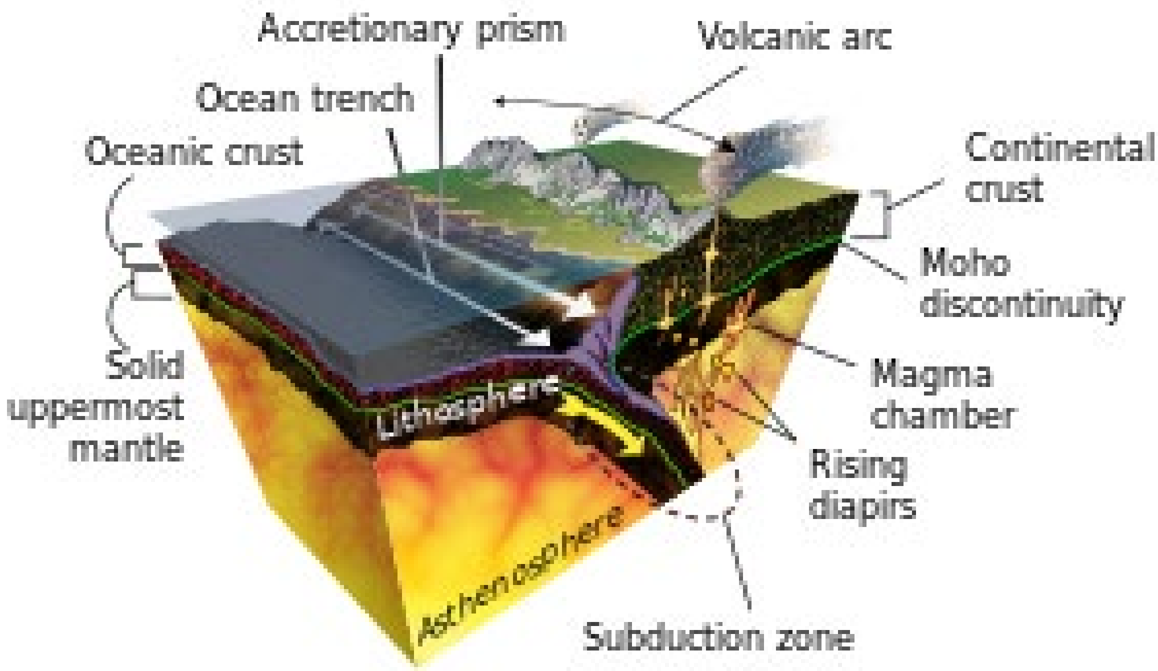

Figure 3. The earths crust and mantle (Remington et al., 2006)

4. **Geothermal Resource Capacities and Development**

3.1. The Energy Content of the earth

The earth has been radiating heat energy for close to 4.5 billion years from its center. It is estimated that some 6437.4 KM (4,000 miles) deep in the crust, the temperature is around 5,500 ºC (9937º F) with scientists estimating that 42 million MW of power flows from the earth's interior mainly through conduction. Figure 4 shows the temperature distribution in the earth (Geothermal Association, 2014).

The energy content of domestic geothermal resources to a depth of 3 km is estimated to be 3 million quads of heat energy, equivalent to a 30,000-year supply of energy at the current rate of consumption by the United States. However, it is not technically possible to recover the entire resource base and most of the geothermal resources are at a low temperature. There is need for new low- temperature electricity generation technology to significantly expand the geothermal resources that can be developed economically today (Di Pippo, 2017). Compared to fossil fuels, Shere (2013) asserts that geothermal power has considerable potential for growth with amount of heat within 10,000 meters of the earth's surface estimated to contain 50,000 times more energy than all oil and gas resources available worldwide(Kabeyi & Olanrewaju, 2021).

According to Karytsas and Mendrinos (2013) the heat content of the earth crust is estimated to at 10, 775, 600 billion TOE corresponding to 10,500 times the known global fossil fuel reserves estimated at 422 billion TOE coal, 234 billion TOE oil and 188 billion TOE natural gas. Geothermal resources in areas with magmatic intrusions located at boundaries of lithosphere plates have about 327, 360 billion TOE or 400 times the global fossil fuel reserves.

1.2. The Earths Thermal Gradient

The geothermal gradient refers to the increase in the temperature with depth in the earth's crust with normal average geothermal gradient is 2.5 to 3 °C/100 m. (Dickson & Fanelli, 2003; Lund, 2009). According to Lund (2009), it is feasible to exploit geothermal resources where temperature gradient is above the average. According to Goldstein, et al. (2010) the global average of land temperature is 15ºC. Therefore with an approximate global geothermal temperature gradient for land areas far from volcanic settings of about 30°C/km, high temperatures greater than 180°C can be obtained at an average depth of 5.5 km below the surface of the earth's surface. Adopted from Geothermal Energy association (2014).

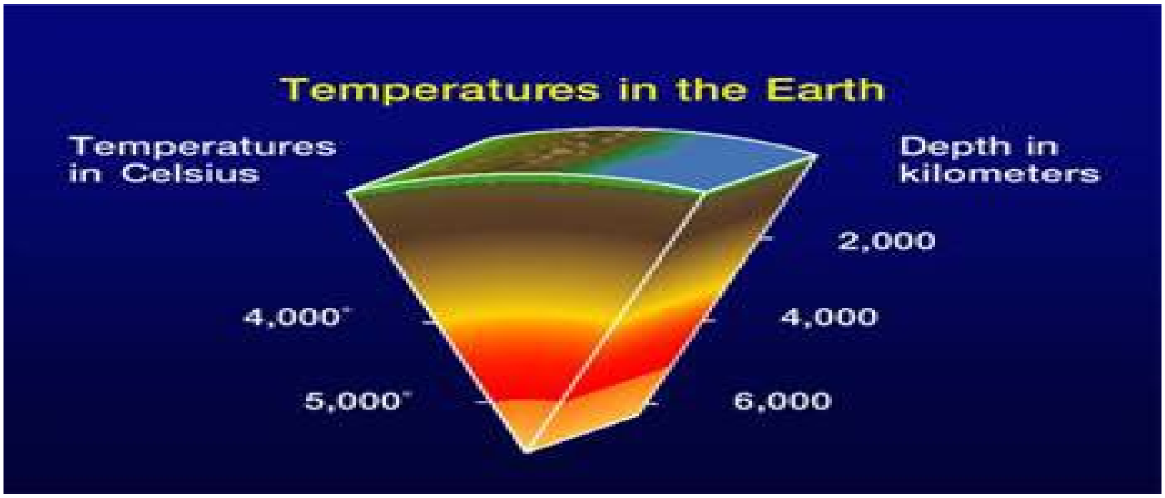

Figure 4. Temperature distribution in the earth

Figure 4 shows that deep in the earth's crust, the temperature is greater than 5,500°C at about 6000Km underneath.

1.3 Global Geothermal Electricity Generation Capacity and Potential

The world geothermal generation capacity has been growing at a rate of 3% to 4% per year, generally proportionate with the rate of world economic growth for the last decade. Most of this growth took place in Kenya (392 MWe), the USA (352 MWe), New Zealand (400 MWe), and Turkey (306 MWe) which together account for 60% of world capacity growth. Economic growth globally coupled with high fossil fuel prices provided ground and incentives for geothermal electricity capacity investment with committed projects expected to add about 2,000 MWe (a 16% capacity increase) between January 2015 and December 2018. Most of this new capacity was installed in Indonesia (636 MWe), Turkey (298 MWe) and Kenya (255 MWe). Additional geothermal generation is expected to extend to Iran, Croatia, Chile, and Honduras an indicator that geothermal has proved attractive and is what investing in (World Energy Council, 2016). These shows global commitment to growth of geothermal power generation especially amongst non-oil producers.

In 1999, 8 GWe of electrical generating plants worldwide was powered by geothermal heat. Geothermal sources generated 49 terawatt hours of virtually pollution-free power that year (Williams, et.al. 2001). According to BP (2017), geothermal electricity capacity grew by 3.4% (440 MW) in 2016, to reach 13.4 GW with the largest additions to capacity taking place in Indonesia (190 MW) and Turkey (150 MW). BP further observed that the United States has the largest geothermal capacity with 3.6 GW (27% of the world total), followed by the Philippines (1.9 GW), Indonesia (1.6 GW) and New Zealand (1.0 GW).

Whereas the US continues to lead the world in geothermal electricity generation with an estimated total installed capacity of just under 3,400 MW and 3,591 MW in 2018, Indonesia has improved significantly to overtake Philippines as the world's second largest producer of geothermal electricity while Italy is currently the fourth largest producer of Geothermal electricity with New Zealand being the fifth based on 2015 statistics (Bradley, 2016). It is also worth noting that Indonesia has the largest global potential of geothermal energy although the country is highly dependent on fossil fuels mainly coal, as its primary source of electricity generation (World Bank, 2017). It is therefore expected that Indonesia should play a leading role in development of geothermal electricity production to substitute coal and other fossil fuels.

In 2017, global geothermal power generation stood at an estimated 84.8 TWh, with a total capacity of 14 GW. Global geothermal power capacity is expected to rise to just over17 GW by 2023, with the biggest capacity additions expected in Indonesia, Kenya, Philippines, and Turkey (International Energy Agency, 2017). In October 2018, global geothermal capacity reached 14,369 MW after new additions capacity s in Turkey and New Zealand (Richter, 2018).

According to Ritcher (2019) global geothermal capacity reached 14.6 GWe by the end of 2018 with 587 MW new capacity in 2018 mainly coming from Turkey at 294, MW, Indonesia at 139 MW, US at 48 MW, New Zealand at 25 MW, Iceland 45 at MW, Italy 134 at MW, Croatia at 18 MW, China at 15 MW, Germany at 3 MW and others contributing 1 MW. A review of geothermal capacity growth for the period between 2009-2018 showed the countries that have registered greatest growth as follows; Turkey (1317 MW), Indonesia (956 MW), US (599), Kenya (509 MW), New Zealand (421MW), Iceland (180 MW), Italy (134 MW) and Others (220 MW). This demonstrates that there is commitment by countries across the globe to promote geothermal power development.

Economically, the geothermal energy market is a signigficant contributor to the gross domestic product of many countries. According to Karytsas and Mendrinos (2013) the global geothermal power market was about 11.6 billion euro in 2012 corresponding to about 11.456 MWe of installed capacity and 71.997 GWhe and 7.2 billion euro in investments. The geothermal steam turbines market is dominated by six major manufacturers. Therefore, the technology market is competitive though with relatively fewer players.

Therefore, geothermal energy development does not only provide substitution for fossil fuels in electricity generation, but also has a significant role to play in economic development by contributing to the gross domestic product.

1.4. Geothermal Capacity and Growth for 2017/2018

As at the end of 2018, the 10 leading countries in installed geothermal electricity capacity were as follows in Table 1.

Table 1. Geothermal capacity growth for year 2017/2018

RANK	**COUNTRY**	**INSTALLED CAPACITY (MW)**
1	United State	3,639
2	Indonesia	1,948
3	Philippines	1,868
4	Turkey	1,347
5	New Zealand	1,005
6	Mexico	951
7	Italy	944
8	Iceland	755
9	Kenya	676
10	Japan	542
11	Other Countries	925
TOTAL GLOBAL CAPACITY		**14, 600**

Table showing production capacity of 10 leading countries.
Table 1 shows that the US leads the world in new geothermal power development followed by Asian countries of Indonesia and Philippines while Kenya leads Africa in geothermal power capacity and generation as per data for the year 2018. Other countries need to identify the initiatives put in place by these countries to accelerate growth of geothermal energy and electricity.

1.5. Growth in Geothermal generation capacity between 1995 and 2018

The development of geothermal generation capacity is summarized in the table below in Table 2 below.

Table 2. Geothermal energy capacity and growth

	YEAR	**INSTALLED CAPACITY (GWe)**	**ELECTRICITY PRODUCTION (GWHr/year)**	**CAPACITY FACTOR (PERCENT)**
1	1960	0.386	2,600	77
2	1995	6.8	38,035	64
3	1999	7.979	49,000	70
4	2000	8.0	49,261	71

5	2005	8.9	56,786	73
6	2010	10.7	67,246	71
7	2014	11.62	73,300	72
8	2015	12.60	73,549	75
9	2017	13.28	84,800	73
10	2018	14.6	-	-

(-) means data not accessed by time of publication.
From Table 2 it is noted that geothermal electricity capacity has shown growth from 6.8 GW in 1998 to 14.6 GW in 2018, representing growth of 115% in capacity. The global average of capacity factor which is the ration of average load to plant capacity was lowest in 1995 reflecting operational challenges for that year but for all other years between 1960 and 2017, the capacity factor has been above 70% showing above average loading and use of operating geothermal power plants globally, a necessary factor for use as base load power plants.

4. Geothermal, Systems, Resources and Characteristics

4.1 Geothermal Systems

A geothermal system is made up of three main elements namely, a heat source, a reservoir, and a fluid, which is the carrier of the heat. The heat source can be either a very high-temperature (greater than 600 °C) magmatic intrusion that has reached relatively shallow depths (5 to 10 km) or, as in certain low-temperature systems.

4.1.1. Geothermal Reservoir

A geothermal reservoir is a volume of hot permeable rocks from which the circulating fluids extract heat. The reservoir is generally overlaid with a cover of impermeable rocks and connected to a surficial recharge area through which the meteoric waters can replace or partly replace the fluids that escape from the reservoir through springs or are extracted by boreholes. The geothermal fluid is water, in most cases meteoric water, in the liquid or vapor phase, depending on its temperature and pressure. This water often carries with its chemicals and gases such as Carbon dioxide (CO_2) and Hydrogen sulfide (H_2S) (Dickson & Fanelli, 2003).

4.1.2. Heat Source

This is the origin of heat in the geothermal system. It can be high temperature magmatic intrusions, radioactivity or low temperature system getting the heat from deep underground through conduction or convection. Thermal energy generated from radioactive sources depends on both presence and level of radioisotopes that may include Uranium-238, Uranium -235 and lithium -232 (Berrizbeitia, 2014).

4.1.3. Geothermal Fluid

This is the media through which heat is conveyed to the surface and is mainly meteoric water in form of liquid, vapor or mixture of liquid and vapor. Geothermal fluid often contains gases and dissolved minerals or chemicals like Carbon Dioxide (CO_2), hydrogen sulphite (H_2S).

4.2. Geothermal Resources

According to Muffler and Catldi (1978), a geothermal resource is one that is accessible. A geothermal resource constitutes quantity of stored energy between the earth surface and specific depth in the earth's crust underneath a specified area and is measured from local mean temperature. The most common criteria to classify geothermal resources is the enthalpy of geothermal fluids which is the energy carrier. It is the enthalpy that influences or determines the classification of the geothermal resource as low enthalpy, medium enthalpy, or high enthalpy geothermal resource.

4.2.1. Conditions for Existence of Geothermal Resource

Geothermal energy refers to the natural heat content of the earth. There are four main conditions for the existence of a geothermal reservoir except for Hot Dry Rock (HDR) type geothermal sources.
i.) A heat source: This heat source can be a magmatic body (> 600 °C) as well as the normal
Geothermal gradient of the earth as in the case of low-temperature geothermal sources. The temperature of the earth increases with a normal geothermal gradient of 3 °C/100 m. It is therefore possible to reach a depth to obtain a temperature of 70-100 °C with the existing drilling technology.

ii.) A heat carrier: This carrier is generally the rainwater seeping the deeper section of the earth.
iii.) A porous and permeable or fractured reservoir rock.
iv.) An impermeable caprock above the reservoir rock.

4.2.2. Types of Geothermal Systems

Geothermal sysems can be classified as convective dominated systems, which include liquid-vapour dominated hydrothermal system, conductive dominated system which include hot rock and hybrid systems which source from convection, conductio and high heat producing source e.g. magma (Goldstein, et al., 2010).

i.) **Convective Hydrothermal Resources**

These resources occur where the Earth's heat is carried upward by convective circulation of naturally occurring hot water or steam in the earth's crust. Some high temperature convective hydrothermal resources result from deep circulation of water along fractures (Goldstein, et al. 2010).

ii.) **Vapor dominated reservoirs.**

These systems produce steam from boiling saline waters in low permeability rocks. Generally, these resources are fewer. Examples include The Geysers in Northern California in the USA, Larderello in Italy, and Matsukawa in Japan where the steam is exploited to produce electric power. Hot water and vapor can co-exist in these reservoirs, but vapor phase is continuous phase and determines the pressure regime of the reservoir.

These systems have lower heat than hot water reservoirs, but with less problems associated with the fluid production from these reservoirs compared to hot water geothermal systems. The production mechanism of vapor-dominated reservoirs is like the natural gas reservoirs, with expansion of reservoir fluid leading to production declines. The amount of fluid produced at the abandonment is generally high at 85-90% by weight of original fluid in place in the reservoir. Most of the heat content of the reservoir resides in rock and extraction of heat from the rock in these systems is relatively low. Re-injection of produced fluid can increase the heat recovery from the reservoir by extracting more heat from the rock and effectively increases the life of the geothermal reservoir (Lund, 2009). Figure 5 below illustrates a vapor dominated geothermal system. Vapor dominated geothermal system (White, et al., 1971).

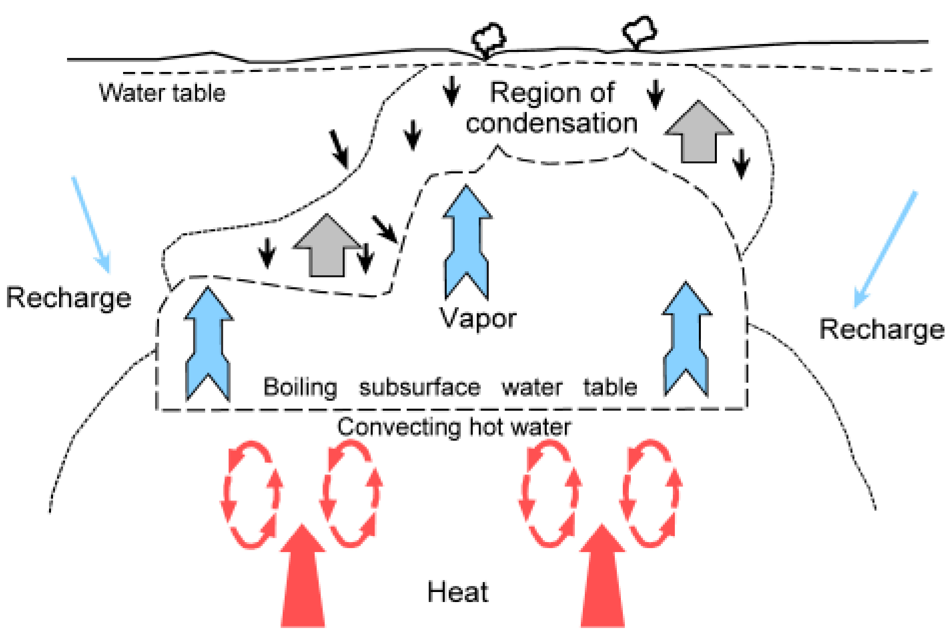

Figure 5. Vapor dominated reservoir

Figure 5 above shows vapor dominated geothermal resource which includes heat source e.g. magma, water source permeable rock

iii.) Liquid/Hot water dominated reservoirs.

These are geothermal resources produced by ground water circulating to depth and ascending from buoyancy in permeable reservoirs that are a uniform temperature over large volume. There is typically an up-flow zone at the center of each convection cell, an outflow zone or plume of heated water moving laterally away from the center of the system, and a down flow zone where recharge is taking place. Surface manifestations include hot springs, fumaroles, geysers, travertine deposits, chemically altered rocks, or sometimes, no surface manifestations or blind resource (Lund, 2009). Liquid phase is the continuous, pressure-determining phase in these reservoirs. The water within these systems is a chemical solution containing sodium, potassium, lithium, calcium, chloride, bicarbonate, sulphate, borate, and silica. Wairakei in New Zealand, Cerro Prieto in Mexico, and Kızıldere in Turkey can be mentioned as the examples of liquid dominated reservoirs. The heat recovery from liquid dominated reservoirs is higher compared to heat recovery from vapor-dominated reservoirs. The main reason of the higher heat recovery is the boiling of reservoir fluid in the reservoir and/or re-injection of the produced fluid. Production problems encountered in liquid dominated reservoirs are worse compared to that of vapor dominated reservoirs (Lund, 2009). Figure 6 below illustrates a liquid or hot water dominated geothermal system. Hot water dominated geothermal system (White, et al., 1971).

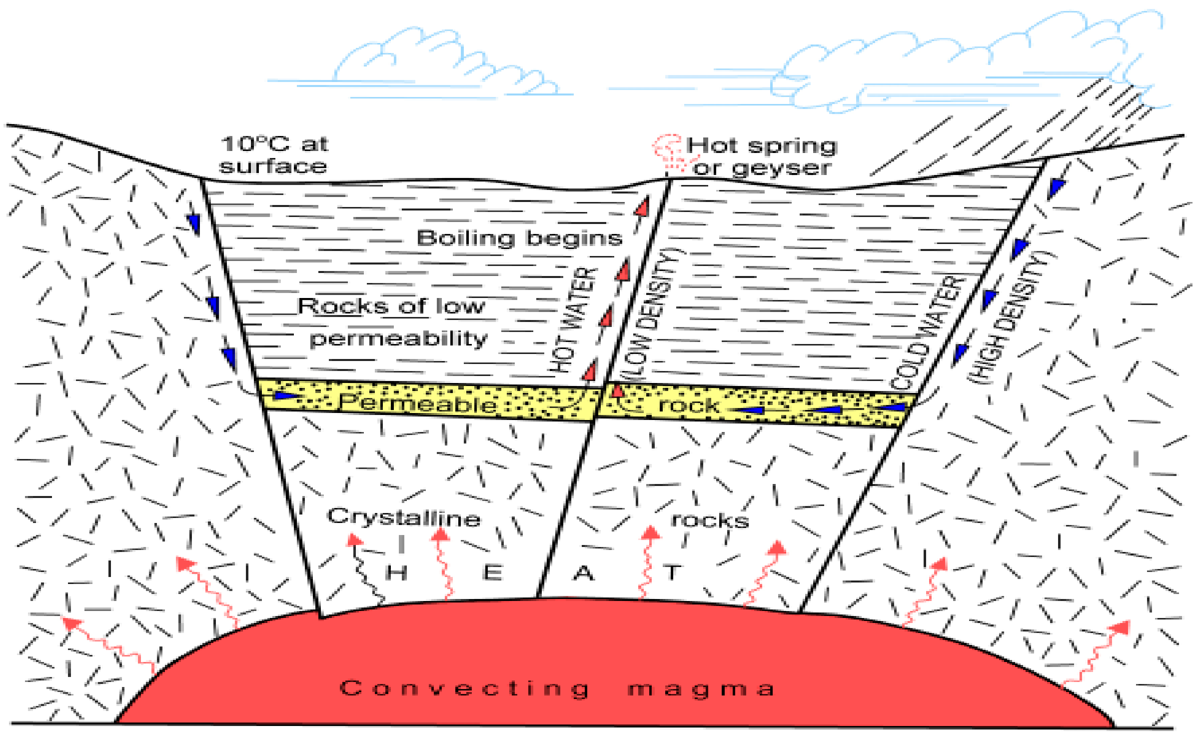

Figure 6. Liquid/Hot water dominated reservoirs.

Figure 6 shows main elements of liquid or hot water dominated resource which include source of heat manly magma, surface manifestations which include hot springs and geysers, low permeability rock, permeable rock structure layers of high-density rocks.

iv.) Geo-Pressurized Geothermal Reservoirs

Geo-pressurized resources are methane-rich fluids often below 4.5 km depth are contained in reservoirs with up to 70 MPa pressure and 150^{O} C temperature. The resource takes the form of geothermal heat and combustible natural gas that can be exploited (Williams et al., 2001).

These geothermal resources occur in basin environments where deeply buried fluids contained in permeable sedimentary rocks are warmed in a normal or enhanced geothermal gradient by virtue of their great burial depth underground. The fluids are tightly confined by surrounding impermeable rock and bear pressure much greater than

hydrostatic pressure. The pressure gradient of the trapped geothermal fluid can increase with further sedimentation and can reach up to 1 psi/ft (normal hydrostatic gradient is between 0.433-0.45 psi/ft). The temperature of these systems increases with low heat conductivity and high specific heats of the fluids. Thermal waters under high pressure in sand aquifers are the target for drilling, mainly as they contain dissolved methane which can be extracted.
Geo-pressurized geothermal resources consist of:
(1) Thermal energy
(2) Mechanical energy and,
(3) Methane gas.

The Texas and Louisiana Gulf Coast in the United States has been tested for the geothermal energy; however, due to the great depths of several kilometers, they have not proved economically viable for exploitation (Lund, 2009). Figure 7 bellow illustrates geo- pressurized geothermal resource. Geopressured geothermal system (Bebout, et al., 1978).

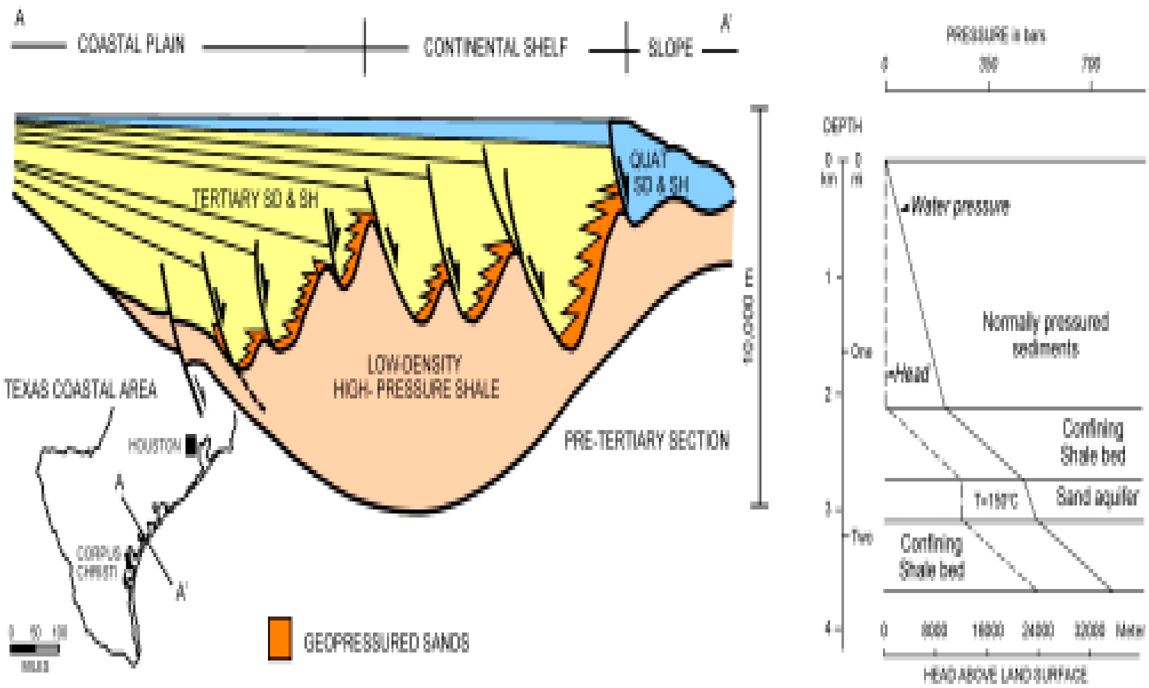

Figure 7. Geo-pressurized geothermal reservoirs

According to Karytsas and Mendrinos (2013) geothermal of geo-pressured basins is estimated as 355.9294 billion TOE (Tons of oil equivalent) or 70 times the world total fossil fuel reserves.

Geopressured geothermal reservoirs are similar in formation to geo-pressured oil and gas reservoirs. In these resources geothermal fluid caught in a permeable rock structure, by crustal motion over millions of years with pressure rise to lithostatic pressure. Geo-pressurized resources are generally relatively deep, from 2 km and deeper, with thermal gradient of over 100°C/km. These reservoirs have been found often during petroleum exploration. In some cases, they are found associated with petroleum, the water which is reach with methane gas which can be exploited as a more important energy source than the heat in the water. Reservoir engineering of such a system is more like a petroleum reservoir than a hydrothermal reservoir or groundwater aquifer. The challenge with these resource as realized from Experiments conducted on existing petroleum exploration wells, in the 1980s in the U.S. Gulf Coast, in an experimental hybrid power system gave discouraging results, with operational problems high concentration of salts and high carbon dioxide. Another challenge is abnormally high pressures involved (Lund, 2009; Karytsas and Mendrinos, 2013).

Therefore, whereas geo-pressurized geothermal resources offer significant potential, challenge remains how to handle high contents of carbon dioxide, high mineral or salts content of the fluid and very high pressures associated with the resource which continue to hold back exploitation of these significant geothermal resource.

V) Hot Dry Rock (HDR)

These resources occur in the form of heat stored in rocks within 10 km of the surface from which energy cannot be economically extracted by natural hot water or steam. These hot rocks have few pore spaces, or fractures, and therefore have little or no water thus no interconnected rock permeability. To extract these heats, rocks are artificially fractured by hydraulic pressure, and cold water circulating down one well to extract the heat from the fractured rocks and then heated water extracted through another well in a closed system. Early experimental projects were undertaken at Fenton Hill (Valdes Caldera) in Northern New Mexico in the US and on Cornwall in Southwest England; however, both projects have been abandoned due to lack of funds and poor results. Current project sites include Soultz-Sous-Foret in the Rhine Graben on the French-German border, in Switzerland at Basil and Zurich, in Germany at Bad Urach, several locations in Japan, and the Cooper Basin of Australia (Tenzer, 2001; Lund, 2009).

These systems do not contain any fluid to extract and transfer the heat energy to the surface for use. The only way of utilizing these systems is to extract the heat energy of the rock by water circulation along an artificial fracture between two wells as illustrated in figure 8 below. According to Tosha, Shimada, and Nakashima (2017) fractures are created in the dry rock, where high temperature is expected with the help of seismic monitoring technology. A production well is then drilled in and connected to the injection well through the artificial fractures. Water injected into the injection well flows through the artificial fractures, absorbs heat from the hot dry rock, and goes back to the surface through the production well while extracting heat.

If Hot Dry Rock (HDR) extraction technology becomes commercially viable, the resource base of geothermal energy will significantly increase magnitude worldwide. The main technology challenges to be addressed for HDR are drilling costs, control of water loss, and better fracture stimulation and mapping techniques. The terms hot wet rock (HWR) and Enhanced Geothermal Systems are also in use to describe research into heat extraction from low permeability geothermal systems (Williams, et al. 2001). Figure 9 below illustrates exploitation for hot dry rock resource. rock exploitation (Anderson & Lund, 1979).

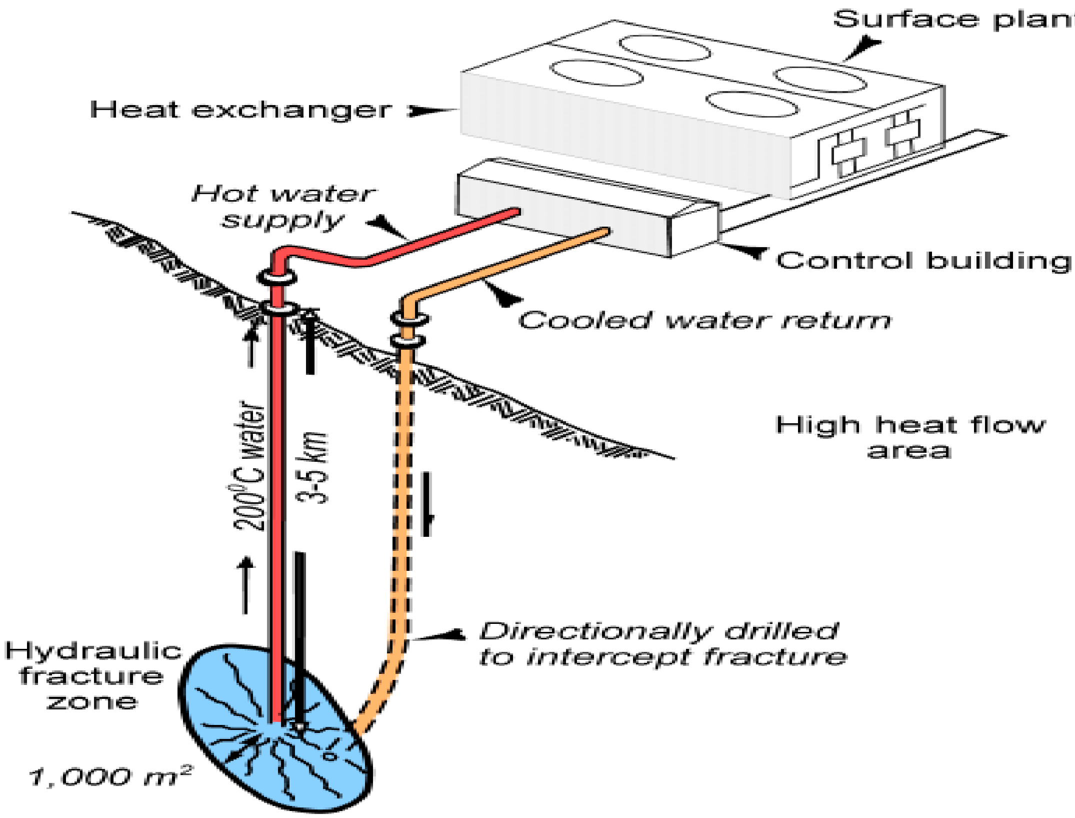

Figure 8. Hot dry rock (HDR)

Hot dry

Quite often hot underground rock is not permeated by water and so there is no medium naturally available to bring the heat energy to the surface. Where hot rock exists close to the surface of the earth, it is possible to create a human-made hydrothermal source. This is realized by drilling into the rock and then pumping water down through an artificial. Pressurized water will cause the rock to fracture. This is like the process of fracking to release shale gas by creating faults and cracks through which the liquid can flow. The fracturing is made easier due to the fact that underground rock often contains natural faults and fractures through which water will force through hence easier fracturing. If a second borehole is drilled adjacent to the first, then water that has become heated as it has percolated through the rock can be extracted for power plant use. (Karytsas and Mendrinos, 2013). These demonstrates the technical feasibility of for exploitation of hot dry rocks as geothermal resources.

v.) Sedimentary Basin Geothermal Resource

Hot sedimentary aquifer system is a geologic aquifer that overlie a radiating source of heat and heat is transferred by conduction and or convection. These geothermal resources produce higher temperature resources than the surrounding formations due to their low thermal conductivity or high heat flow or both producing geothermal gradients >30$^{\circ C}$/km. These resources spread over large areas. Examples include the Madison Formation of North Dakota, South Dakota, Montana and Wyoming area in the United States. In Europe these resources are found in the Pannonian Basin of Central Europe where it has been used extensively in Hungary (Tenzer, 2001; Lund, 2009). Figure 9 below illustrates sedimentary basin geothermal resources. Figure 9 below is an illustration of sedimentary geothermal resource. Sedimentary basin resources (Anderson & Lund, 1979).

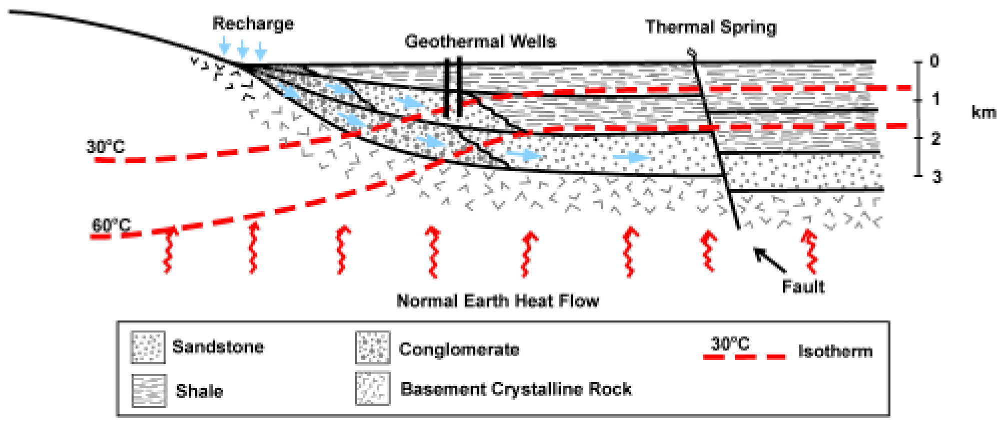

Figure 9. Sedimentary Basin Geothermal Resource

vi) Radiogenic Resources

These geothermal resources are found in areas where granitic intrusions are near the earth's surface causing heating up of the local groundwater from the decay of radioactive materials like thorium, potassium and uranium. This localized heating increases the normal geothermal gradient providing hot water at economical drilling depths for applications like space heating and other low to medium temperature applications. These resources are illustrated in figure 10 below. Radiogenic geothermal system (Anderson & Lund, 1979).

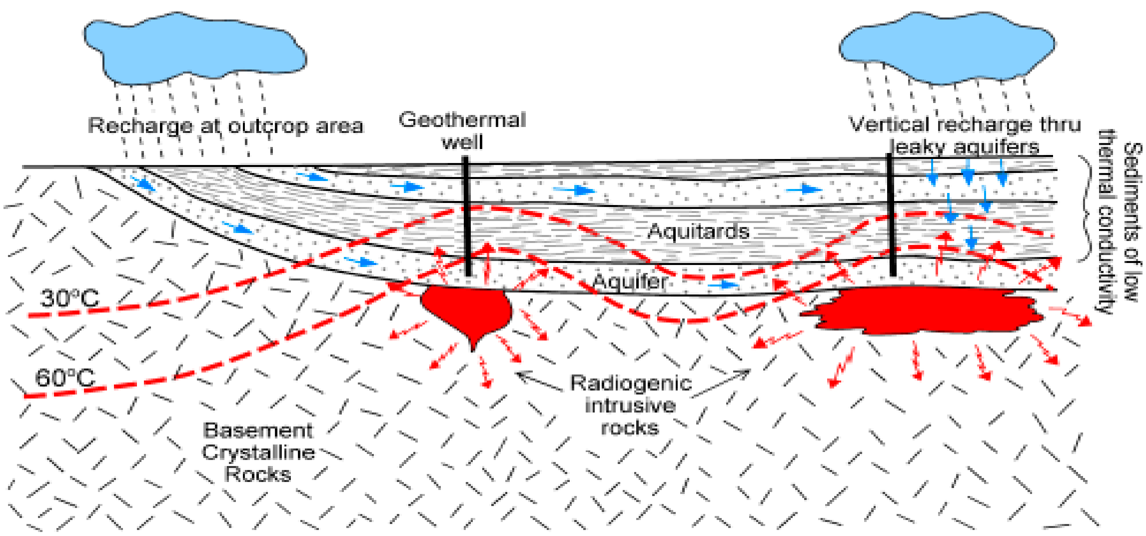

Figure 10. Radiogenic Resources

vi.) Molten Rock or Magma Resources

In magma geothermal resources heat is extracted directly from cooling magma on active volcanoes in the crust with high heat. Surface manifestations for such resources are hot springs and fumaroles making the easy to site. However, it is likely that many magmatic geothermal systems have no surface manifestations making them hard to discover., and remain to be discovered (Williams, et al., 2001). Drilling into magma is a huge engineering challenge but its success may mark a new age of geothermal power generation. Whereas existing geothermal projects around the world use water or steam heated to less than 300°C, magma can yield very high temperatures beyond critical temperature for steam. Water at the most extreme temperatures exists in a state described as "supercritical", where it behaves as neither a true liquid, nor a true gas, and can retain a phenomenal amount of energy. Supercritical water with temperature up to 1,000°C and saturated with corrosive chemicals has higher capacity and can generate up to ten times more power than conventional geothermal sources (Rowley, 2016).

The discovery of magma as a geothermal resource was more of an accident. According to Schwartz (2011), it happened in 2009 when a team of researchers drilling a 15,000-foot-deep geothermal well in Iceland's Krafla volcano stumbled upon magma, which was flowing into the well at a depth of 6,900 feet–only the second time magma has slipped into a geothermal well during drilling.

Molten rock or magma resources contain significant heat energy which can be extracted. This has been experimentally done in Hawaii by drilling into molten rock to directly extract heat energy through a heat exchanger. It has also been used successfully in Iceland at Heimaey after the 1973 volcanic eruption. In this case, a heat exchanger was constructed on the surface of the lava flow to recover heat from boiling water that percolated from the surface. In this project, the heat was used for space heating for over 10 years but was then shut down as the lava cooled down (Lund, 2009). Therefore, this geothermal resource is not yet sustainable since the resource is not permanent and more research and development is needed to improve the conversion efficiency and sustained heat recovery from lava or magma. Karytsas and Mendrinos (2013) estimate that magmatic resources have about 327, 360 billion TOE which is about 400 times the total fossil fuel reserves. A plant using magmatic resource adopted from (Roley, 2016).

Figure 11. Plant in Iceland using magmatic power.

In Iceland (Figure 11), The Iceland Deep Drilling Project (IDDP) drilled to depths below 4km in the Icelandic crust. In 2009, during their first drilling leg, they accidentally hit a magma pocket, and eventually stabilized the system to create the hottest steam ever produced in geothermal exploration which was 450°C. As a development, the second borehole to follow had an objective of tapping the deep circulating water which penetrates the rock around a magma chamber below the Reykjanes peninsula near Reykjavik (Rowley, 2016).

vii.) Supercritical Geothermal Resource

Supercritical resources are very high temperature systems located close to the brittle-ductile transition zone in the earth's crust. If the resource exists as water, the temperature of such a resource would be above 374 and pressure of 221 bars. Supercritical fluids or resources are found at the foot of volcanic heated hydrothermal system. These systems have been encountered at Menengai in Kenya, Krapla in Iceland, Los Humeros in Mexico, The Geysers at Salt Sea, Kakkonda in Japan and Larderello in Italy. (Reinsch, 2017). According to Younger (2015) supercritical root zones do occur just above young magmatic intrusions than often exist under a high enthalpy reservoir. He remarked that there are several engineering limitations to accessing and harvesting resources with temperatures above 400ºC and high pressure above 22 Mpa.

In several cases, magma has been encountered in supercritical resources for example wells MW-04 and MW-06 in Kenya's Menengai geothermal field where temperature of 390 was encountered pressure of 140 bar during shut down. Such conditions lead to challenges like delay in am drilling. Drilling under such conditions leads to metal fatigue and trouble with cement setting some wells in supercritical resources are dry indicating very low permeability. The wells also experience issues regarding rock-physical and fluid properties, leading to challenges related to well drilling, well completion, and fluid handling and control. Cases of well violently blowing out have been encountered hence formation cave-in, blockage of the drill string, and debris accumulation in the well (Reinsch et al, 2017).

To manage supercritical resources exploration and imaging technologies prior to drilling, and better reservoir modeling is necessary. To improve reservoir understanding at supercritical conditions, laboratory experiments at these conditions and numerical models capable of handling supercritical fluid conditions necessary. Tsuchiyaa, and Yamadab (2017) noted that whereas supercritical resources contain significant quantities of recoverable energy, drilling technology to this resource is the limiting factor. Figure 12 gives an illustration of supercritical geothermal resource.

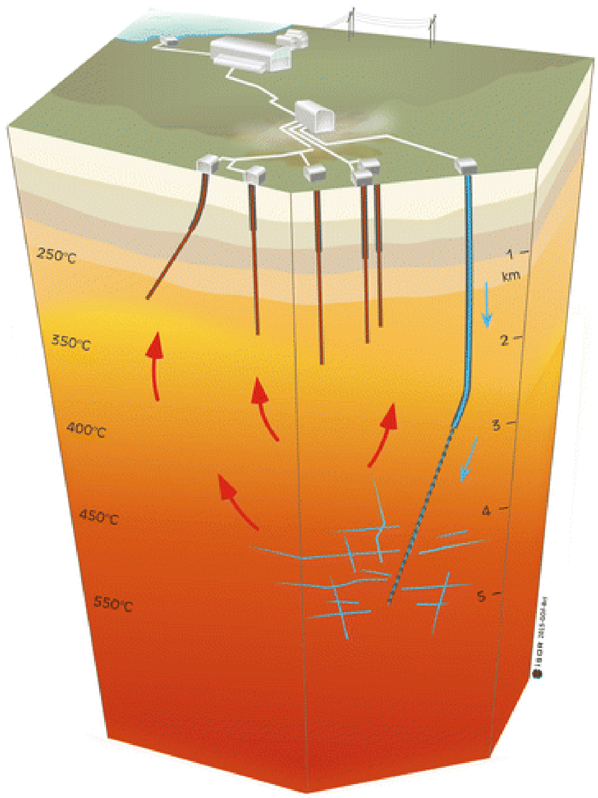

Figure 12. Supercritical Geothermal Resource

Super critical geothermal resource (Adopted from Yamadab, 2017).

Figure 12 shows main elements of a supercritical geothermal resource which include very high temperature source and very high pressure of geothermal fluid.

viii.) Low-Temperature and Co-Produced Resources
Low-temperature and co-produced geothermal resources are typically found at temperatures of 300F (150C) or less. Some low-temperature resources can be harnessed to generate electricity using binary cycle technology. Co-produced hot water is a byproduct of oil and gas wells in the United States. This hot water is being examined for its potential to produce electricity, helping to lower greenhouse gas emissions and extend the life of oil and gas fields (National Renewable Energy Laboratory, n.d.). According to Matek (2016) the technology involves use of fluids resulting from oil and gas field development for production of geothermal power/energy.

5. Environmental Impact of Geothermal

The commonly observed manifestations of geothermal energy are related to convective heat flow, and they include hot springs, geysers, fumaroles, volcanic activities like movements of magma to land and sea floors and existence of some economically Significant ant minerals deposits that are geothermally heated by geothermal fluids and deposited and regions of low temperature on or near the surface of the earth (Goldstein, et al. 2010).

While geothermal power plants (GPP) remain much more environmentally friendly and clean than traditional power plants, but no technology is without negative environmental impacts, as various research have emphasized (Figure 13) (Sayed et al., 2020; Bošnjaković et al., 2019; DiPippo, 2012; Dhar et al., 2020; Bravi and Basosi, 2014). The various environmental impacts related to geothermal power systems are summarized, which include land usage, geological hazards, workers' health, biodiversity impacts, the release of contaminated wastewater, solid waste, gaseous emissions, thermal pollution, noise, waste heat, and social impacts (Bošnjaković et al., 2019; Dhar et al., 2020). GPP can also increase water and air pollution levels. In this regard, the typical noise level during different phases of GPP power production includes air drilling, mud drilling, discharging wells, well testing, heavy machinery operation, and the machines that provide electricity should be 120 dB, 80 dB, up to 120 dB, 70–110 dB, up to 90 dB, and 55 dB, respectively (Bošnjaković et al., 2019; Dickson and Fanelli, 2004). Bravi and Basosi (2014) conducted a comprehensive assessment of GHG emissions resulting from four GPP in Italy and found that the emissions rate in terms of global warming: 80–1045 kg CO_2eq/MWh, acidification: 0.1–44.8 kg SO_2eq/MWh, and human toxicology: 1.1–31.6 kg, 1.4-dB eq/MWh. The major contributors to the effects are the high levels of NH_3, CO_2, CH_4, and H_2S gases found in each plant's effluent. Moreover, arsenic (As), mercury (Hg), selenium (Se), antimony (Sb), and chromium (Cr) are also found in geothermal gases released by GPP(Bakken et al., 2012).

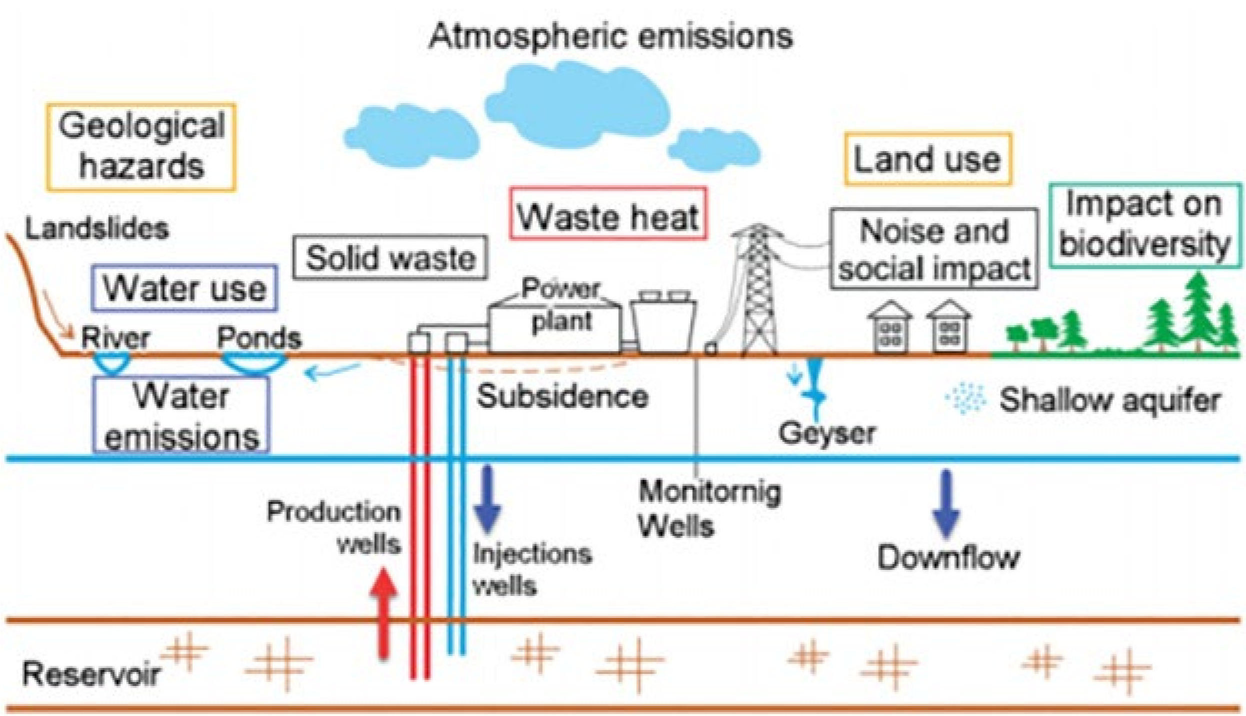

Figure 13. Geothermal power plants' environmental impact (Bošnjaković et al., 2019).

6. Conclusion

A feasible geothermal resource is accessible, and it constitutes quantity of stored energy between the earth surface and specific depth in the earth's crust underneath a given area and obtained based on the local mean temperature of the resource. There are many ways classifying geothermal resources, but the most common criteria are to classify geothermal resources based on the enthalpy of geothermal fluids. The geothermal fluid which is the energy carrier has varying characteristics for different geothermal fields in terms of energy content, thermal and chemical properties. Based on enthalpy, geothermal resources can be classified as low enthalpy, medium enthalpy, or high enthalpy geothermal resources. Geothermal energy sysems can be classified as convective dominated systems, which include liquid-vapour dominated hydrothermal system, conductive dominated system consisting of hot rock and hybrid systems ehich include convection, conductio and high heat producing source e.g. magma. The three elements of a geothermal system are the heat source, a reservoir, and a fluid which is the energy carrier. The heat source can be a very high-temperature (greater than 600 °C) magmatic intrusion located at relatively shallow depths (5 to 10 km) or, some certain low-temperature systems. Most geothermal resources are located close to the boundaries of the earth's tectonic plates where most volcanoes are located.

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