# DEVELOPMENT OF A METHODOLOGY TO ASSESS THE GEOTHERMAL ENERGY POTENTIAL IN SRI LANKA

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**University of Moratuwa**

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**This thesis submitted in partial fulfillment of the requirements for the degree Master of Philosophy**

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# DECLARATION

“ I hereby certify that this thesis does not incorporate any material previously submitted for a degree or diploma in any university and to the best of my knowledge and belief, it does not contain any material previously published, written or orally communicated by another person except where due reference is made in the text”

……………………………………

(Signature of the applicant)

G.D.Nanayakkara

“The above given particulars are true and correct to the best of our knowledge”

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# ABSTRACT

Assessing geothermal potential is a difficult task. It is a time and money consuming process. There are many methodologies, such as deep drilling bore holes and measure temperature by using thermal sensors, silicon solubility measurement, magneto telluric, etc.

The used equipment for these methods, especially for drilling of deep bore holes are much expensive. If geothermal gradient is very low, the area cannot be effectively used to establish a geothermal power plant. Another method based on contents of amorphous silica in hot spring water is also used to determine the geothermal gradient. Main task of this study is to find a suitable cost effective method to assess the geothermal potential in Sri Lanka and to develop a lab scale plant. As a cheaply available geophysical technique, ground resistivity measurement was also used to measure the temperature. Increasing temperature again increases their resistance. This natural phenomenon has been used to develop a methodology to assess the geothermal potential in various countries.

Resistivity surveys have been carried out in various places in Sri Lanka. Gathered resistivity data has been analyzed. Geothermal gradient calculation was done in Bogala Graphite Mines to study about the temperature gradient in Sri Lanka. Also this selected place was far away from hot spring areas and hence those hot springs had no influence to the collected data. This method is suitable to find temperature gradient of Sri Lanka. The average values of temperatures in those levels were computed and then geothermal gradient was calculated which is 28.046$^0$C/km. This method gave some reliable information as to how the temperature gradient varies at crustal level of rocks in Sri Lanka.

To calculate power generation, a laboratory model was developed with the possibility of applying varying parameters. Collected the annual average temperature data and predicted the temperature gradient of various districts. According to the calculations done, geothermal gradient in Sri Lanka is varying between 23 $^0$C and 30 $^0$C per km. This information has been used to develop the geothermal map of Sri Lanka.

Laboratory plant was developed and its performances were studied for varying hot spring temperatures and all data gathered and analyzed. According to that the geothermal temperature gradient in Sri Lanka is suitable to generate electricity. But the water flow rate is not sufficient to produce more power.

The research team who studied about the Mahapelessa hot springs has observed that during the period of one minute, 10 liters of geothermal hot water have been released. Another research team exposed that underground reservoir temperatures are higher in some areas by applying geochemical method. Considered all possible geothermal gradient assessment methods and the best system suitable for Sri Lankan territory is the borehole drilling, out of all of them. The reason for this is borehole can be drilled at any selected location, without facing difficulties out of all of them.

# ACKNOWLEDGEMENT

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## List of abbreviations, terms and symbols

| | |
|---|---|
| kW | Kilo Watt |
| kWh | Kilo Watt Hour |
| MW | Mega Watts |
| GW | Giga Watt |
| VOC | Volatile Organic Compound |
| EGS | Enhance Geothermal Systems |
| MT | Magneto Telluric |
| GENI | Global Energy Network Institute |
| GSI | Geological Survey of India |
| IOE | Institute of Engineers |
| DEDE | Department of Energy Development and Efficiency |
| AfDB | African Development Bank |
| TEC | Theoretical Cycle Efficiency |
| $CO_2$ | Carbon dioxide |
| CO | Carbon monoxide |
| $H_2S$ | Hydrogen Sulfide |
| $SO_2$ | Sulfur dioxide |

# CHAPTER 1

## INTRODUCTION

Energy crisis creates many problems to people all over the world. We cannot create or destroy energy, but it is possible to convert them from one form to another. Most of the energy used in the world is for heat and motion.

The entire world is facing energy crisis. Most of the major oil deposits and reserves are found along the Persian Gulf and the biggest oil deposits and reserves in the world are found in Saudi Arabia, mainly along the Persian Gulf. Saudi Arabia (18 % of global reserves), Canada (12 %, mostly oil sands), Venezuela (12 %, mostly tar sands), Iran (9 %), Iraq (8 %), Kuwait (7 %), UAE (7 %) and Russia (5 %) [1] .

Present oil reserves in the world will last for 40 years at most, it is time to find renewable energy resources without delay to fulfill this gap. Most of the countries in the world use fossil fuel, hydro power, wind power, solar power, nuclear power, ocean power and geothermal etc. Sri Lanka uses all of the power resources mentioned above, except geothermal and nuclear power.

We mainly depend on fossil fuel imported from various countries and that will consume large amount of foreign exchange. Thermal power generation in Sri Lanka is very high. Hydro power systems, i.e.; large hydro, mini hydro and micro hydro are also make very high contribution to our power systems.

The thermal power plants pollute the environment creating many adverse effects due to emission of an asphyxiate gas like Carbon dioxide ($CO_2$, an asphyxiate gas is non toxic or minimally toxic gas, which reduces or displaces the normal oxygen concentration in breathing air. Breathing of oxygen depleted air can lead to death by suffocation), and Carbon monoxide (CO) this is odorless, colorless gas that can cause sudden illness and death. Coal power gas plants emit gases, such as carbon dioxide, nitrogen dioxide and sulfur dioxide in to the environment. Acid rain is caused by the emission of nitrogen dioxide and sulfur dioxide. They react with atmosphere and form sulfurous, nitric and sulfuric acids and they fall as rains [2] .

## 1.1 WHAT IS GEOTHERMAL ENERGY.

The word which uses to denote the heat coming from the earth is GEOTHERMAL. With the help of two Greek words *geo* and *therme* made this word. Geo means earth and therme means thermal.

Geothermal energy is thermal energy generated and stored in the Earth. Thermal energy is, energy that determines the temperature of matter. Earth's geothermal energy originated since the original formation of the planet, from radioactive decay of minerals and from volcanic activity. Due to difference in temperatures between the core of the planet and its surface area, drives a continuous conduction of thermal energy in the form of heat from the core to the surface. Depth/ temperature plot for geothermal resource is given in Fig 1.1

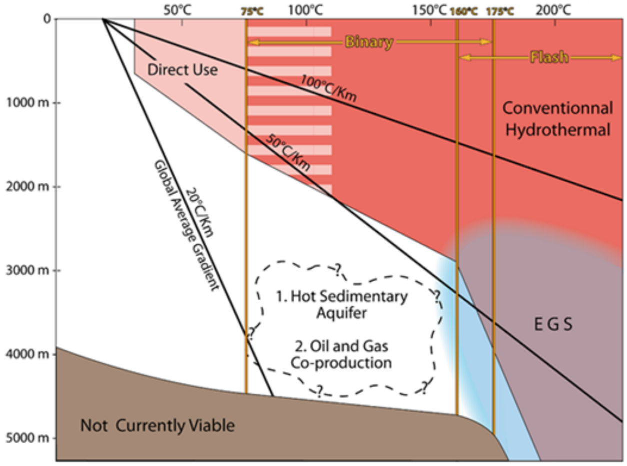

Fig 1.1 Depth temperature plot for geothermal resources [3].

Electricity is now produced from geothermal energy in 24 countries, including the United States. They produce 3450 MW power from geothermal resources per year and that is 0.3% of the national requirement.

Then Philippines 1870 MW, that is 27% of national requirement, Indonesia 1340 MW, Mexico 1017 MW, New Zealand 1005 MW, Italy 916 MW, Iceland 665 MW, Kenya 594 MW, Japan 519 MW, Turkey 397 MW, Costa Rica 207 MW, El Salvador 204 MW , Nicaragua 159 MW, Russia 82 MW, Guatemala 52 MW, Papua New Guinea 50 MW, Portugal 29 MW, China 27 MW, Germany 27 MW, France 16 MW, Ethiopia 7.3 MW, Australia 1.2 MW, Austria 1.1 and Thailand 0.3 MW [4] .

Due to high initial construction cost wind, ocean and solar power resources usage is less compared with others. At present in some of the areas of Sri Lanka wind power systems and solar power systems are available.

The output power level of them depend upon environmental factors, such as rain fall, wind speed, solar radiation etc. Most of them belong to private sector organizations.

In Sri Lanka, several numbers of hot springs are spread out in a boundary between Highland complex and Vijayan complex. That means there may be a high geothermal potential in this area. To find out geothermal potential in Sri Lanka, available several methods can be used, however most of them are very expensive methodologies.

Determination on geothermal potential is key factor for estimating the capacity of power generation using geothermal energy. Thus use of geothermal energy to generate power will be more viable action to be taken at the moment.

## 1.2 GEOTHERMAL ENERGY AND HOT WATER SPRINGS

Many ancient people, including the Romans, Chinese, and Native Americans, used hot mineral springs for bathing, cooking, and heating. Water from hot springs is now used world-wide in spas, for heating buildings, and for agricultural and industrial uses. Many people believe hot mineral springs have natural healing powers.

Using geothermal energy to produce electricity is a relatively new industry**.** It was initiated by a group of Italians who built an electric generator at Lardarello in 1904. Their generator was powered by the natural steam erupting from the earth.

The first attempt to develop geothermal power in the United States came in 1922, at the Geysers steam field in northern California. The project failed because the pipes and turbines of the day could not stand up to the abrasion and corrosion of the particles and impurities that were in the steam. Later, a small but successful hydrothermal plant opened at the Geysers in 1960 [5].

## 1.3 HEAT IN THE EARTH

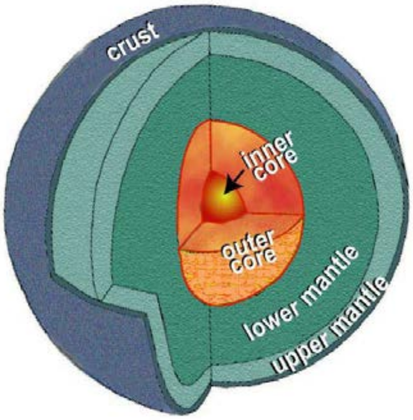

Fig 1.2 Interior structure of the earth [6] .

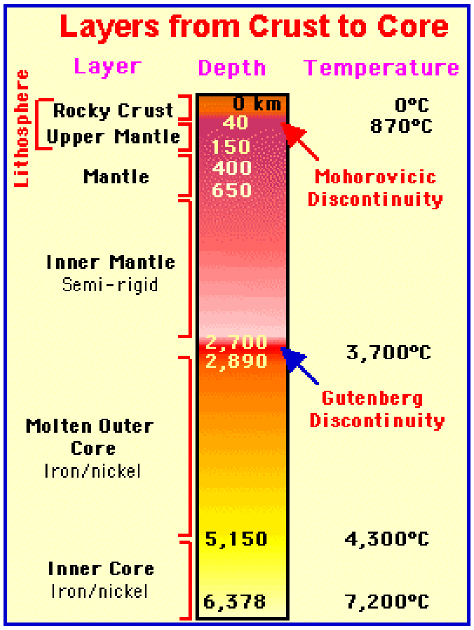

Fig 1.3 Temperature variation in the earth's interior [7] .

People are living in the outer surface of the earth and the temperature is average about 27 $^0$C but it increases when goes to inside of the earth (Fig 1.2) Earth consists major three parts such as core, mantle and crust. The core contains two layers as inner core and outer core. (Fig 1.2 and Fig 1.3)

**Inner core** is a solid iron sphere, and its center is located in 6,378 km away from the earth surface. Radius of inner core is 1228 Km. this consists of Iron and Nickel. Estimated temperature of center of inner core is about 7200$^0$ C, and boundary between inner core and outer core is about 6100$^0$ C.

**Outer core** is a molten liquid layer that is placed in between solid inner core and Mantle of the earth. Outer boundary of this is beneath 2890 Km and inner boundary 2260 Km below that, ie 5150 Km underneath the earth surface. The thickness of this core is 2260 Km and it consists of Iron and Nickel.

Temperatures at the boundary between outer core and mantle varying from $4400^0$ C to $6100^0$ C near the inner core.

**Lower mantle** is a semi rigid layer, which is spreading 300 Km (190 miles) from the earth surface till 2890 Km (1800 miles) depth. Average temperature is around $3000^0$ C ($5400^0$ F). The lower mantle for the biggest part probably consists of sulphides and oxides of silicon and magnesium. This has almost 80% of earth's total volume. The density of Lower mantle is between 4.3g/cm³ and 5.4g/cm.³This is tough solid rock and formed such a way due to high pressure.

**Upper Mantle** is thinner than the inner mantle. It is spreading 10 Km (7 miles) from the earth surface and running till 300 km ( 190 miles) below the surface of the earth. The upper mantle can be divided into two different layers. The bottom layer is tough liquid rock and probably consists of silicates of iron and magnesium. The temperature in this part is in between 1400° C ( $2520^0$ F) and 3000° C ( $5400^0$F). The density of the upper mantle is between 3.4g/cm³ and 4.3g/cm³. The upper layer of the outer mantle consists of the same material but is stiffer because of its lower temperature.

**Crust** is the outermost layer of the earth and it is ranging from 5 Km to 70 Km, the thin parts of the crust are the oceanic crust, which underlie the ocean basins the thicknesses of them vary from 5Km to10 km. The temperature of the crust increases with depth that is in between from about 200°C to 400°C.

The earth's crust is divided into parts, they are called plates. The magma is the outer mental comes out close to the earth's near the corners of these plates. Volcanoes can be found in such places. Lave leaving from the volcanoes is to some extent magma. Rocks and water in deep underground places absorb the heat from the magma. Therefore a temperature of water and rocks inside the earth increases with depth.

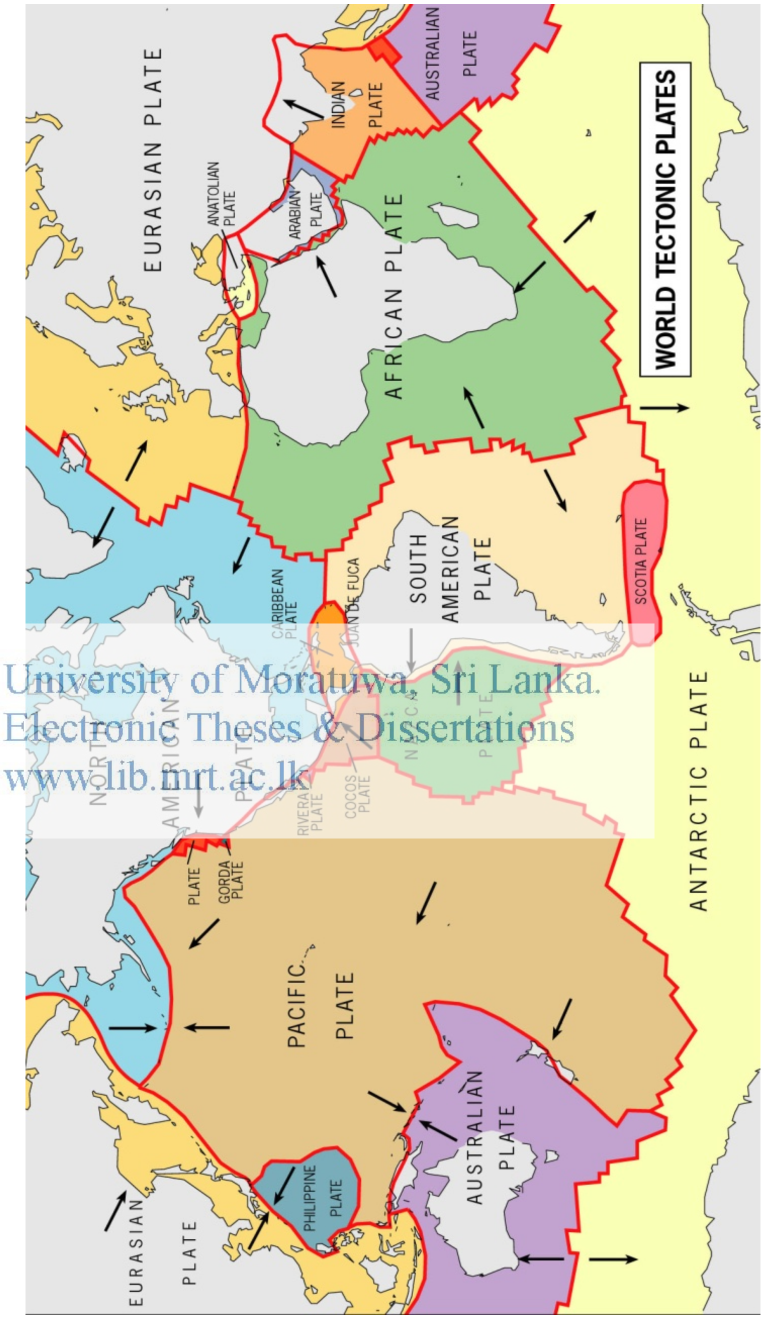

Fig 1.4 World tectonic plates [8].

## 1.4 GENERATION OF HEAT INSIDE THE EARTH.

There are three main sources of heat in the inside of the earth, they are;

(a) Heat, when the earth formed and accreted, which has not yet been lost;

(b) Frictional heating, caused by denser core material sinking to the center of the earth;

(c) Heat, from the decay of radioactive elements.

It takes a rather long time for heat to move out of the earth. This occurs through both "convective" transport of heat within the earth's liquid outer core and solid mantle and slower "conductive" transport of heat through non convecting boundary layers, such as the earth's plates at the surface. As a result, much of the earth's ancient heat, from when the earth first accreted and developed its core, has been retained.

The amount of heat that can arise through simple accretionary processes, bringing small bodies together to form the proto-earth, is large: on the order of $9980^0$ C. The critical issue is how much of that energy was deposited into the growing earth and how much was reradiated into space.

Additionally, fall of the dense iron-rich material that makes up the core of the planet to the center would produce heating on the order of $1650^0$ C. The magnitude of the third main source of heat--radioactive heating--is uncertain. The precise abundances of radioactive elements (primarily potassium, uranium and thorium) are poorly known in the deep earth.

In sun, there was no shortage of heat in the early earth, and the planet's inability to cool off quickly results in the continued high temperatures of the Earth's interior. In effect, not only do the earth's plates act as an insulator on the interior, but not even convective heat transport in the solid mantle provides a particularly efficient mechanism for heat loss.

The center of the earth lies 6,400 kilometers (4,000 miles) beneath our feet, but the deepest that it has ever been possible to drill to make direct measurements of temperature (or other physical quantities) is just about
Rice University 10 kilometers (six miles).

The temperature in the earth's deep interior estimate using indirect method. Observing the speed at which of passage of seismic waves pass through the earth allows geophysicists to determine the density and stiffness of rocks at depths inaccessible to direct examination. If it is possible to match up those properties with the properties of known substances at elevated temperatures and pressures, it is possible (in principle) to infer what the environmental conditions must be deep in the earth.

The problem with this is that the conditions are so extreme at the earth's center that it is very difficult to perform any kind of laboratory experiment that faithfully simulates conditions in the earth's core. Nevertheless, geophysicists are constantly trying these experiments and improving on them, so that their results can be extrapolated to the earth's center, where the pressure is more than three million times atmospheric pressure [9].

## 1.5 OCCURRENCE OF GEOTHERMAL ENERGY SOURCES.

Due to various actions of geothermal energy, volcanoes, hot springs, geysers, and fumaroles are created. Most geothermal energy sources cannot be seen. Usually geothermal energy is available in deep underground. Geologists use several methods to find geothermal resources. They may study aerial photographs and geological maps, analyze the chemistry of local water sources and the concentration of different metals in the soil. Also measure variations in gravity and magnetic fields surrounded.

But only way they can be sure there is a geothermal resource is by drilling borehole and measure underground temperatures. To obtain correct and more accurate results at least 100 to 300 m depth bore hole required [10].

The earth is a hotbed of geothermal energy. The most active geothermal resources are usually found along major plate boundaries where earthquakes and volcanoes are concentrated. Most of the geothermal activity in the world occurs in an area known as the "Ring of Fire “( Fig 1.5). The Ring of Fire rims the Pacific Ocean and is bounded by Japan, the Philippines, the Aleutian Islands, North America, Central America, and South America.

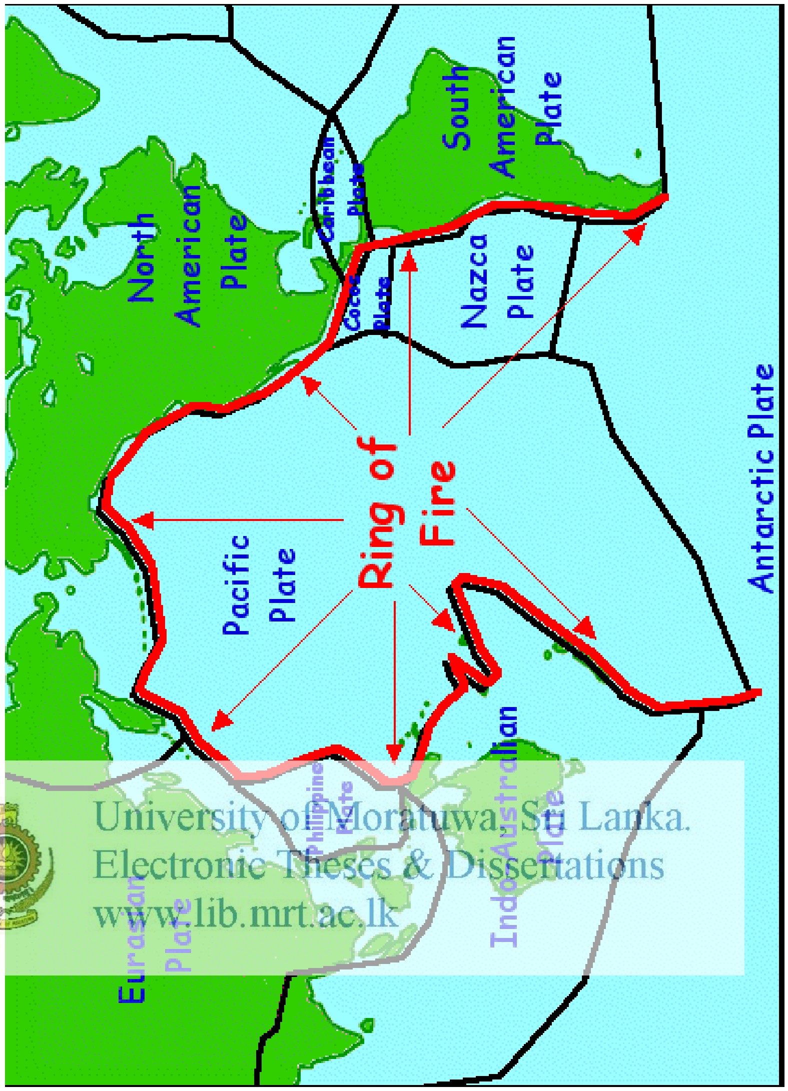

Fig 1.5 Ring of Fire [11].

Generally, four main kinds of geothermal resources are considered for electrical power generation after think about the temperature of the resource. They are, hydrothermal, geo pressured, hot dry rock, and magma.

The hydrothermal resources are the only one of geothermal resource which is widely used. The other three resources are still in the child stages of development, Geologists providing their full effort to develop these valuable resources. Many countries use this valuable resource for various works.

## 1.6 HYDROTHERMAL RESOURCES

The world hydrothermal word can be divided to two parts, they are water (hydro) and heat (thermal). Geothermal reservoirs, which produce steam or hot water, occur naturally where magma comes close near to the surface to heat ground water trapped in fractured rock or porous rocks, or where water circulates at great depth along faults. Hydrothermal resources are used for different energy purposes depending on their temperature and depth. The below given Fig. 1.6 clearly show the process.

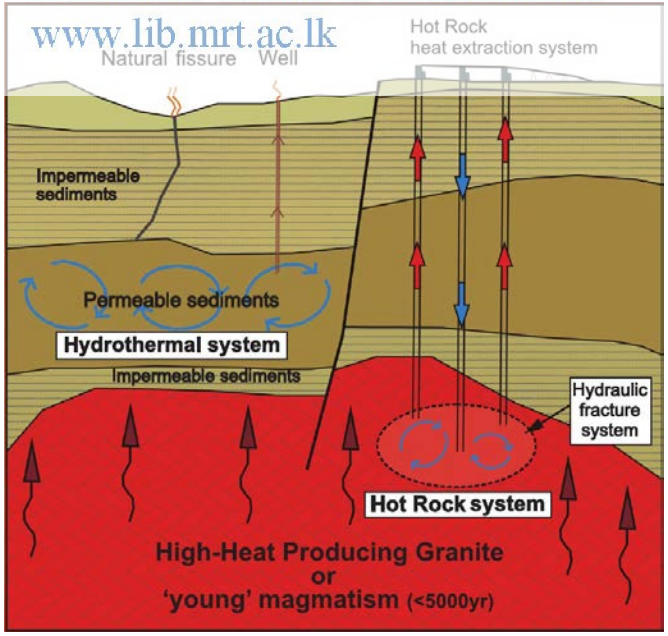

Fig 1.6 Hydrothermal resources[12].

## 1.7 GEOTHERMAL RESERVOIRS

The heat from the Earth's core continuously flows outward or to the surface of the earth. Sometimes the heat, as magma, reaches the outer surface as lava, but it typically remains below the Earth's crust, heating nearby rock and water, sometimes to levels as hot as 700°F. When water is absorb the earth’s heat and increase its temperature to higher level, then the hot water or steam generates from hot water can be trapped in permeable and soft rocks under a layer of impermeable rock and a geothermal reservoir can form. This hot geothermal water can be visible itself on the surface as hot springs or geysers, but most of it stays deep underground, trapped in cracks and porous rock. This natural collection of hot water inside the ground is called a geothermal reservoir. That may be small, large and very large in capacity.

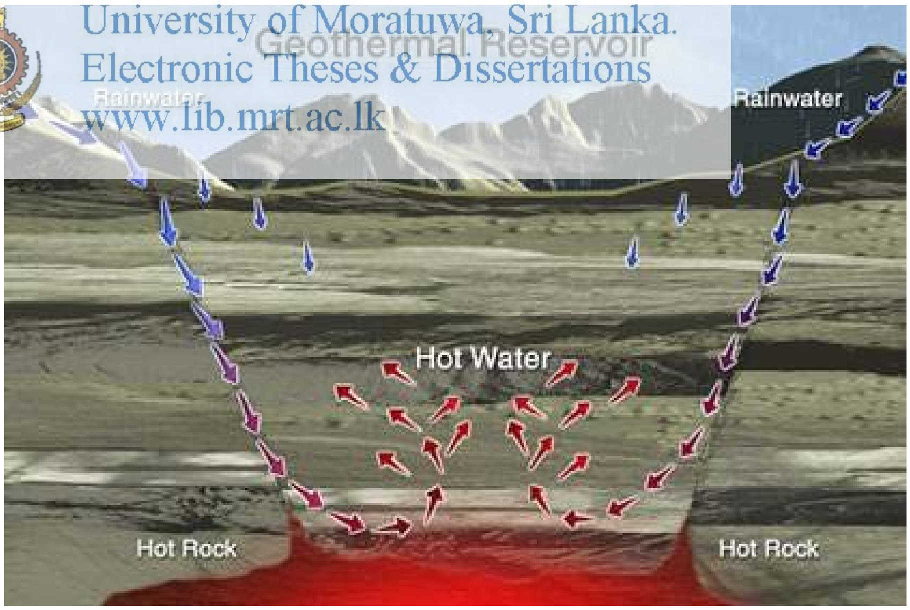

Fig 1.7 Geothermal Reservoir [13].

The temperature of the and volume of the water trapped in geothermal reservoir decide the power capacity. Most of the geothermal reservoirs are in the underground.

They cannot be seen, but geo heat comes to surface by different ways, such as, Volcanoes, and holes where volcanic gases are released called fumaroles, Hot springs and geysers.

### 1.7.1 VOLCANOES

This is an opening, in an earth’s surface or crust. This allows hot magma, volcanic ash and gases to escape from below the surface. There are many volcanoes as much as 1900 in the world they activate time to time and release large amount of heat energy. At any time there are about 20 volcanoes actively erupting around the world, and about 50-70 volcanoes have erupted in the last year or so. There are a total of 550 volcanoes that have erupted in all of recorded history. Some of the famous volcanoes are Arenal, Barva, Irazu and Poas in Costa Rica, Fuego, Santa Maria and Pacaya in Guatemala, Cotopaxi, Chimborazo and Cayambe in Equador,Thera in Greese, etc.

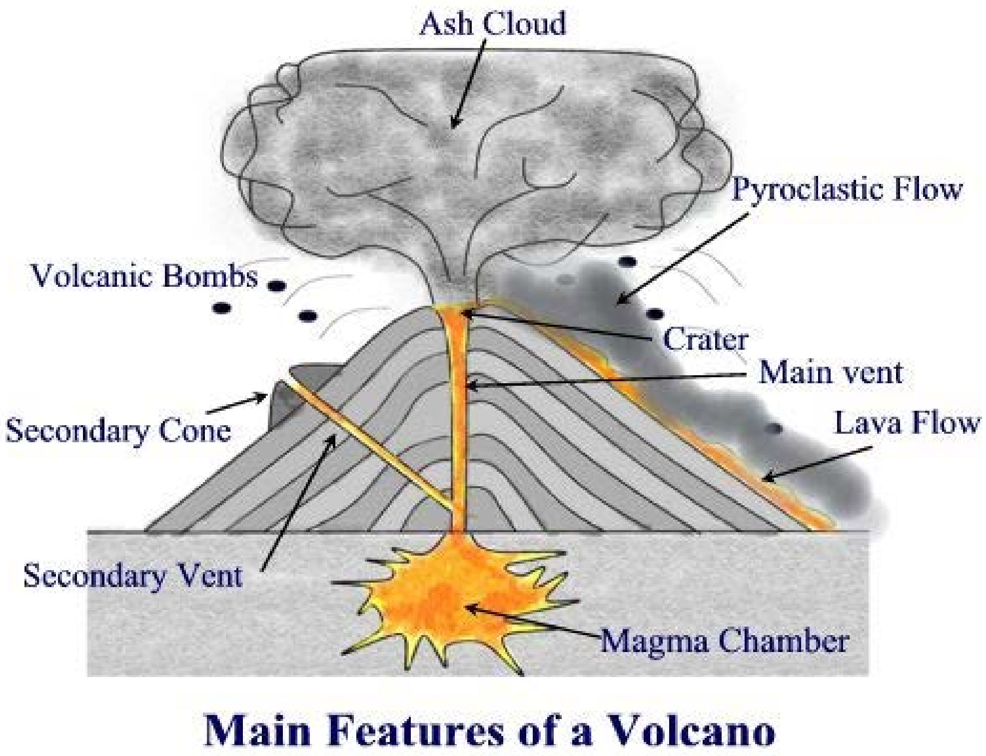

Fig 1.8 Volcano [14]

Volcanoes are mountains, but they are very different from other mountains, they are not formed by folding and crumpling or by uplift and erosion. Instead, volcanoes are built by the accumulation of their own eruptive products lava, ash flows etc.

A volcano is most commonly a conical hill or mountain built around a vent that connects with reservoirs of molten rock below the surface of the Earth. The term volcano also refers to the opening or vent through which the molten rock and associated gases are pushing out.

The molten rock, which is lighter than the surrounding solid rock, forces its way outward and may finally break through weak zones of the Earth's crust. The molten rock may pour from the vent as non explosive lava flows, or it may be sprayed vertically into the air as dense clouds of lava fragments. Larger fragments fall back around the vent, and accumulations of fallback fragments may move down slope as ash flows under the force of gravity. Some of the finer ejected materials may be carried by the wind only to fall to the ground many miles away. The finest ash particles may be spread several kilo meters into the atmosphere and carried many times around the world by stratospheric winds before settling out.

Technically, volcanoes fall under the category of geothermal power, but they aren't the typical hole-in-the-ground suitable for geothermal wells. Ormat Technologies (ORA) has tapped into the Pacaya volcano in Guatemala. The country's goal is to have 60% of its energy generated from volcanoes, along with hydro power. Guatemala is not the only country tapping into this source of power. There are plenty of other Central American countries including Costa Rica, El Salvador, and Nicaragua [15].

Developers of geothermal energy, or energy used to generate electricity, are preparing to put a whopping 24 million gallons of water into the side of a dormant volcano in Central Oregon called Newberry Volcano, situated near Bend, Ore. The plan is for the water to rise to the earth’s surface quickly enough and at a high enough temperature, thus serving as another alternative green energy source [16].

### 1.7.2 FUMAROLES

Fig 1.9 Fumaroles [17].

A fumaroles (Latin *fumes*, smoke) is an opening in a earth's crust, often in the neighborhood of volcanoes, which emits steam and gases such as Carbon dioxide, Sulfur dioxide, hydrochloric acid, and Hydrogen Sulfide. The steam is created when superheated water turns to steam as its pressure drops when it emerges from the ground. The name solfatara, from the Italian *solfo*, sulfur (via the Sicilian dialect), is given to fumaroles that emit sulfurous gases.

Fumaroles may occur along tiny cracks in disordered clusters or fields, and on the surfaces of lava flows and thick deposits of pyroclastic flows.

A fumaroles field is an area of thermal springs and gas vents where magma or hot igneous rocks at shallow depth are releasing gases or interacting with groundwater. The fumaroles could be described as a hot spring that boils off all its water before the water reaches the surface [18].

### 1.7.3 HOT SPRINGS

This is a water spring that is produced by the emergence of geothermal heated groundwater from the Earth's crust. Hot springs are available in many places of the world. More of them are in countries, those who have rich geothermal resources.

Temperatures of hot springs are not very high, they are use for various work. In Sri Lanka there are around 10 hot springs and some of them have low temperature water and some of them is around 70 $^{0}$C. But the temperatures are not constant they varies.

Besides Ayurveda, hot springs are also considered for natural healing benefits. A hot spring is produced by the emergence of geothermal heated groundwater in the Earth’s crust. The healing effect comes mostly, from the mineral composition of these springs and the geothermal energy of this underground water.

Hot spring water facilitates healing in a number of ways:

Helps the body get rid of toxins, increases circulation, pain killing power, stimulates the immune system, reduces tension, calming effects on the body and mind, muscle relaxing effects, nourishes the skin and much more [19].

Fig 1.10 Hot Spring [20].

### 1.7.4 GEYSERS

A geyser is a spring characterize by intermittent discharge of water ejected turbulently and accompanied by a steam.

Due to particular hydro geological conditions geysers are formed, they are available in few places of the earth. Generally all geyser field sites available near active volcanic areas and due to availability of high temperature of magma the geyser effect is created. Generally, surface water works its way down to an average depth of around 2,000 m and its reach to hot rocks. Finally, pressurized boiling water spaying out to the ground.

Fig 1.11 Geysers [21].

## 1.8 GEOTHERMAL ENERGY AND THE ENVIRONMENT

Geothermal energy is a renewable energy source that does little damage to the environment. Geothermal steam and hot water contained Hydrogen Sulfide ($H_2S$) and other gases and chemicals that can be harmful in high concentrations. Geothermal power plants use "scrubber”, systems to clean the air of Hydrogen Sulfide and the other gases.

Sometimes the gases are converted into marketable products, such as liquid fertilizer. Newer geothermal power plants can even inject these gases back into the geothermal wells.

The geothermal energy conversion process generates a Sulfur containing off-gas which passes through a thermal oxidizer to destroy volatile organic compounds (VOC’s). The sulfur compounds are oxidized to Sulfur dioxide ($SO_2$) and must be removed before exhausting to atmosphere. A packed bed absorber treats the thermal oxidizer exhaust to remove $SO_2$. Always geothermal plants are located in desert environment with summer temperatures reaching > $49^{o}$C.

The scrubber equipment must be designed to achieve high removal efficiency, continuous operation and withstand the extreme environment.

Geothermal power plants do not burn fuels to generate electricity as do fossil fuel plants. Geothermal power plants release less than one to four percent of the amount of Carbon dioxide ($CO_2$) emitted by coal plants. Emissions of sulfur compounds from motor vehicles and fossil fuel plants are also major contributors to acid rain.

Geothermal power plants, on the other hand, emit only about 1% to 3% of the sulfur compounds that coal and oil-fired power plants do. Well-designed binary cycle power plants have no emissions at all. Geothermal power plants are compatible with many environments. They have been built in deserts, in the middle of crops, and in mountain forests [22].

## 1.9 DIRECT USE OF GEOTHERMAL ENERGY, FROM LOW TEMPERATURE SOURCES

Geothermal reservoirs, which producing low temperature to moderate-temperature water ie. 20°C to 150°C provide direct heat for residential, industrial, and commercial uses. This resource is widespread in the Europe, and is used to heat homes and offices, spas, commercial greenhouses, fish farms, food processing facilities, gold mining operations, and a variety of other applications. In addition, spent fluids from geothermal electric plants can be subsequently used for direct use applications in so-called "cascaded" operation. Direct use of geothermal energy in homes and commercial operations is less expensive than using traditional fuels. Savings can be as much as 80% over fossil fuels [23].

Direct use is also very clean, producing only a small percentage (and in many cases, none) of the air pollutants emitted by burning fossil fuels. Heat from geothermal resources is also used to dry ceramics, grain, vegetables, fish and other products.

Hydrothermal resources are suitable for heating public buildings, schools, and homes etc in cold countries, those have geothermal resources.

Low-temperature geothermal resources are available throughout the western United States, and there is great potential for new direct-use applications [24][25].

A survey of 10 western states have identified more than 9,000 thermal wells and springs, more than 900 low temperature to moderate temperature geothermal resource areas, and hundreds of direct use sites.

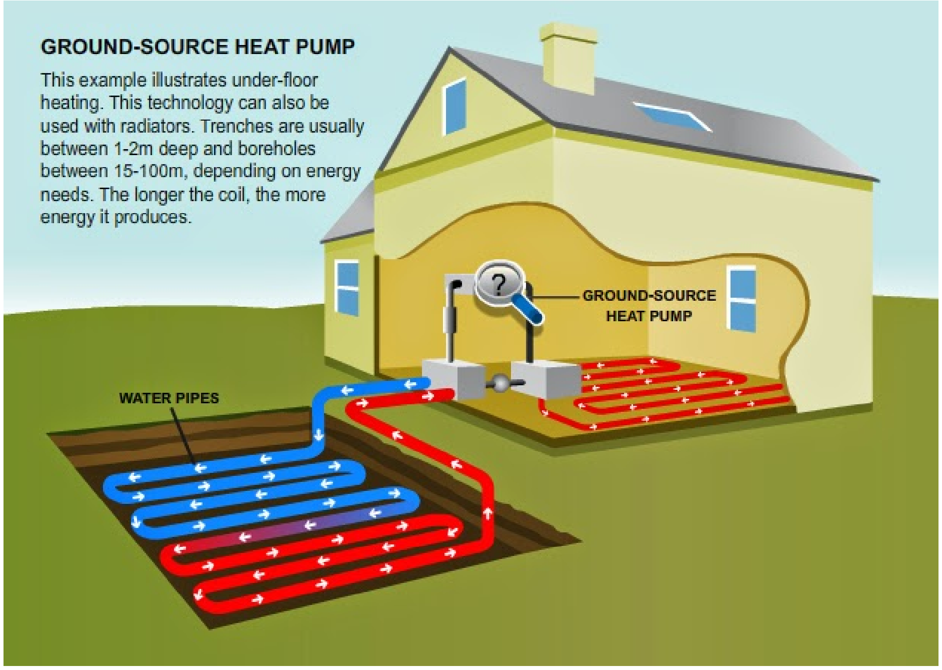

Fig 1.12 Building heating by geothermal heat [23].

The survey also identified 271 collocated sites, cities within 8 kilometers of a resource hotter than 122 $^0$F (50 $^0$C), that have excellent potential for near-term direct use.

If these collocated resources were used only to heat buildings, the cities have the potential to save 18 million barrels of oil per year. That saves foreign exchange.

Generally direct-use systems have three components, they are,

1. Production facility means usually a well to bring the hot water to the surface;
2. Mechanical system includes piping, heat exchanger, controls to deliver the heat to the space or process; and

3. Disposal system is injection well or storage pond to receive the cooled geothermal fluid.

## 1.10 PRODUCING ELECTRICITY, HIGH TEMPERATURE SOURCES

When the temperature of a hydrothermal resource is around 105 $^0$C and up, it can be used to generate electricity. Most electricity-producing geothermal resources have temperatures from 150 $^0$ C to 370$^0$C, but according to researcher's, the temperature of geothermal reservoirs can reach nearly 530 $^0$C.

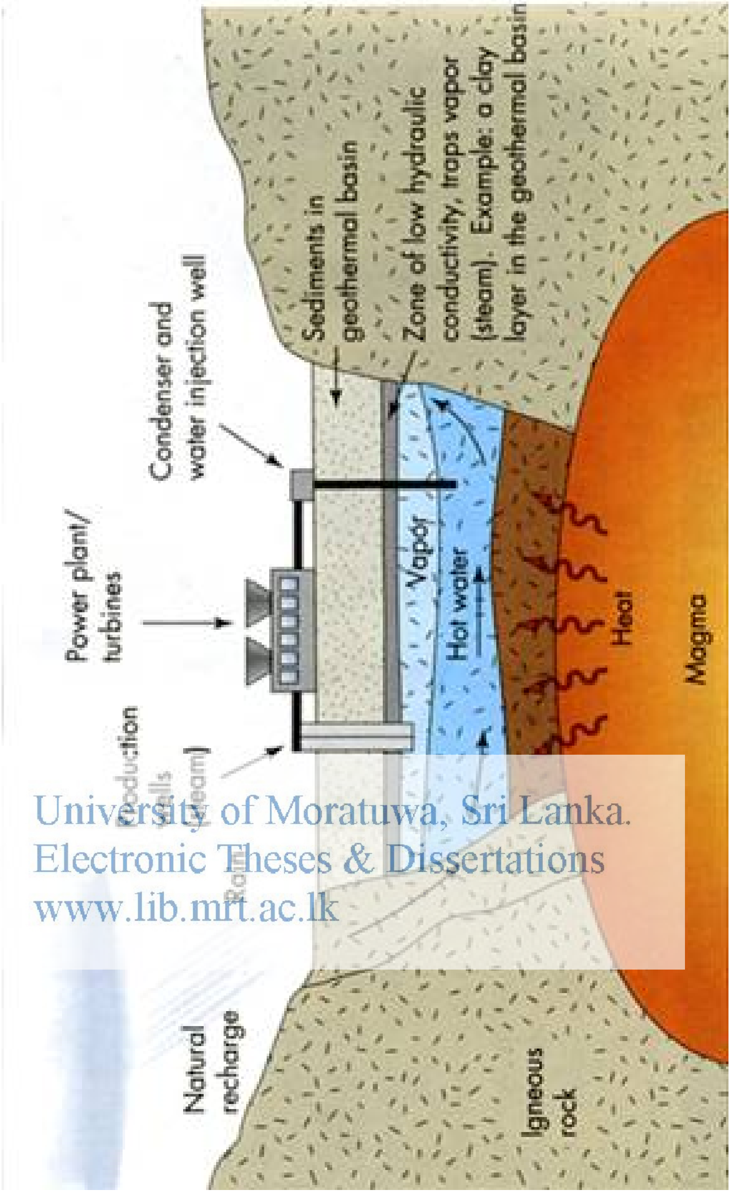

Fig 1.13 High temperature geothermal resources [26].

## 1.11 ENERGY AND ECONOMICAL PROBLEMS IN SRI LANKA

Sri Lanka is a developing country and annual growth of power requirement increasing rapidly. Sri Lanka generates 3,139 MW of electricity at present. Today, the number of households with electricity coverage is around 90%. It is expected to cover the remaining 10% by next year. The Government invests continuously in electricity sector. A provision of Rs. 33,583 million has been allocated by the budget of 2012 for this purpose.

The primary objective was to generate 70% of electricity by hydro power and 30% by petroleum. Due to the constraints of extending hydroelectricity only 35% of the electricity requirement can be generated from hydro sources while generating the remaining 65% using alternative sources. The demand for electricity increases rapidly owing to the exposure of the public to the modern technology and the extension of commercial and technical opportunities in the country. Growth of annual electricity requirement is 7% - 8%.

Although hydroelectricity generation is profitable, it is advisable not to depend heavily on hydro electricity due to lack of adequate rain and hydro sources. In this background, thermal power has to be used in generation of electricity to meet the rising demand. That consume large portion of national income to purchase fossil fuels [27].

To develop the country, one of the major requirements is to minimize the import expenditure and maximize the export income. More than 40% of our country's gross income is being spent on fuel import, transportation and production of thermal power. Crude oil which is our primary source of generating power is rising in cost and is facing dramatic increase in the cost of energy during the past few years [28].

Fossil fuel energy consumption in Sri Lanka was last measured at 48.66 % in 2011, according to the World Bank. Fossil fuel comprises coal, oil, petroleum, and natural gas products [29].

Discovering of rich geothermal resources will lead to generation of power using those resources and that will cut down fuel import cost to some extent.

This research attempt to develop a method to assess the geothermal energy potential of geothermal resources in Sri Lanka. The developed system will help us to find available potential at various areas of the country and improve electricity generation and fulfill the gap of energy requirement in the Sri Lanka to some extent

By following the below given steps, it is possible to reach successful goal.

1. Calculate the geothermal gradient of Sri Lanka.
2. Identify the suitable locations to install power plants.
3. Design and develop laboratory model plant
4. Predict the performance of power plant.
5. Prepare geothermal map for future use.

## 1.12 OBJECTIVES OF THE RESEARCH

Main objectives of the research are given below.

1 To detaminine potential of geothermial energy to genarate power in Sri Lanka

2 Develop a laboratory scale geothermal plant which can be tested at a selected location and analyze the feasibility of the process and to be develop as commend module.

3 To prepare a geothermal map using avail be data and out suitable areas in Sri Lanka to implement the system.

# CHAPTER 2

## LITERATURE SURVEY

### 2.1 HOT SPRINGS IN SRI LANKA

Sri Lanka has several hot water springs those are distributed around the lithological boundary of Highland complex and Vijayan complex. There are several thermal spring existing near this boundary and implies some heat source is available under this region. Two hypotheses have been proposed to explain the existence of thermal springs in Sri Lanka. Above normal geothermal gradient is proposed by [30] while some researchers proposed a deep penetrating fracture system. The temperature of the spring waters varies from place to place.

Though Sri Lanka has no active high enthalpy geothermal regimes either volcanic or tectonic, the use of low enthalpy sources are evident in the form of thermal springs. By using new drilling technologies, Geologist and Engineers can develop hot dry rock (HDR) or enhanced geothermal systems (EGS) in Sri Lanka. State-of-the-art non-invasive techniques such as Magneto-Telluric (MT) deep sounding methods can be used in future research [31].

Many research have been carried out by,[32][33][34] and [35] to identify chemical properties, temperature, flow rate and other characteristics of hot springs in Sri Lanka. Generally hot water springs in the world commonly available in near volcanic areas. But in Sri Lanka it is not. They do not have any connection with volcanic activities. Volcanic zones are little bit far away from Sri Lanka.

Prospects of low to medium temperature geothermal resources can be spread over the hot water springs belt in Sri Lanka. There is also potential for direct-use applications in the food processing, fruit drying, refrigeration, fish hatchery and farming, recreation and tourism spheres.

Geothermal energy is not dependent on the weather, ie rain fall, wind speed, solar radiation unlike solar, wind or hydro power. Therefore, potential geothermal energy reserves in the country could provide at least part of the electricity requirements.

However, to develop the potential geothermal prospects for industrial exploitation, systematic geological, geochemical and geophysical techniques are required to locate and delineate shallow producing geothermal fields. Such work will pinpoint with accuracy the particular depths of hot-water reservoirs for drilling exploratory investigation of boreholes [36].

The reason being that these thermal waters contain medicinal properties to cure ailments like skin eruptions and other rheumatic pains, even our ancients, particularly the Buddhist monks living in ancient cave hermitages had made the best use of these healing hot springs for body and skin ailments.

According to recent research many scientists have analyzed the water samples and found that many chemical properties are existence in the water discharging from the springs.

The Table 2.1 given above shows some of the presently available hot springs in Sri Lanka. The discharged hot water indicates different temperatures, the temperature of the springs changes. Sometimes, the temperature variation of the well can be observed to be dependent upon the discharge water volume.

Some of the temperature values are suitable for binary cycle power generation. But power capacity depends upon the discharge volume of water and temperature of the water.

Table 2. 1 Hot springs and their water temperatures [38]

| No. | Location | Temperature $^0$C |
|---|---|---|
| 01 | Kapurella ( Ampara) | 73.5 |
| 02 | Maha Oya | 56 |
| 03 | Marangala (Padiyathalawa) | 44 |
| 04 | Mahapelessa ( Soorirya Wewa) | 46 |
| 05 | Meda Wewa | 45 |
| 06 | Nelum Wewa ( Polonnaruwa) | 62 |
| 07 | Kanniya ( Trincomalee) | 42 |
| 08 | Kiwulegama (Jayanthiwewa} | 34 |
| 09 | Rankihiriya ( Gomarankadawala) | 42 |

According to collected data the water flow rates of those springs are low and the recommendations to improve them are given in future development stage.

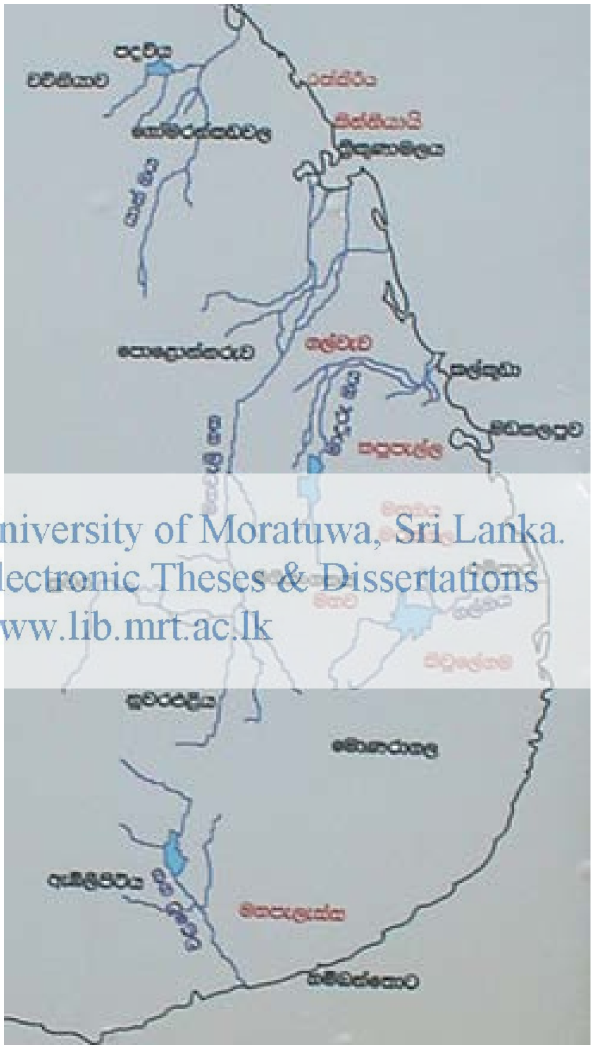

Fig 2.1  Locations map of hot springs in Sri Lanka [37].

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### 2.1.1 KAPURELLA HOT SPRINGS

This is located Inside the Kapurella Buddhist Viharaya about 8km away from Maha Oya town towards Batticaloa. Average temperature of discharges water is $55^0$C. The highest temperature recorded at Kapurella hot spring in Ampara District was $73.5^o$C.

Fig.2.2 Kapurella Hot Springs in Sri Lanka [39].

### 2.1.2 MAHAOYA HOT SPRINGS

Mahaoya Hot Springs is located about 2km off Mahaoya town. There are well maintained 7 wells with different temperatures in the location. The temperature of the hottest well is about $56^0$C. Continuous evaporation of steam from the other wells can be observed.

The site can be accessed by Mahiyangana road (Arannaganwila Road) 400 meters from the junction. There is a display board at the turn off to Arannaganwila Road. Travel approx 2 km on this road and take a right turn. The wells can be reached by travelling 400 meters on this lane.

Fig. 2.3 Mahaoya Hot Springs in Sri Lanka [38].

### 2.1.3 MAHAPELESSA HOT SPRINGS.

This natural resource is situated in a remote area of Sooriyawewa of Hambantota district, Southern province of Sri Lanka. This is also called Madunagala hot water springs, This is the only natural hot water spring available in Southern province of Sri Lanka and its recorded temperature was 46 $^{0}$C.

Fig 2.4 Mahapelessa Hot Springs Sri Lanka [40].

### 2.1.4 NELUMWEWA HOT SPRINGS

This spring lies close to the Nelumwewa and Galwewa reservoir on the foot hills of the famous Dimbulagala mountain range in the Mahaweli B Zone. The measured temperature of the water was 61 $^{0}$C, which makes this this is one of the hottest spring in Sri Lanka. This spring is also unique in the sense that it is inside a wewa (reservoir) and submerges during the October rains.

The location can be accessed from the Polonnaruwa town towards Manampitiya on the A11 route and turn left to Nelum wewa from Sewanapitiya junction. Traveling about 6 kilometers off from the junction along this road will take you to the springs are located.

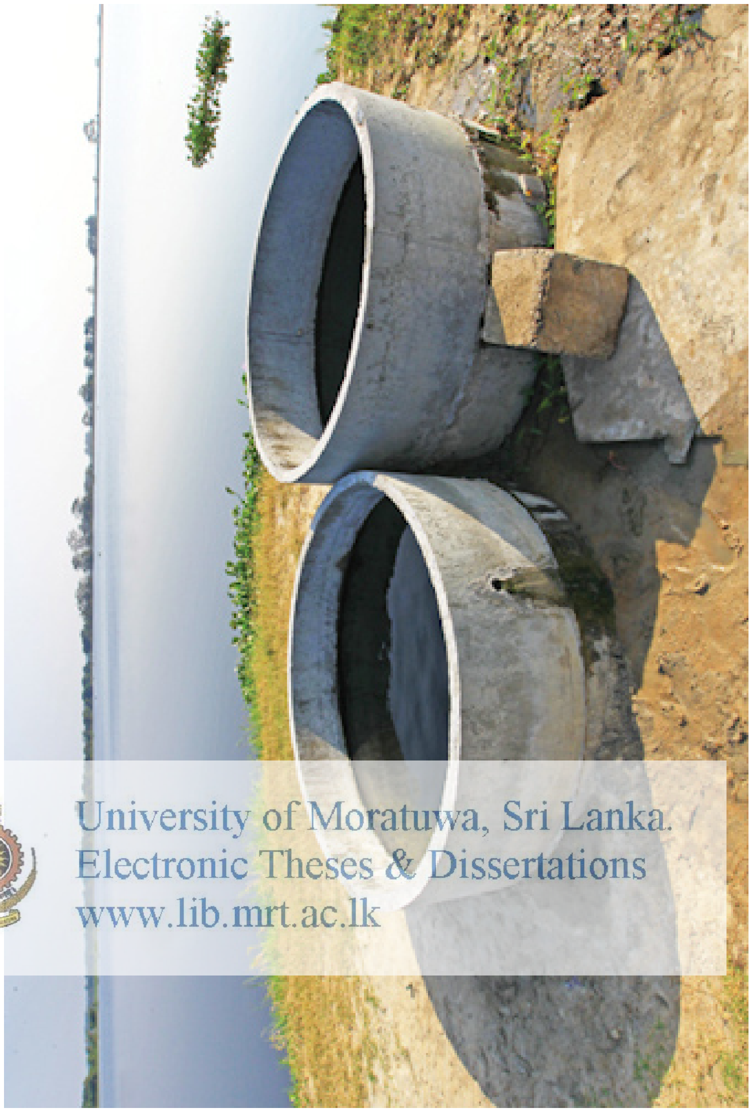


Fig 2. 5 Nelumwewa Hot Springs in Sri Lanka [41].

### 2.1.5 KIWULEGAMA / JAYANTHIWEWA HOT SPRINGS

It is located along the Pallan Oya Road near Jayanthi Wewa it is in the Kiwulegama Village in Ampara Distric.t The temperature of discharged hot water stream is 34 $^{0}$C. From the Wadinagala Junction, take the Pallanoya Road which leads to Inginiyagala. The spring is in a private land close to the road crossing over the Pallanoya bridge.

2. 6 Kiwulegama / Jayanthiwewa Hot Springs in Sri Lanka [38].

### 2.1.6 RATHKIHIRIYA / GOMARANKADAWALA HOT SPRINGS.

Gomarankadawala can be reached by the Trincomalee - Horowpathana road. Travel past Kannia, Pankulama and turn off to right at Kambakotte ( tamil : Kambakoddai). Gomarankadawala is few kilometres in to this route. Temperature of the hot water discharged is $46^0$C.

Fig 2.7 Rathkihiriya / Gomarankadawala Hot Springs in Sri Lanka [38].

### 2.1.7 WAHAWA (AMPARA) HOT SPRINGS

Padiyatalawa is area of the Ampara District, Eastern Province of Sri Lanka. It can be reached from Bibile or Mahiyangana from one end and from Mahaoya from the other end. The turn off to Whawa is just before the Padiyatalawa Police station if you travel from Bibile or Mahiyangana.

The hot springs lies in a rural village off Padiyatalawa. East of Ekiriya kumbura and south of Padiyathalawa, find the Wahawa village. There are 18 springs scattered over the village and the surrounding paddy fields. They are built in form of tanks but it seems that only a few that are being used. Among these wells is the above flowing artesian well which is used by the villages for bathing and washing.

Fig 2.8 Wahawa Hot Springs [42].

### 2.1.8 MUTHUGALWALA ( GURUKUMBURA) HOT SPRINGS

Mutugalwela lies inside the Maduru Oya National Park on the boarders of the Maha Oya - Padiyathalawa - Mahiyangana Road. This rural village is populated by the Dambana aborigines but lies deep inside the jungles of Maduru Oya about 15 km away from Dambana. Temperature data and pictures were not found.

There has been two springs in the area of Mutugalwela which had been a guaranteed water supply to this rural village. One spring called *kurutiyavinna* has been gone under the waters of Kirawanagalkanda reservoir when it was built. The second spring has has been inside the Maduru Oya National Park which is now not accessible to the villagers.

## 2.2 GEOTHERMAL IN ASIAN REGION

Many countries in Asian region reported about their geothermal potentials and hot springs. Potential of some of them are very rich and some moderate and low. Many of them are producing electricity using this natural resource. Different technologies adopted to generate electricity from those resources. Dry steam, Flash steam and binary cycle power plants used for power generation.

### 2.2.1 INDIA

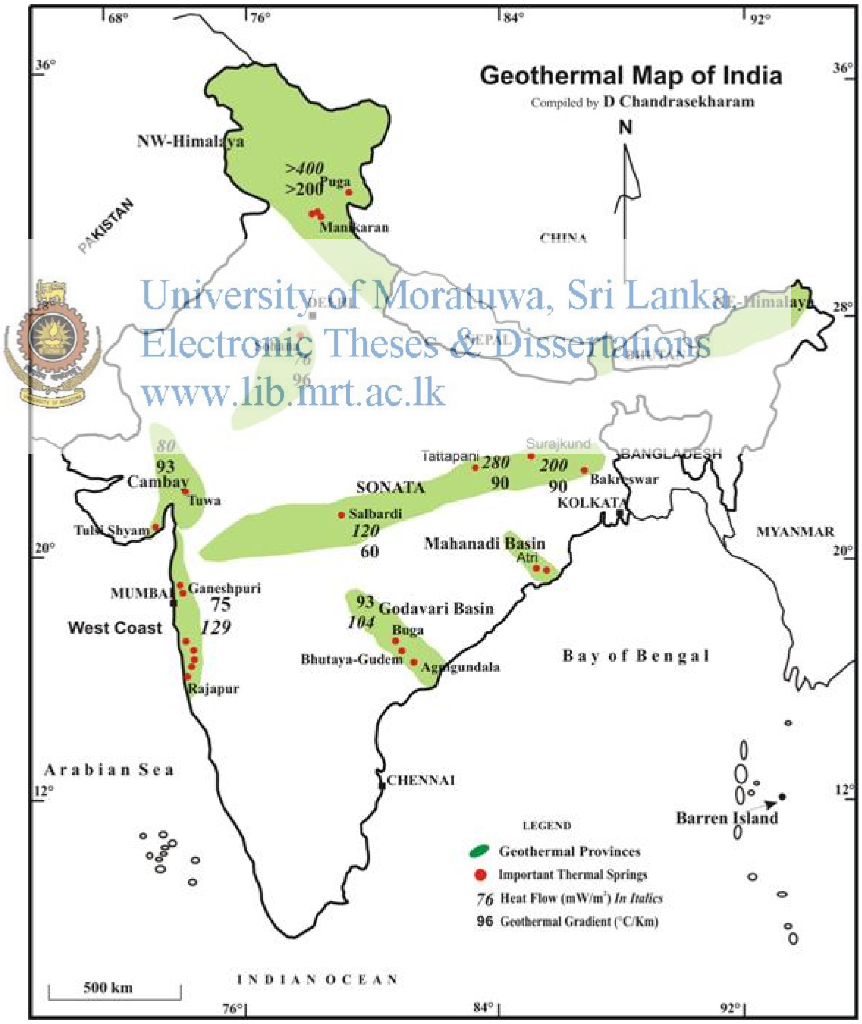


Fig. 2.9 Geothermal Map of India [43].

According to Global Energy Network Institute (GENI) in India, exploration and study of geothermal fields started in 1970. The Geological Survey of India has identified 350 geothermal energy locations in their country. According to researchers the estimated potential for geothermal energy in India is about 10000 MW ( 10 GW).

There are seven geothermal provinces in India , they are the Himalayas, Sohana, West coast, Cambay, Son-Narmada-Tapi), Godavari, and Mahanadi. The important sites are being explored in India and are shown in the above given map of India. (Figure 2.9)

The main Indian organizations working in geothermal energy field are, Central Electricity Authority, Geological Survey of India, Indian Institute of Technology, Mumbai, Regional Research Laboratory, Jammu, National Geophysical Research Institute, Hyderabad, Oil and Natural Gas Corporation, Dehradun. Some of smaller organizations are also assisting them to reach to success.

Magneto-telluric investigations in Tattapani geothermal area in Madhya Pradesh and Puga geothermal area in Ladakh region, Jammu & Kashmir are now on progress.

Geothermal Atlas of India, prepared by the Geological Survey of India (GSI) gives information/data for more than 300 geothermal potential sites. Applications of geothermal energy for small-scale power generation and thermal applications are being explored. At present they use this energy for, Power generation, Cooking, Space heating, greenhouse cultivation and Crop drying [44].

### 2.2.2 PAKISTAN

A global seismic belt passes through Pakistan and the country has a long geological history of geotectonic events. This geotectonic framework suggests that Pakistan should not be lacking in commercially exploitable sources of geothermal energy. This view is further strengthened by the fairly extensive development of alteration zones and fumaroles in many regions of Pakistan, availability of a fairly large number of hot springs in different parts of the country, and indications of Quaternary volcanism.

Geothermal energy are found within three geotectonic or geothermal environments, i.e., (i) geo-pressurized systems related to basin subsidence, (ii) seismotectonic or suture related systems, and (iii) systems related to Neogene Quaternary volcanism.

Pakistan, despite the enormous potential of its energy resources, remains energy deficient and has to rely heavily on imports of hydrocarbon products to satisfy hardly its needs.

Moreover, a very large part of the rural areas does not have the electrification facilities because they are either too remote and/or too expensive to connect to the national grid. Pakistan has wide spectrum of high potential renewable energy sources, conventional and as well non-conventional, which have not been adequately explored, exploited and developed. Geothermal energy is one of them. Pakistan can be benefited by harnessing the geothermal option of energy generation as substitute energy in areas where sources exist.

Fig. 2.10 Map of Pakistan [45].

### 2.2.3 BANGLADESH

Dhaka based private company namely Anglo MGH Energy has initiated a project to setup the country’s first geothermal power plant with a capacity to produce 200 MW of electricity close to Saland in Thakurgaon district. They have planned to set up 28 deep tube wells to lift hot steam and the lifted steam will be used to run a turbine and the turbine is connected to the generator to generate electricity.

Fig. 2.11 Map of Bangladesh [46].

Geothermal resources of Bangladesh have yet to be explored in detail. Current knowledge about these resources and their utilization is very limited compared to other renewable energy sources available in the country. Thus far no systematic field investigation has been done to evaluate the prospects of these resources and their utilization.

Only few authors have discussed the potential of geothermal resources of Bangladesh. It is therefore of utmost importance to evaluate the geothermal resources of the country and how they can play a part in the renewable energy scenario of Bangladesh. The geothermal energy resources are considered environmentally friendly, local and sustainable, independent of wind and sun variations. The electricity production cost using geothermal resources (steam/hot water system) is still very low compared to other available energy sources.

Due to the different geo-tectonic setups in Bangladesh, geothermal resources of the country may be broadly classified into two different geothermal provinces: the northwest part of Bangladesh known as the shield areas of the country and, to the southeast, the deep sedimentary basin known as the Bengal Fore deep region which consists of several basement highs and lows as well as the hill ranges of the Chittagong-Tripura folded belt, where a few thermal springs are known to occur.

In the northwest part of the country, in the Thakurgaon district, thermal manifestations and related evidence in some shallow aquifers tend to suggest the presence of a geothermal resource. The reported high-temperature water wells show a much higher geothermal gradient compared to the surroundings. In the Bogra shelf region, the Singra-Kuchma-Bogra areas offer potential zones for geothermal exploration. The Madhyapara hard rock mine area and the Barapukuria coal basin are also zones of interest for geothermal exploration (In the northwest shield, the underlying basement complex is intensely faulted and highly fractured.

Some of these major deep seated faults can be delicately identified from gravity and magnetic surveys. These fault systems are thought to act as conduits for transferring heat through the fluid within the pore spaces from beneath to the overlying sedimentary aquifer.

The prevailing geological features, including the hydro geological settings, clustering of basement faults, seismicity and earthquakes, and surface thermal anomalies all point to the existence of possible heat sources at a few km depth beneath the earth’s surface.

In the Bengal Fore deep region along the tertiary hill ranges, the Sitakund hilly area, with a few thermal springs, may also be considered an area with geothermal prospects [47].

### 2.2.4 NEPAL

Geothermal energy is one of the important resources of renewable energy in Nepal. In Nepal, it is recorded that more than 33 hot springs are available containing temperature range from $21^0$C to $73^0$C and flow rate of water 0.2 to 8.0 liters per second. In order to harness these god-gifted resources in creative manner, it is essential to determine the actual potential of these resources.

According to potential and other specifications of each geothermal resource, there was an urgent need to conduct study on its feasible utilization. Realizing this fact Alternative Energy Promotion Center initiated the study entitled feasibility study of geothermal resource in Nepal. Center for Energy Studies, Institute of Engineering (CES/IOE) is conducting this study. Singa Tatopani of Myagdi district and Kodari Tatopani of Sindhupalchowk district were selected for field study.

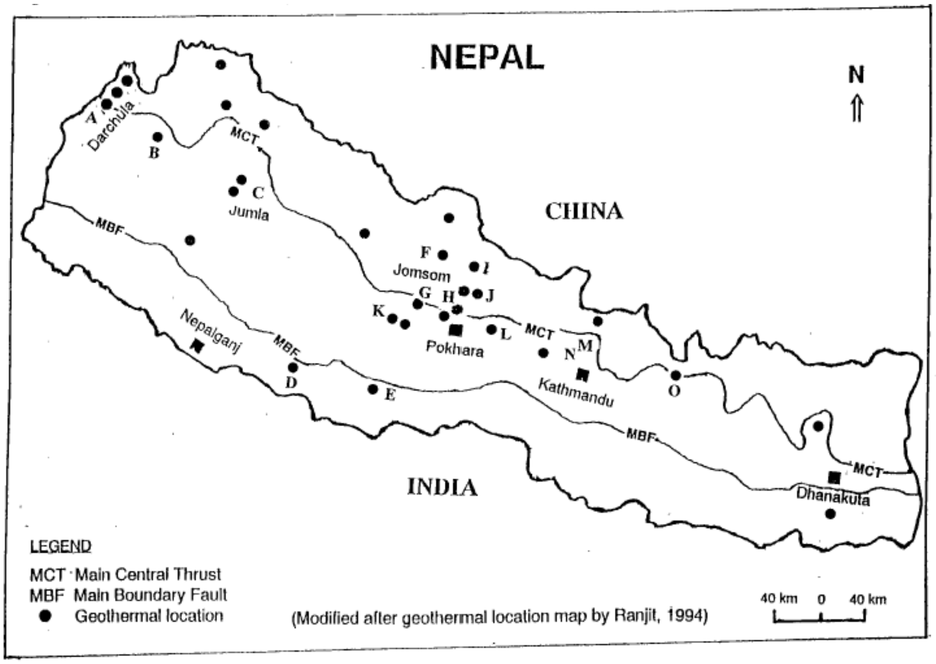


Fig 2.12 Geothermal locations of Nepal [48].

Singa Tatopani stands on latitude of 28$^0$N and longitude of 82.7$^0$E. This hot water resource is about 150 km from Pokhara in northwest direction. The rate of discharge of hot water is 1.37 liters per second and water temperature is 55$^0$C. Tourists are visiting this site for therapeutic treatments, who believe reduction of body ache and getting well from rheumatism and gastric.

Utilization of hot springs for therapeutic purpose and its heat energy to biogas digester seems to be more feasible for Singa Tatopani. Similarly, Kodari Tatopani lies at Sindhupalchowk district and is located about 114 km from Kathmandu valley. It stands at latitude of 27.9$^0$N and longitude of 83.9$^0$E. It lies on the bank of Bhotekoshi River at Kodari. This resource seems to be utilized as a recreational place rather than therapeutic treatment of diseases. The discharge from the main source is 2.27 liter per second and the temperature of water at source is 47.5$^0$C. Utilization of this hot water resource for recreational purpose seems to be more feasible.

In this study only surface temperature and water analysis is carried out but it is also desirable to determine the temperature at origin and flow. Singa Tatopani spring could be utilized for space heating purpose, heating biogas digester, bathing and laundering. However, promotion of tourist trade seems feasible at each location [49].

### 2.2.5 THAILAND

There are one hundred eighteen hot spring manifestations in Thailand, exposed in the north and extended towards western and southern Thailand, with surface temperature ranges of 40-100°C. Northern Thailand has 16 hot spring systems with surface temperatures near or greater than 80°C with potential for binary plant power generation. Presently only Fang system generates power from wells flowing a total of 8.3 l/s of 116°C water to a 300 kW single module Ormat binary plant.

Current production is 150-250 KW, which potentially can be increased by constructing new wells and increasing flow by pumping. Of the other 15 systems, 4 are in national parks and not considered for development.

Several of the hot springs systems have silica geothermometry >130°C suggesting significant undeveloped resources exists in northern Thailand.

Certainly the San Kamphaeng hot springs have the greatest known potential (estimated ~5MW) but like most of the systems it is associated with high-angle faulting and drilling has yet to find permeable zones yielding high flows (>11 l/s).

The current project of the Thailand Department of Energy Development and Efficiency (DEDE) will survey these prospects with the intention of installing a small plant of 2-10 MW [50]. Thailand identifies 5 potential areas for geothermal development, Thailand is studying its potential of geothermal power development having identified 112 hot springs in the country and 5 potential areas for development. A recent report by the Ground Water Resources Department of Thailand, revealed progress in establishing an inventory of geothermal features in Thailand. The survey was done in a bid to develop the country's geothermal energy potential for electricity production.

Thailand is neither situated in a recent volcanic area nor in a seismicity zone. There are one hundred eighteen hot springs with surface temperatures ranging from 40oC to 100oC, scattered from the north through the south, occurring in Thailand. The regional N-S trending tensional and extensional normal faults, widespread in Southeast Asia during Tertiary, play a key role in providing channels to heat sources at depth. High geothermal gradients near the hot spring areas may be affected by uprising of deep circulating waters to the surface [51].

Fig. 2.13 Hot springs in Thailand [52].

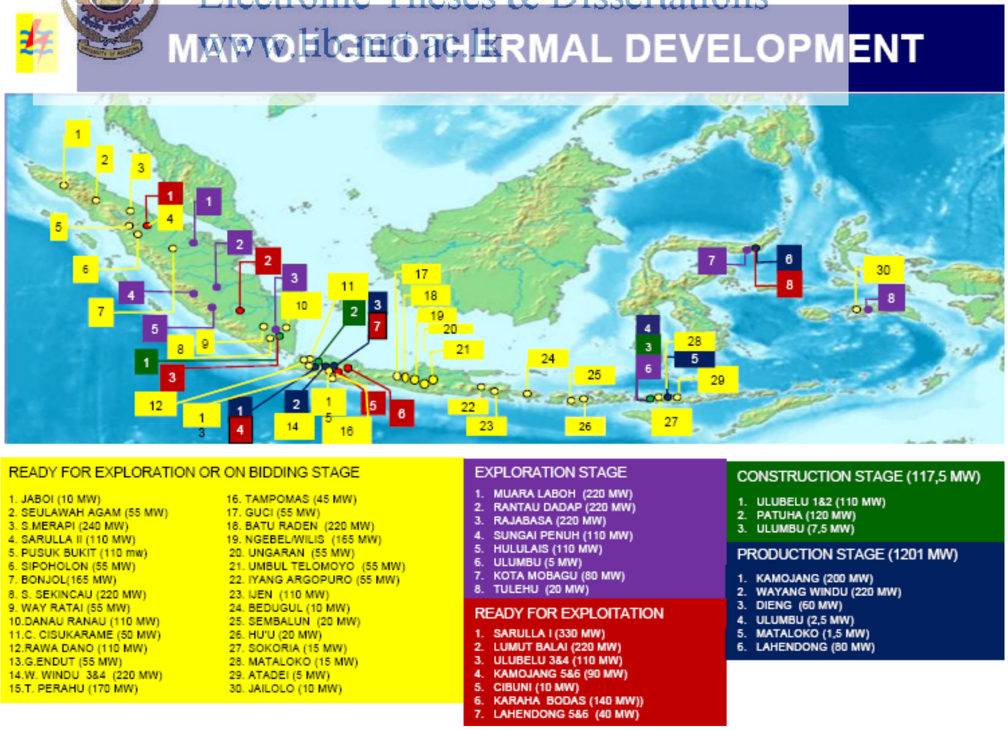
### 2.2.6 INDONESIA

Indonesia is one of the world's fastest growing economies and its energy demands are growing rapidly. Although the country has great potential in renewable energy, most notably geothermal, these resources remain largely unexploited and the country remains largely dependent on fossil fuel energy. However, the predicted growth in energy demand along with increasing environmental awareness and depleting oil reserves are forcing the Indonesian government to focus on developing the country’s enormous geothermal potential [53].

As a result of its volcanic geology, Indonesia has 40% of the world's potential geothermal resources, estimated at 28,000 MW.

Currently Indonesia is the world's third largest geothermal electricity producer after the United States and the Philippines. Installed production capacity (2014) is almost 1,340 MW from six geothermal fields in Java, North Sumatra and North Sulawesi. In2007, geothermal energy represented 1.9% of the country's total energy supply and 3.7% of its electric power.

They planned to triple the capacity to 4,000 MW. By 2025, Indonesia aims to produce more than 9,000 MW of geothermal power, becoming the world's leading geothermal energy producer. This would account for 5% of Indonesia's total energy needs.



MAP OF GEOTHERMAL DEVELOPMENT

READY FOR EXPLORATION OR ON BIDDING STAGE

1. JABOI (10 MW)
2. SEULAWAH AGAM (55 MW)
3. S.MERAPI (240 MW)
4. SARULLA II (110 MW)
5. PUSUK BUKIT (110 mw)
6. SIPOHOLON (55 MW)
7. BONJOL(165 MW)
8. S. SEKINCAU (220 MW)
9. WAY RATAI (55 MW)
10. DANAU RANAU (110 MW)
11. C. CISUKARAME (50 MW)
12. RAWA DANO (110 MW)
13. G.ENDUT (55 MW)
14. W. WINDU 3&4 (220 MW)
15. T. PERAHU (170 MW)
16. TAMPOMAS (45 MW)
17. GUCI (55 MW)
18. BATU RADEN (220 MW)
19. NGEBEL/WILIS (165 MW)
20. UNGARAN (55 MW)
21. UMBUL TELOMOYO (55 MW)
22. IYANG ARGOPURO (55 MW)
23. IJEN (110 MW)
24. BEDUGUL (10 MW)
25. SEMBALUN (20 MW)
26. HU'U (20 MW)
27. SOKORIA (15 MW)
28. MATALOKO (15 MW)
29. ATADEI (5 MW)
30. JAILOLO (10 MW)

EXPLORATION STAGE

1. MUARA LABOH (220 MW)
2. RANTAU DADAP (220 MW)
3. RAJABASA (220 MW)
4. SUNGAI PENUH (110 MW)
5. HULULAIS (110 MW)
6. ULUMBU (5 MW)
7. KOTA MOBAGU (80 MW)
8. TULEHU (20 MW)

READY FOR EXPLOITATION

1. SARULLA I (330 MW)
2. LUMUT BALAI (220 MW)
3. ULUBELU 3&4 (110 MW)
4. KAMOJANG 5&6 (90 MW)
5. CIBUNI (10 MW)
6. KARAHA BODAS (140 MW))
7. LAHENDONG 5&6 (40 MW)

CONSTRUCTION STAGE (117,5 MW)

1. ULUBELU 1&2 (110 MW)
2. PATUHA (120 MW)
3. ULUMBU (7,5 MW)

PRODUCTION STAGE (1201 MW)

1. KAMOJANG (200 MW)
2. WAYANG WINDU (220 MW)
3. DIENG (60 MW)
4. ULUMBU (2,5 MW)
5. MATALOKO (1,5 MW)
6. LAHENDONG (80 MW)

Fig. 2.14 Geothermal development map Indonesia [54].

## 2.3 AFRICAN COUNTRIES

### 2.3.1 AFRICA:

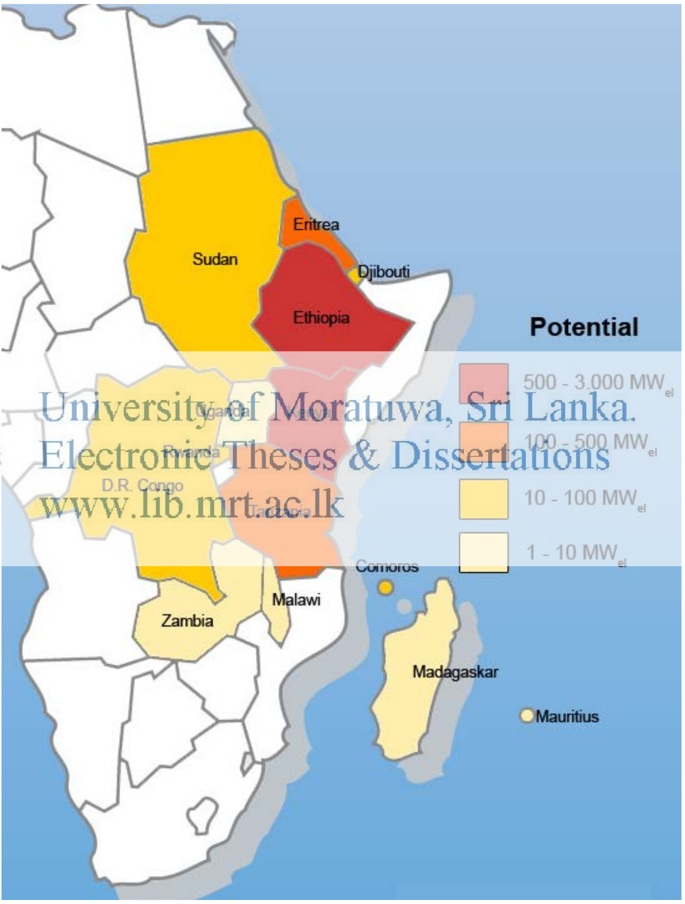


Fig 2.15 African geothermal potential [55].

The African Development Bank (AfDB) and the Government of Djibouti working for a geothermal exploration project in the region of Lake Assal.

The exploitation of geothermal potential in the Lake Assal region will enable the Djiboutian population to access reliable, renewable and affordable source of energy [56].

The contribution from the AfDB and SEFA will be used to continue to raise more financing and will serve as a catalyst to rally independent geothermal electricity producers.

The private sector will be responsible, in a second phase, for the production drilling, steam gathering system and electricity production and evacuation to the national grid.

Those innovative models help overcome the several risks associated with geothermal development, among which the most important one is the exploratory drilling risk, which is related to the probability of hitting dry wells during the exploration and appraisal drilling phase.

Menengai Geothermal Development Project, supported by concessional financing to the tune of US $150 million. The Menengai project, once completed, will increase the energy supply in the country by an amount equivalent to the current consumption needs of 500,000 Kenyan households, 300,000 small businesses and some 1,000 GWh for other businesses and industries.

At a much smaller scale, the Lake Assal geothermal exploration project will help expand geothermal development, by building regional capacities, to other Rift Valley countries in Sub-Saharan Africa such as Ethiopia, Uganda, Tanzania and Rwanda, which have considerable geothermal resource development potential.

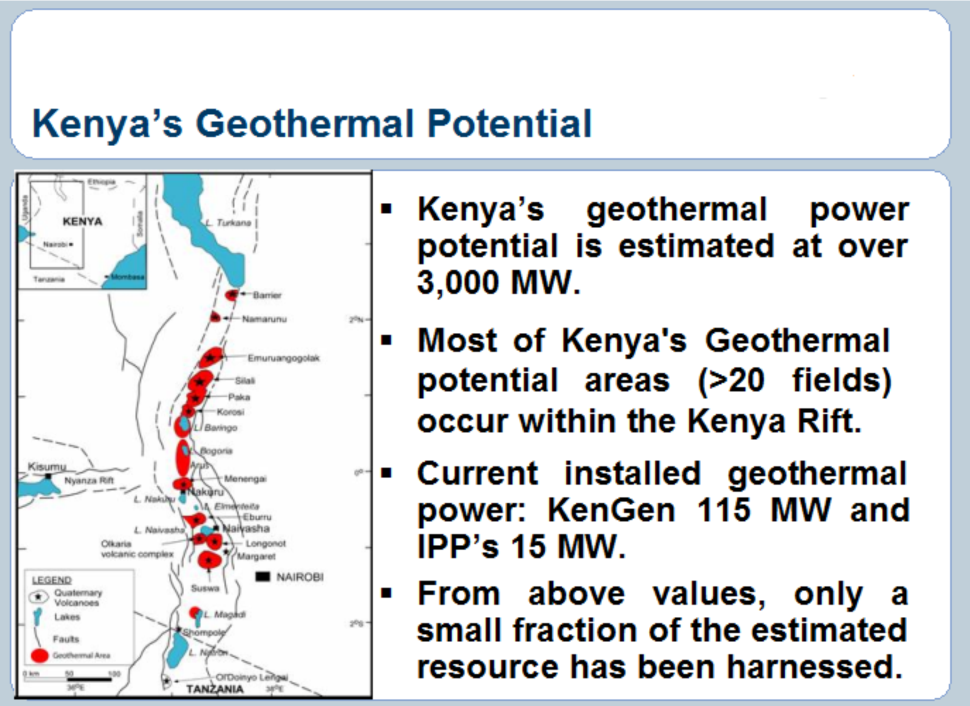
### 2.3.2 Kenya

More than 14 high temeprature potential sites occur along the Kenyan Rift valley with an estimated electrical power potential of more than 15,000 MWhr. Other locations include: Homa Hills in Nyanza, Mwananyamala at the Coast and Nyambene Ridges. These places are at different stages of development.

Geothermal efficiency and reliability is some 2 - 4 times higher than other renewable energy sources and the ability to use geothermal power as a base load power source is possibly the most important and major benefit of this type of generation.

An additional benefit of geothermal energy is the scalability of the plant through technological innovation, as wells can be put to use almost immediately upon verification of the source, using wellhead units, instead of being used only as part of a larger generation plant. These units are placed next to a well, and supplied with steam or hot water.

The biggest benefit from this involvement is that money can be generated from the sale of electricity fairly early into the certification of the resource, without having to have a large number of wells developed and verified. Additionally, “well head generators negate the needs of traditional power plants for well redundancy or an excess steam buffer to cater for well failures and allow all wells to be utilized [57].



**Kenya's Geothermal Potential**

- Kenya's geothermal power potential is estimated at over 3,000 MW.
- Most of Kenya's Geothermal potential areas (>20 fields) occur within the Kenya Rift.
- Current installed geothermal power: KenGen 115 MW and IPP's 15 MW.
- From above values, only a small fraction of the estimated resource has been harnessed.

Fig 2.16 Geothermal map Kenya [58].

## 2.4 EUROPEAN COUNTRIES AND THEIR GEOTHERMAL USAGE

Europe is the world leader in geothermal direct use. Geothermal is used in 32 European countries mainly for space heating, and bathing, than for heating greenhouses, aquaculture, and industrial use. In a number of countries the development is based on waters exploited from deep wells. Some countries have been dynamically developing shallow geothermal based on heat pumps.

Power generation using geothermal steam takes place in six European states and contributes to ca. 12% to the world total. Recently, the first small binary installations based on ca. 100-120˚C waters were launched in Austria and Germany. Except for Iceland, geothermal is not a main source among renewable energy in Europe, although many regions have prospective resources which can be applied on a wide scale especially for heating. In the geothermal heating sector, Europe has achieved a lot of experience, positive results, and developed modern and reliable technologies [59].

Thermal and geological conditions result in the fact that Europe possesses mostly low-enthalpy resources. They are predominantly found in sedimentary formations. However, at attainable depths in several regions, high-enthalpy resources are also found, as in Iceland, Italy, Turkey, Greece, Portugal (Azores), Russia (Kamchatka), Spain (the Canary Islands) and at some other islands and overseas territories of France (Guadeloupe). The main geothermal fields under exploitation are in the Larderello region (Italy); the Paris Basin (France); the Pannonian Basin (Hungary, Serbia, Slovakia, Slovenia, Romania); several sectors of the European Lowland (Germany, Poland); the Palaeogene systems of the Carpathians (Poland, Slovakia); and other Alpine and older structures of Southern Europe (Bulgaria, Romania, Turkey).

Most of the above given countries are in Ring of Fire or very closed to that. According to the data presented at the World Geothermal Congress 2005, direct geothermal use takes place in 32 European countries.

The total installed thermal capacity was 13,628 MWt, while heat production amounted to 140,398.9 TJ (42,916 GWh/a, i.e. 56% of the world total) [60].

Geothermal resources are not common geological features. Several countries use this natural resource for power generation and other work. The above given Fig 2.17 clearly showing the geothermal regions in the world. Places like

Yellowstone (USA), North Island (NewZealand), Iceland, Kamchatka (Russia), and Japan have good geothermal potential.

The red coloured area have high geothermal gradient, North and South America, Japan, Indonesia, part of Africa, Europe, Pacific ocean area, are some of them.

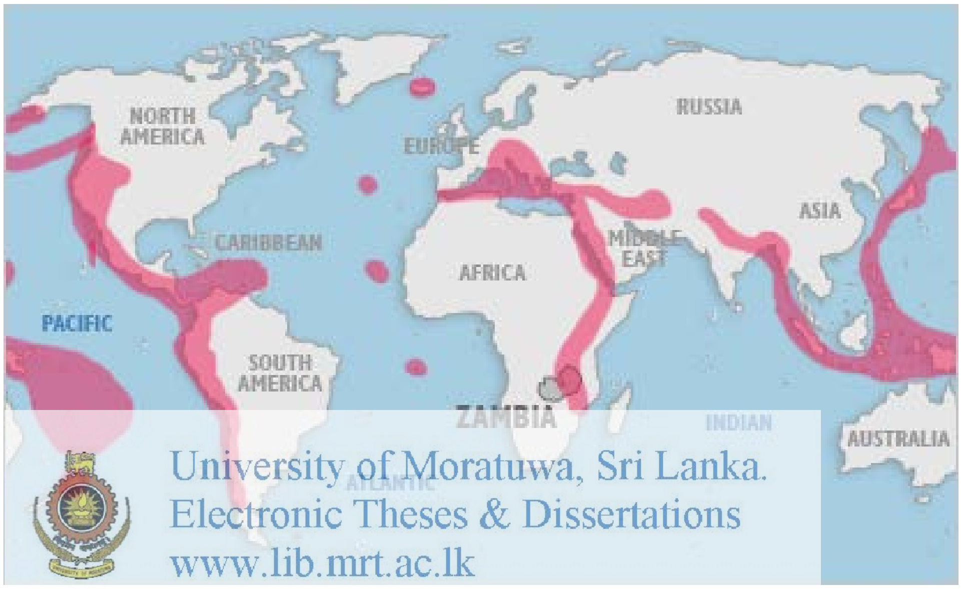


Fig. 2.17 World Geothermal regions [61].

## 2.5 WORLD RICH GEOTHERMAL POWER PRODUCERS

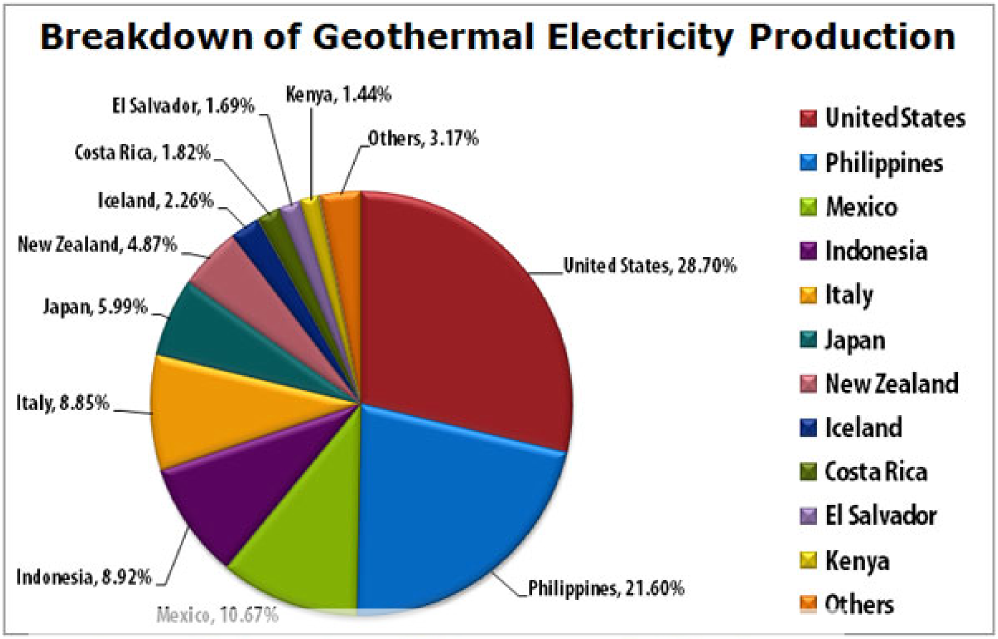


Fig. 2.18 Breakdown of Geothermal Electricity Production [62].

### 2.5.1 UNITED STATES

3,450 MW Installed Capacity, 0.3% National Energy Production. The United States is always in the top level for world in geothermal energy production, with 3,450 MW of installed capacity. 77 geothermal power plants and growing generate 15 billion kilowatt hours of electricity per year. The majority of the United States' geothermal energy comes from the western states, and if tapped to their full capacity, geothermal reserves beneath just nine of the United States' 50 states could provide upward of 20 percent of the nation's electricity needs.

The largest known dry steam field in the world is just north of San Francisco, California. "The Geysers" geothermal hotspot has over 1,500 MW of installed capacity. Calpine Corporation currently taps 15 of the 18 power plants operating in the Geysers, making it the largest geothermal energy producer in the United States. Northern California Power Agency, Santa Clara Municipal Electric Utility and US Renewable Group own and operate the remaining three facilities in the Geysers and a nineteenth plant is soon to be opened by Ram Power.

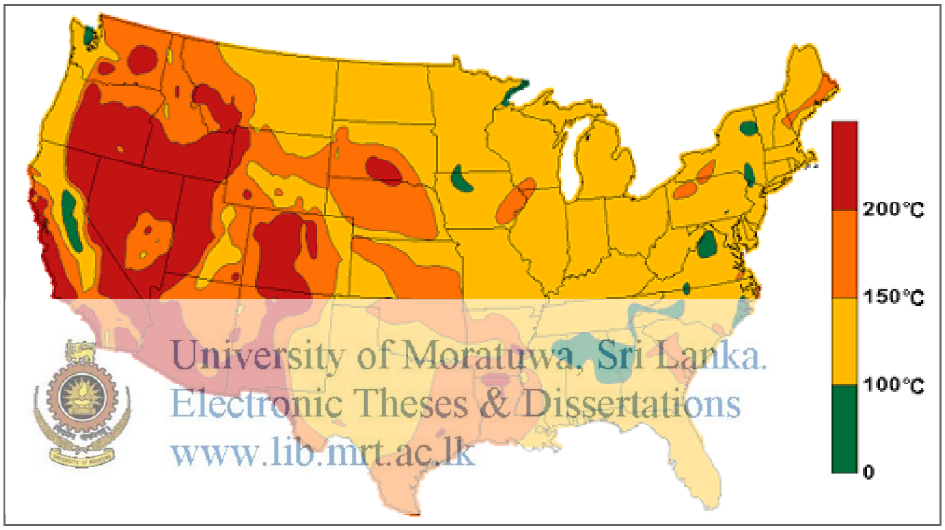


Fig 2.19 Estimated temperatures at depth of 6 Km, USA [63].

### 2.5.2 THE PHILIPPINES

Next to United States the Philippines is the second largest producer of the geothermal power in the world. Historically, among countries' indigenous resource, it is the largest supplier of electricity to the country. Apart from providing substantial amount of electricity to the country, geothermal resources, at the same time, help them to save large amount of foreign exchange through the displacement of a large fraction of imported fossil fuel [64].They have 1,870 MW installed capacity and this is 27% National Energy requirement.

The Philippines has been using geothermal energy to power the multi-island nation since 1977, when the country’s first geothermal power plant was built on the island of Leyte.

Chevron-the largest geothermal producer in the world has invested over $2

billion into Philippine geothermal energy installations, escalating the Philippines to number two in top ten geothermal energy producers in the world.

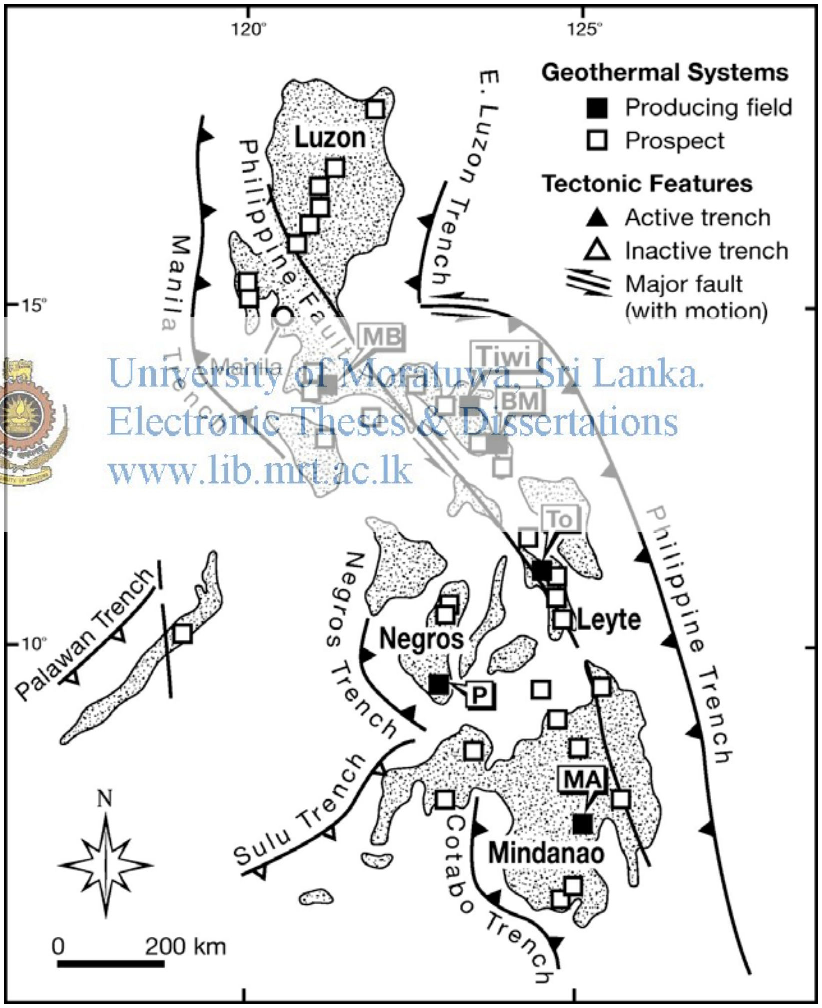


Fig 2.20 Geothermal system Philippines [65

### 2.5.3 INDONESIA

1,340 MW Installed Capacity, 3.7% National Energy Production. Indonesia holds 40 percent of the world's geothermal potential beneath its thousand of volcanic islands, accounting for an estimated 28,000 MW of potential energy. Indonesia is on track to develop 44 new geothermal power plants by 2014, raising capacity to 4,000 MW, and the country plans to produce 9000 MW from geothermal by 2025.

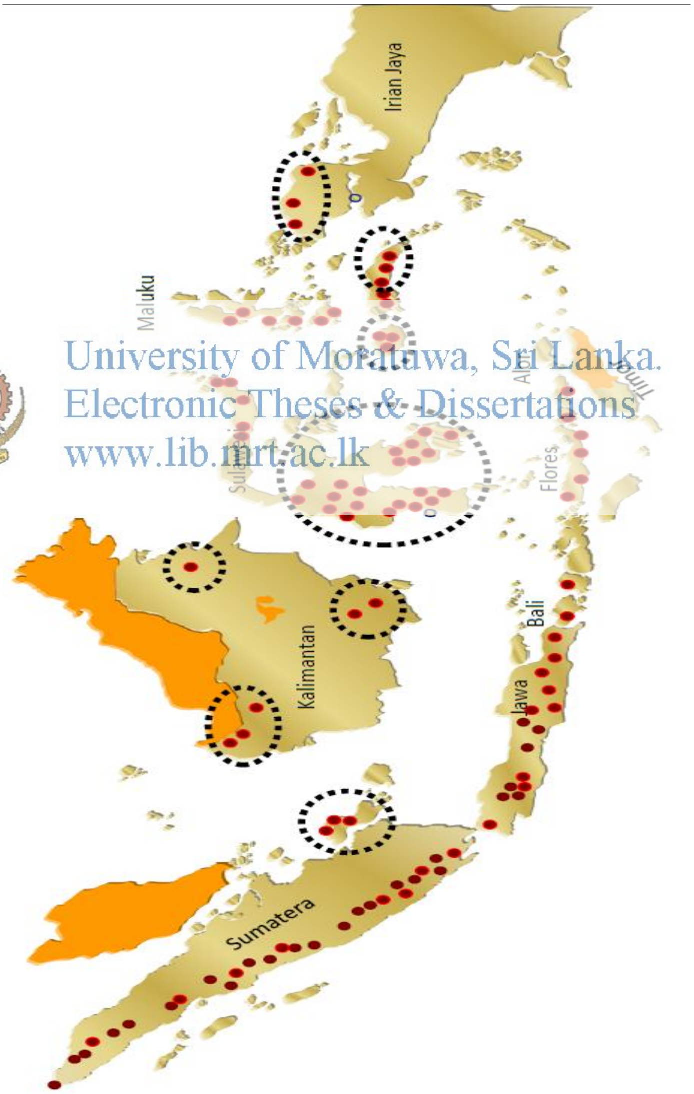


Fig 2.21 Geothermal areas Indonesia [66].

### 2.5.4 MEXICO

1017 MW Installed Capacity, 3% National Energy requirement.

Mexico is home to the largest geothermal power plant in the world. The Cerro Prieto Geothermal Power Station has a 720 MW installed capacity, and plans are in place for expansion to 820 MW by 2012. Cerro Prieto is located on the border of the Mexican states of Sonora and Baja California Norte, just south of California USA.

Fig 2.22 Geothermal power plant at Mexico [67].

### 2.5.5 ITALY

916 MW Installed Capacity, 10% National Energy Production

Italy was where the very first geothermal power plant was built at the Larderello dry steam field in Tuscany. Larderello is where the first modern geothermal plants were constructed as well. Destroyed in World War II, the plants have since been rebuilt. Ancient Romans used the geothermal heat in the region to warm their water and run heat vents to keep buildings warm.

Fig 2.23 Geothermal Power plant in Italy.[68].

### 2.5.6 NEW ZEALAND

1005 MW Installed Capacity, 10% National Energy Production.New Zealand is the second country after Italy to apply geothermal energy at a national scale. With unpredictable weather patterns, New Zealand’s geothermal installations have provided consistent energy generation over all other renewable energy sources in the country.

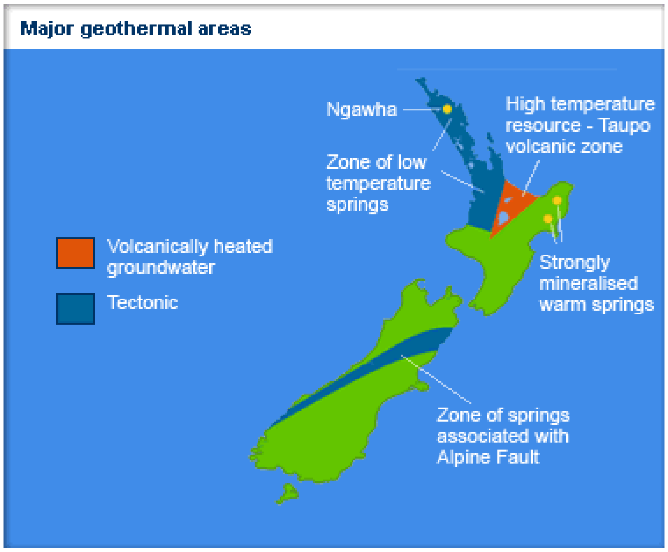


Fig 2.24 New Zealand geothermal resources. [69].

### 2.5.7 ICELAND

Due to the special geological location of Iceland, the high concentration of volcanoes in the area is often an advantage in the generation of geothermal energy, the heating and production of electricity. They have 665 MW geothermal power plants. During winter, pavements near these areas are heated up. This causes heat to come to the surface.

Five major geothermal power plants exist in Iceland, which produce approximately 26.2% (2010) of the nation's energy. In addition, geothermal heating meets the heating and hot water requirements of approximately 87% of all buildings in Iceland. Apart from geothermal energy, 73.8% of the nation’s electricity is generated by hydro power, and 0.1% from fossil fuels.

Consumption of primary geothermal energy in 2004 was 79.7 penta joules (PJ), approximately 53.4% of the total national consumption of primary energy, 149.1 PJ. The corresponding share for hydro power was

17.2%, petroleum was 26.3%, and coal was 3%. Plans are underway to turn Iceland into a 100% fossil-fuel-free nation in the near future.

For example, Iceland's abundant geothermal energy has enabled renewable energy initiatives, such as Carbon Recycling International's carbon dioxide to methanol fuel process. The following are the five largest power stations in Iceland.

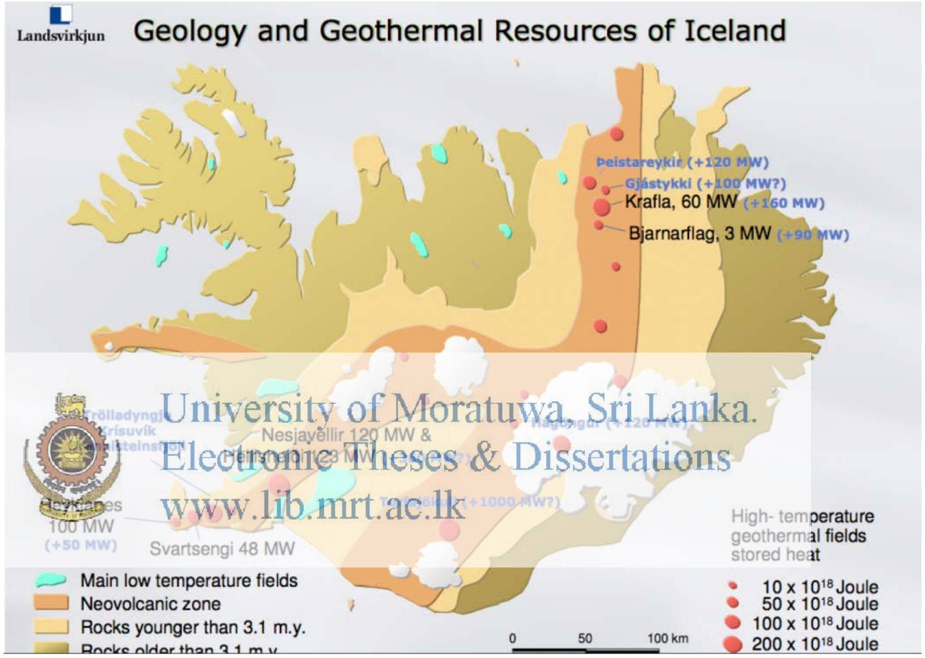


Fig 2.25 Iceland geothermal resources [70].

### 2.5.8 JAPAN

519 MW Installed Capacity, .3% National Energy Production. Due to its close proximity to the Izu-Bonin-Mariana Arc, a convergent boundary of four tectonic plates in the Pacific “Ring of Fire,” Japan is ideally located for geothermal activity.

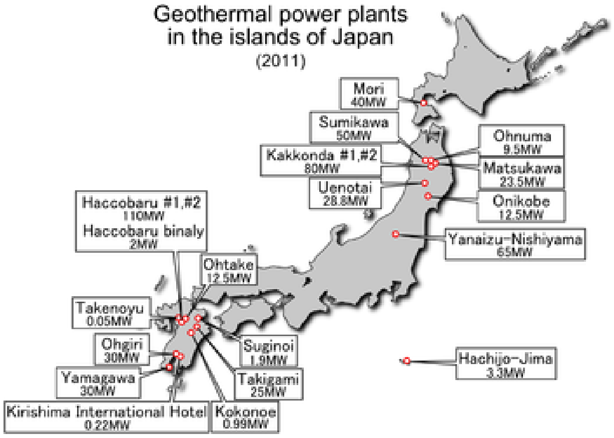


Fig 2.26 Japan geothermal resources [71].

### 2.5.9 EL SALVADOR

204 MW Installed Capacity, 14% National Energy Production. El Salvador’s Ahuachapán geothermal field has provided energy to the country since 1975. Only two geothermal facilities exist in the small Central American country, the second being the Berlin power plant. El Salvador, known as the “land of volcanoes,” is the largest producer of geothermal electricity in the region with 204 MW of production. With approximately 24 percent of its total electrical power production is coming from geothermal resources, El Salvador is a world leader in the good level development of geothermal power[72].

Fig 2.27 El Salvador geothermal resources map [73].

### 2.5.10 KENYA

594 MW Installed Capacity, 11.2% National Energy Production. Kenya was the first country in Africa to exploit geothermal energy commercially. Kenya is ideally positioned in Africa's Great Rift Valley, a divergent plate boundary with excessive geothermal potential. Kenya plans to increase geothermal capacity by an additional 576 MW by 2017, reducing fossil fuel dependency and covering 25 percent of the country's electricity needs.

## 2.6 METHODS OF POWER GENERATION USING GEOTHERMAL ENERGY IN THE WORLD.

Many countries generate electricity using geothermal resources and various technologies adopted for that process. The technology depends on type of resources available, its temperature, water flow rate etc.

The world richest geothermal power producer, United States have installed Dry steam, Flash steam, double flash steam and binary cycle power plants at various locations of the country. Dry Steam technology is used today at The Geysers in northern California, the world's largest single source of geothermal electricity.

These plants emit only excess steam and very minor amounts of gases. Hydrothermal fluids above 182°C (360 $^0$F) can be used in flash plants to make electricity. Fluid is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize, or "flash." The vapor then drives a turbine, which drives a generator. If any liquid remains in the tank, it can be flashed again in a second tank (double flash) to extract even more energy.

Most geothermal areas contain moderate-temperature water ie, below 200$^0$C (392 $^0$F). Energy is extracted from these fluids in binary-cycle power plants. Hot geothermal fluid and a secondary (hence, "binary") fluid with a much lower boiling point than water pass through a heat exchanger. Heat from the geothermal fluid causes the secondary fluid to flash to vapor, which then drives the turbines [73].

Because this is a closed-loop system, virtually nothing is emitted to the atmosphere. Moderate-temperature water is by far the more common geothermal resource, and most geothermal power plants in the future will be binary-cycle plants.

Philippine is second rich geothermal power producer, they utilize all types of geothermal power plants given above for their power production. Those countries that have rich geothermal potentials make use of all major four type power plants.

### 2.6.1 DRY STEAM POWER PLANTS

Dry Steam power plants draw from underground resources of steam. The steam is piped directly from underground wells to the power plant, where it is directed into a turbine/generator unit. Dry steam reservoirs are rare but highly efficient at producing electricity.

The Geysers in California is the largest and best known dry steam reservoir. Here, steam is obtained by drilling wells from 7,000 to 10,000 feet deep. In a dry steam reservoir, the natural steam is delivered directly from a geothermal well to power a turbine generator. The condensed water can be used in the plant's cooling system and injected back into the reservoir to maintain water and pressure levels.

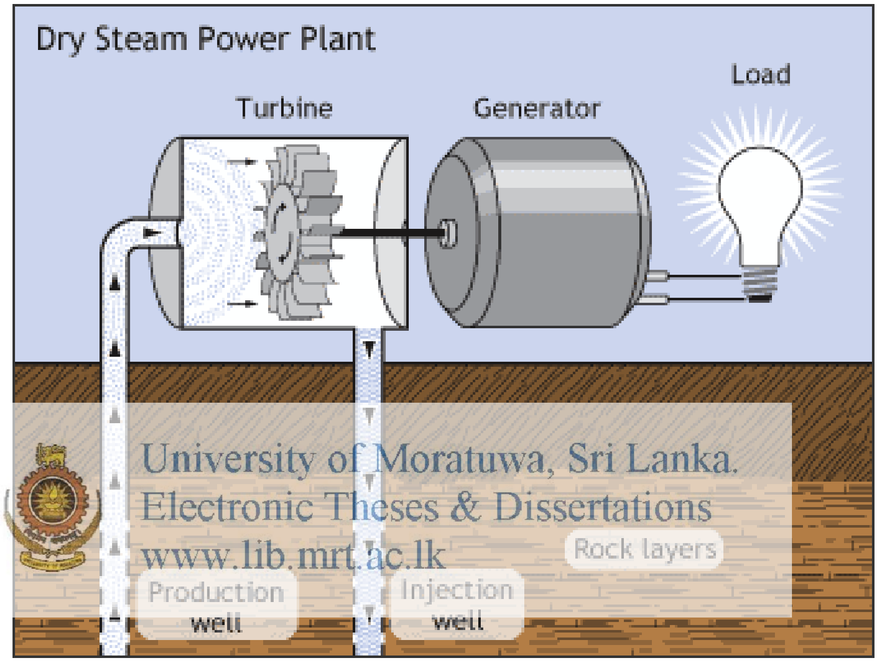


Fig 2.28 Dry steam power plant [74].

### 2.6.2 FLASH STEAM POWER PLANTS

Flash steam power plants are the most common. They use geothermal reservoirs of water with temperatures greater than 182°C. This very hot water flows up through wells in the ground under its own pressure. As it flows upward, the pressure decreases and some of the hot water boils into steam. The steam is then separated from the water and used to power a turbine/generator. Any leftover water and condensed steam are injected back into the reservoir, making this a sustainable.

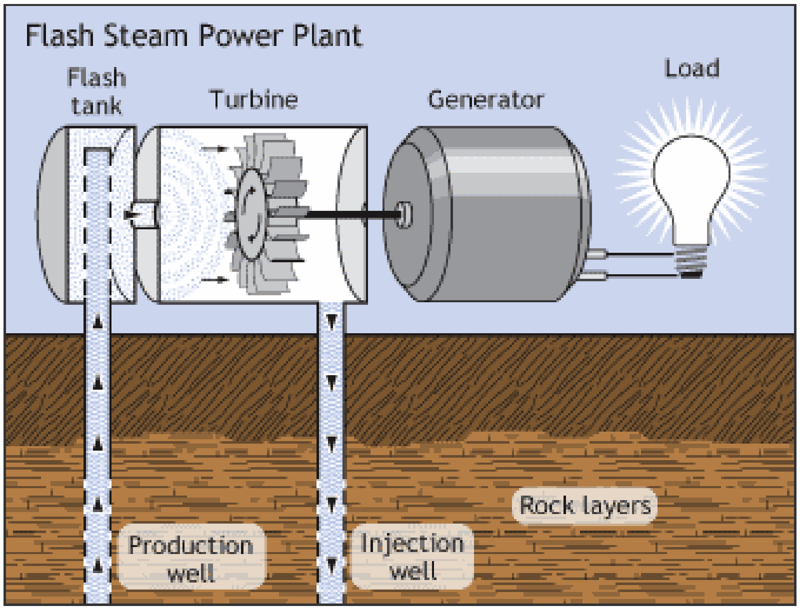


Fig 2.29 Flash steam power plant [74].

### 2.6.3 BINARY CYCLE POWER PLANTS

Binary plants specifically use a second working fluid , that's why it is calling "binary" with a much lower boiling point than water. The binary fluid is operated through a conventional Ranking cycle. Generally, the working fluid is a hydrocarbon such as isopentane, or a refrigerant like Amonia ($NH_3$).

The geothermal fluid (predominantly water vapor) and working fluid pass through a heat exchanger, as shown in the below given Fig.2.30 where the working fluid flashes to vapor and drives the turbines. The cooled water vapor is then released back into the underground reservoirs, so the cycle can begin

.

No gas is emitted to the atmosphere, as the binary cycle is a closed system. This process is similar to reverse process of refrigeration system.

The binary cycle can operate with lower geothermal fluid temperatures. Depending on the temperatures, different working fluids are selected based on appropriate boiling points. The upper temperature limit is restricted by the working fluids well, as they are generally organic molecules that become thermally instable at higher temperatures.

The low temperature limit is restricted by economic and engineering concerns. The heat exchanger size for a givencapacity becomes impractical and costly at low temperatures. Parasitic loads that drive the plant also require larger percentages of the output energy.

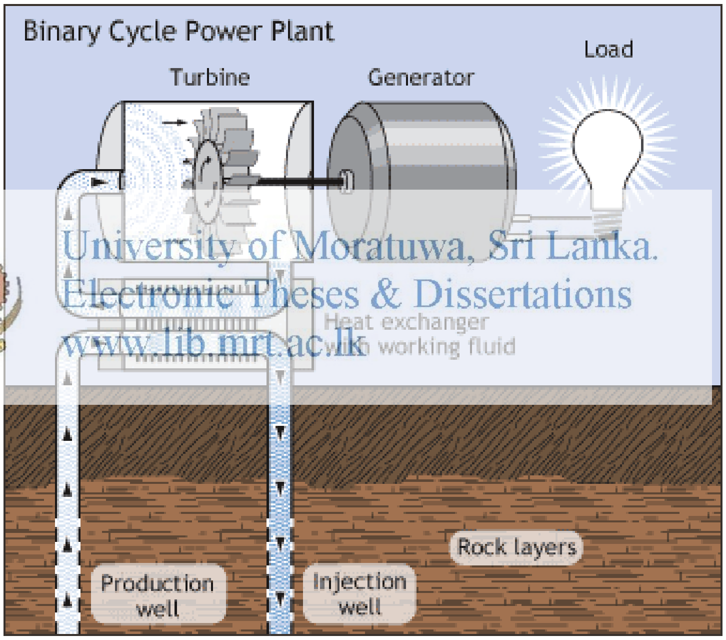


Fig 2.30 Binary cycle power plant [74].

In the geothermal industry, "high temperatures" are characterized by vapor temperatures above 150°C. Less than $150^0$C resources are falling to low temperature resources category

$\eta < 1 - T_c/T_h$ where $\eta$ is the efficiency, $T_c$ is the absolute temperature of the cold reservoir and $T_h$ is the absolute temperature of the hot reservoir.

Dry plants and flash plants use the geothermal brine to directly power the turbines. Therefore, they cannot be utilized for lower-temperature resources. Binary plants can exploit low temperature fluids, so can be used in more widespread applications.

Environmentally, binary plants possess key advantages in that they do not release geothermal fluids into the environment. Earth's gases do not just include water vapor. They include nitrogen, carbon dioxide, hydrogen sulfide, ammonia, mercury, radon, and boron. Most of the environmental hazards are released through disposal water or into the environment.

Although it is a matter of common practice for power stations to remove hydrogen sulfide from emitted geothermal steam, this toxic gas can still pose an environmental or health hazard. Also, the greenhouse ($CO_2$) emissions are generally around 13-380 g/kWh, which is small compared to the 906 g/kWh from oil, 453 g/kWh from natural gas, or the 1042 g/kWh from coal, but still substantial. Binary plants skirt these issues altogether by returning the cooled geothermal gas back to its underground reservoir.

### 2.6.4 ENHANCED GEOTHERMAL SYSTEMS (EGS)

Enhanced Geothermal Systems are also sometimes called engineered geothermal systems, offer great potential for dramatically expanding the use of geothermal energy. Present geothermal power generation comes from hydrothermal reservoirs, and is somewhat limited in geographic application to specific ideal places in the various countries.

The EGS concept is to extract heat by creating a subsurface fracture system to which water can be added through injection wells. Creating an enhanced or engineered, geothermal system requires improving the natural permeability of rock. Rocks are permeable due to minute fractures and pore spaces between mineral grains.

Injected water is heated by contact with the rock and returns to the surface through production wells, as in naturally occurring hydrothermal systems. EGS are reservoirs created to improve the economics of resources without adequate water and/or permeability. The below given Fig 2.31 shows the Enhanced Geothermal Systems power plant.

The below given benefits available with EGS. EGS has the potential to be an important contributor to the energy requirement as a source of clean, renewable energy. This emits little to no greenhouse gases. Most geothermal power plants use a closed-loop binary cycle power plant and have no greenhouse gas emissions other than water vapor that may be used for cooling. EGS can supply base load energy with limited to no intermittency, eliminating the need for energy storage technologies. [75].

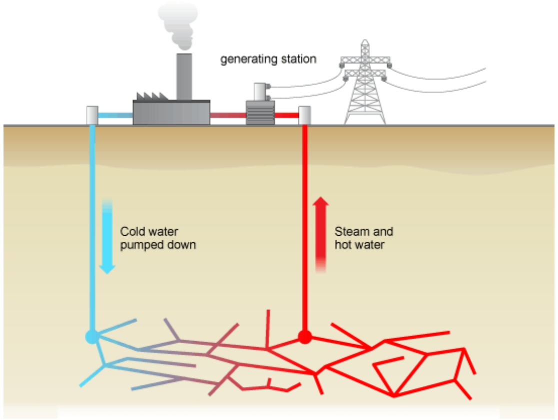


Fig 2.31 Enhanced Geothermal Systems power plant [76].

## 2.6.5 WORLD TOP 10 GEOTHERMAL POWER PLANTS

The below given Table2.2 contain most useful information of world top 10 geothermal power generating plants. Two numbers from USA, having capacities 1.517 MW and 340 MW. Second biggest capacity belongs to Italy is 769 MW plant. Mexico has third largest geothermal power plant with 720 MW capacities.

Philippines have three plants of 458 MW, 289 MW and 232.5 MW. 303 MW plant is belongs to Iceland and Indonesia has 259 MW and 227 MW plants.

The Geysers is the world's largest geothermal field, containing a complex of 22 geothermal power plants, drawing steam from more than 350 wells, located in the Maya camas Mountains approximately 72 miles (116 km) north of San Francisco, California.

The geysers provide the power to Sonoma, Lake and Mendocina countries, as well as a part of the power needs of Marin and Napa areas. The geyser is the most reliable energy source in California, USA. It is delivering power to consumers with high availability.

The Cerro Prieto Geothermal Power Station is a large complex of geothermal power stations, in Mexico, it has an an installed capacity of 720 MW (this is not up to date according to the List of largest power stations in the world, with plans for expansion up to 820 MW by 2012.

The Makban Geothermal Power Plant complex is located in the towns of Bay and Calauan in Laguna and Santo Tomas in Batangas , Philippines. It consists of Plants A and B with two 63-MW units each, Plant C with two 55-MW units, Plants D and E with two 20-MW units each, and a binary plant with five 3-MW and one 0.73-MW units.

Table 2.2 World top 10 geothermal power plants [77].

| No | Country | **Location** | Plant Name | Power capacity MW |
|---|---|---|---|---|
| 1 | USA | **San Francisco** | Geysers Geothermal Complex | 1,517 |
| 2 | Italy | **Tuscany** | Larderello Geothermal Complex | 769 |
| 3 | Mexico | **Baja California** | Cerro Prieto Geothermal Power Station, | 720 |
| 4 | Philippines | **Santo Tomas** | Makban Geothermal Complex | 458 |
| 5 | USA | **California** | CalEnergy Generation, Salton Sea Geothermal Plants. | 340 |
| 6 | Iceland | **Reykjavik** | Hellisheidi Geothermal Power Plant. | 303 |
| 7 | Philippines | **Albay** | Tiwi Geothermal Complex. | 289 |
| 8 | Philippines | **Leyte Island** | Malitbog Geothermal Power Station, | 232.5 |
| 9 | Indonesia | **Pangalengan** | Wayang Windu Geothermal Power Plant. | 227 |
| 10 | Indonesia | **Garut** | Darajat Power Station. | 259 |

# CHAPTER 3

## METHODOLOGY

### 3.1 EXPLORATION TECHNICS

The scientific information are now available for better characterization of resources before the deep well drilling**.** Initially the following steps should be taken to identify feasibility of the area. Geological Survey, Geochemical Survey, Geophysical Surveys and then to drill shallow wells to find temperature gradient.

Several methods are available for this task, but many of the researches in Sri Lanka have mostly used the below given methods. Therefore only these methods have been considered for this study namely schlumberger resistivity method and temperature gradient measurement method.

### 3.2 GEOCHEMICAL SURVEYS

This survey is used to find out the following data, such as identify the resource type, estimate the temperature of the fluid, determine the chemical properties and characterise the recharge water.

Kenya, Arus an Bogoria springs and boreholes have been sampled and their chemical composition determined and evaluated[82],[95]. The steam jets of Lake Bogoria discharge mixed fluid of different proportions of lake water, deep geothermal fluid, and shallow ground water.High flows of discharging fluids were recorded around Lake Bogoria and Maji Moto springs.

Reservoir temperature estimates using Quartz geothermometer range from 124 – $175^0$C for Lake Bogoria springs, while the Na/K geothermometer gave temperature values ranging from119 - $325^0$C for the same springs. The Arus hot springs give estimated temperatures ranging from 115 – $161^0$C using the quartz geothermometer.

However, the high temperature estimates calculated using the Na/K ratio geothermometer could not be reflective of the actual reservoir temperature and could have been influenced by other factors like mixing of reservoir fluids and shallow ground waters or lack of fluidmineral equilibrium.

Some Sri Lanka scientists[30] have investigated geothermal springs from the Precambrian high-grade metamorphic terrain of Sri Lanka to assess their formation processes and to determine reservoir temperatures based on their chemical compositions.

Silica-based geothermometric calculations for the Marangala and Nelumwewa springs showed the highest average reservoir temperatures of 122 $^0$C and 121 $^0$C respectively( Fig. 4.22). Samples of low temperature (<$35^0$C) groundwater from nearby springs, piezometers and open wells were also collected for comparison[30].

The geothermal waters from Sri Lanka likely stem from much shallower depths because fast conduit circulation systems are unlikely to reach down to depths of several thousand meters. This would argue for steepergeothermal gradients.

This is also confirmedby the geochemical characteristics. The steeper thermal gradient may be related to the residual heat along the Highland-Vijayan boundary zone, which has been recognized as a possible Precambrian tectonic or thrust zone [78].

## 3.3 GEOPHYSICAL SURVEYS

This is the application of principles of mechanics, thermal science and the electric science to determine the geothermal systems. The following useful technics used for this process. They are heat flux measurement, temperature gradient survey, electrical resistivity survey, seismic surveys and gravity surveys.

Based on their findings of the present study, they proposed that the Nelumwewa thermal spring, Sri Lanka, is a result of deep percolation of groundwater through a regional fault zones, heated up by Hot Dry Rock beneath the Dimbulagala Mountain and then returning to the surface along a NE-SW trending regional vertical fault plane in the area. Thus, deep groundwater percolation thorough a fault zone and associated Hot Dry Rock is proposed as the hydro geological model for the Nelumwewa thermal spring in the North Central Province, Sri Lanka [79].

### 3.3.1 RESISTIVITY SURVEY SCHLUMBERGER METHOD

This is the most common method of sounding in Europe and is common in the United States. It saves moving the potential electrodes every time the current electrodes are moved. The electrodes are in a straight line, the outer electrodes are the current electrodes and the inner electrodes are the potential electrodes.

The potential electrodes, usually designated **M** and **N**, should never be separated by more than one-fifth of the separation between the current electrodes. The current electrodes are usually designated **A** and **B**.

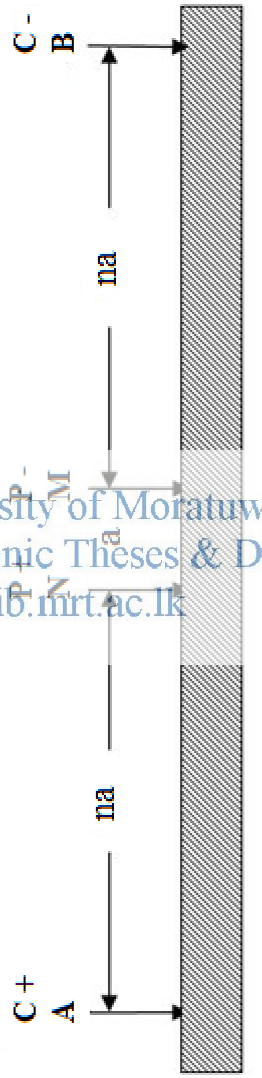


Fig 3.1 Schlumberger method arrangement of electrodes

Apparent resistivity is given by the following formula where **π** is 3.14, **AB** is the distance between the current electrodes, **MN** is the distance between the potential electrodes and **R** is the resistance read on the meter. MN can also be designated **a** and the distance between a current electrode and the nearest potential electrode designated as **na**.

$$\mathbf{R}_a = \rho\, \mathbf{R}\ (\mathbf{AB})\,(\mathbf{AB})/4(\mathbf{MN}) = \boldsymbol{\rho}\, \mathbf{R}\ \mathbf{a}\ \mathbf{2}\ (\mathbf{n}+1)$$

Before recording the data, current electrodes are extended as far as possible, then for the different separations, the potential difference between the fixed potential electrodes becomes smaller and smaller.

Finally the signal to noise ratio becomes noticeably small. Then the potential electrodes are stretched and an observation is made with the current electrodes at the same spacing. Theoretically, the apparent resistivities should be the same. However, they will always change by at least a small amount. This may be due to lateral inhomogeneities in the earth or to a localized irregularity near one of the potential electrodes.

The survey is resumed with the several more observation made with the current electrodes being placed at greater and greater separation. For a single sounding there may be three, four or even five separations used for the potential electrodes. This, in turn, generates three, four or five segments of sounding curve, each with at least a small offset from the adjacent segments [80],[81].

### 3.3.2 RESISTIVITY SURVEY IN BOGALA.

Bogala in Sabaragamuwa province is located in Sri Lanka - about 64 km East of Colombo. Area selected near Bogala mines to conduct the survey, road running parallel to mines almost straight line. Area of private lands and play ground used to make straight long line. Here Schlumberger method for resistivity measurements.[82] said about resistivity survey method in New

Zealand,[83] [84] the same for Iceland, [85][86] for Kenya and [87] for Eretria.

Resistivity data were obtained with respect to increasing the current electrode distance according to the pre defined table up to possible traverse distance and readings were obtained.

The above procedure was repeated after selecting each location points to carry on the Vertical Electrical Sounding (VES) resistivity survey and the data recorded.

For this survey Resistivity meter, Tetrameter SAS 1000 used and Vertical Electrical sounding method used. The survey was carried out using Schlumberger electrode configuration.

### 3.3.3 RESISTIVITY SURVEY AT KOTIYAKUMBURA.

Kotiyakumbura village is situated in Kegalle district, Sabaragamuwa province. Very long straight line in a large coconut estate selected to conduct the survey. Resistivity measurements were obtained with respect to increasing the current electrode distance according to the pre defined table up to possible traverse distance and readings were obtained. The above procedure was repeated after selecting each location points.

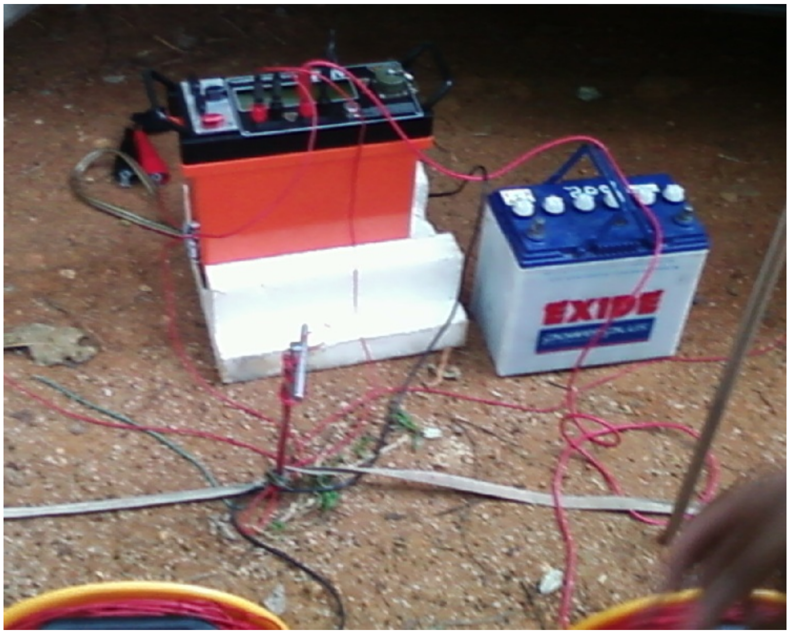


Fig 3.2 Resistivity survey in Kotiyakumbura.

Fig 3.3 Preparing Equipment for resistivity survey

## 3.4 GEOTHERMAL GRADIENT MEASUREMENT AT BOGALA GRAPHITE MINES

Underground temperature gradient measurement is a popular method used to find geothermal gradient in an area. Initially drill boreholes vertically to the ground and placed several thermal sensors to at different heights of the boreholes. Then all sensors were connected to the temperature loggers to record real time temperature data. Those data were used to calculate the temperature gradient of the researched area. Many geoscientists have used this method to find out geothermal gradient, but this is expensive and difficult to make several hundreds of meters boreholes vertically on the earth. Some occasions several numbers of bore holes were needed to maintain the accuracy.

Other method is to, use abandoned mines and petroleum wells to measure temperatures at different depths and calculate geothermal gradient and assessed geothermal potential.

The researchers [88] explain the method used to recover geothermal energy from underground mines. [89],[90] explained about this method, [91] Poland,[92],[93] in various territories used this method to find geothermal gradients. Especially in Canada and Europe already use geothermal energy from abandoned mines. Tunnels and adits in mines filled with heat radiated from surrounding rock, hence temperature inside those tunnels are high.

Due to very high cost in drilling deep bore holes for research study, another alternative low cost method was used to measure temperatures inside the earth.

In this study, initially one deep graphite mines, Bogola mines having 476 m depth was selected to find out internal temperature gradient and internal temperatures at different depths were recorded for several days. Data logging started on 25th February 2011.

### 3.4.1 LOCATION OF BOGALA VILLAGE

The Bogala situated in Aruggammana village, Kotiyakumbura area of Galigamuwa Division which is one of the Divisional Secretary area of Kegalle District, Sabaragamuwa Province of Sri Lanka. This village is located 5 km away from Avissawella – Kegalle road. The famous Bogala Graphite Mines are in Aruggammana village (Fig 3.4).

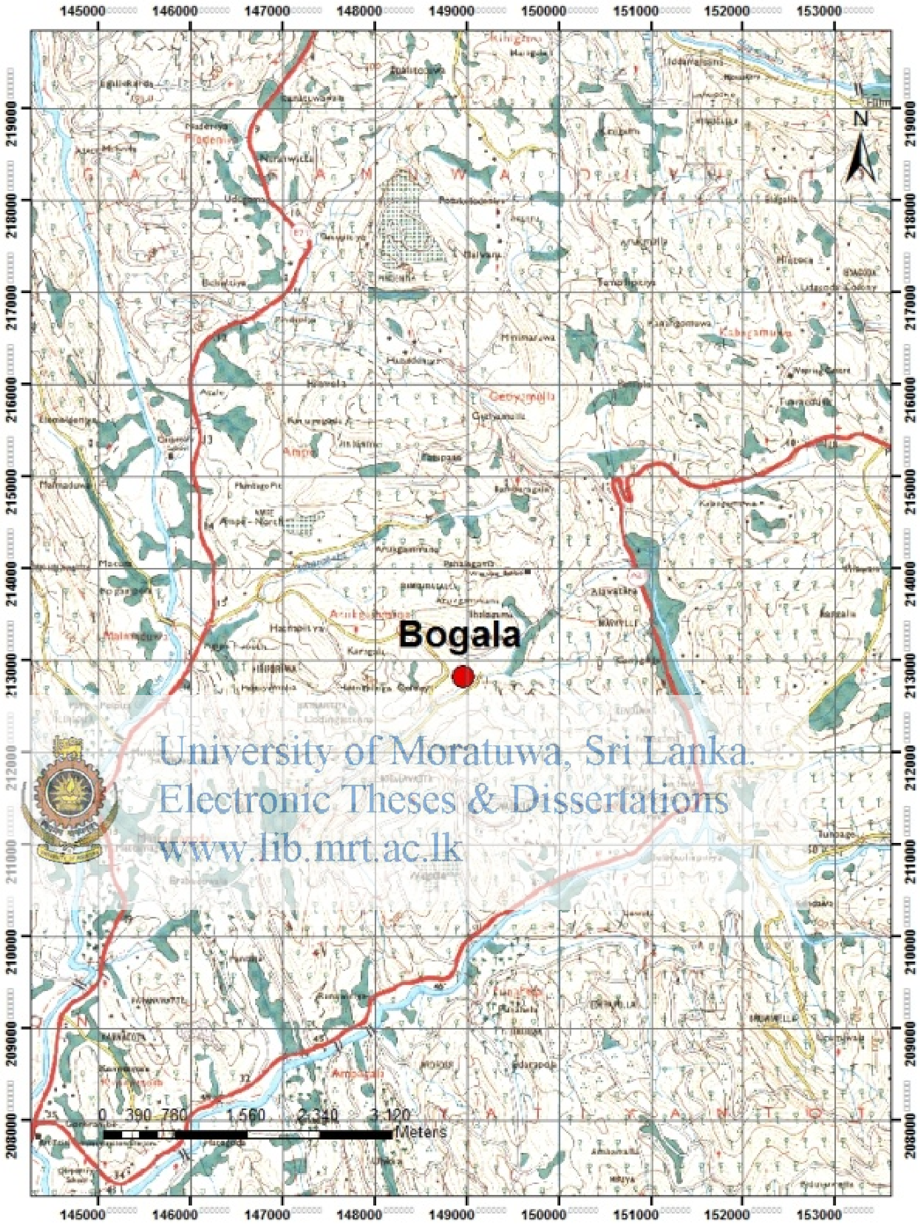


Fig 3.4 Topographic Map of Bogala area [117].

### 3.4.2 BOGALA GRAPHITE MINES

The mines were discovered during the reign of the Dutch and later developed by the British in 1920.Complete depth of this mines is 476 meters from the ground level.

GPS positions of Bogala Mines entrance is, 07.06’.86” N, 80.18’.60”E, Altitude of the mines entrance is 198 m above sea level. Bogala mine consists of network of adits, shaft and few tunnels.

In the mine entrance there are two shafts running to the earth. One tunnel runs vertically to 124 meters (m) from the ground level. From that level, a second shaft runs vertically to 476 meters depth. Cross sectional diagram is given in Fig 3.5.

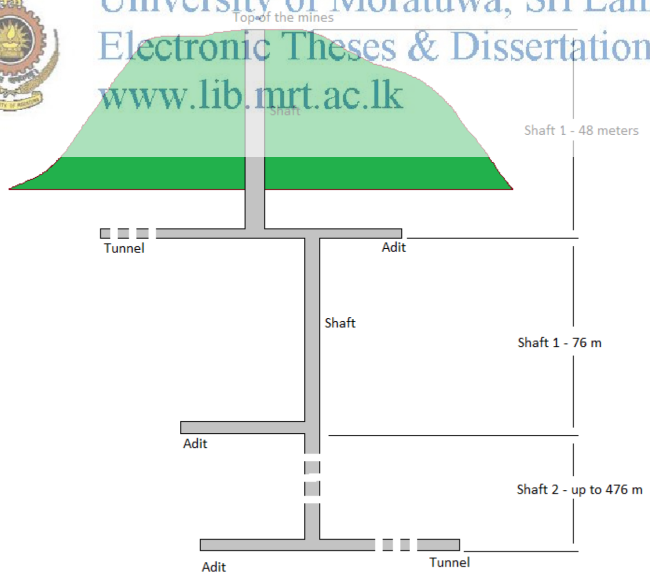


Fig 3.5 Cross section of Bogala mines.

There are some abandoned tunnels and adits in different depths. These tunnels and adits do not have ventilation mechanism for many years.

Therefore inside temperatures of these tunnels are higher than places close to shaft. Areas near shaft properly ventilated to provide fresh air for mine workers.

### 3.4.3 TEMPERATURE LOGGING METHOD

First selected several abandoned tunnels those have not been ventilated for a period of many years , therefore the temperature inside far end of such places were higher than normally ventilated tunnels. To place temperature probes horizontally, bore holes were drilled on the walls of selected abandoned tunnels.

The dimensions of them were 32 mm diameter and 180 mm in depth. All drill holes, made far ends of the abandoned tunnels. These holes used to measure inside temperature of bed rock. Opening of all drill holes properly closed by cork plugs, and thermocouples inserted through center of cork plug to the center line of the drill holes.

Five numbers of temperature loggers were installed inside the mines at different depths. All bore holes made at the depth of 124 m, 191 m, 300 m, 361 m, and 476 m.

All thermocouples connected to the temperature loggers and activated them to record temperature data. The arrangement given in Fig. 4 below was kept continuously for 72 hours period to record data from 25th February 2011 to 28th February 2011.

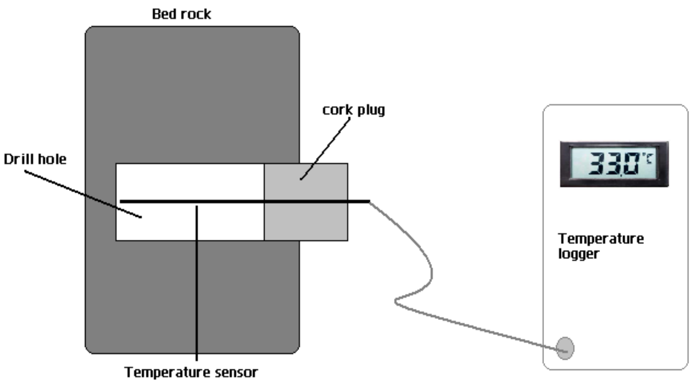


Fig 3.6 Arrangement used to measure bed rock temperature.

Before installing the temperature loggers, measured the difference between the temperatures at starting point of the tunnel and at end point of the tunnel. That shows the temperatures close to shaft is less than tunnel end. This happens due to lack of ventilation.

Measured temperatures near shaft and far end of the tunnel by using digital thermometer to confirm the difference as shown in Fig 3.7.

Fig 3.7 Direct reading of temperatures.

71 numbers of averaged temperature data were recorded with a one hour gap. The recorded temperature data were averaged and are given in the below table. Different columns show the recorded temperature data for the selected depths, approximately, 124 m, 190 m, 300 m, 360 m and 470 m.

### 3.4.4 GROUND TEMPERATURE VARIATION

Variation of ground temperature with time is natural phenomenon. When sun is rising ground temperature increases and it reach to maximum value at 12 o'clock. Again reduces when sun is setting. The outside temperature depends upon rain fall pattern and behavior of wind and availability of sun shine.

From 25th February 2011 to 28th February 2011, temperature variation of ground surface near shaft mouth was also measured.

Fig 3.8 During underground research work

## 3.5 TEMPERATURE MEASUREMENT AT HOT WATER SPRINGS

Temperatures of some hot springs were measured by using both digital IR thermometer and probe type thermometer. Distances between water wells are not much but they have shown different temperatures without much variation of the values. The layouts of Kanniya hot springs are given in Fig 3.10.

North eastern area, Eastern area, South eastern area and southern area there are many hot springs. They spread near boundary between Vijayan complex and highland complex. In section 2.1 more details about hot springs are given.

Fig 3.9 Temperature measurement, hot spring at Kanniya, Trincomalee

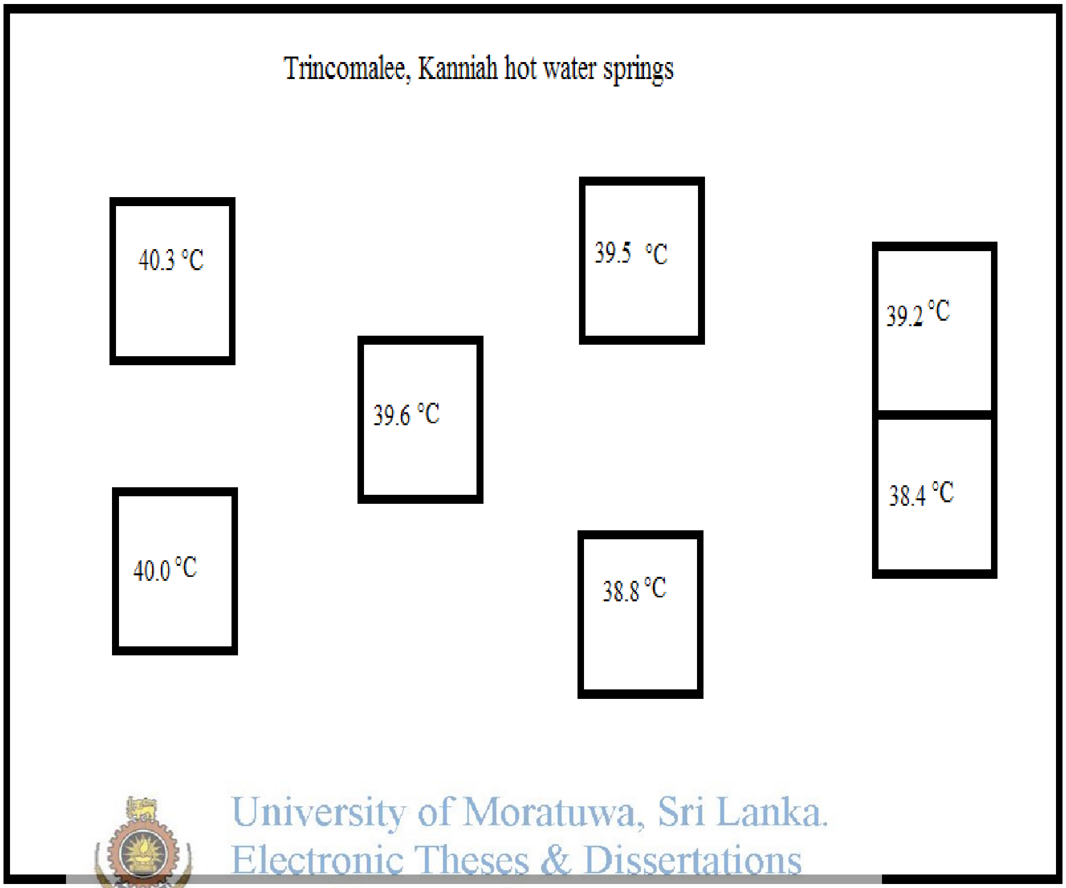
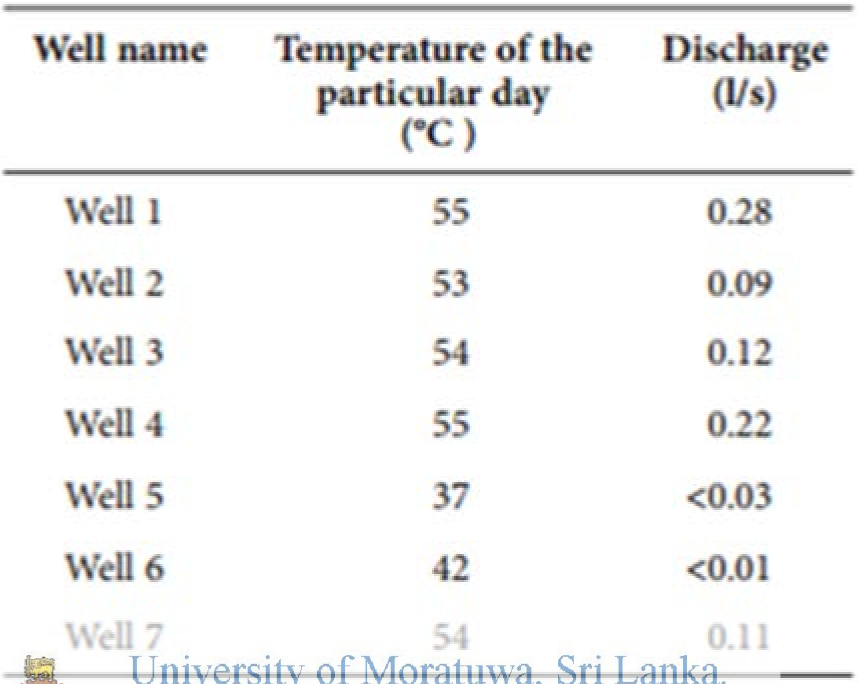


Fig 3.10 Temperatures of hot water wells Kanniya, Trincomalee

Fig. 3.11 Locations of wells Mahaoya, hot springs [88].

Locations of hot water wells in Mahapelessa are given in the Fig. 3.11. There are seven hot water wells and they have shown different temperatures. There are no very high temperature differences between them.

Table 3.1 Temperatures of hot water and their discharge rates, Mahaoya hot springs [88].



| Well name | Temperature of the particular day (°C ) | Discharge (l/s) |
|---|---|---|
| Well 1 | 55 | 0.28 |
| Well 2 | 53 | 0.09 |
| Well 3 | 54 | 0.12 |
| Well 4 | 55 | 0.22 |
| Well 5 | 37 | <0.03 |
| Well 6 | 42 | <0.01 |
| Well 7 | 54 | 0.11 |

Table 3.2 Hot water flow rate for few locations

| No | Location | Flow rate L/s |
|---|---|---|
| 1 | Mahapelessa | 0.17 |
| 2 | Madunagala | 0.645 |
| 3 | Kapurella | 0.5 |
| 4 | Maha Oya | 0.28 |

The hot water flow rate of, Mahapelessa, Madunagala, Kapurella and Mahaoya are respectively, 617, 2322, 1800 and 1008 liters per hour.

## 3.6 LABORATORY MODEL OF A GERTHERMAL POWER PLANT

### 3.6.1 DESIGN DETAILS

This model plant fabricated using defective ventilation fan. That has rotating blades incorporated with ring magnet. Non rotating steady coil assembly is fixed to the body of the fan. This coil assembly re wound according to our requirement. Here stator coils are not rotating hence carbon brushes and slip rings are not necessary. That leads to reduction of losses and increase the efficiency of the plant. This unit has been designed only for laboratory testing purpose.

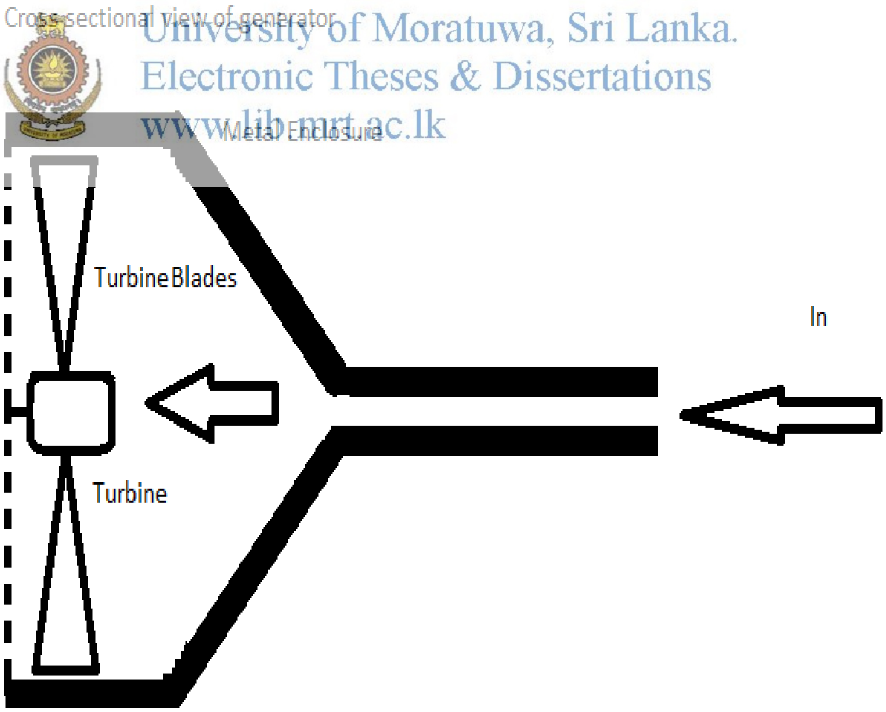


Fig 3.12 Cross sectional view of laboratory model of the power plant generator.

The below given Fig. 3.13 shows the heat exchanger used for model power plant. A heat exchanger is a device used to transfer heat between one or more fluids. The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact.

Fig 3.13 Heat exchanger used in model power plant.

## 3.6.2 CONSTRUCTION DETAILS OF MODEL GENERATOR

Fig 3.14 Preparing armature of alternator of model generator.

Fig 3.15 Turbine blade with circular magnets

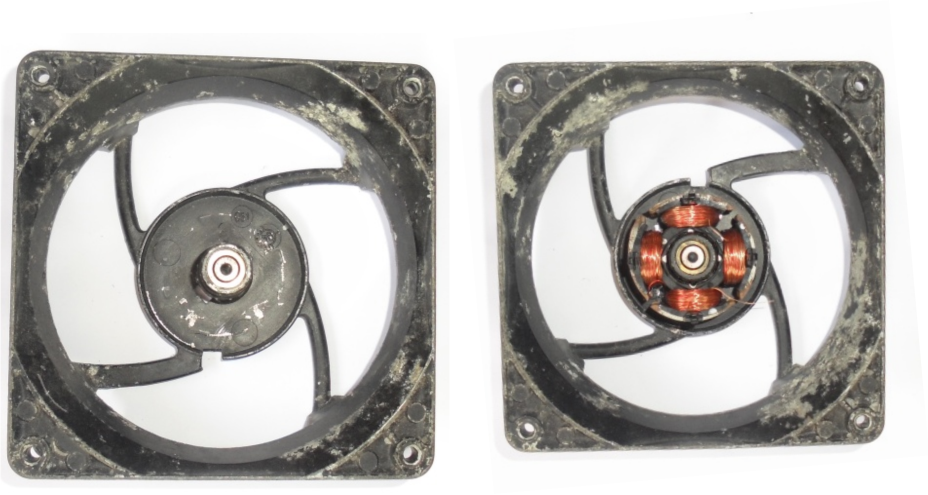


Fig 3.16 Stator holder and stator after fixed to the holder

Fig 3.17 Stator and turbine

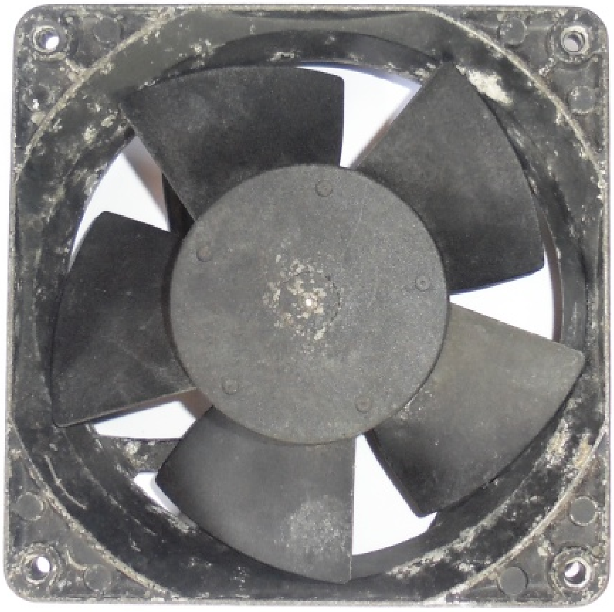


Fig 3.18 Completed alternator with turbine

This alternator produces 15 Volts no load voltage. This is good enough to take measurements for this research study. Compressed air flows through copper tube and that blow to the turbine with constant temperature for different speeds. Then collect the no load voltage readings.

In second step blow the air for constant speeds and vary the air temperature. For this process heat exchanger was used. Water filled to the heat exchanger and immersed an immersion heater to water tank for heat exchanger. Then external supply voltage connects to the heater and control temperature of the water according to research study requirements.

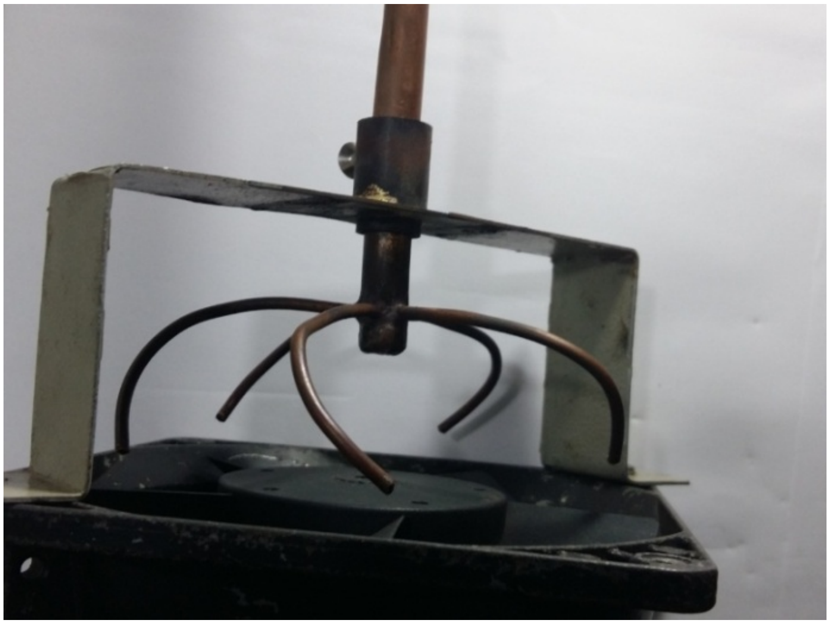


Fig 3.19 Air jets of plant turbine

Fig 3.20 Constructed model Plant

### 3.6.3 PRINCIPLE OF OPERATIONS

The volume of air flow sends to the turbine chamber through a heat exchanger copper tube, the tube is immersed to hot water bath which arrangement is called heat exchanger. When temperature of the water in the bath increases, the air volume tapped in the coil absorb them and suddenly expand the volume of air and then pressure builds up and air moving fast to the turbine and rotates the blades. This arrangement generates electricity when the turbine is rotating. Air flow is continuous and small compressor supply air to the laboratory model. The generated voltage converted to dc voltage. That will minimize the frequency changes due to temperature and water flow rate variations.

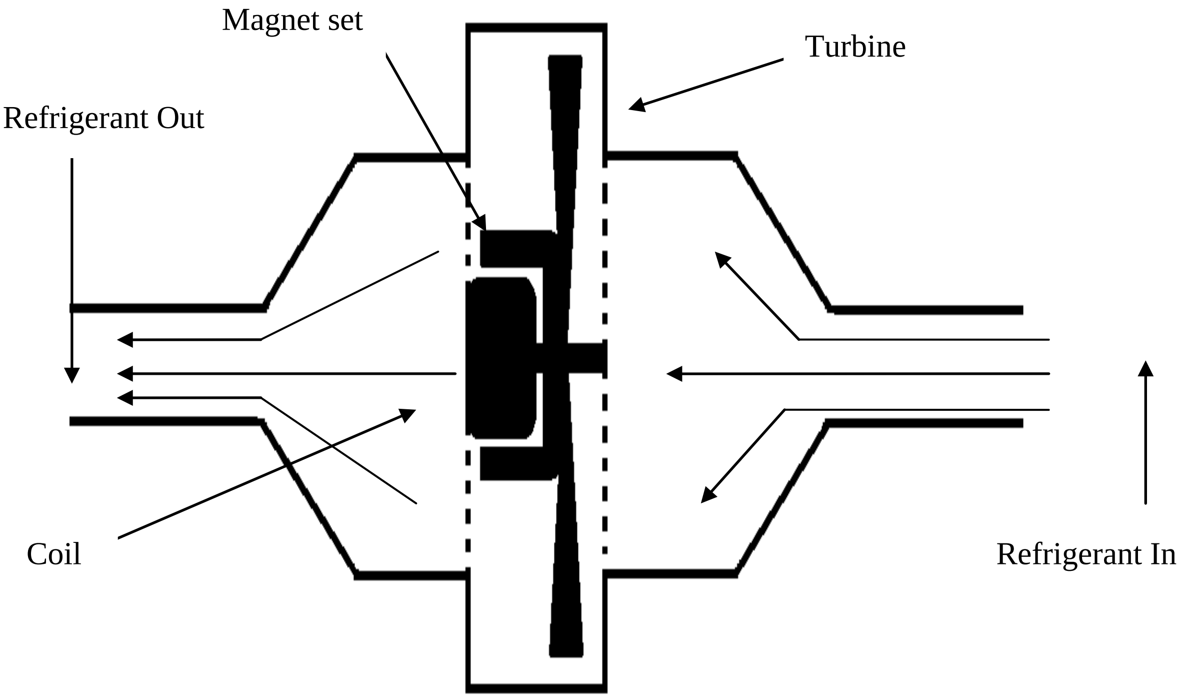


Fig. 3.21 Cross section of actual Generator

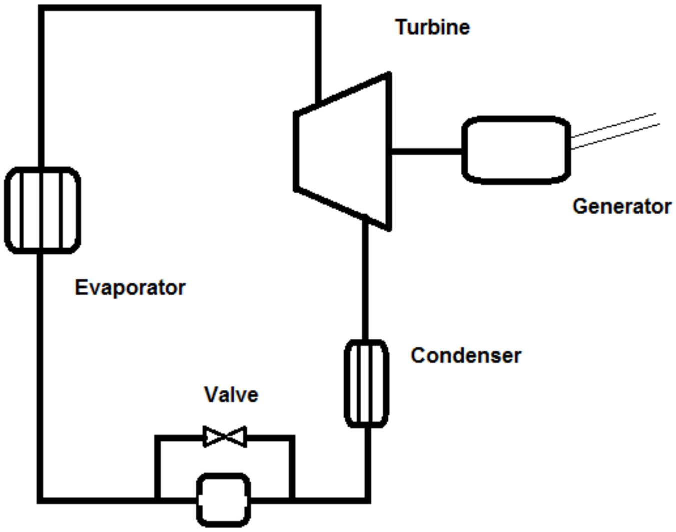


Fig. 3.22 Designed binary cycle plant

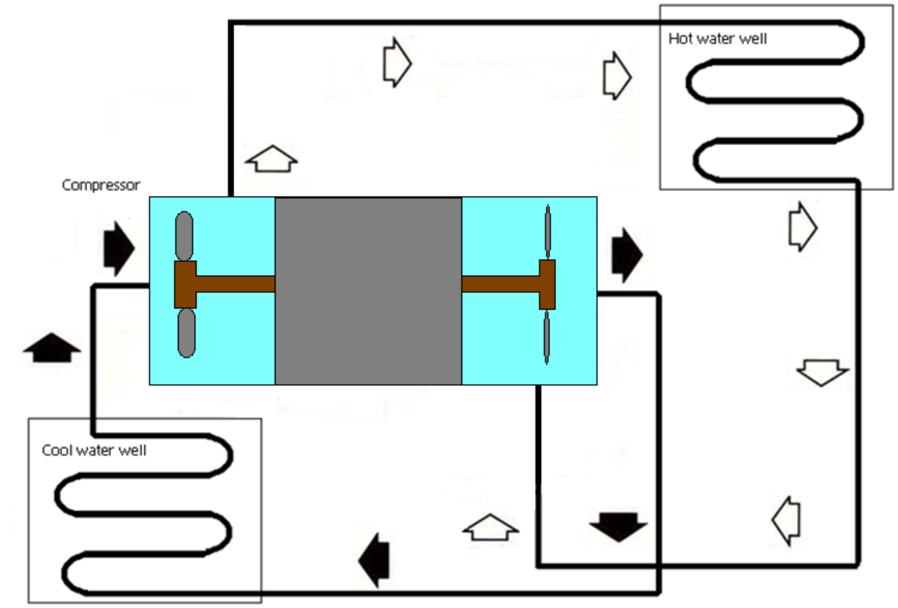


Fig. 3.23 Power Plant Design Drawing

## 3.7 GEOTHERMAL GRADIENT

Geothermal gradient is the rate of increasing temperature with respect toincreasing depth in the Earth's interior. Away from tectonic plate boundaries, it is about 25 °C per km of depth near the surface in most of the world.

Heat flows constantly from its sources within the Earth to the surface. Total heat loss from the Earth is estimated at 44.2 TW ($4.42 \times 10^{13}$ watts). Mean heat flow is 65 mW/$m^2$ over continental crust and 101 mW/$m^2$ over oceanic crust. This is 0.087 watt/square meter on average (0.03 percent of solar power absorbed by the Earth ), but is much more concentrated in areas where thermal energy is transported toward the crust by convection such as along mid-ocean ridges and mantle plumes. The Earth's crust effectively acts as a thick insulating blanket which must be pierced by fluid conduits (of magma, water or other) in order to release the heat underneath. More of the heat in the Earth is lost through plate tectonics, by mantle upwelling associated with mid-ocean ridges. The final major mode of heat loss is by conduction through the lithosphere, the majority of which occurs in the oceans due to the crust there being much thinner and younger than under the continents.

## 3.8 GEOTHERMAL MAP

Geothermal maps contain existing and developing geothermal power plants, geothermal resource potential estimates, and other information related to geothermal power. They are updated as information becomes available, but may not represent all available geothermal data. These maps are useful for Researchers, Consultants, Decision makers, Geologists, Academics etc, interested in assessing the geothermal potential at any location of Sri Lanka. The below given Fig 3.24 shows some ongoing major projects and already completed in the world.

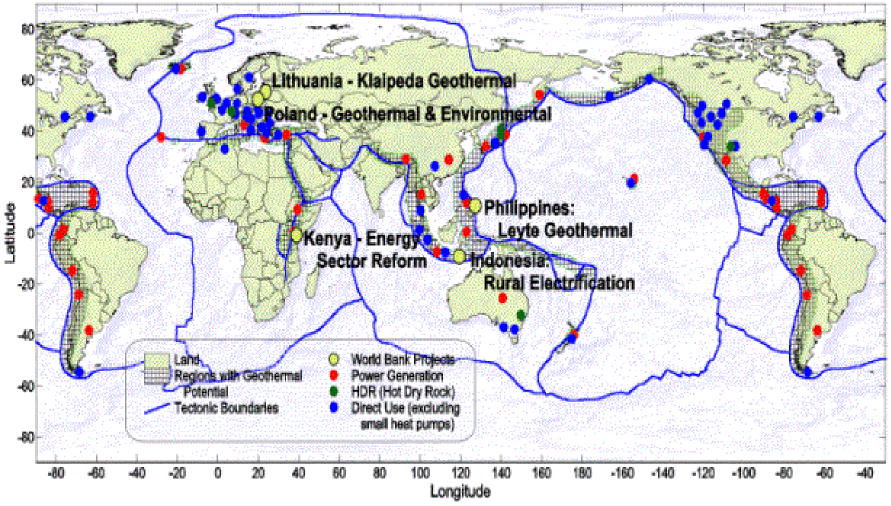


Fig. 3.24 Geothermal energy utilization map of the world[8].

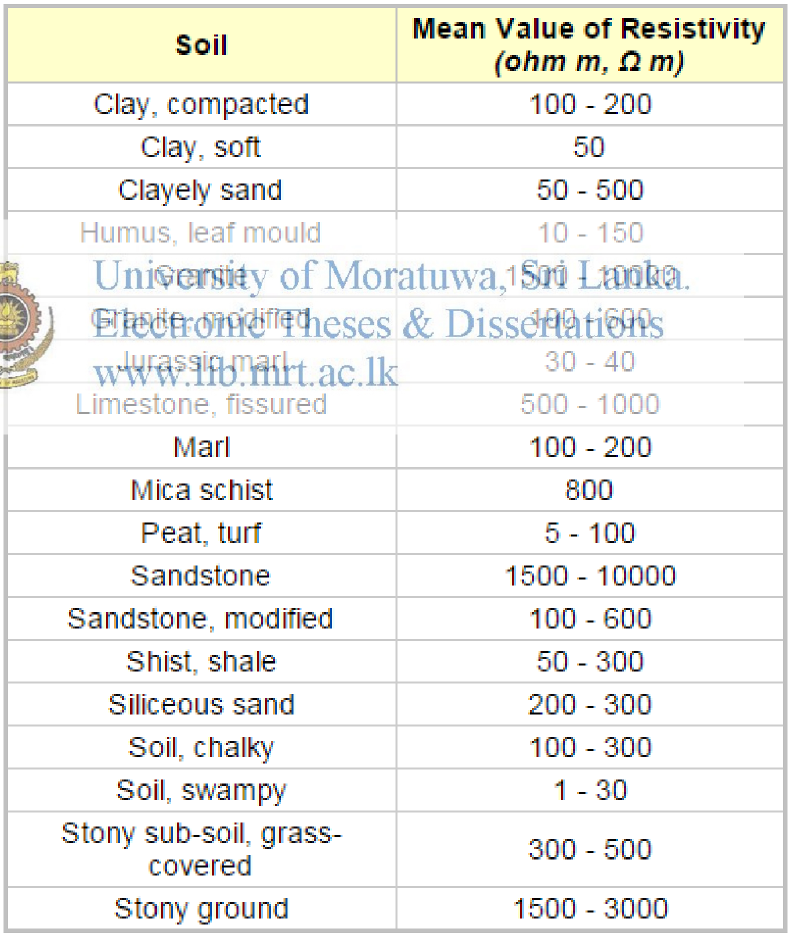
# CHAPTER 4

## 4.0 RESULTS AND DISCUSSION

## 4.1 RESISTIVITY DATA

The below given Table 4.1 showing resistivity value for different ground conditions. With help of these data and resistivity data gathered possible to analyze the ground layers and their locations.

Table 4.1 Resistivity values for different ground conditions [96].



| Soil | Mean Value of Resistivity *(ohm m, Ω m)* |
|---|---|
| Clay, compacted | 100 - 200 |
| Clay, soft | 50 |
| Clayely sand | 50 - 500 |
| Humus, leaf mould | 10 - 150 |
| Granite | 1500 - 10000 |
| Granite, modified | 100 - 600 |
| Jurassic marl | 30 - 40 |
| Limestone, fissured | 500 - 1000 |
| Marl | 100 - 200 |
| Mica schist | 800 |
| Peat, turf | 5 - 100 |
| Sandstone | 1500 - 10000 |
| Sandstone, modified | 100 - 600 |
| Shist, shale | 50 - 300 |
| Siliceous sand | 200 - 300 |
| Soil, chalky | 100 - 300 |
| Soil, swampy | 1 - 30 |
| Stony sub-soil, grass-covered | 300 - 500 |
| Stony ground | 1500 - 3000 |

### 4.1.1 RESISTIVITY DATA IN BOGALA

Resistivity survey was carried out at very near location at Bogala graphite mines. The famous schlumberger method used and all data recorded, Resistivity data collected from near location at Bogala graphite mines is given in the Table 4.2.

Table 4.2 Bogala resistivity data.

| Resistivity Ωm | Depth m | Resistivity Ωm | Depth m |
|---|---|---|---|
| 922.46 | 1.00 | 388.94 | 13.33 |
| 1071.6 | 1.33 | 233.26 | 20.00 |
| 960.59 | 2.00 | 138.66 | 26.67 |
| 1001.3 | 2.00 | 203.6 | 26.67 |
| 646.86 | 3.33 | 156.83 | 33.33 |
| 566.29 | 6.67 | 300.24 | 33.33 |
| 879.35 | 6.67 | 356.57 | 43.33 |
| 702.03 | 8.33 | 187.96 | 46.67 |
| 606.38 | 10.00 | 200.66 | 56.67 |
| 590.14 | 10.67 | | |

Data gathered from Bogala location are in Table 4.2 Comparing facts in Fig. 4.3 the following statement made. From A to B one meter depth layer displays, resistivity around 1200 Ω/m.

C to D 1.5 meters thick layer, it is almost 100 Ω/m and E to F is 3.5 meters thick layer goes up to 7 meters depth, with resistivity of 1500 Ω/m and G to H, it fall to approximately 10 Ω/m level up to 22 meters. From 22 meters up to more than 100 meter finally again reach to 220 Ω/m.

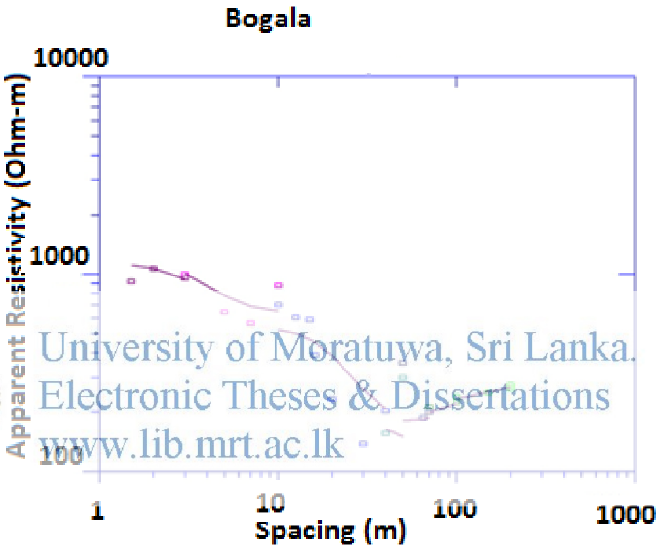


Fig 4.1 Analyzed results of Bogala resistivity data

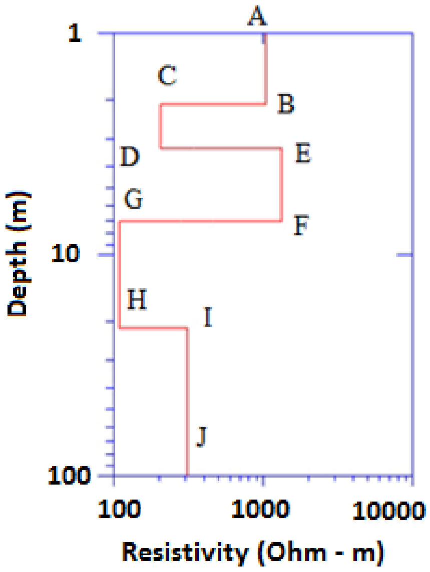


Fig 4.2 Analyzed results of Bogala resistivity data.

### 4.1.2 RESISTIVITY DATA IN KOTIYAKUMBURA

Resistivity survey was carried out at Kotiyakumbura, little bit away from Bogala graphite mines. Here also used famous schlumberger method to measure resistivity, all data recorded, Resistivity data collected from near location at Bogala graphite mines is given in the Table 4.2

Table 4.3 Kotiyakumbura resistivity data

| Resistivity (Ωm) | Depth( m) | Resistivity (Ωm) | Depth( m) |
|---|---|---|---|
| 1136.50 | 1.00 | 810.52 | 20.00 |
| 1167.40 | 1.33 | 402.00 | 26.67 |
| 1009.80 | 2.00 | 1067.30 | 33.33 |
| 1020.30 | 2.00 | 1628.10 | 33.33 |
| 710.21 | 3.33 | 1354.70 | 43.33 |
| 677.29 | 4.67 | 1451.70 | 46.67 |
| 720.18 | 6.67 | 1912.50 | 66.67 |
| 658.51 | 6.67 | 47.74 | 100.00 |
| 623.93 | 8.33 | 1111.20 | 100.00 |
| 651.34 | 10.00 | 2226.90 | 100.00 |
| 657.91 | 10.67 | 1024.70 | 133.33 |
| 690.04 | 13.33 | | |

Data gathered from Kotiyakumbura location are in Table 4.3. Comparing facts in Fig 4.5 the following statement made. From A to B 0.65 meter depth layer displays, resistivity around 140 Ω/m.

C to D it is almost 68 Ω/m and E to F runs up to 68 meters depth and its average resistivity 6500 Ω/m and it fall to approximately 68 Ω/m level, finally again reach to 220 Ω/m.

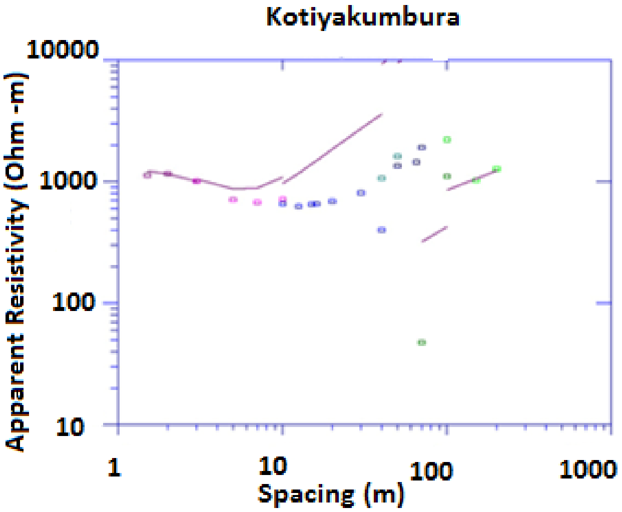


Fig 4.3 Analyzed results of Kotiyakumbura resistivity data

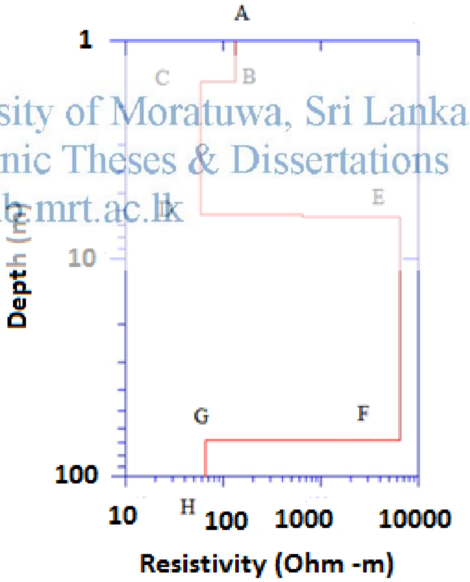


Fig 4.4 Analyzed results of Kotiyakumbura resistivity data

## 4.2 TEMPERATURE GRADIENT IN BOGALA MINES

Averaged outside temperature data collected from Bogala Graphite mines entrance are given in the Table 4.3. The final value of averaged temperature of the same place was 25.26 °C

Table 4.4 Averaged Temperature data at ground level, Bogala.

| Bogala Temperature data- 25.02.2011 to 28.02.2011 Outside | | |
|---|---|---|
| Date | Time | Temperature °C |
| 2/25/2011 | 12:00:00 noon | 27.68 |
| 2/25/2011 | 18:00:00 | 26.06 |
| 2/26/2011 | 12:00:00 night | 24.03 |
| 2/26/2011 | 6:00:00 AM | 24.12 |
| 2/26/2011 | 12:00:00 noon | 27.02 |
| 2/26/2011 | 18:00:00 | 25.76 |
| 2/27/2011 | 12:00:00 night | 23.61 |
| 2/27/2011 | 6:00:00 AM | 24.06 |
| 2/27/2011 | 12:00:00 noon | 27.11 |
| 2/27/2011 | 18:00:00 | 25.68 |
| 2/28/2011 | 12:00:00 night | 23.03 |
| 2/28/2011 | 6:00:00 AM | 23.39 |
| 2/28/2011 | 12:00:00 noon | 26.87 |

The underground temperature of the bedrock in the mine varies with depth from the ground level. This is natural process due to very high internal temperature level of the earth core. The collected temperature data averaged and calculated the daily average for different depths.

And also temperature gradients for different levels of mines were calculated. Resultant values are given in the Table 4.5

Table 4.5 Averaged Underground temperature variation with depth at Bogala mines.

| No | Depth Z meters from mines entrance | Average Temperature t $^0$C | Temperature Gradient $G_t$ ($\Delta T/\Delta Z$) between two levels, $^0$C / 100 m |
|---|---|---|---|
| 1 | 124 ($Z_1$) | 25.76 ($T_1$) | N/A |
| 2 | 190 ($Z_2$) | 28.31 ($T_2$) | 3.8 = ( 36 / Km) |
| 3 | 300 ($Z_3$) | 32.46 ($T_3$) | 3.7 = ( 37 / Km) |
| 4 | 360 ($Z_4$) | 34.53 ($T_4$) | 3.4 = ( 34 / Km) |
|  | 476 ($Z_5$) | 38.61 ($T_5$) | 3.5 = ( 35 / Km) |

The geothermal gradient is difference in temperature with depth in the Earth. The temperature gradually increases with the increased depth.

The way to calculate a temperature gradient is to take the difference of the temperature and divide it by the difference of the depth. The general equation to show the temperature gradient of a system can be written as follows.

Here T is temperature in degrees centigrade and Z is depth in meters.

The temperature gradient $G_t$, is $^0C$ / m is given by,

$$G_t = \frac{T_5 - T_0}{Z_5 - Z_0} \qquad G_t = \frac{38.61 - 25.26}{476 - 0} = 0.028046\ ^0C/m$$

Here $Z_5$ = 476 m, $Z_0$ = 0 m, $T_5$ = temperature at 476 m and $T_0$ = temperature at ground level. From this research temperature gradient calculated as 28.046 $^0C$ /Km.

Two resistivity surveys carried out in Bogala and Kotiyakumbura areas, those locations are very close to the Bogala Graphite Mines. Those were conducted to compare resistivity data and temperature gradient.

Due to practical problems arose, ie difficult to install electrodes in very long straight lines of several 100 meters to get the resistivity readings for analyzing internal structure of the earth, and limitations of functioning of equipment, ie generated voltage is not sufficient to measure resistivity of deeper earth. By considering these bottle necks and difficulties this method also dropped. Then finally bore hole temperature logging method selected.

## 4.3 TEMPERATURE DATA HOT SPRINGS.

Temperature data collected for various hot springs are listed below, marked as Table 4.6, its theoretical efficiencies also given there.

Data in Table 4.7 is related to underground reservoir, if those reservoirs are discharging same volume as in Table 4.8, the related power capacity is given.

Table.4.6 Reservoir temperatures

| No. | Location | Hot spring's water temperature $^0$C | Underground reservoir temperature $^0$C | Theoretical Cycle Efficiency (TCE) % |
|---|---|---|---|---|
| 1 | Nelumwewa | 62 | 120 | 22.37 |
| 2 | Mahaoya | 56 | 117 | 21.77 |
| 3 | Kapurella | 73.5 | 115 | 21.37 |
| 4 | Rathkihiriya | 42 | 114 | 21.17 |
| 5 | Mahapelessa | 46 | 101 | 18.43 |
| 6 | Marangala | 44 | 97 | 17.55 |
| 7 | Kanniya | 42 | 88 | 15.49 |

Table.4.7 Underground Reservoir power capacity

| No | Location | Reservoir Temp. $^0$C | Water flow rate of spring | Power generation kW | kWh per day (24 hours) |
|---|---|---|---|---|---|
| 1 | Kapurella | 115 | 10 L/min | 3.30 | 79.31 |
| 2 | Mahapelesa | 101 | 10 L/min | 2.74 | 65.93 |
| 3 | Mahaoya | 117 | 5 L/min | 1.69 | 40.61 |
| 4 | Nelum wewa | 120 | 10 L/min | 3.50 | 84.08 |

Table 4.8 shows the new power generation capacity, if hot water of underground reservoirs used. This clearly shows the increase of power capacity, when water temperature increases.

## 4.4 POWER PLANTS

### 4.4.1 EFFICIENCY OF THE POWER PLANT

One of the most important features of the power plant is its efficiency. This depends upon the temperature difference between the boiler and the condenser

Theoretical Cycle Efficiency (TCE) is given by,

$$\mathbf{TCE} = \frac{\mathbf{T_h - T_l}}{\mathbf{T_h}} \mathbf{x\ 100}$$

Where, $T_h$ is absolute temperature of the steam leaving the boiler $^0$R.

$T_l$ is absolute temperature of the condenser $^0$R.

Absolute temperature $^0$R is determine by adding $460^0$ to the temperature in $^0$F. The $100^0$F is given by (100+460) $^0$R or 560 $^0$R.

According this formula the efficiency of Kapurella (section 2.2.2) hot spring, which recorded maximum temperature recorded was $73.5^0$C or 164.3 $^0$F the calculation is as follows. The temperature of the cold water in the Kapurella area is assumed as $32^0$C or 89.6 $^0$F.

Absolute temperature of steam leaving the boiler = $T_h$

$$= 164.3 + 460 = 624.3\ ^0R$$

Absolute temperature of the condenser = $T_l$ = 89.6 + 460 = 549.6 $^0$R.

Therefore TCE = [624.3 – 549.6 / 624.3] x 100

$$= 11.96\ \%$$

By applying same principle it is possible to calculate average efficiencies of the plants of selected hot springs as follows. Here the given temperatures are not the maximum temperatures of the springs. The average temperature of the cold water in the all areas is assumed as $32^0$C or 89.6 $^0$F.

The required geothermal water flow from various hot springs, having different temperatures can be selected by following the given method. Calculate the required heat input, for that multiply capacity kW by 3413 to convert the value to BTU. Then divide the answer by factor 0.075, then possible to calculate capacity in BTU/hr.

Finally divide this value by 500 and again by temperature difference of plant supply in $^0$F. Then the answer is water volume requirement to generate expected power output. Efficiency of the plant $\eta$ =11.96%

Apply this to Kapurella hot spring its temperature $t_1$ is 164.3 $^0$F, if the temperature of the leaving water is say $t_2$ 89.6 $^0$F. To generate Pe kW, required water volume V gallons per minute. The plant heat input is $P_h$, BTU/hr is given by, $P_h$= Pe x 3413/ η ,  V = $P_h$ / 500($t_1$– $t_2$) = 6.826 Pe / η ($t_1$ – $t_2$) gpm

The volume of water $V_k$ required to generate 1 kW power for Kapurella is given by, $V_k$ = 6.826 / 11.96% x ( 164.3 -89.6) = 0.764 gallons per minute or 3.44 Liters per minute.

Common equation for this process can be developed as,

$$V = \frac{Ph}{500(t1-t2)} = Pe\frac{3413}{500(t1-t2)\eta} = 6.826\frac{Pe}{\eta(t1-t2)}$$

$$\boxed{\boldsymbol{V = 6.826\frac{Pe}{\eta(t1-t2)}} \quad \text{(here } t_1 \text{ and } t_2 \text{ values are measure in } {}^0\text{F).}}$$

$P_e$ α V and $P_e$ α η also $P_e$ α ($t_1$ – $t_2$)

$$\boxed{\text{Generated electrical power, } P_e = V\ \eta\ (t_1 - t_2)\ /\ 6.826}$$

Table 4.8 power generation capacity.

| No | Location | Temp. $^0$C | Water flow rate V gpm | Efficiency of the plant η | Power generation $P_e$ in kW | Energy E kWh per day |
|---|---|---|---|---|---|---|
| 1 | Kapurella | 73.5 | 10 L/min | 11.96% | 13.08 | 314.12 |
| 2 | Mahapelesa | 46 | 10 L/min | 4.38% | 1.61 | 38.80 |
| 3 | Mahaoya | 56 | 5 L/min | 7.28% | 2.30 | 55.28 |
| 4 | Nelum wewa | 62 | 10 L/min | 8.94% | 7.07 | 169.73 |

Table 4.9 Performance analysis of the power plants.

### 4.4.2 TESTING POWER PLANT

| No. | Location | Temperature $^0$C | Estimated Efficiency | Estimated Loss | Hot water requirement to generate 1 kW/ gpm |
|---|---|---|---|---|---|
| 01 | Kapurella<br>( Ampara) | 73.5 | 11.96% | 88.04% | 0.76 or<br>3.42 L/min |
| 02 | Maha Oya | 56 | 7.28% | 92.72% | 2.17 or<br>9.76 L/min |
| 03 | Marangala<br>(Padiyathalawa) | 44 | 3.78% | 96.22% | 8.36 or<br>37.62 L/min |
| 04 | Mahapelessa<br>( Soorirya Wewa) | 46 | 4.38% | 95.62% | 6.18 or<br>27.81 L/min |
| 05 | Meda Wewa | 45 | 4.08% | 95.92% | 7.14 or<br>32.13 L/min |
| 06 | Nelum Wewa<br>( Polonnaruwa) | 62 | 8.94% | 91.06% | 1.41 or<br>6.34 L/min |
| 07 | Kanniya<br>( Trincomalee) | 42 | 3.17% | 91.83% | 11.9 or<br>53.55 L/min |
| 08 | Kiwulegama<br>(Jayanthiwewa} | 34 | 0.65% | 99.35% | 291.7<br>1312.65 L/min |
| 09 | Rankihiriya<br>(Gomarankadawala) | 42 | 3.17% | 96.83% | 11.9 or<br>53.55 L/min |

Fig 4.5 Testing the turbine and alternator

Testing work conducted to find out performance of the plant. That gave acceptable output. The above given Fig 4.6 shows the testing stage of generator of the power plant. Output voltage waveform is shown in Fig 4.7.

Fig 4.6 Output voltage waveform of model generator

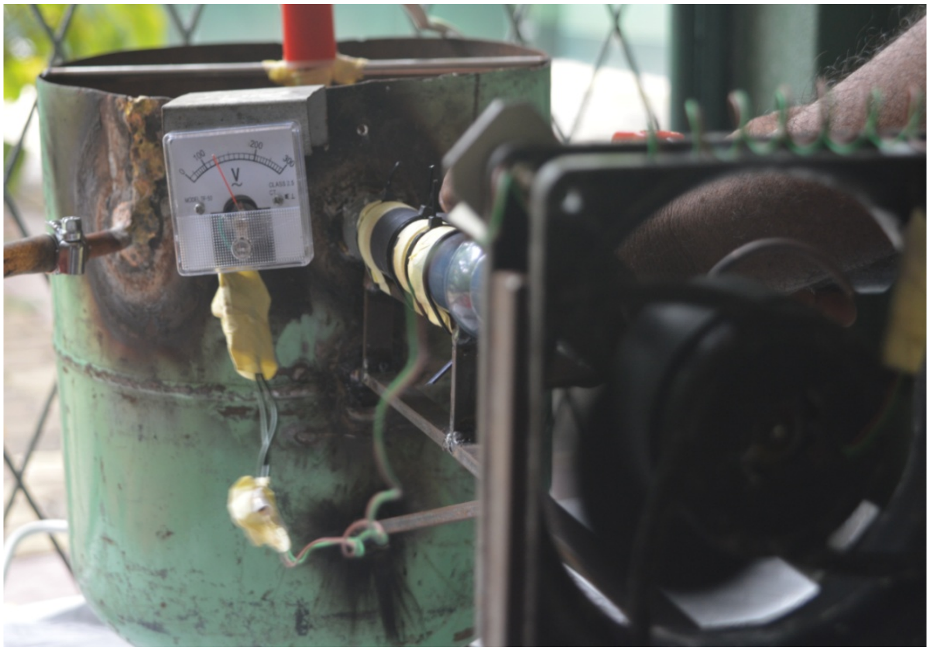


Fig 4.7 Plant Testing

Fig 4.8 Voltage build up 1

Fig 4.9 Voltage build up 2

Fig 4.10 Voltage build up 3

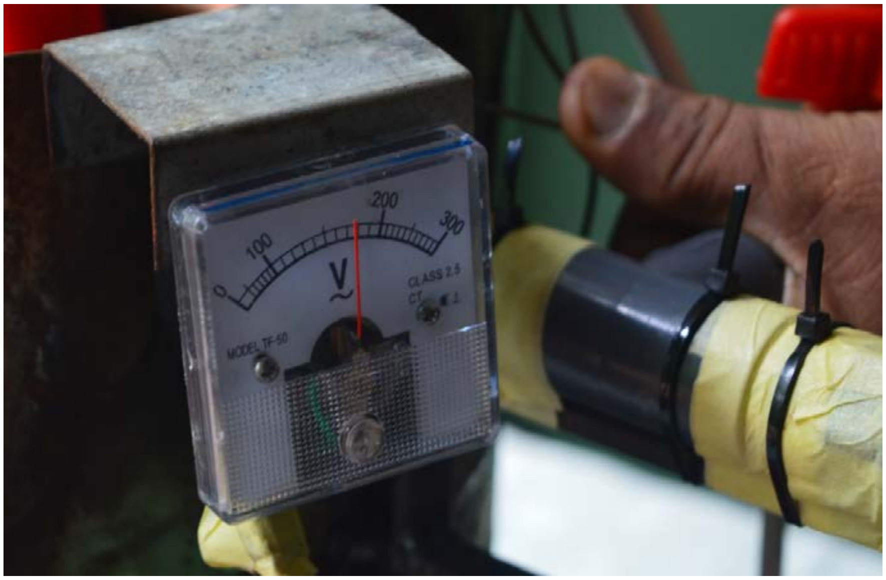


Fig 4.11 Voltage build up 4

Fig 4.12 Voltage build up 5

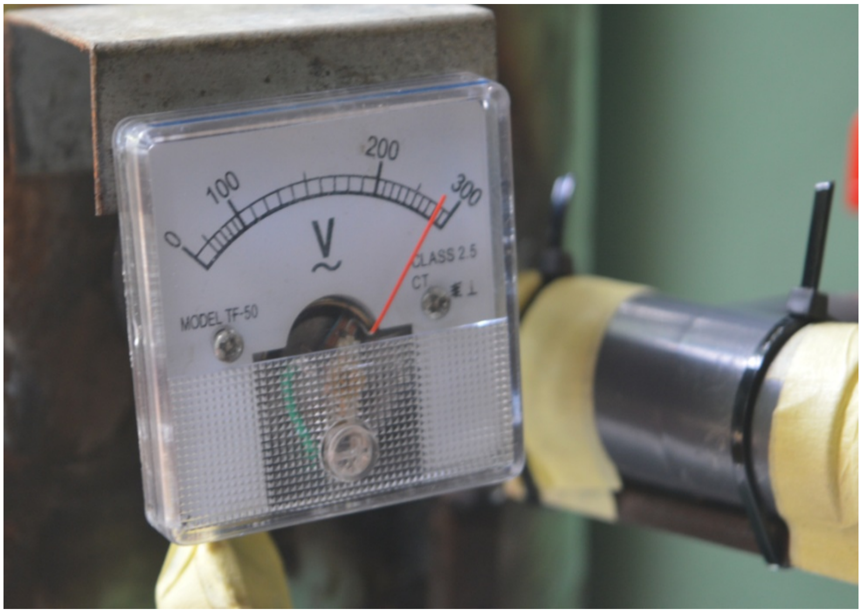


Fig 4.13 Voltage build up 6

Fig 4.14 Air flow rate testing 1

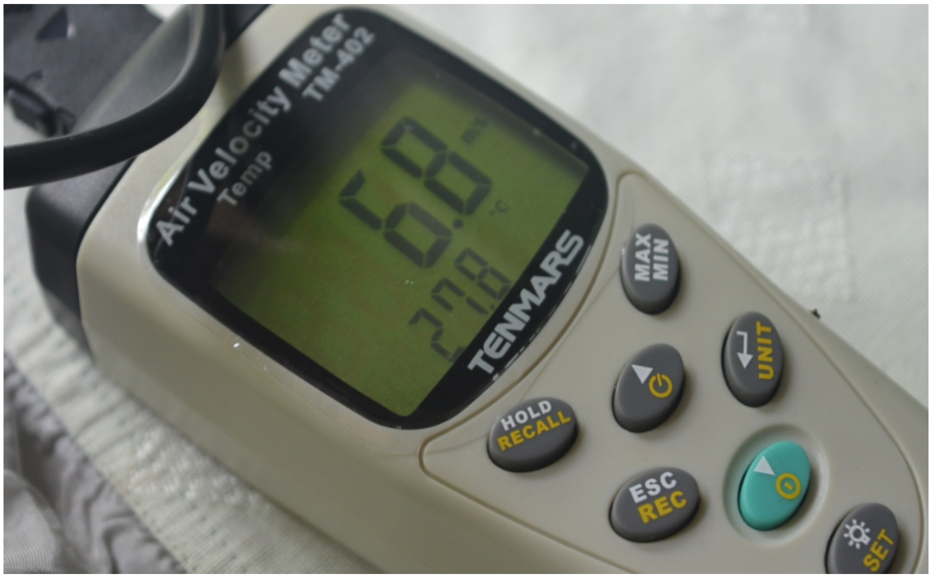


Fig 4.15 Air flow rate testing 2

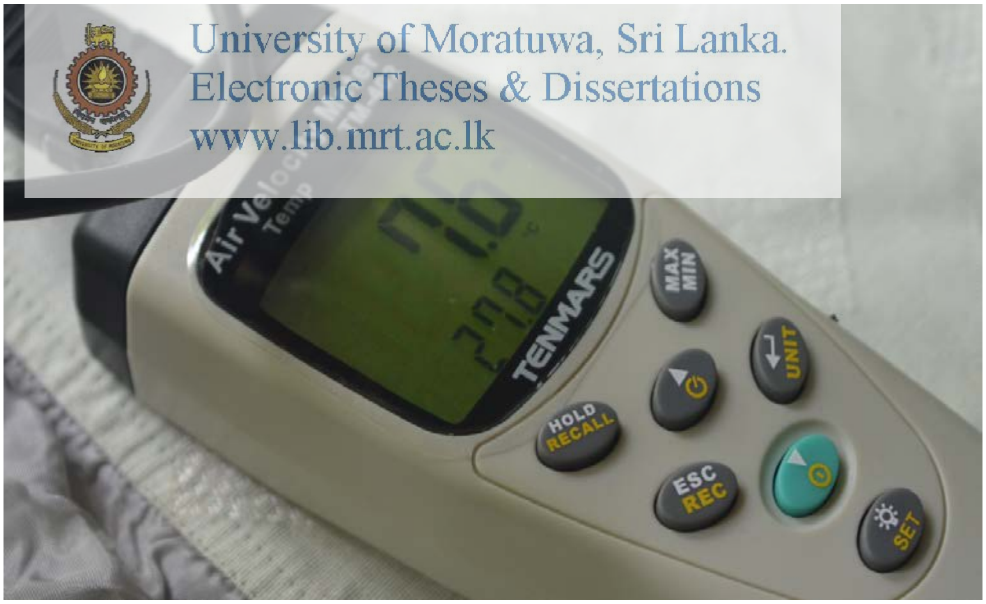


Fig 4.16 Air flow rate testing 3

Fig 4.17 Water filling to heat exchanger

Fig 4.18 Temperature monitoring 1

Fig 4.19 Temperature monitoring 2.

| Air velocity m/s | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| Generated Voltage V | 0 | 5 | 5.8 | 6.2 | 6.8 | 7.6 | 8.4 | 9.2 | 11 |

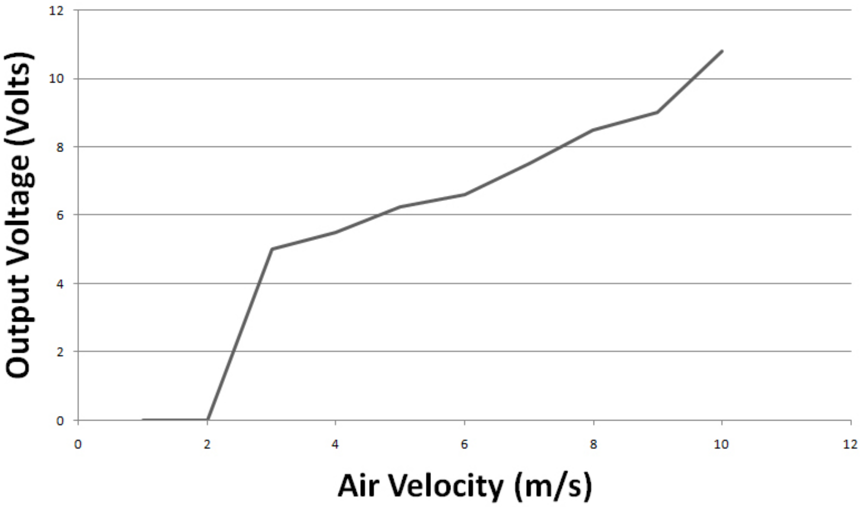


Fig 4.20 Generator output voltage/ Air velocity (Temperature constant)

| Water Temperature $^0$C | 40 | 50 | 55 | 60 | 70 | 80 |
|---|---|---|---|---|---|---|
| Generated Voltage V | 5.50 | 6.38 | 7.50 | 8.00 | 8.50 | 8.85 |

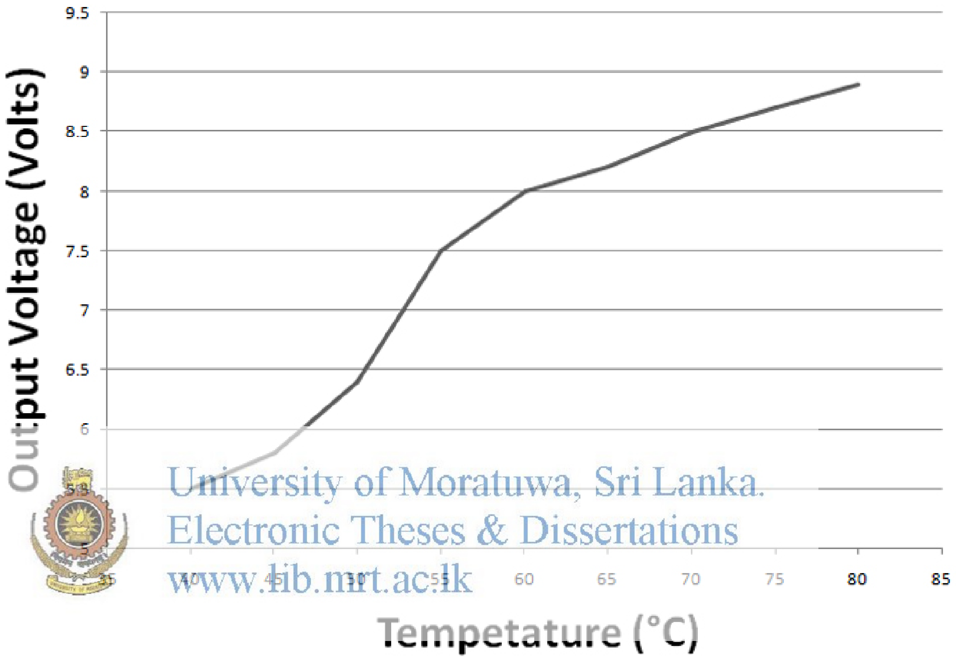


Fig 4.21 Generator output voltage/ Temperature (Air velocity constant)

Fig 4.20 and 4.21 used to check performances of plant. Fig 4.20 plotted for air velocity against output voltage of generator. That clearly indicates when more air or gas passes through turbine of the plant, the generation of power increases. Fig 4.21 also same and shows same results whence the volume of air flow rate is considered instead of the velocity. During that period temperature of air flow is kept constant.

Fig 4.20 plotted for constant air flow rate and variable temperature. Temperature of air volume changed using heat exchanger of the power plant.

That shows, the air volume absorbs the heat and it expands and there by the speed of air flow increases. Due to increased air velocity again boost the output voltage level. If refrigerant gas was used instead of natural air the efficiency will increase and output will take a higher value.

### 4.3.3 POWER PLANTS PRESENTLY SUITABLE FOR SRI LANKA

The most suitable power plants for Sri Lanka are binary power plants. Reason is temperatures of hot springs are lower, normally resource having less than 150 $^{0}$C are categorize for binary plants.

According to [30] that temperatures of all geothermal reservoirs identified was showing less than 150 $^{0}$C temperature. The Fig 4.22 shows graphical representation of the underground reservoirs and their temperatures.

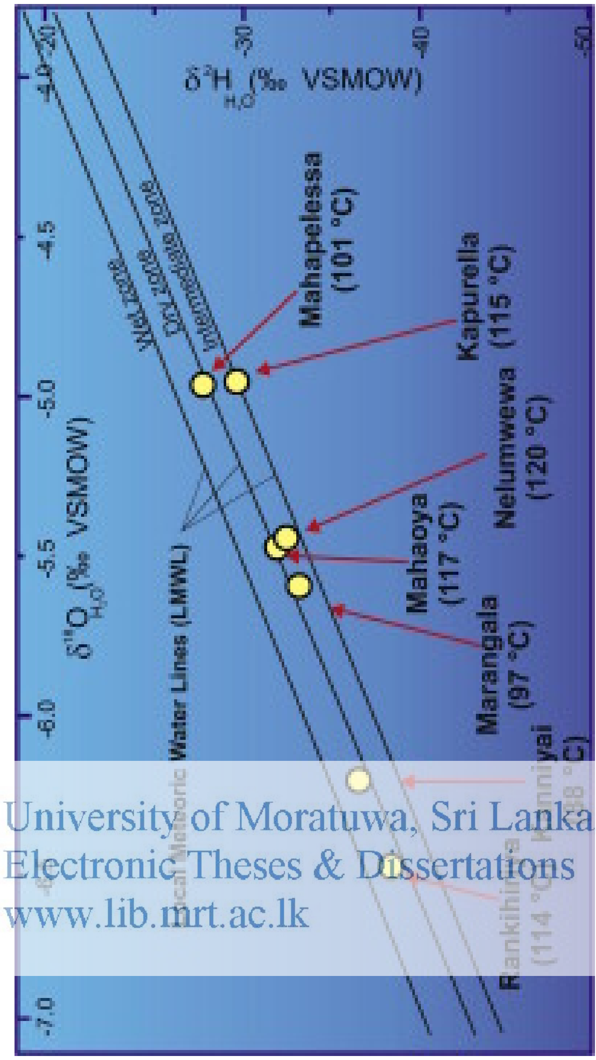


Fig 4.22 Isotope compositions and reservoir temperature [30]

[30] studied geochemical and an isotope composition of geothermal and natural springs.

According to previous studies, Geo thermometric calculation indicated mean reservoir temperatures of about 120 °C. Hot water springs are recharged by local meteoric rain. During subsurface circulations, water is heated by a steep geothermal gradient.

The actual underground reservoir temperatures and water temperatures of hot springs are listed in the below given Table.4.7. Theoretical efficiency of the system increases.

| Temperature of water $^{0}$C | 87 | 90 | 95 | 100 | 105 | 110 | 115 | 120 |
|---|---|---|---|---|---|---|---|---|
| Required water flow rate L/min | 1.9 | 1.7 | 1.6 | 1.36 | 1.27 | 1.22 | 0.92 | 0.85 |

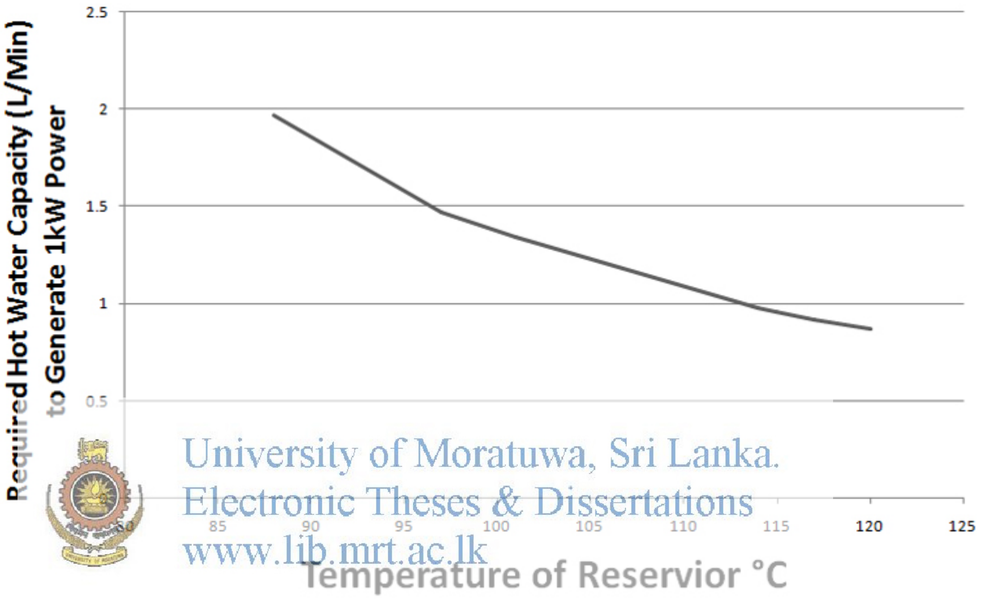


Fig 4.23 Variation of water volume with temperature.

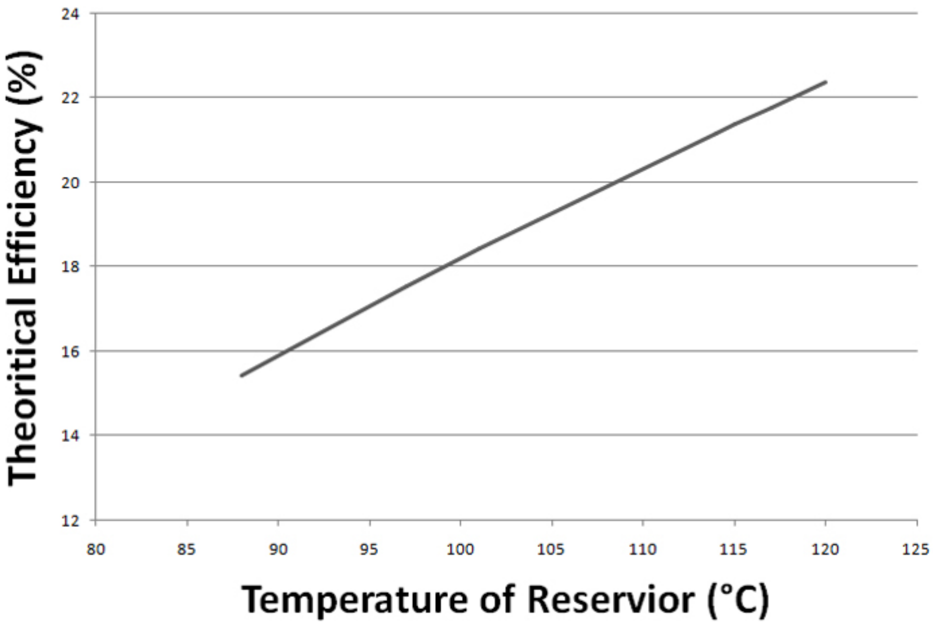


Fig 4.24 Variation of theoretical efficiency with reservoir temperature,

(Related to Table 4.7)

Table 4.10 Testing plant output power.

| **No.** | **Water Temperature, $^0$C** | **Generated voltage, Volts** | **Current drain to the load, Amperes** | **Power generated, Watts** |
|---|---|---|---|---|
| 1 | 40 | 5.50 | 0.46 | 2.54 |
| 2 | 50 | 6.38 | 0.53 | 3.37 |
| 3 | 55 | 7.50 | 0.62 | 4.60 |
| 4 | 60 | 8.00 | 0.66 | 5.22 |
| 5 | 70 | 8.5 | 0.70 | 5.87 |
| 6 | 80 | 8.85 | 0.73 | 6.40 |

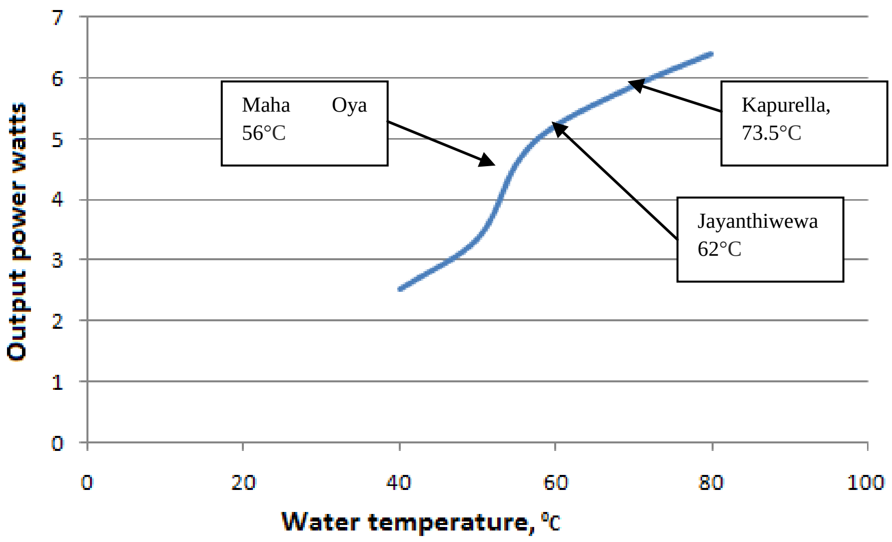


Figure 4.25 Temperature/ Output power of developed plant.

The developed power plant connected to the 12 Ohms pure resistive load and measured the output voltage of the generator for different temperatures. The collected data plotted and it is shown in Fig. 4.25. According that graph, possible to mark places for kapurella, Nelumwewa and Mahaoya as shown.

### 4.3.4 FLUIDS FOR BINARY PLANTS

Principles behind binary plants are refrigeration reverse cycle. There are several types of binary plants, ie Ideal binary, Dual pressure binary, Dual fluid binary and Kalina binary plants. Due to low temperature of hot water springs, refrigerant having low boiling temperature is being used in this instant.

Generally there are a number of refrigerants, ie, Propane, Butane, Pentane, Ammonia and water [10]. Applicable for Temperatures of hot springs which are less than 100 °C, therefore not possible to use water, but for these plants other fluids are properly selected. [99] Studied about their properties and found that ammonia is the better fluid for binary cycle geothermal plants.

The underground reservoirs have less than 150 °C and more than 100 °C brine. For those places, water could be used as possible fluid. At those temperatures water boils and makes steam that can be used for running turbine and generates power.

## 4.4 GEOTHERMAL MAP

Table 4.11 Geothermal map data

| No | Location | Water flow rate L/Min | Water temperature $^0$C | Reservoir temperature $^0$C | Geothermal gradient $^0$C/ |
|---|---|---|---|---|---|
| 1 | Bogala | - | - | - | 28.046 |
| 2 | Kanniya | 10.8 | 42 | 88 | - |
| 3 | Kapurella | 10 | 73.5 | 115 | - |
| 4 | Maha Oya | 10 | 56 | 117 | - |
| 5 | Mahapelessa | 5.0 | 46 | 101 | - |
| 6 | Nelum Wewa | 10 | 62 | 120 | - |

Most of the hot springs in Sri Lanka located in between, two circles marked in the below given Fig 3.39. The minimum radius 124 km and maximum radius 197 km.

Geothermal maps contain existing and developing geothermal power plants, geothermal resource potential estimates, and other information related to geothermal power.

They are updated as information becomes available, but may not represent all available geothermal data. These maps are useful for Researchers, Consultants, Decision makers, Geologists, Academics etc, interested in assessing the geothermal potential at any location in Sri Lanka.

These maps present the following data,
Sub surface temperatures at depths of 100, 500,1 km, 2.5 km, 5.0 km,
Modeled surface temperatures at 100, 500,1 km, 2.5 km, 5.0 km depths,
Geological regions and rock types etc.
Temperature gradient of Bogala area. Other springs water temperature / reservoir temperature are given in the below given map..

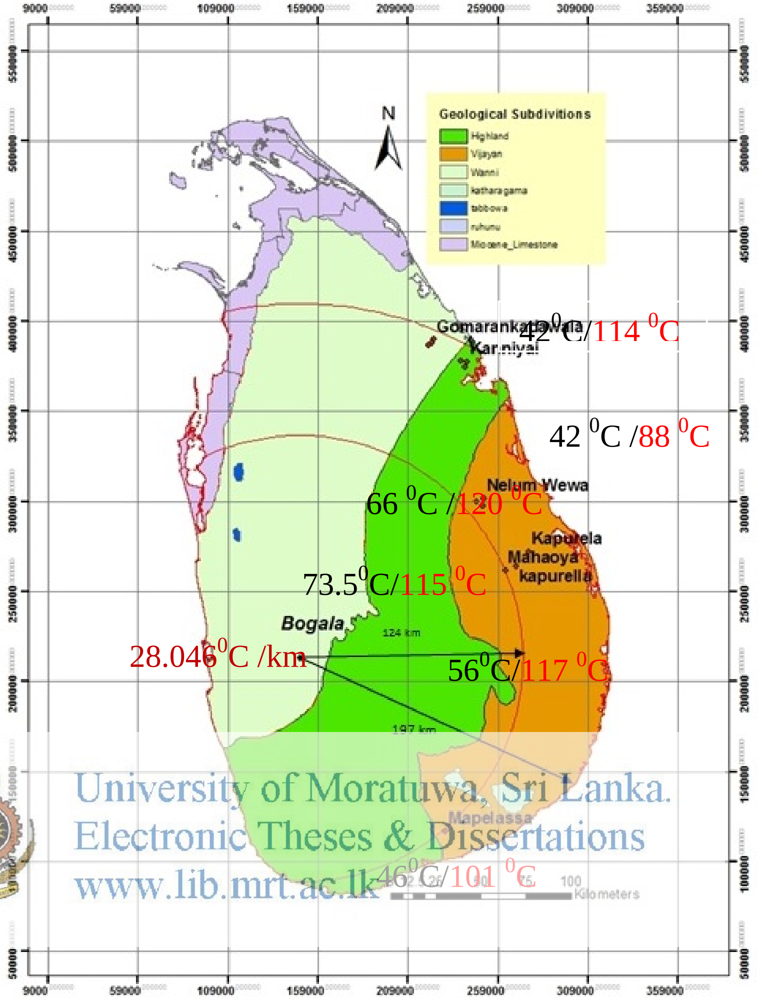


Fig. 4.25 Locations of some hot water springs.

# CHAPTER 5

## 5.1 CONCLUSION

Many countries located around Sri Lanka, ie Indonesia, India, Pakistan and Bangladesh have high and good geothermal potentials. Indonesia is located on Ring of Fire, which shows highest geothermal areas. Sri Lanka is in 1600 km away from the Ring of Fire. Therefore, this country should have better geothermal potential.

There are many methods, used by scientists to determine geothermal potential of selected area. For this study initially two methods selected and considering practical difficulties and limitations in equipment, arose during the research work the geophysical method, ie resistivity survey was dropped.

Geothermal Researchers and Scientists in the world use the abandoned oil well to find out geothermal gradient in surrounding areas. For this research, temperature logging practiced by using abandoned graphite mines leading to reach the goal successfully. After deep studying abandoned non ventilated tunnels and adits of Bogala graphite mines selected to establish geothermal gradient of Bogala area Sri Lanka. The calculated geothermal gradient is 28.046 $^{0}$C/ km.

Nine hot springs spread along the boundary between Highland complex and Vijayan complex, identified. They are Kapurella, Maha Oya, Marangala, Mahapelessa, Meda Wewa, Nelum Wewa, Kanniya, Kiwulegama and Rathkihiriya. After considering temperatures of discharging hot water, theoretical efficiencies and their hot water flow rates, Kapurella, Maha Oya, Mhapelessa, Meda Wewa and Nelum Wewa areas selected to set up geothermal plants to generate electricity. All of the above given selected hot wells have shown more than 4% theoretical efficiencies.

Laboratory model power plant developed and tested for various conditions such as constant temperature, variable flow rate and constant flow rate, variable temperature. One of the major requirements to run a practical power plant is to avail a high hot water flow rate. Also the higher temperature of hot spring water is also one of the essential factors. Estimated the heat and power generation capacity of geothermal hot springs to find out potential for power generation.

Laboratory model power plant used to check its performance by setting water temperatures to different levels identical to the water temperatures of selected hot springs. This process clearly proved the ability of power generation. The calculated values of power levels by using flow rates and temperatures of indicated remarkable figures.

According to collected data and calculations hot springs in Kapurella and Nelumwewa are most suitable to generate geothermal power. Both of them can generate 13 kW and 7 kW power respectively. If we use hot dry rock system possible to locate power plants in any place of the Island.

Considerable quantity of most required data to start preparing geothermal mapping in Sri Lanka was gathered. The initial map prepared with available data but may not represent all geothermal data. This consists of much information about geothermal related activities. They are updated as information becomes available.

The geothermal gradient of Bogala area, temperatures of hot springs and temperatures of hot water in underground reservoirs will be helpful for future research work. This map is useful for Researchers, Consultants, Decision makers, Geologists, Academics etc, interested in assessing the geothermal potential at any location in Sri Lanka. This information is adequate to do further studies of geothermal potential and develop commercial level power plant.

Bore hole logging is another famous method use to determine geothermal gradient. The drilling depth varies from place to place. But, geothermal experts say that 100 m to 300 m depth is good enough to compute geothermal temperature gradient of respective areas.

By considering practical difficulties in geophysical methods, non availability of expensive equipment to conduct geochemical investigations, the borehole logging suggest as better method for Sri Lanka.

## 5.2 FUTURE GEOTHERMAL RESOURCES.

### 5.2.1 HOT DRY ROCK GEOTHERMAL RESOURCES

Hot dry rock geothermal power is a specific type of geothermal power. Geothermal power generation depends on capturing the heat produced naturally by the earth and transforming it into a more useful form of energy. In the case of hot rock geothermal power generation, that more useful form of energy is steam. To approach generating the steam that is needed, boreholes are drilled into the earth to gain access to hot rocks below. Water is then fed into these boreholes and comes into direct contact with the hot rocks. Contact between water and the hot rocks produce high pressure steam. This steam is returned to the surface to be utilized in a steam turbine as one of the cleanest forms of power production known to date.

This form of power generation has the potential to be very beneficial for several different reasons. When a hot dry rock geothermal power plant is operating at a steady state there are virtually no emissions. No adverse elements are returned to the environment aside from a small amount of waste heat. The emissions of dry rock geothermal power are negligible when compared to, for example, the thousands of tons of sulfur dioxide and millions of tons of carbon dioxide released into the environment by coal power plants. Another advantage of this form of power production is that it is a very sustainable process. Hot water used in the process of power generation can be re-introduced into the boreholes to produce more steam. These qualities allow hot dry rock geothermal power generation to easily adhere to the demands of a world yearning for a greener future. Lastly, there is the matter of location convenience.

A hot dry rock geothermal power plant can be located anywhere that it is possible to access hot rock within the earth by drilling.

This allows for large freedom of choice with regards to location and may even allow for more power production in areas where it is inconvenient for other methods to be implemented. An example schematic of a HDR plant is shown in Fig 5.1. [98]

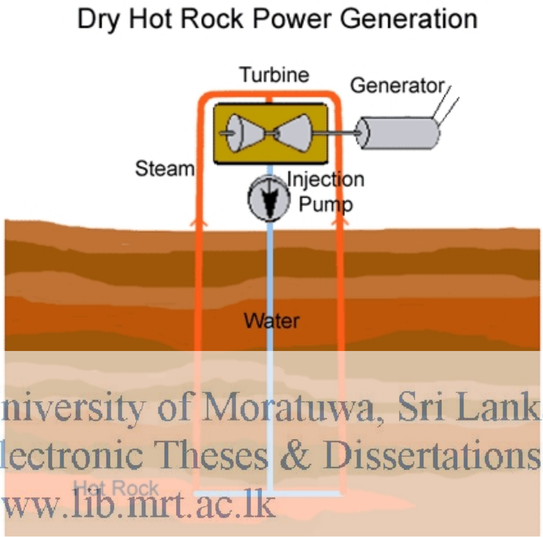


Fig 5.1 Hot dry rock geothermal power generation [99]

### 5.2.2 MAGMA GEOTHERMAL ENERGY

This has been called the ultimate energy source. A magma power plant would use a process similar to hot dry rock—water would be injected directly into the magma, cooling and hardening the rock around the well. The resulting steam would be pumped out through a pipe in the well.

Scientists in Iceland have been studying and utilizing the power of geothermal wells for years. In 2009 one such study hit a standstill when a group ran into magma halfway into their dig. The roadblock has become a blessing in disguise, and research has shown that the magma can act as a potent new source of geothermal energy powerful enough to heat 25,000 to 30,000 homes.

When drilling for the government-sponsored Iceland Deep Drilling Project, a team of scientists hit magma about 7,000 feet into the planned 15,000 feet. The project was initially testing the power of supercritical water (very hot water under a high pressure), but the project had to be abandoned because of the magma flow.

Iceland has taken advantage of the power of their local geothermal wells, sourcing nearly all of their home heating and one-third of their electricity from them. Each geothermal well can generate up to five to eight megawatts of electricity, but this magma fluke has shown a production of up to five times that. The magma well produces dry steam at 750 degrees Fahrenheit, which can generate about 25 megawatts of electricity.

Fig 5.2 Lori Zimmer, Iceland May Tap Liquid Magma as New Geothermal Energy Source [100]

### 5.2.3 GEO PRESSURIZED RESOURCES

They are deep reservoirs of high-pressured hot water that contain dissolved natural gas. A geo pressurized reservoir is formed in sedimentary formations when water percolates into the pores of a layer of sand.

When non-porous shale settles on top, it traps the fluid into the sand layer at very high pressures. Over millions of years, this pressure increases even moreas additional sedimentary layers build on top of the reservoir. If the sand body in which the water is trapped is large enough, the reservoir can economically produce energy for quite a long time.

An important characteristic of geo pressurized reservoirs, at least from an energy perspective, is that they contain dissolved methane, or natural gas. This, therefore, yields three sources of energy that can be utilized from the reservoir.[101]

1. Hydraulic energy from extreme pressure.

2. Heat energy from the fluid.

3. Dissolved natural gas.

Comparing to other natural gas reservoirs, the amount of dissolved methane in these types of reservoirs is very small. For the natural gas alone, the reservoir would be uneconomical. However, with two more sources of energy, their utilization becomes worthwhile.

Development activities are currently in progress to utilize the thermal and hydraulic energy available in geo pressured-geothermal resources for a variety of direct uses. The higher pressure and temperature found in geo pressured resources create the opportunity for many new applications.[102].

## 5.3 FURTHER DEVELOPMENT

Most of the locations spring water temperature is low, also discharged water volume is less. Suitable step has to be taken to improve both of them to improve the power capacity. Most of the hot water springs are located in dry zone. Those areas they have enough sun shine. Long duration of a year these places have dry and hot weather. Therefore, I suggest to further heat the water volume taken from well by using solar in day time. That will help to improve the efficiency of the plant as well as the generated power volume can be taken to higher level than now.

Second solution is to further heat that hot water by using rice husk. The said bio mass is mostly available in those areas, and they use this for few works, ie for poultry farming etc. They can be used to even for generating highly pressurized steam. After conducting deep study about solar radiation and capacity of non used rice husk in the respective area, the water volume used, expected efficiency considering plant parameters, the overall efficiency of the plant may be improved by considerable level.

# CHAPTER 6

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