POLITECNICO DI TORINO

Department of Environment, Land and Infrastructure Engineering

Master of Science in Petroleum Engineering

MASTER THESIS

GEOTHERMAL ENERGY AND POWER PLANTS: A BRIEF COMPARISON OF GEOTHERMAL POTENTIAL IN PAKISTAN AND ITALY

Supervisor:

Prof. STEFANO LO RUSSO

Student:

AKASH PALH
S224957

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I ABSTRACT

Use of Geothermal energy has been around with us over the centuries, with its uses ranging from bathing from the hot springs and space heating in ancient times. Generally, regarding the power production more focus had been given on fossil fuels and their usage has been somewhat extensive resulting in the exhaustion of such resources in many parts of the World, resulting in the debate for renewables to take over.

Renewables are still way behind when it comes to electricity generation, but they are gaining ground and many countries like Sweden, Scotland, USA, and even China (although the largest emitter of Greenhouse Gases) are adopting and even currently amending their energy policies in favor of renewable energy.

Geothermal energy, like the other sources of renewable energy is fast growing due to its positive results wherever it has been exploited for power production and direct uses. Being sustainable and acclaimed mostly as environmental friendly, Geothermal energy is a thing of today and future. Countries like USA, Iceland, Indonesia, Italy (first ever geothermal plant was set up in Larderello) and more recently Philippines and Turkey have taken major steps to produce cheap and sustainable energy (electricity and heating). Due to the effective exploration, production from innovative power plants and devising positive industrial incentives and policies, these countries are truly benefitting from this wonderful natural resource. The steps for exploration strategies, drilling of geothermal wells and geothermal power plants have been discussed in this work.

Pakistan, like many other developing countries is in energy deficiency from a long time and a talk of energy crisis is spreading in Government circle. This energy deficiency is majorly due to the country's extensive use of fossil fuels that are mainly imported (although the country also uses its own resources for thermal power plants). Pakistan has every sign to become an energy sufficient country considering its vast potential in Geothermal resources that are yet to be exploited. In this work preliminary study is presented which points to the potential geothermal areas. To exploit geothermal energy, the Government has yet to take a major step to devise a strategy and policy that will help major companies to invest and motivate institutions for more research concerning it. A brief review has been given regarding Pakistan's Geography, Geology and Tectonic buildup of the country.

Italy is the 4th largest economy in Europe. As per "Energy from Renewable Sources in Italy – 2015", on the Italian energy landscape, renewables play an important role. Renewables are extensively used for electricity production (Electric sector) and heat production (Thermal sector). although hydrocarbons, natural gas, remains the major contributor for electricity generation in Italy, in 2015 renewable sources contributed to almost 38.5% to total gross national electricity production. The average contribution of the geothermal power to the total electricity produced (from all the sources) in Italy, has been almost constant at 1.6-2% during its timespan. in 2015, from all the renewable sources, geothermal power contributed to 5.6% of the electricity produced and 1.8% of the national production of electricity. All the 34 installations found in Italy are concentrated in Tuscany. In 2015, 6.185 GWh of electricity was produced at these installations. Italian Government in 2013, took a major step by announcing an "incentive fee" which will encourage the companies to invest and acquire more leases.

Even though geothermal extraction is an important resource, it is not devoid of some environmental impacts caused by: gas is released to the atmosphere, chemicals contaminate watercourses and seas, and moreover it produces noise and it increases the seismic risk. But these environmental risks are minimum or either negligible when compared to other resources like fossil fuels. Greenhouse gases, known as GHGs are naturally present in the geothermal resources and they are usually emitted by intermediate and high temperature fluids. They are released in the atmosphere without drilling or power production and this is probably the reason why they are not so concentrated in the outflows than the traditional fossil supply power generation units. Special regulations are devised by various countries regarding these emissions.

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III DEDICATION

I would like to dedicate my thesis to my late lovely Mother, who was and is an absolute motivation for me. I would also dedicate this work to my Father and my Brother whom I hold close to my heart. This work is for You!

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VII List of abbreviations

BCV Ball check valve

C Condenser

CP Condensate pump

CS Cyclone separator

CSV Control & stop valves

CT Cooling tower

CW Cooling water

CWP Cooling water pump

IW Injection well

MR Moisture remover

PH Power house

PW Production well

S Silencer

SE/C Steam ejector/condenser

SP Steam piping

SR Steam receiver

T/G Turbine/generator

WP Water (brine) piping

WV Wellhead valve

F Flasher

G Generator

HPT High pressure turbine

LPT Low pressure turbine

TV Throttle valve

PR Particulate remover

ACC Air cooled condenser

FF Final filter

HPE High pressure evaporator

HPFP High pressure feed pump

HPPH High pressure pre-heater

LPE Low pressure evaporator

LPFP Low pressure feed pump

LPPH Low pressure pre-heater

M Make up water

P Pump

PH Pre-heater (Binary power plants)

RH Re-heater

RPH Recuperative pre-heater

S Separator (Binary power plants)

SH Super heater

SR Sand remover (Binary power plants)

1. WHAT IS GEOTHERMAL ENERGY?

1.1 The Origin of Geothermal Concept "The Continental Drift theory"

In 1915, in his book *The Origins of Continents and Oceans,* A.L. Wegener conceptualized the theory of continental drift. Albeit Wegener endeavored to clarify said theory in the later editions of his book, it was still highly contentious. The continental drift theory was devised after his scrutiny that the continents of South America and Africa were global pieces of a jig-saw puzzle that had been sundered. He propounded that all masses of land were once connected and formed a supercontinent delineated as "Pangaea". (DiPippo, 2013) According to Wegener, the formerly-connected continents were separated and repositioned through highly viscous sea floor, which was later proven to be a flawed theory. However, his fundamental notion of drifting contents was correct.

Later studies in the 1950s and 1960s revealed that the ages of rocks found along the Northeastern Coastal South America and Northwestern Africa were a match; the rocks were corresponded. Further oceanic research down the line indicated that new land was being formed on both sides of mid-Atlantic ridge by means of sea-floor spreading. By taking the aforementioned data into consideration, the motion of plates comprising the Earth's crust was proven by scientists. Continents are part of the earth's crust and since the dawn of time billions of years ago, they have been constantly and perennially drifting.

1.2 Plate Tectonics

The earth's crust is sundered into pieces limned as tectonic plates. Under compression, the plates can alleviate the stress by folding; thrusting and fracturing one piece atop the other; trenching and fracturing underneath the following; and finally, through thickening. Trenching –subduction– is considered as one of the most extensive mechanisms that causes geothermal regions of high temperature. On the other hand, a plate subjected to tension can mitigate the stress by rifting and fracturing; down-dropping through fracturing in various places; and finally, via thinning. Furthermore, there is a phenomenon known as "transform fault" in which two plates may slide past each other. (DiPippo, 2013) The most notorious quintessence of this is the San Andreas Fault. Whilst this fault and other transform faults have led to immense financial loss and casualties from multitude earthquakes, they have, as well, given rise to many lucrative geothermal resources. The plate boundaries interact in various ways as shown in fig1.1.

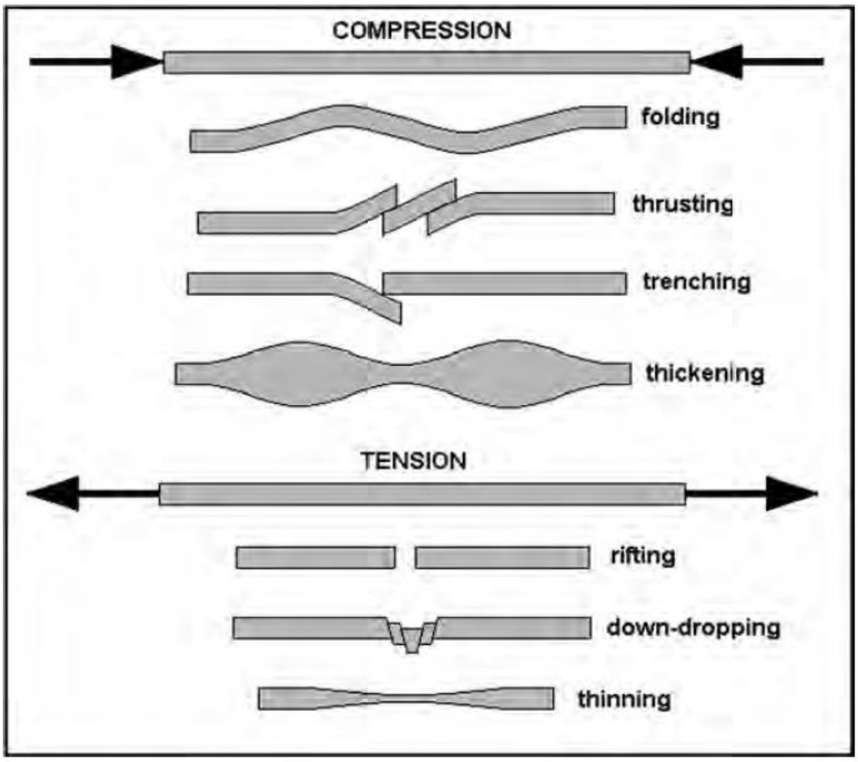

Figure 1-1 plates responding under compression and tension

From Geothermal energy exploitation point of view, the most prominent of such interactions transpire along the Pacific plate edges depicted as “Pacific Ring of Fire”. If we are to add the Cocos and the Nazca plates, which are adjacent to the Pacific plate and the Philippine plate which is located in the west, then there are around 21 countries –clockwise order– from North America (USA, Mexico, Guatemala, etc.), South America (Colombia, Ecuador, Peru, etc.), Oceania (New Zealand, Micronesia, etc.), and eastern Asia (Indonesia, China, Japan, and Russia) which are affected. There are exploitable geothermal resources in the aforementioned countries, and more than half of these countries have operational power plants. Generally, every land mass in contiguity with the Cocos, Nazca, and Pacific plates have subduction zone beneath them, except for Mexico and the United States where a transform boundary is present.

The Azores and Iceland are noted for being two volcanic islands that lie on the rift zone of the mid-Atlantic ridge where the geothermal resources have been used for many years. Other zones such as the Himalayan belt, Mediterranean, and the East African rift zone offer a prospect for geothermal power and are being exploited (DiPippo, 2013)

1.3 The Basic Concept of Geothermal Energy

The word geothermal is derived from two Greek words, the first being “GEO” which means earth, whilst the second is “THERM” which means heat. Near the edges of the previously mentioned tectonic plates, magma comes closer to the earth’s surface where many volcanoes exist, and heat is absorbed by the rocks from magma deep underground. Internal thermal energy flows by means of conduction at a rate of 44.2 terawatts (TW) to the surface, and its recharge rate is 30 TW which is done through the radioactive decay of minerals. The majority of this energy flow cannot be recovered, albeit such power rates are extremely high that they are more than twofold the current energy consumption of mankind from all primary sources combined. Sometimes rain water also percolates down through the cracks and geological faults; causing it to become superheated by the hot rocks underneath. Hot springs and geysers are formed due to the gush of the superheated water back to the earth's surface. Oftentimes, however, said hot water gets trapped beneath the surface and turns into a geothermal reservoir. (US department of Energy website, n.d.) Additionally, wells that reach a depth of mile or more are subsequently drilled into the reservoirs underground to broach steam and hot water to be used for an array of applications, such as direct use, cooling/heating, and generation of electricity.

The earth has various different layers:

- The inner core, which is solid iron and at approximately 6000 kilometers, is surrounded by an outer core. Temperatures are known to be at least 5000 °C.
- The mantle, which has a thickness of about 2,800 kilometers and surrounds the core. The outer layers of mantle are heated by conduction from earth's internal heat. Consequently, such kind of rock becomes molten and turns into magma (Technology student website, n.d.).
- The outermost layer of the earth is called the crust. Continents and ocean floors are formed by the crust. The crust's thickness under the oceans is approximately 5 to 8 kilometers and 24 to 56 kilometers on the continents.

The geothermal gradient through the crust is 25–30 °C/kilometer or 2.5-3°C/100m of depth in most parts. The thermal gradient of propitious geothermal prospects is several times greater than the usual. In non-thermal areas, the normal heat flux is about 1.2x10-6 cal/cm^{2}s. This value has a proclivity of being much higher close to tectonic plate ambits where the crust is thinner (Wikipedia, n.d.).

1.4 Heat Flow

Heat flow is described as the motion of heat from the earth's interior towards the surface. The majority of this heat stems from the heat generated by radioactive elements in the upper part of the earth's crust and the cooling of the earth's core. Heat generated by radioactivity is a product of an agglomeration of high concentrated radioactive elements, such as thorium (Th), potassium (K), and uranium (U). Areas with the properties of high radioactivity or thin crust usually have high heat values. Moreover, some areas have heat flow anomalies; higher than average heat flow values sans a clear radioactive or tectonic interpretation, which is mostly associated with fluid flow. Table 1.1 lists the rock types and their radioactive components.

Rock	Concentration			Heat generation, 10^{-6} cal/g·yr		
	U, ppm	Th, ppm	K, %	U	Th	K
Granite	4.7	20	3.4	3.4	4.0	0.9
Basalt	0.6	2.7	0.8	0.44	0.54	0.23
Peridotite	0.016	0.004	0.0012	0.012	0.001	0.0003

Table 1-1 Radioactive elements in some common rocks forming Earth's crust

The heat flow, which has the unit of milli-Watts per meter squared (mW/m^2), can be calculated by multiplying the temperature gradient with the thermal conductivity of the rock. For simplicity, imagine a 1x1 flat plane, the energy amount transferred through said plane is The heat flow (see Geophysical survey)

The value of thermal conductivity can be devised utilizing a device –usually a divided bar or needle probe– which measures the amount of energy that can be transferred by a rock sample. The thermal conductivity units are in Watts per meter Kelvin (W/mk). The inclusion of Kelvin in the unit is a result of the dependency of the thermal conductivity values of a rock on temperature values (DiPippo, 2013).

The determination of the temperature gradient of earth at a certain site is achieved by measuring the temperature in a well at particular depths. The units used are °C/km or °C/100m (see Geophysical survey). If the measurements are taken in the instant where the well is not influenced by the drilling fluid, it can be said it is at equilibrium. The following are the highest quality values and comprehend a set of data that helps in identifying the alterations in the earth's structure (Southern Methodist University Website, n.d.).

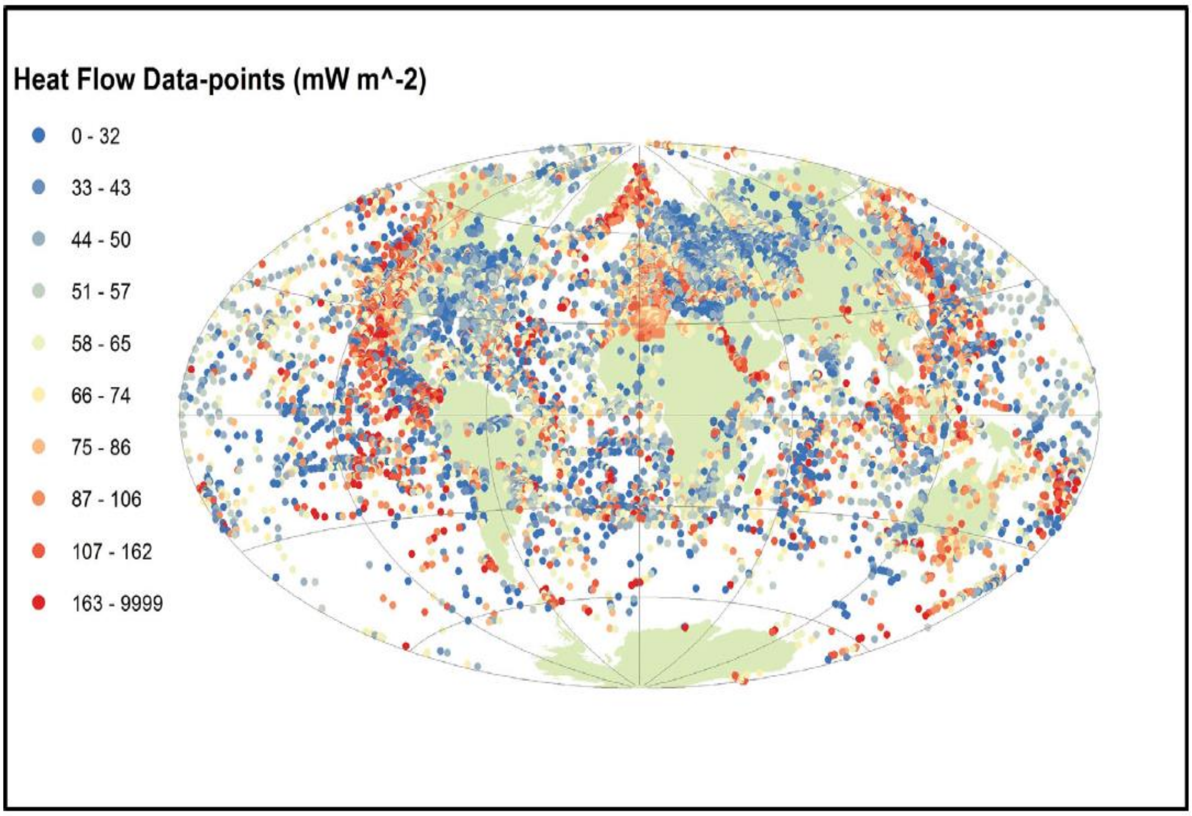

Figure 1-2 Map of heat flow measurement points

2. TYPES OF GEOTHERMAL ENERGY

2.1 Hydrothermal Resources

Fluid, heat, and permeability are essential for a geothermal resource to generate electricity. Conventional hydrothermal resources contain all these three elements naturally (US department of Energy website, n.d.).

These geothermal reservoirs consisting of hot water or steam are normally found where magma comes near the surface where it heats the ground water confined in fractured or permeable rocks. Hydrothermal systems are formed in widely diverse geologic settings, sometimes lacking clear surface manifestations. Hydrothermal resources can be exploited depending on their depth and temperature for several energy purposes.

2.1.1 Low Temperature: "Direct Use" or Heating

Hydrothermal resource with a temperature around 10°C and above can be utilized to heat buildings, warm fish ponds, grow crops, etc (University of Colorado Boulder web site, n.d.).

2.1.2 High Temperature: Producing Electricity

Hydrothermal resource with temperatures around 100°C and above can be utilized for electricity generation. The majority of geothermal resources that produce electricity have temperatures ranging from 150 up to 370°C, sometimes geothermal reservoirs can go as high as 500°C and above (University of Colorado Boulder web site, n.d.).

Hydrothermal resources used to generate electricity are of two types:

- Liquid-dominated hot water reservoirs.
- Vapor-dominated dry steam reservoirs.

Dry steam reservoirs are uncommon; however, they are extremely efficient when it comes to electricity production. The Geysers in California is the largest dry steam reservoir where steam is obtained by drilling almost 2000 to 3000 meters deep wells. For electricity generation, geothermal well produces natural steam to power a turbine generator. Subsequently, to perpetuate water and pressure levels, condensed water is used in the cooling system of the plant and is injected back into the reservoir.

Hot water reservoirs –amongst the hydrothermal reservoirs– are the most common. In such systems, as a result of the hot water not being vaporized into steam, the reservoir is usually under pressure and saturated with water. To generate electricity, geothermal wells produce hot water, which is then fed to separators where, with lowering pressure, the water flashes into steam. Afterwards, a turbine generator is derived by the steam; to produce electricity. Condensed steam thereupon is used in the cooling system of the plant and is injected back to the reservoir.

2.2 Low-Temperature & Coproduced Resources

Low-Temperature

These resources are considered as non-conventional hydrothermal resources. The heat acquired at temperatures less than 150°C from a geothermal fluid is used typically in direct-use applications, which include but not limited to mineral recovery, greenhouses, industrial process heating, and district heating. Nonetheless, using binary cycle technology, some resources with low temperature can be broached for generating electricity, in which heat is transferred from geothermal fluid –usually water– to another fluid –butane or iso-pentane– which, compared to water, is vaporized at higher pressure and lower temperature. Eventually, the vapor generated from this process is used to drive a turbine to produce electricity. This process can be described as a closed-loop system with nigh negligible emissions. (Low Temperature and Co-produced resources, February 2016)

Co-produced

On average, 25 billion barrels of hot water are produced every year from gas and oil wells solely in the United States. In the past, the disposal of hot water was an inconvenience for it was costly. Owing to the advancement of technology, hot water is now considered as a potential resource that can be sold to the grid or used for producing electricity for field operations. Not only can co-produced geothermal resources prolong the economic life of oil and gas fields due to having minimal greenhouse gas emissions, but also can be exploited to profit from abandoned oil and gas fields' infrastructure. (Low Temperature and Co-produced resources, February 2016)

2.3 ENHANCED GEOTHERMAL SYSTEM (EGS)

Three key elements outline a natural geothermal system (hydrothermal system): heat, fluid, and permeability. An Engineered Geothermal System (EGS), also known as Enhanced Geothermal System, is a man-made reservoir, developed in the existence of a hot rock. Nonetheless, the natural permeability and fluid saturation of the reservoir are inadequate. In an EGS, under controlled conditions, the subsurface is injected with high pressure with fluid; ergo ameliorating permeability by re-opening the pre-existing fractures.

Fluid can circulate throughout the fractured –rock thanks to this improved permeability– as well as transporting heat to the surface, where it is utilized for electricity generation. Although still under development, EGS has been carried out successfully on a small scale in the United States and Europe.

A major issue discussed recently in various studies was that rocks may slip along pre-existing fractures during EGS reservoir formation and contribute to micro seismic events. According to researchers, these micro seismic events, also known as induced seismicity, is a very effective tool for diagnosing and accurately determining the direction and position of re-opened or created fractures, therefore helping us to characterize the ambit of a reservoir. In almost every case, these events are not felt at the surface; for having a very low magnitude because they occur in deep reservoirs. (Enhanced Geothermal System (EGS) Fact Sheet US department of Energy, May 2016)

2.3.1 Process

Injection Well

Drilling of a production-injection well into hot basement rock with trammeled permeability and fluid saturation.

Injecting Water

Injection of water at an adequately high pressure for fracturing, or re-opening existing fractures within the hot basement rock and reservoir.

Hydro-fracture

Continuous water pumping to increase the distance of fractures from the injection well and throughout hot basement rock and reservoir.

Doublet

Drilling of a second production well to intersect the stimulated fracture network formed in the aforementioned step, and then extracting the heat from the previously dry rock through water circulation.

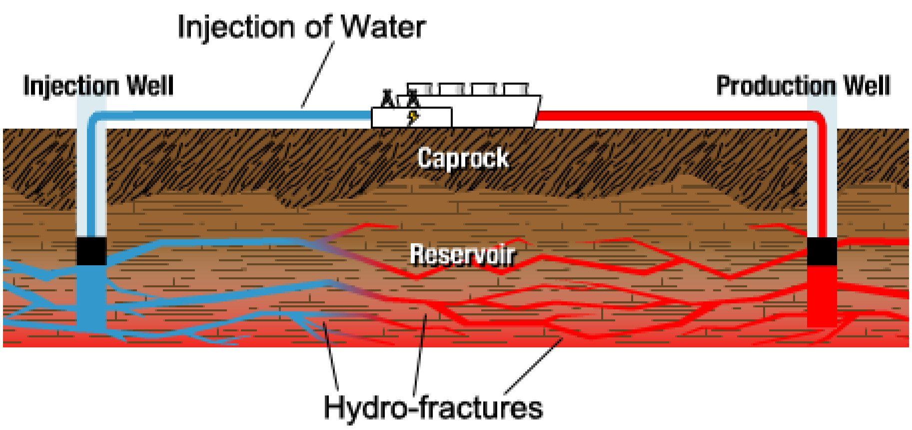

Figure 2-1 shows the injection well, Injection of water, fracture network and a production well

Multiple Wells

Drilling of multiple production-injection wells in order to extract heat in large volumes; to meet the requirements of power generation.

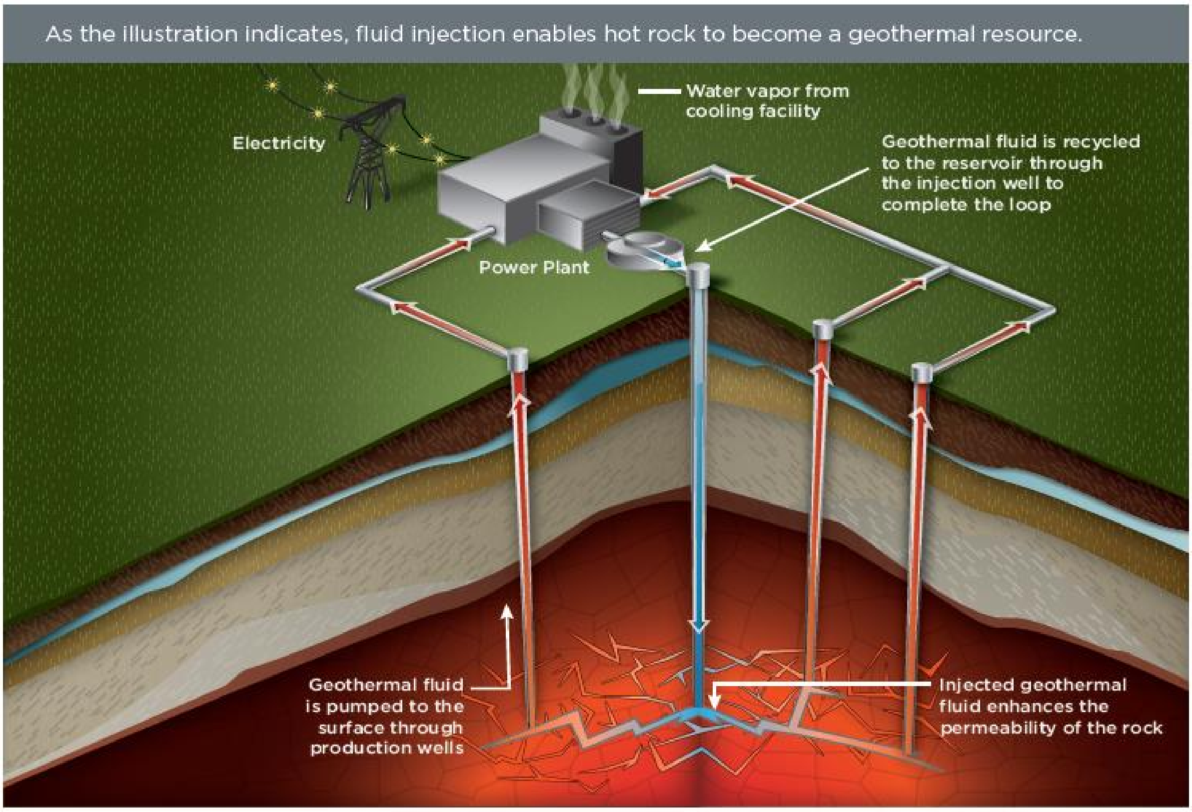

Figure 2-2 Enhanced Geothermal System. (US department of Energy website, n.d.)

2.4 GEO PRESSURIZED Geothermal resources

Geopressured resources typically have a temperature ranging from 90°C to 200°C. Being highly pressured requires less energy to pump the resource, making geopressured resources attractive. Reservoir brines of certain sedimentary basins contain geopressured geothermal energy and should have a clear distinction from the geothermal energy that is usually correlated with volcanic –igneous– formations. (OpenEI organization, n.d.)

Geopressured geothermal resources are formed when, between shale formations, the reservoir waters are confined within lenticular sedimentary bodies, and are hydrologically secluded by rapid burial and subsidence. Reservoir waters are heated and over pressurized due to the rapid compaction, entrapment and thermal expansion of excess water. Fig 2.2 shows a simplified Cross-section of a geopressured reservoir

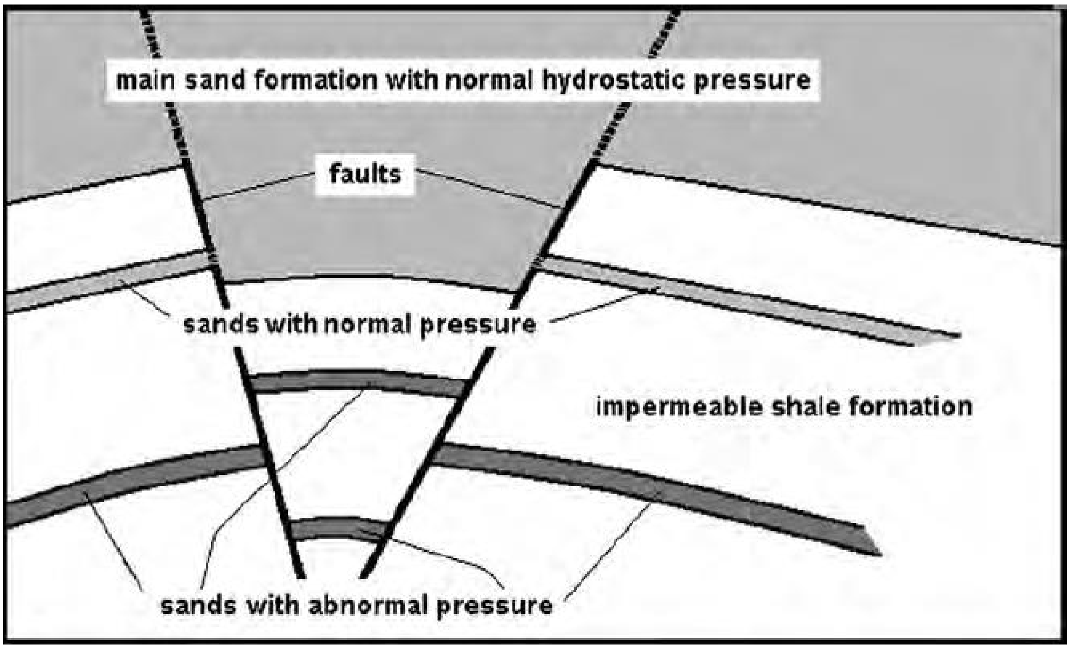

Figure 2-3 cross-section schematic of a geopressured reservoir.

The characteristics of geopressured geothermal reservoirs include relatively high temperature and pressure gradients. The pressure gradient of said formations usually approaches that of lithostatic (~1 psi/ft), close to the overburden rock effective pressure, in contrast to a typical hydrostatic gradient (~0.465 psi/ft) close to a ground-water column effective pressure. The pressure gradient exceeds lithostatic in some geopressured geothermal reservoirs (for example "superpressured" systems in California), owing to tectonic stresses. Notwithstanding, compared to the geopressured regions formed by shale dewatering or rapid compaction, such tectonically-aided geopressured reservoirs may not proffer a high temperature gradient. Usually in a geopressured geothermal reservoir, the brines, which can be produced at high flow rates through well-bores, are entrained with natural gas. (Nitschke, 2006)

The criteria that must be fulfilled prior to developing geopressured reservoirs commercially include:

- Is the fluid adequately hot? For example, the temperature is >230C?
- Is the pressurized sand adequately permeable?
- Is the pressurized sand amply thick?
- Is the methane dissolved in the fluid sufficient?
- Is the formation of sand bordered by a fault(s) yet not too fractured?
- Can we ensure that there will be no subsidence?

For a geopressured geothermal project to be economically viable a "yes" answer is required to all the above queries.

3. EXPLORATION TECHNIQUES AND DRILLING

3.1 Introduction

Conventionally in the geothermal industry, usually the wells were drilled in the areas where thermal manifestations such as mud pots, fumaroles, hot spring, and geysers transpire. Consequently, manifestations were exterminated, although some well production still existed on the short term. (DiPippo, 2013) However, the real geothermal energy source was very much missed this way.

To determine a more reliable drilling site, subsurface nature of the field must be defined which will increase the likelihood of a successful well discovery; leading to the planning of a successful field development.

3.2 Objectives of an exploration phase

Five things should be accomplished for a geothermal exploration phase:

- Finding areas that are underlain by hot rock.
- Reservoir volume estimation, fluid temperature inside it, and formation permeability.
- Predicting whether the fluid produced is a liquid, a two-phase mixture, or a dry steam.
- Defining the chemical nature of geofluid.
- Estimating for a minimum of 20 years the electric power potential.

3.3 Steps of an exploration phase

Following are the necessary steps to fully characterize a geothermal resource:

1. **Literature survey**: It is rather likely that someone, at some point, espied whichever site that is being considered now. It is quite simple to look for existing literature of anterior studies using the internet. Now, most geothermal prospects have comprehensive databases available online.

2. **Airborne Survey**: by the help of aerial photography of the potential site, the following information can be yielded:

    - Field's structural nature.
    - Through infrared imaging (IR) locating the thermal anomalies and manifestations.
    - Aeromagnetic data.
    - The imperative Geographic benchmarks to assist and regulate upcoming ground surveys.
    - Geologic mapping (affiliated with the geologic survey).

An IR survey should have the capability of detecting minute anomalies in temperature, of the order of 0.05-0.5°C across a large area. Fifty times greater than the norm heat flux can be resulted from a rise of 0.5°. Besides sensitivity, an IR survey should be capable of differentiating between a pure geothermal effect and the one resulted from topography, hydrology, weather, or terrain.

Hydrothermally altering of rock, a process known to change a magnetic rock to a non-magnetic, areas having such rocks are revealed by aeromagnetic measurements. Thus, the corroboration of scorching geothermal fluids can be discerned by the existence of a magnetic low. Nonetheless, in several cases, this procedure has not proven to be decisive in outlining a hydrothermal area; the results of these measurements should be integrated with the result of other methods.

3. **Geologic survey**: generally, the first real work carried out "on the ground" is a geologic survey. Following are the objectives of a geologic survey:

   - Stratigraphic and tectonic setting.
   - Neoteric faulting.
   - Age determination of young rocks and their distribution (volcanic radix).
   - Nature of thermal manifestations and their location.
   - Hydrothermally-permuted rocks.

A geovolcanologist, who is an idiosyncratic geologist with concentrated adroitness and expertise in volcanic systems, normally conducts this phase. (DiPippo, 2013) The creation and evolution of a geologic site can provide present insights, i.e. deep formation state. Several geothermal fields are linked to former volcanism, occasionally rather new. All in all, to explain the present, geologists must envision the past. Formulating the area's geologic map is the first product of a geologist, whilst the second product is drafting the very first conceptual model of a hydrothermal system. The geothermal system's conceptualized model graphically limns the key subsurface characteristics of the system, including the location of rock units, the faults, and the fluid flow paths. A geologic survey is the starting point to create a map which is rejuvenated by more data from other surveys. The conceptual model may gradually develop posterior to field production; for injection and production wells constantly send information anent the reservoir.

4. **Hydrologic survey**: since the presence of ample quantities of water in the formation is considered as a crucial necessity for a geothermal field to be commercial, the exploration phase heavily relies on the hydrologic survery. The objective should be to foregather profuse knowledge and information apropos the system's fluids, their chemical and physical properties, flow paths, abundance, their age, and the recharge modes.

This survey involves the study of the following:

- Hot springs flow rates and temperature (if any).
- Chemical examination of said springs.
- Meteorological data.
- Water level in existing water wells.
- Movement of water in the reservoir and on the surface.

A mass balance can be done on all perceived streams and subsequently, the hydrologist can evaluate the rates of throughput and the volume of fluid information. These are regarded as critical for appraising the reservoir's production capacity.

5. **Geochemical survey**: important responsibilities of a geochemist are:

    - Differentiating between liquid-dominated and vapor-dominated resources.
    - Estimating the minimum temperature of the geofluid.
    - Finding the chemical properties of the fluid (both produced and, in the reservoir,).
    - Characterizing nature and sources of recharge water.

6. **Geophysical survey**: this exploration phase generally proffers the final answer and should help in determining the best locations for drilling our first deep well. Techniques involved in a geophysical survey are:

    - Measurements of heat flux.
    - Temperature gradient surveys.
    - Electrical resistivity surveys.
    - Active and passive seismic methods.
    - Gravity surveys.

During a geophysical survey, the following properties are measured:

- Density.
- Waves velocity propagating in solid material
- Temperature.
- Electrical conductivity or resistivity.
- Local gravitational acceleration.
- Magnetic susceptibility.

The data provided from shallow wells (around 100-200m deep) helps the geophysicist to determine the heat flux and thermal gradients. As mentioned earlier, the normal temperature gradient in non-thermal locations is at an average of 3.1°C/100m, whilst the normal heat flux has an average of 1.2×10^{-6} cal/cm^2 .s. Conventionally, 1 HFU (heat flow unit) is equal to 1×10^{-6} cal/cm^2.s or 1 µcal/cm^2.s. When pure conduction is the mean of heat transfer, the phenomenon satisfies Fourier's law, and is denoted by:

$$\dot{Q} = -kA\, dT/dx \tag{3.1}$$

Or

$$q = -k\, dT/dx \tag{3.2}$$

Where:

- $\dot{Q}$ depicts the heat flow per unit time (J/s) or the thermal power.
- k is the thermal conductivity of the material (W/m .°C or J/m .s.°C).
- A represents the area (m^2).
- dT/dx denotes the temperature gradient (°C/m).

Upon dividing eq. (3.1) by A, one can obtain eq. (3.2), i.e. the heat flux equation. The negative sign is an indication that the heat flow follows the decreasing temperature direction, which conforms to the second law of thermodynamics. (DiPippo, 2013)

Following are the approximated thermal conductivity values of some typical rocks:

- Marble 2.07-2.94 W/m .°C
- Granite 1.73-3.98 W/m .°C
- Limestone 1.26-1.33 W/m .°C
- Sandstone 1.60-2.10 W/m .°C

The heat transfers predominant mean (neglecting the circulation of fluid) in the near-surface formation will be conduction. The thermal conductivity will have an increasing propensity directly proportional to depth as the formation condenses beneath the increasing overburden weight. In steady state conditions the heat flux remains constant. Hence, from eq. (3.2) in a conductive environment, it is expected that with depth, the temperature gradient will decrease. This step is crucial in the exposition of shallow gradients as we will get erroneously high values by extrapolating to deeper depths. It can be observed in fig 3.1 below.

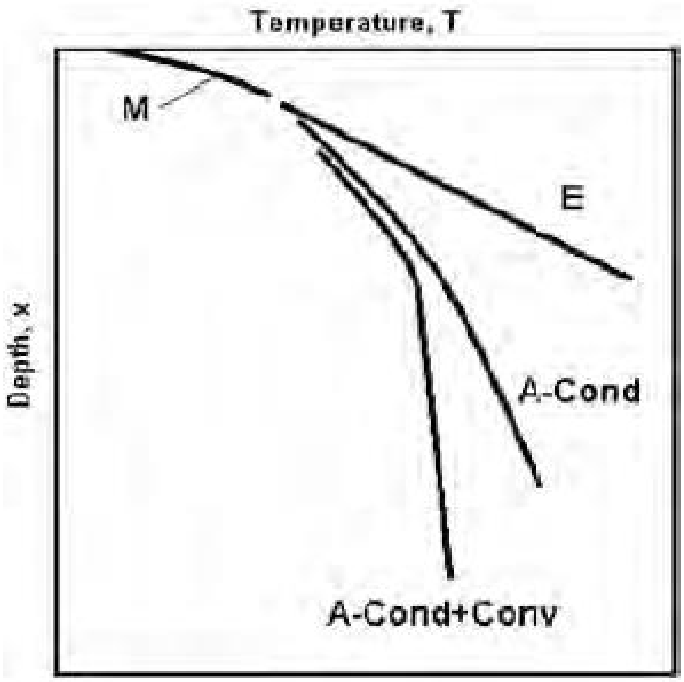

Figure 3-1 Temperature gradients. M= measured; E= linear extrapolation; A-Cond=actual with pure conduction; A-Cond+Conv= actual with a deep convective zone.

An isothermal zone will be created as usually found in a permeable geothermal formation when convection is prevalent: as shown in fig 3.1 lower end of A-Cond + Conv curve.

A good geothermal system can be indicated by a high heat flow. High heat flux near the surface can be deceiving as to the hottest sub-surface zone. Probable causes of a high heat flow are as follows:

- Availability of hot water close to the surface.
- High radioactivity of the country rocks.
- Friction along the faults.
- Exothermic reactions in the formation.

Geophysical surveys are tailored to observe the first amongst the above as the key indicator of thermal anomaly. Nonetheless, due to the lateral and vertical movement of hot fluid in porous media, highest heat flow surface may not correspond with the hottest reservoir region and might move us away from the geofluid's source.

Another essential element of the geophysical exploration phase is the electrical measurement. Electrical resistivity ρ: measured in ohm.m is a commonly measured quantity. Low resistivity can be resulted from the existence of hot water in a porous medium with dissolved minerals. Rocks are known as poor conductors of electricity (they are highly resistive), but the average resistivity reduces, when pore spaces are filled by an electrolyte. The rocks which have been remolded trough a hydrothermal process to clayey material are observed to be superior conductors when compared to the native country rock. Therefore, a hydrothermal reservoir characterized by high temperature may exist whenever low resistivity is found. (DiPippo, 2013)

Furthermore, since gases are notorious for being poor conductors of electricity, generally a dry steam reservoir transpires as a high resistivity in the middle of a relative low. Upon confirmation by other indicators, such as a high temperature gradient, resistivity of less than 5-10 ohm.m is taken as an apt indicator of a hot hydrothermal resource.

By observing the field for seismic activity, active faults and fissures areas can be identified. Possible fluid flow paths and indications for good drilling sites are indicated by swarms of micro-earthquakes.

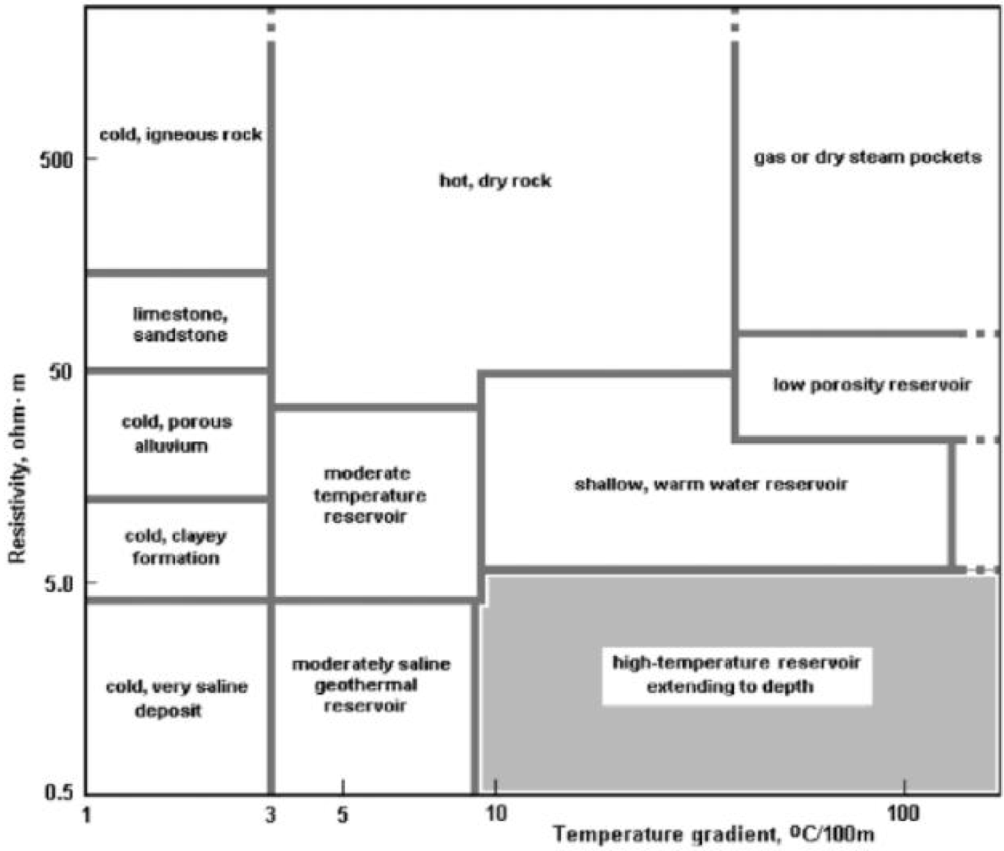

Figure 3-2 Resistivity vs temperature with possible interpretations.

From fig 3.2 we could have a rough idea where electrical resistivity is cross-plotted vs the temperature gradient. The most desirable section is in the shaded region.

3.4 Synthesis and interpretation

Subsequent to the completion of geoscientific surveys, it is essential to gather all the data obtained and ratiocinate conclusions based on the provided evidences, keeping in mind that any one of the surveys can be misleading. To imagine the most thorough picture of the geothermal potential, it is better to set up either a composite or synthesis map of the site. The prominent goal of constructing this map is to locate the best places for drilling the first few deep wells.

By using latest technologies, like modern 3D computer graphics, we can present the synthesis in an easier, user-friendly and visually appealing format. This computer representation must be updated periodically as more wells are drilled. This well assist the next steps to follow. A better description of the subsurface can be abstracted from Lithologic logs which in turn will ameliorate the likelihood of successful wells. During the field development, further geoscientific work may be needed for better field planning and drilling.

3.5 Drilling

Generally, in the initial step concerning the confirmation stage of the field, three wells are drilled. Wells are drilled at the most auspicious sites as ascertained by the help of exploration studies. If possible the productive area of the field should form a triangle. As these first wells are part of an exploration program, more and more information should be gathered during their drilling. During this information gathering step, core samples should be taken to fathom the formation lithology. Prior to progressing to the next step (development wells), the collected data must be integrated with the field conceptual model.

A significant preparation is required prior to drilling operation can instigate because geothermal fields are usually distant and far from developed areas. The first well drilled –discovery well– is a vertical well of around 2500m depth, which allows us to gather ample information from our formation. Some major equipment used at a drill rig are shown in figure 3.3

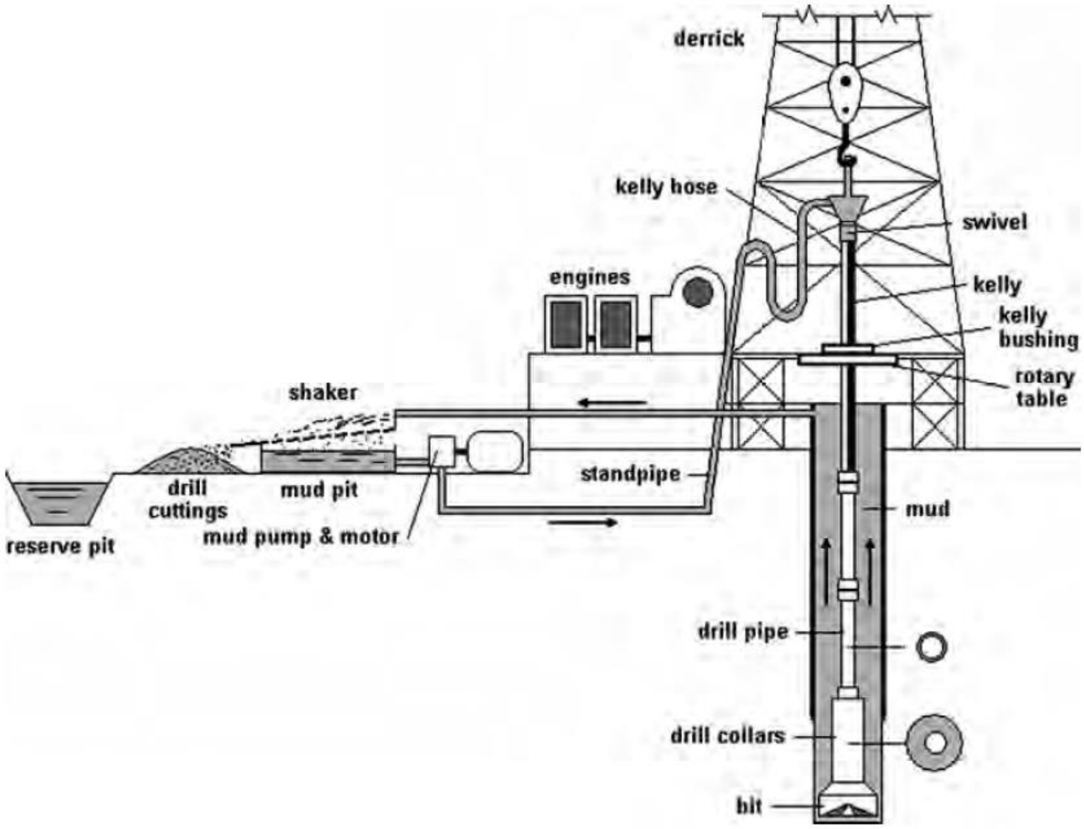

Figure 3-3 A typical drill rig.

3.5.1 Drilling operations

Compression forces applied on the rock through the multi-toothed drill bit play an active part in the creation of the hole. The standard method of drilling in geothermal drilling is the rotary drilling whereby a typical diesel engine operates the string of drill pipes hung from a derrick. The top section of the pipe –known as Kelly– which has a cross-section in the shape of a square, enables rotation by the action of rotary table through which it passes. The basic function of the bit used here is to provide highly concentrated loads on the rock, which causes said rock to crack. Typical bit used is a tri-cone roller bit.

Critical element in the operation of the above function is the drilling fluid (mud). Its vital functions are:

- Removing the rock chips.
- Cooling of the drill bit and string.
- Drill string lubrication.
- Preventing the collapsing of wells during the drilling operation.

The drilling fluid (mud) is forced down towards the drill pipe center until it reaches the part where nozzles expedite the fluid and redirect it on the rock underneath the bit. Drill cuttings are swept as the mud flows under the bit, transporting them along to the surface via the annulus between the drill string and the wall of the well. At the surface the mud can flow over a screen and shaker, where the cuttings are dislodged. The geologist subsequently examines the cuttings. The mud is then returned to the bottom through the mid pump. It is imperative to cool the mud prior to running it back into the well when the formation is hot. The drill pipe may encounter the wall over some length, because of the deviation of the bit during drilling; causing friction. Mud helps to reduce that friction. Lastly, until a permanent casing is run by exerting pressure against the wall, the formation can be kept intact by the mid.

Basically, the drilling fluid (mud) is an engineered fluid, having specific functions to specific tasks. To change the density and viscosity, numerous additives can be added into water. Density ranges from 62.4 lbm/ft^3 (pure water) to 150 lbm/ft^3. (DiPippo, 2013)

The next critical task is the running of casings and cementation. Standard modus operandi is depicted in fig. 3.4. Upon digging a hole to the desired depth, the casing is lowered into the hole (fig 3.4A). Using a plug (fig 3.4B) the mixed cement (its volume should be higher than the annular volume between the outside of the casing and the inside of the hole) is forced down the inside of the casing. Drilling mud acts as a pusher. By the time the plug comes to halt on the float collar (fig 3.4C), the annulus should be filled with the cement (via direct displacement of the cement). Surplus cement returning to the surface indicates a successful job.

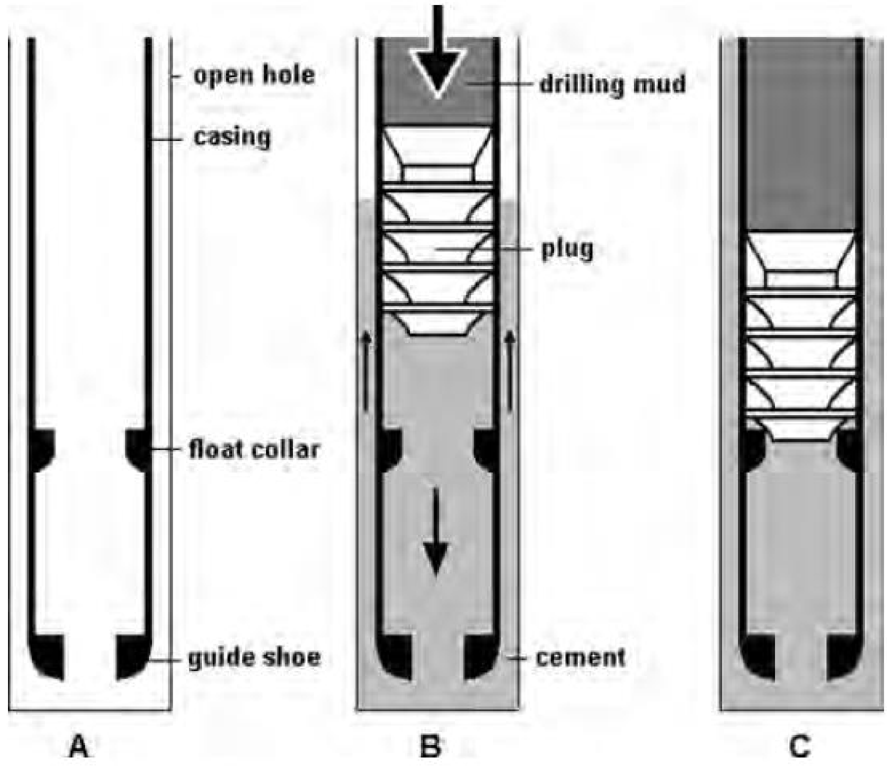

Figure 3-4 **cementation of casing in 3 steps.**

Drilling is a multi-stage process. The surface casing is preceded by a shallow anchor casing. The longest one is the production casing and it ends just short of the chief zone of production, shown in fig 3.5. Two options are considered for the drilled well, either leaving it as an open hole or fitting a slotted liner in a way where the slots are aligned with the production zone.

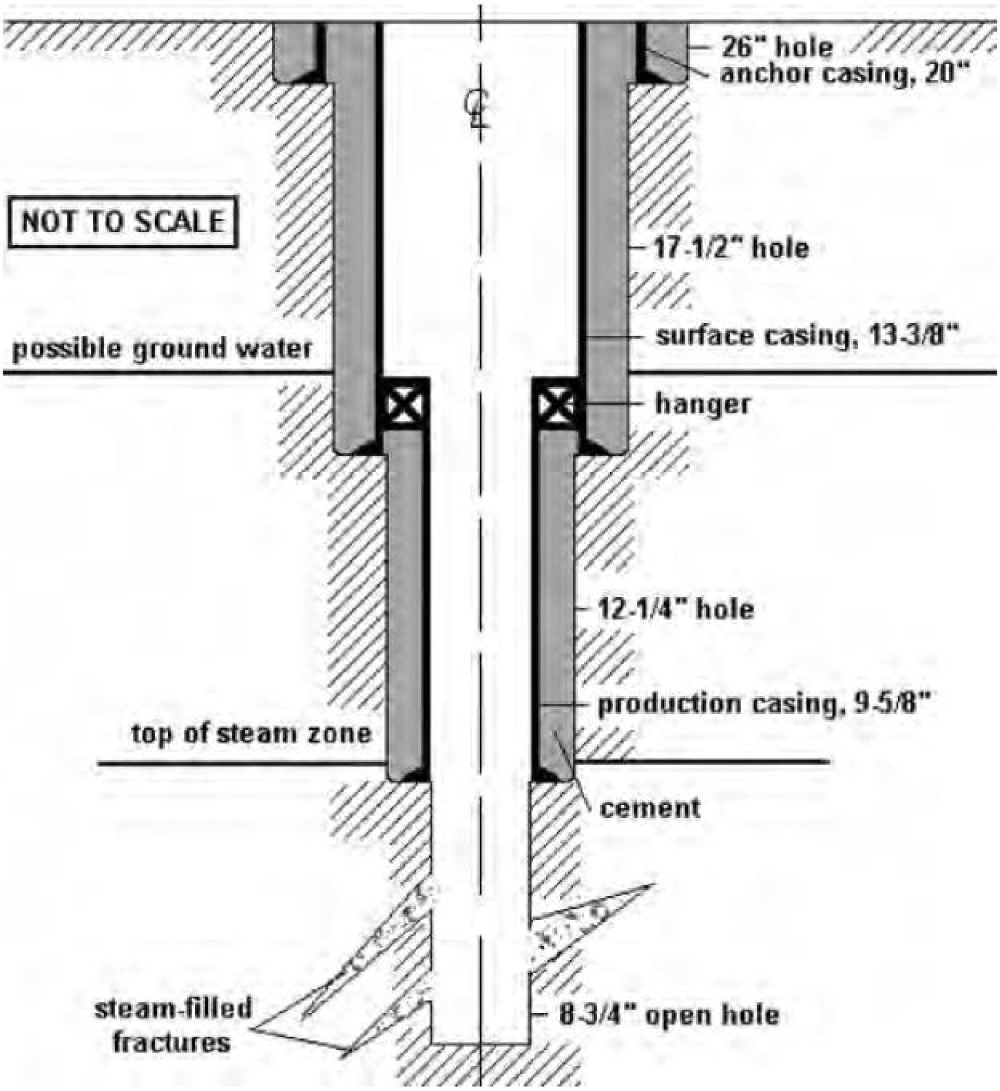

Figure 3-5 **Well completion for a dry-steam reservoir.**

3.5.2 Safety precautions

While drilling a geothermal well, there is always a risk of a blowout. Blowout occurs when an unpredicted, high-pressure permeable zone is encountered. Nowadays, the utilization of blowout preventers is obligatory. A typical blow out preventer is shown in fig 3.6; consisting of fast-acting ram-type valves which are connected to the surface casing, through which the drill pipe rotates. The previously mentioned valves are slammed tight around the drill string in an event of a "kick" from the well. This is called killing off the well.

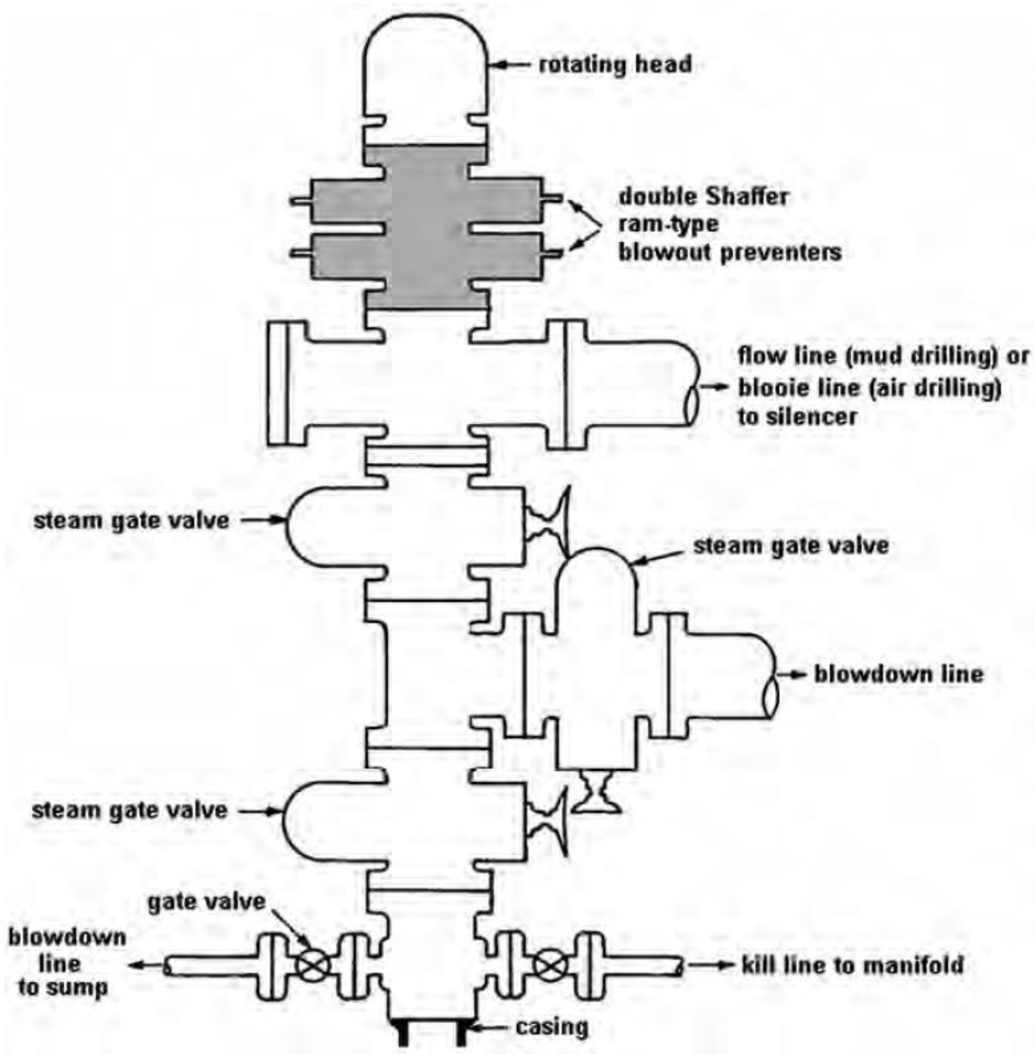

Figure 3-6 Typical blowout preventer that is being used at The Geysers, CA.

Grave injuries and even casualties are caused by the existence of toxic gases such as H_2S. Proper procedures are followed during the operation. H_2S and CO_2 might accumulate in the cellar of the well if any leakages from the well or casing are present; as they are both heavier than air. Wherever we have the possibility of high concentrations of these gases, sensors should be installed.

Casing failure is a genuine issue in the presence of these gases and others owing to their corrosive nature. We should be careful in selecting material. The pressurized geo-fluid can escape outside the wellbore, if the casing string breaks. This can result in injuries to nearby personnel and severe damage to surface equipment. These sorts of failures cannot be stopped by blowout preventers during drilling.

4. GEOTHERMAL POWER PLANTS

4.1 Single-Flash Steam Power Plants

According to a 2011 survey, 169 units based on this single-flash steam technology were in operation in almost 16 countries, constituting 29% of all geothermal plants. Out of the total installed geothermal power capacity in the world single-flash steam power plants constitute nearly 43% of it.

Geothermal wells that are producing a mixture of steam and liquid, are ideal candidates for producing electricity with the single-flash steam technology. It is relatively simpler and convenient way to convert geothermal energy into electricity. The first step involves the separation of the mixture into steam and liquid phases with minimal pressure loss. A cylindrical cyclonic pressure vessel, usually a vertical separator is used for this operation where the two phases dissociate because of their inherently large density difference.

5 to 6 production wells and 2 to 3 injection wells are needed by a typical 30 MW single-flash power plant. These wells maybe drilled across the field or a single pad can be used to drill several using directional drilling to intercept a wider reservoir. (DiPippo, 2013) In both the cases, a piping system is necessary to gather the geofluids from the wells and then transport them to the power plant and then to the disposal points. The initial piping system is often modified if new power units are needed later.

4.1.1 Piping layouts for gathering system

we can set the separators at the power plant, at the satellite stations or at near the well (well heads). In the figure 4.1 we can see 5 production wells feeding the fluid mixture (two-phase) to a separator located at a power house. After separation, the steam is fed to a turbine and the liquid is sent for the injection using two injection wells.

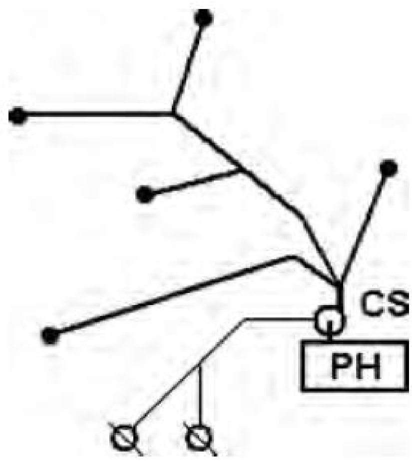

Figure 4-1 Cyclone separator (CS) at the Powerhouse (PH), filled circles are production wells while open circles are injection wells.

In the figure 4.2 we can see the production wells feeding the separators at the satellite stations. The separated steam is sent to the steam receiver prior feeding a power house while the liquid is sent for injection.

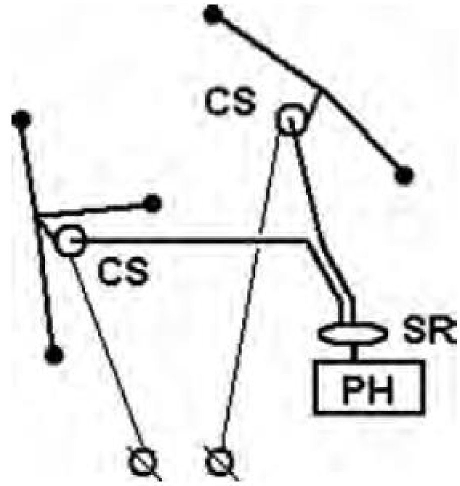

Figure 4-2 Gathering system with satellite separator depots: steam to the steam receiver (SR) close to the powerhouse (PH)

In the figure 4.3 we can see the separators collecting the mixture from each production well, the separated liquid being sent to the injection wells using separate pipelines while the steam is sent to a steam receiver prior feeding to a power house.

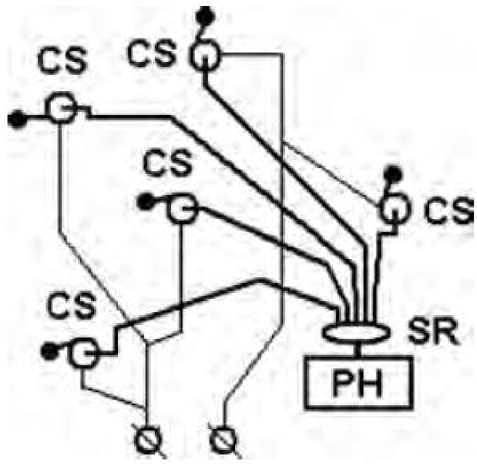

Figure 4-3 Gathering system with individual wellhead separators.

4.1.2 Energy conversion

The term single-flash means that the pressurized liquid (geofluid) has encountered a process of conversion due to the lowering of pressure and as a result been flashed to a mixture of vapor and liquid. This flashing process can occur (1) inside a reservoir while the fluid moves through the permeable rock resulting pressure drop; (2) along the length of the production well due to frictional losses and gravity head; or (3) at the inlet of the separator due to the throttling caused by an orifice plate or due to presence of a control valve

Often in a new developed field, initially the geofluid flashes in the wellbore but with more exploitation as the pressure of the reservoir declines, the fluid might flash even inside the formation.

Actual point of flashing might be important considering the power plant's operation, but it is insignificant if we consider the thermodynamics of the conversion process. The simple assumption here is that the geofluid is a compressed liquid at somewhere in a reservoir, gets flashed somewhere so that we get two separated phases, and then the separated steam drives a turbine which operates the electric generator. In the figure 4.4 the scheme diagram shows the operation and key components of such power plant.

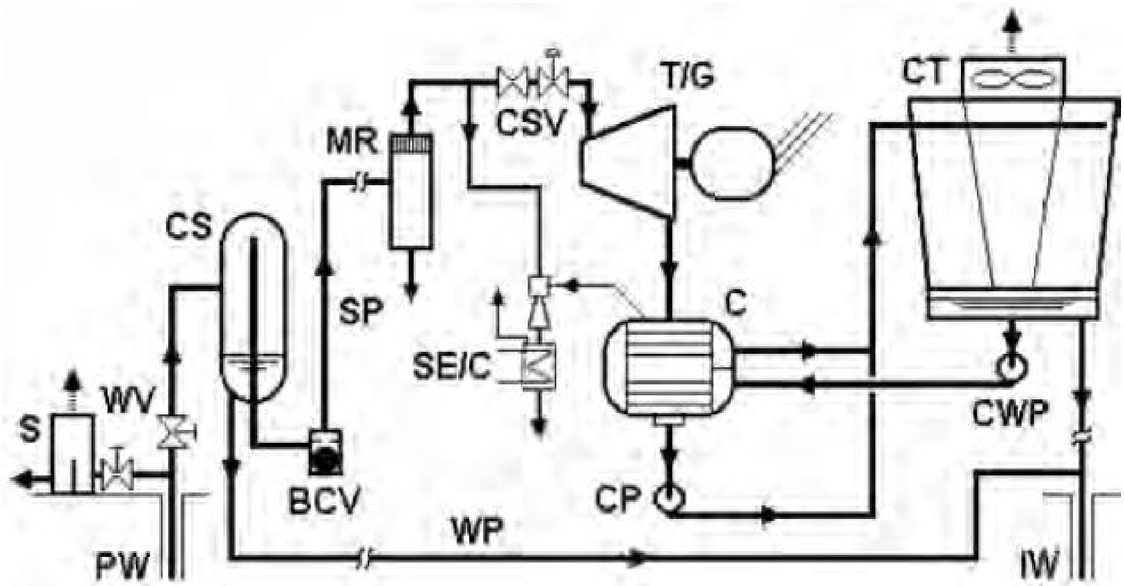

Figure 4-4 Schematic of a simple single-flash power plant.

There are a lot of monitor and controlling equipment at each wellsite. The geofluid flow is scrutinized from the well to the power plant. The list of equipment includes: well control valves WV, a small cyclone separator used for venting referred as silencer S, and several pressure and temperature gauges. A cyclone separator CS, will be on the same pad close to the well site.

We must ensure the efficient separation of the two phases before the steam is fed to the turbine, because we can face problems like scaling and erosion of turbine units due to the trapped liquid droplets in the steam. Usually the steam's quality should be 99.9 % dry. (DiPippo, 2013)

Now horizontal separators are used in industry replacing the vertical ones since 1995. Gravity being the basis of separation in horizontal separators, improved by the introduction of vane baffle plates at the bottom and a perforated horizontal plate for droplet removal at the entry point of steam exit section.

Both type of separators has their pros and cons. The pros of vertical separator are cleaner steam, a wide range of pressure, easy to maintain along with sharper cut-off, while the size limitations and height of construction being its cons. The advantages of a horizontal separator are no size limitations along with greater output per vessel; whereas its cons are requirement of horizontal mist removers for better maintenance and better-quality steam. The added economic advantage of a horizontal design is that they are less expensive to build and operate.

In a geothermal power plant, the turbines must be corrosion resistant because the presence of corrosive gases such as hydrogen sulfide can affect the ordinary steel. Numerous alloys are used for turbine unit equipment.

Either a surface-type condenser C, or a direct-contact condenser is used to condense the steam after it feeds a turbine. There are two types of direct-contact condensers (barometric type and low-level type). Most of the power plants opt for surface condensers. Like most conventional condensers the steam flows through the shell while the coolant (water) flows through the tube. both the phases are physically and chemically separated and are maintained like that. Non-condensable gases are also treated and removed effectively like this. Gases like CO_2 and H_2S are present in the natural steam, which normally do not condense in the condenser. Removal of such gases is important using steam jet ejectors (SE/C in figure 4.4) because with their presence the overall pressure in the condenser increases and the power output of the turbine decreases. Vacuum pumps can also be utilized for removal.

The source of cooling water is the cooling tower. A portion of the condensed steam is fed to a cooling tower where it is cooled by partial evaporation with the help of a moving air stream and then it recirculates to the condenser. This means that we do not need abundant supply of cooling water which is an advantage of flash-steam plants specially if we are in arid areas. however only a small amount of fresh water is required for tower blowdown.

4.2 Double-Flash Steam Power Plants

Double-flash steam power plants can be regarded as an upgrade to their single-flash counterparts. Double-flash steam power plants can produce more power output (say 15-25% more) for the same geofluid conditions. Considering more power output as an extra favourable point to install such plants, these plants can be costly and require additional maintenance. As of 2011, 59 such plants are operating in the World which accounts for 10% of total geothermal power plants. The range of power capacity of double-flash steam plants is from 4.7 to 110 Megawatts with an average power of 31 Megawatts per unit.

As double-flash steam power plants are almost like the Single-flash systems in basic functioning, the same layout will be followed here regarding the gathering systems and components. The vital new feature in the double-flash power plants is a second flash process. The second flashing process is enforced on the liquid which is separated using a primary separator, to produce more steam. This secondary steam is generated at a lower pressure than the primary steam.

4.2.1 Piping layouts for gathering system

The introduction of a second flashing process further increases the number of arrangements mentioned previously in section 4.1.1. the other possibilities are as follows:

- As depicted in figure 4.5, separators and flashing units are available at each wellhead. High and low-pressure steam lines are fed to the power plant whereas for injection purposes, hot water pipeline goes to the injection wells from the production wells.
- As depicted in figure 4.6, the separators and flashing units are present at the power plant, the two-phase mixture is transported to the power plant via pipeline where it is separated and flashed. High and low-pressure steam is fed to the turbine while the hot water is sent via pipelines to the injection wells.
- As depicted in figure 4.7, we can have satellite separator/flashing unit stations in our field, two-phase mixture from several wells are sent to the satellite stations. High and low-pressure steam from the satellite stations are sent to the power plant. The hot water is sent to the injection wells from the satellite stations.
- As depicted in figure 4.8, we have satellite separators in the field. Two phase-mixture is fed to the separators, the separated hot water and steam are sent via pipelines to the power plant. Flasher(s) at the power plant, low pressure steam is fed to the turbine whereas water is sent for injection.

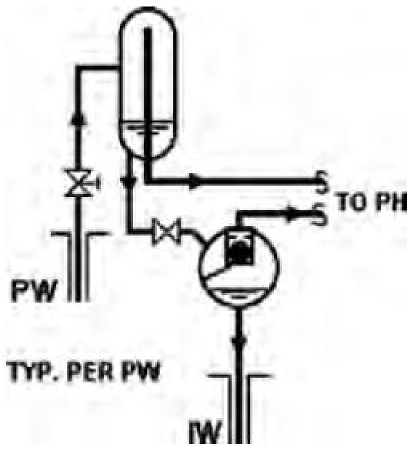

Figure 4-5 **Wellhead separators and flashers, with several production wells; injection wells may serve to multiple production wells.**

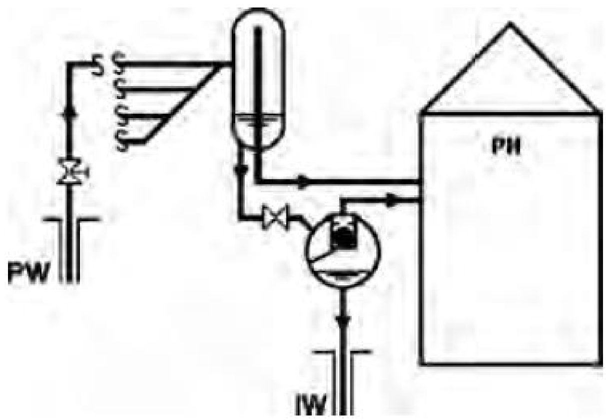

Figure 4-6 **Separators and flashers are present at powerhouse. Two-phase flow lines from multiple production wells gather at the separators and flashers at the powerhouse.**

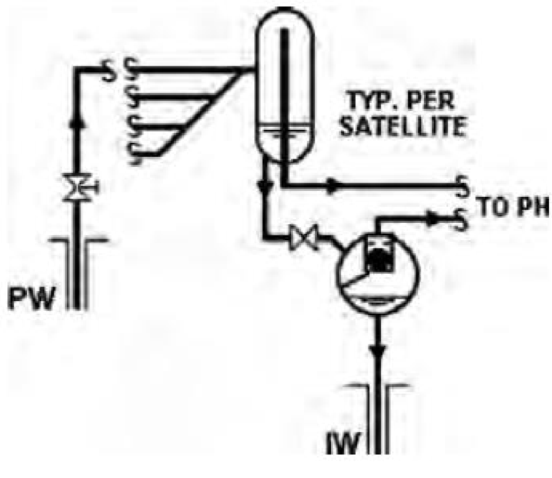

Figure 4-7 **Separators and flashers at satellite stations, several sets can be found at the field.**

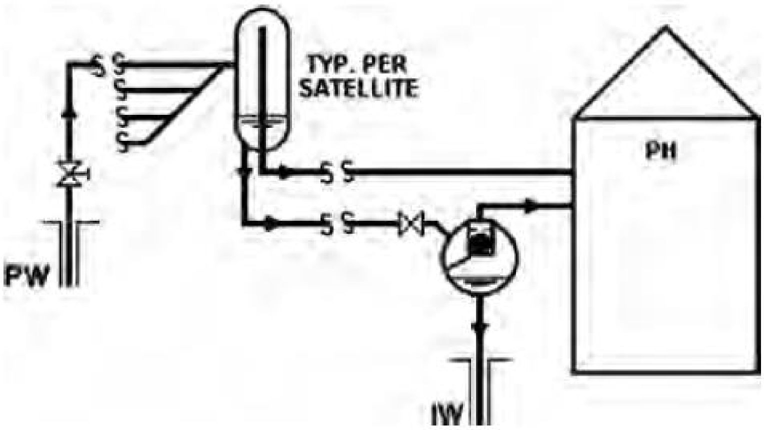

Figure 4-8 satellite separator stations and flasher(s) at the powerhouse.

There are a lot of factors to consider the best configuration which includes the thermodynamics and economics, temperature, pressure and chemical properties of the geothermal fluid while also considering the topography of the site. Scale control techniques are emphasised as they are a key factor in the operation of any plant. These techniques involve both the down well treatment in the production well to avoid calcite scaling, and treatment to avoid deposition of silica in injection wells.

4.2.2 Energy conversion

Figure 4.9 shows the operation of a typical double-flash power plant. As we can see the added component in the figure is the flasher F and the emergence of a low-pressure steam line from it. This low-pressure steam is fed to the turbine separately. Due to convention, the cooling tower, which is a source of cooling water CW is not shown in this figure.

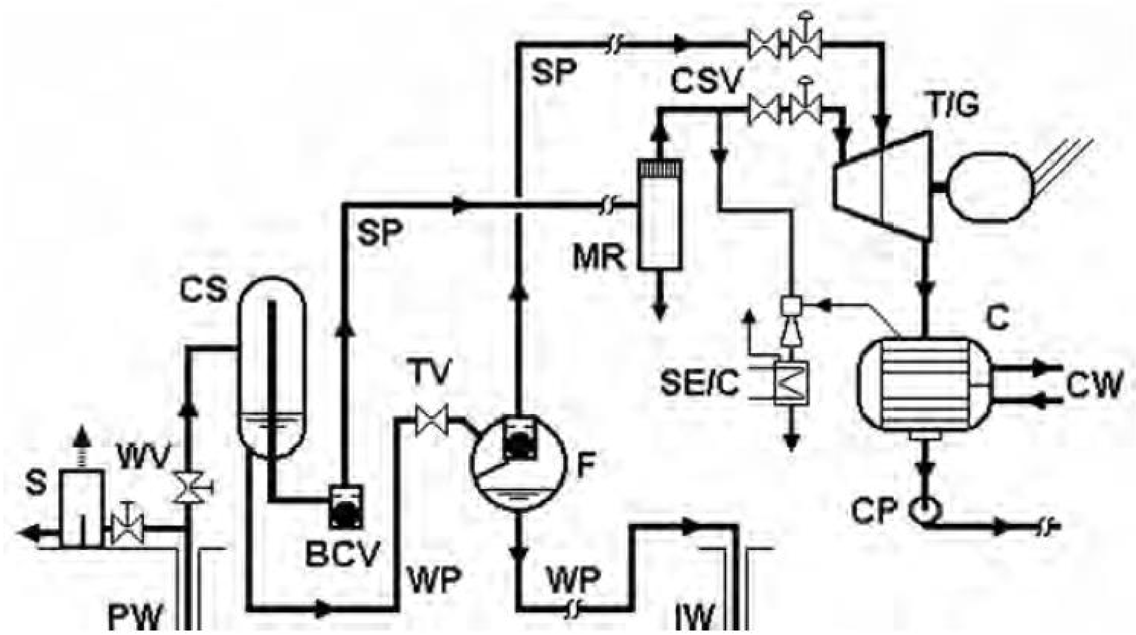

Figure 4-9 **Schematic of a double-flash power plant.**

The turbine shown in the schematic is a dual admission, single-flow equipment. The low-pressure steam is introduced to the already operative steam path at suitable time and stage so that it can merge smoothly with the high-pressure steam. Other possible configuration involves the operation of two turbines instead of one. One can be used for high-pressure steam and the other for the low-pressure steam. In this configuration, the two separate turbines could lead to a common condenser (figure 4.10) or could lead to two separate condensers (figure 4.11).

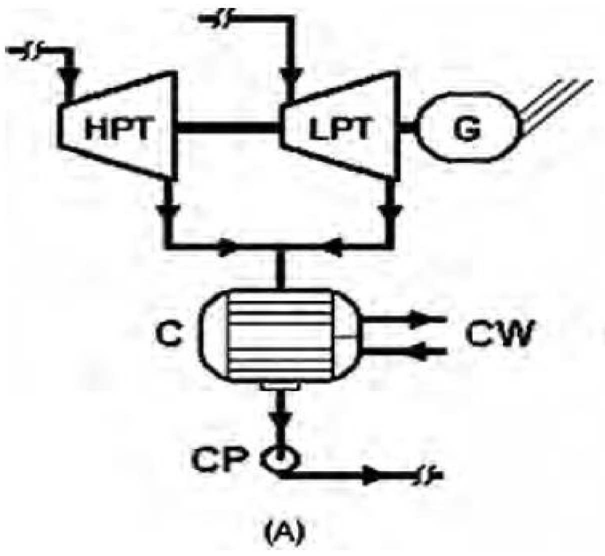

Figure 4-10 **Double-flash plant with separate high and low-pressure turbines with a single condenser.**

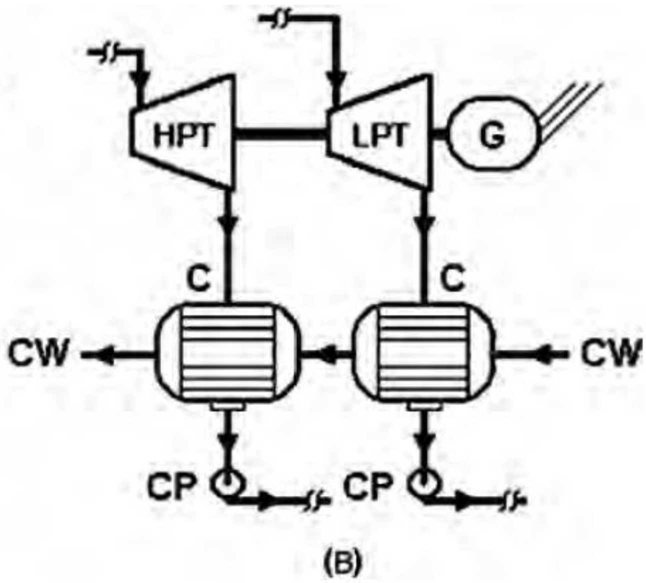

Figure 4-11 Double-flash plant with separate high and low-pressure turbines with two condensers.

4.3 Dry-Steam Power Plants

The first ever commercial geothermal power plant was a dry-steam power plant. The history dates all the way back to 1904 when a tiny steam engine was built by Prince Piero Ginori Conti. (DiPippo, 2013) This steam engine was driven by natural steam jets that aroused from the ground. The location was Larderello in Tuscany, Italy. Although this tiny steam engine generated very less electrical power, but it proved to be a starting point for larger power plants.

As in dry-steam plants, we don't have to deal with geothermal brine as it was with the flash-steam plants. This makes dry-steam power plants simpler and less expensive. Two major dry-steam fields are The Geysers, in the U.S and Larderello, in Italy. 71 such power plants are in operation as of 2011, about 12% of the total geothermal power plants. The installed capacity of these plants is 2893 Megawatts which makes about 27% of the total geothermal capacity in the World.

4.3.1 Dry steam resources and their origin

Several studies show that only 5% of all the hydrothermal resources (having a temperature greater than 200°C) are dry-steam resources.

A dry steam reservoir comprises of porous rock having fractures and fissures, either isolated or connected. These fractures and fissures are filled with steam with very little amount of liquid or no liquid present. The steam may also contain traces of gases like CO_2, H_2S and Methane. The source of the hot steam maybe magmatic (the slow rising of vapor from deep and hot magma chambers) or meteoric (the rain water leaks and flows through the faults and fissures where it encounters hot rock).

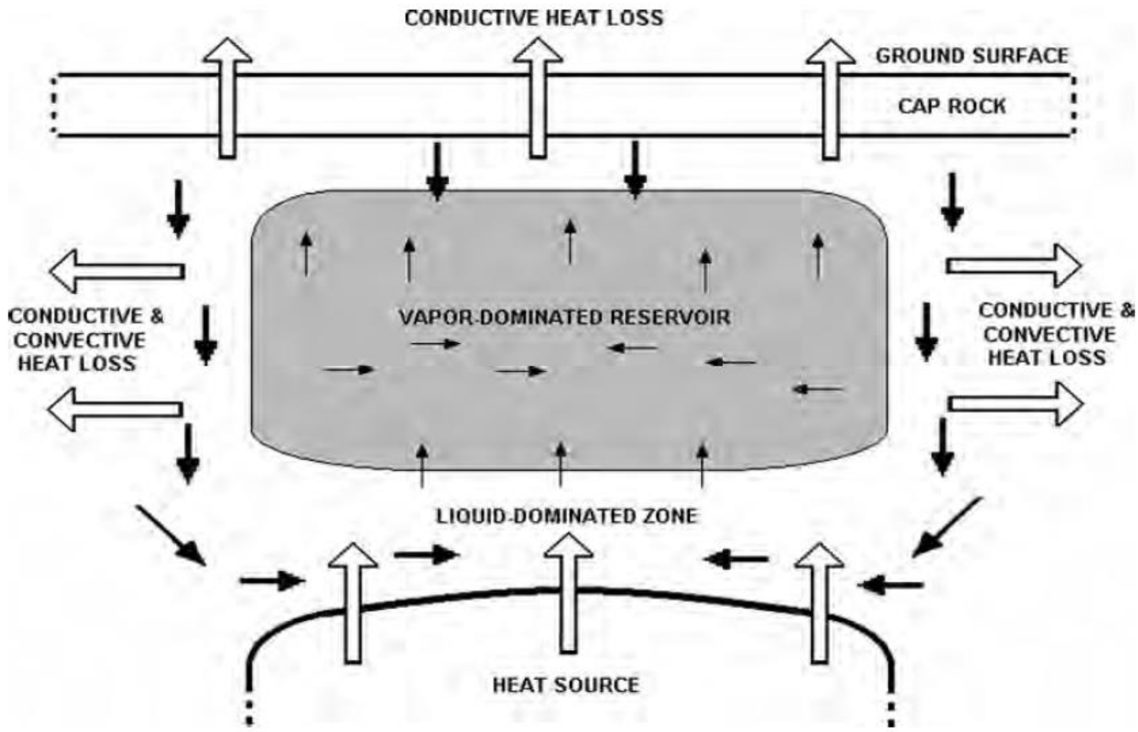

Figure 4-12 model of a dry-steam reservoir, white arrows indicate heat flow; black arrows show the movement of liquid, small arrows show steam movement.

In the figure 4.12 these mechanisms are shown. We can see that the boundaries of the vapor-dominated reservoir are totally impermeable. If not, then the liquid would easily flood the steam from the sides, resulting in the collapse of the steam. The only possible presence of liquid in this vapor dominated zone is the water entrapped in the fissures and the condensate. A favored path is created when a production well is drilled to remove the steam. This removal of steam induces a depression of pressure in the rest of the formation. Further steam is produced due to this pressure reduction due to the evaporation of the trapped liquid, eventually causing the formation to completely dry out. Now only the condensate and deep liquid provides the further steam.

Faults play a major role in the natural recharge of the system. Through these faults the surface water can reach liquid-dominated region. The liquid zone may even fall to greater depth if the rate of recharge is slower than the rate of production, this is due to more evaporation caused by reduced pressure.

Before the Larderello and The Geysers were exploited for geothermal energy, both the fields had a lot of thermal manifestations such as fumaroles, steam-heated pools and mud volcanoes. Due to continued production over time, permeability of the upper layer of formation decreased as the minerals in the geofluid precipitated and they sealed the fractures and fissures.

In 1989, a process of fluid restoration was carried out on a dry steam field when an injection program was carried out in The Geysers. The main purpose of it was to counterbalance the drying out of the reservoir although that region had a considerable high temperature. The outcome of this experiment was the increased steam output from the production wells (almost additional power of 20 Megawatts). This experiment also helped to plan out larger injection programs like wastewater taken from Santa Rosa and Lake County.

In summary, the circumstances for the existence of dry-steam geothermal system are highly fortunate. Primarily, a heat source must be present close to the surface (let's say 5 km deep) so that the connate water can reach its boiling point. Ample permeability of the above formation so that the steam can escape to the surface over longer geological time, which will cause the liquid level to lower. Fissures and fractures should be enough interconnected so that the fluid can circulate inside the reservoir. Enough lateral impermeability of the steam formation region and the surrounding rock so that cooler groundwaters can't flood the steam. Lastly, the top most formation largely should have almost no permeability caused by the mineral precipitation (self-sealing).

4.3.2 Gathering System for Steam

Compared to the gathering system in flash-steam plants, the gathering system and configuration in dry-steam plants is simple. The well site consists of some valves and a normal axial centrifugal separator (steam purifier), which is used to remove particles from the steam before it enters the pipes. Usually the pipes are insulated and are held firm by beams. Along the length of the pipes, steam traps are used to collect the condensate. The condensate is sent to the holding pools via separate pipelines and then for reinjection.

We usually have pressure relief valves (a station) near the powerhouse for emergency purposes. So that if a turbine trips steam can be temporarily released. The steam is forced through a silencer before it can be released in the atmosphere.

The equipment found at the power plant are, steam header, a final moisture remover before feeding the steam to a vertical cyclone separator or a baffled demister can be used instead, and for measuring the flow-rate of the steam a venturi meter is used.

4.3.3 Energy Conversion

Basically, the dry-steam plant is identical to a single flash-steam plant. The turbines that are used in a dry-steam plants are single-pressure units with impulse-reaction blading. Both type of condensers can be used (i.e. direct-contact or surface-type). Side by side setting of condenser and turbine is favorable for small units, opposite to the condenser below turbine setting in most plants.

In the figure 4.13 we can see the schematic of a dry-steam plant. As we can see the Particulate remover PR is an added component. except that, the schematic is very similar to the one of single-flash plant.

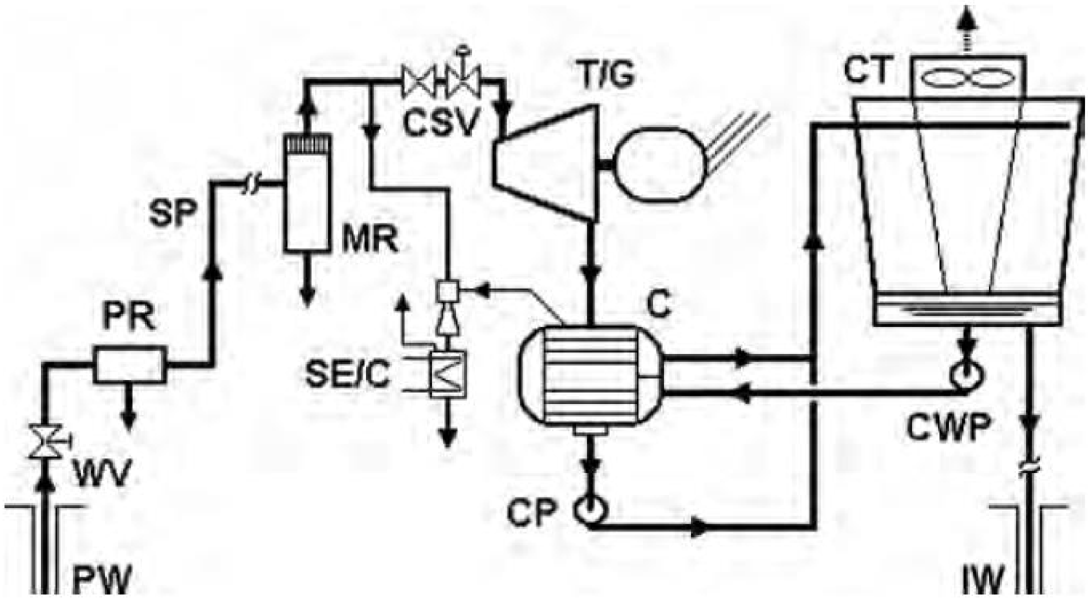

Figure 4-13 Schematic of a dry-steam plant.

4.4 Binary Cycle Power Plants

If we compare the conventional fossil or nuclear plants with the binary cycle geothermal plants, the latter follow the thermodynamic principle nearly. In the binary cycle geothermal power plants, the working fluid goes through the actual closed cycle. A working fluid is selected having suitable thermodynamic properties. The function of the working fluid is that it receives heat from the geofluid, it evaporates and expands through a prime-mover. After it's condensation, the working fluid is returned to the evaporator using a feed pump.

It is widely believed that the first geothermal binary cycle power plant was set up in 1967 at Paratunka, in Russia's Kamchatka peninsula. Whereas there is some evidence that a binary power plant existed before 1967, in DR Congo (Africa). In 1952 a small 200 kilowatts binary unit was set up at Kiabukwa near the city of Kamina in the southern province of Katanga. The site mentioned above is almost 300 kilometres west of East African Rift system. (DiPippo, 2013)

Binary cycle power plants are the most widely used geothermal power plants in the World, with 235 such plants in operation in 201. Over 700 Megawatts of power is generated by 15 countries using this power plant. 40% out of all geothermal plants are binary cycle power plants but they generate only 6.6%of the total power. which means the power outing per unit is only 3 Megawatts/unit. But using an advanced cycle design (in which a pair of turbines run a single generator), units with an output average of 20 Megawatts are in use now. Even binary units can be added to flash-steam power plants for more power output, using the hot waste brine.

4.4.1 Basic Binary Systems

Constructing a flash-steam plant that can efficiently flash a geofluid having a temperature of 150°C or less is difficult. Having a resource with lower temperature is usually a problem for flash technology. Wells flowing naturally at this low temperature is improbable, only except when there is a possibility of calcium carbonate scaling in the wells.

Figure 4.14 shows a schematic of a basic binary power plant. Pumps P can be seen usually fitted with the production wells PW. By studying the reservoir properties, the pumps can be set below flash depth. To avoid the erosion and scrubbing of the pipelines, heat exchanger tubes and other equipment, a sand remover SR is used. In the pre-heater PH, where the process of heating and boiling takes place in two stages, a working fluid is brought to boil and then from the Evaporator E it comes out as a saturated vapor. It is made sure that during all steps the geofluid pressure is kept above its flash point so that steam and non-condensable gases are not liberated which can cause problems like calcite scaling in the pipes. Also, it is made sure that the temperature of the fluid does not drops to the point where we can have silica scaling problem in the preheater and the injection wells.

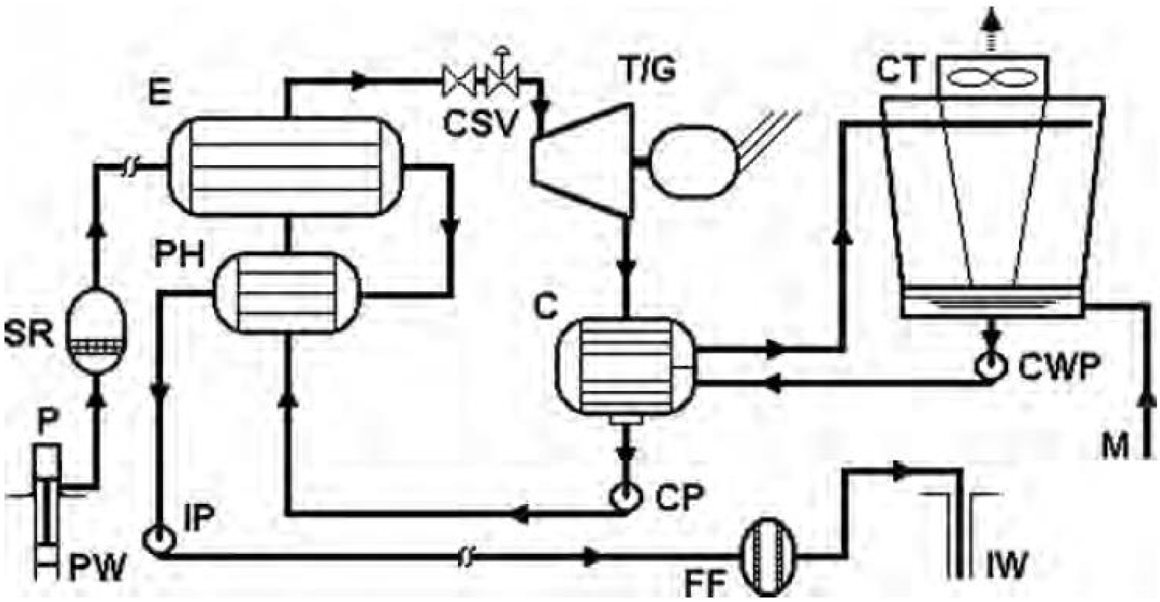

Figure 4-14 Schematic of a basic binary geothermal power plant.

4.4.1.1 Working Fluid Selection

Selecting the working fluid for our operation is of paramount importance. This selection is significant for the binary plant's performance.

Some possible working fluids and their thermodynamic properties are listed in table 4.1 (note that pure water is in the table for comparison purpose). As we can see that critical temperature and pressure values of all the candidate fluids are lower than water.

Fluid	Formula	T_c °C	T_c °F	P_c MPa	P_c lbf/in^2	P_s@ 300 K MPa	P_s@ 400 K MPa
Propane	C_3H_8	96.95	206.5	4.236	614.4	0.9935	n.a.
i-Butane	i-C_4H_{10}	135.92	276.7	3.685	534.4	0.3727	3.204
n-Butane	C_4H_{10}	150.8	303.4	3.718	539.2	0.2559	2.488
i-Pentane	i-C_5H_{12}	187.8	370.1	3.409	494.4	0.09759	1.238
n-Pentane	C_5H_{12}	193.9	380.9	3.240	469.9	0.07376	1.036
Ammonia	NH_3	133.65	272.57	11.627	1686.3	1.061	10.3
Water	H_2O	374.14	705.45	22.089	3203.6	0.003536	0.24559

Table 4.1 some candidate working fluids for binary plant with their thermodynamic properties. (DiPippo, 2013)

4.4.2 Advanced Binary Cycles

In this section we will briefly shed light over some new and complex binary cycles like:

- **Dual-pressure binary cycle**: a smaller difference in average temperature is attained by the two fluids in the dual-pressure binary cycle. It is because of the heating/boiling is carried out in two stages. Figure 4.15 depicts the schematic of a such plant. We can see the dual admission turbine in the figure. The low-pressure steam (saturated vapor) is fed along the path of the high-pressure vapor. This mixing allows the smooth creation of a modest super-heated vapor. An alternate design can be considered having two individual turbines as shown in figure 4.16. as we have noted, binary plants are distinct from flash-steam plants or dry-steam plants because there is no need for condensers as no steam condensate is generated which can act as makeup for cooling tower. Because of this reason, we would need an alternate cooling medium, i.e. air or fresh water. Since the supply of fresh water (for cooling towers) is scarce in many geothermal sites, ACC (air-cooled condenser is shown in the schematic). The first use of the dual-pressure system was in the 5 Megawatts Raft River dual boiling plant in Idaho, USA, demonstrated by the Idaho National Engineering Laboratory operating for the US department of Energy in 1981.

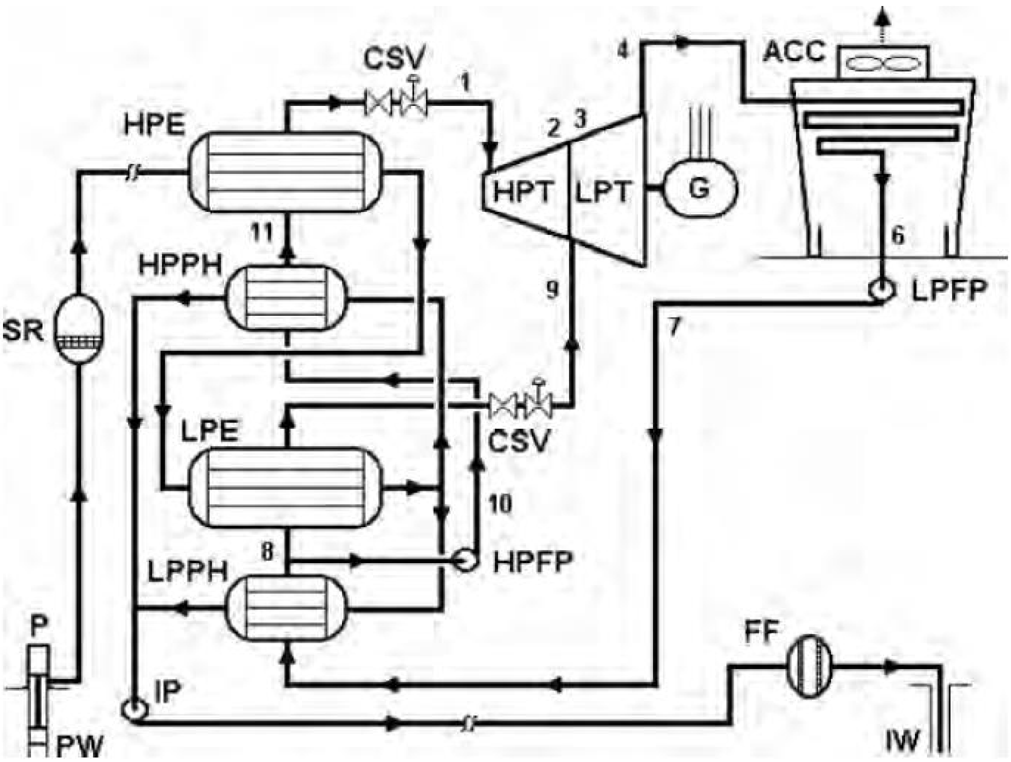

Figure 4-15 schematic of Dual-pressure binary plant.

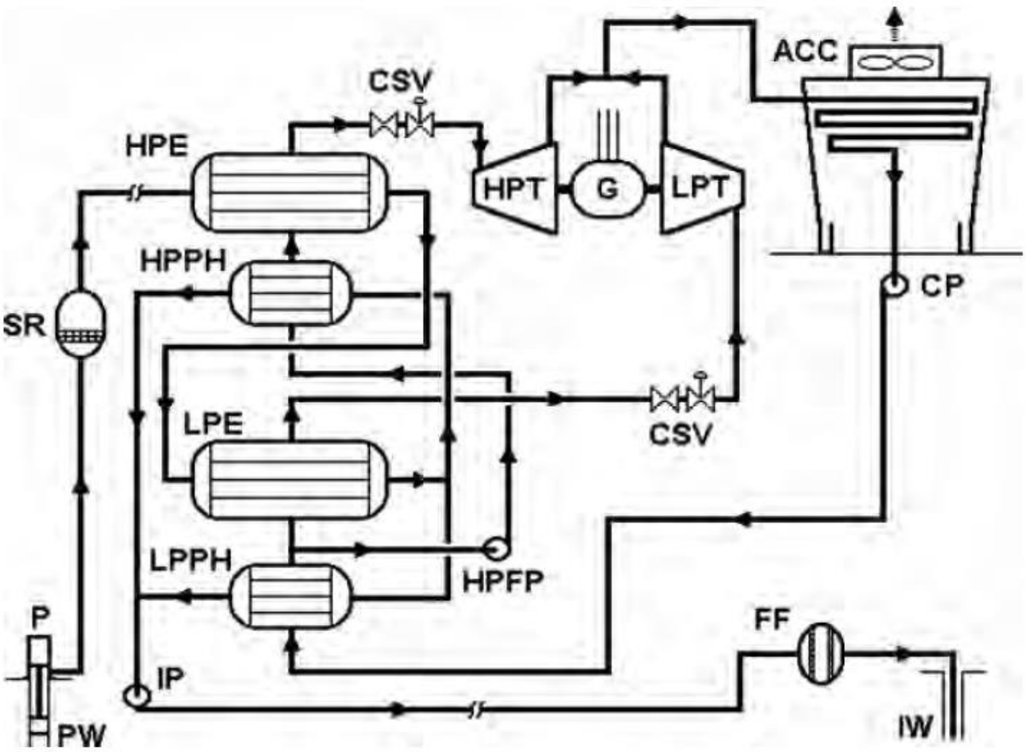

Figure 4-16 **Dual-pressure plant with a separate high and low-pressure turbine.**

- **Dual-fluid binary cycle**: the first binary plant commercially operated in the US had an unusually advanced design, Magmamax plant in California's Imperial Valley. Operations began in 1979 when the capacity was 12.5 Megawatts. It used a dual fluid cycle, utilizing two different types of hydrocarbon in interlocking Rankine cycles (a subcritical cycle and a supercritical cycle). A heat recuperator E2 is shown in the figure 4.17 that depicts a schematic of a dual-fluid system. This E2 connects the upper cycle holding fluid 1 and the lower cycle holding fluid 2. So far, all the cycles we have gone through in the binary cycles, have been subcritical. Concept of subcritical is that the working fluid pressure in the brine heat exchangers is kept below the critical pressure. In our case, the pressure of fluid 1 is raised to a supercritical pressure before it enters the preheater. However, we can face difficulties in raising the pressure to its supercritical value. To raise the pressure, more costly and thicker tubing inside the heat exchangers maybe required to equalize pressures on each side.

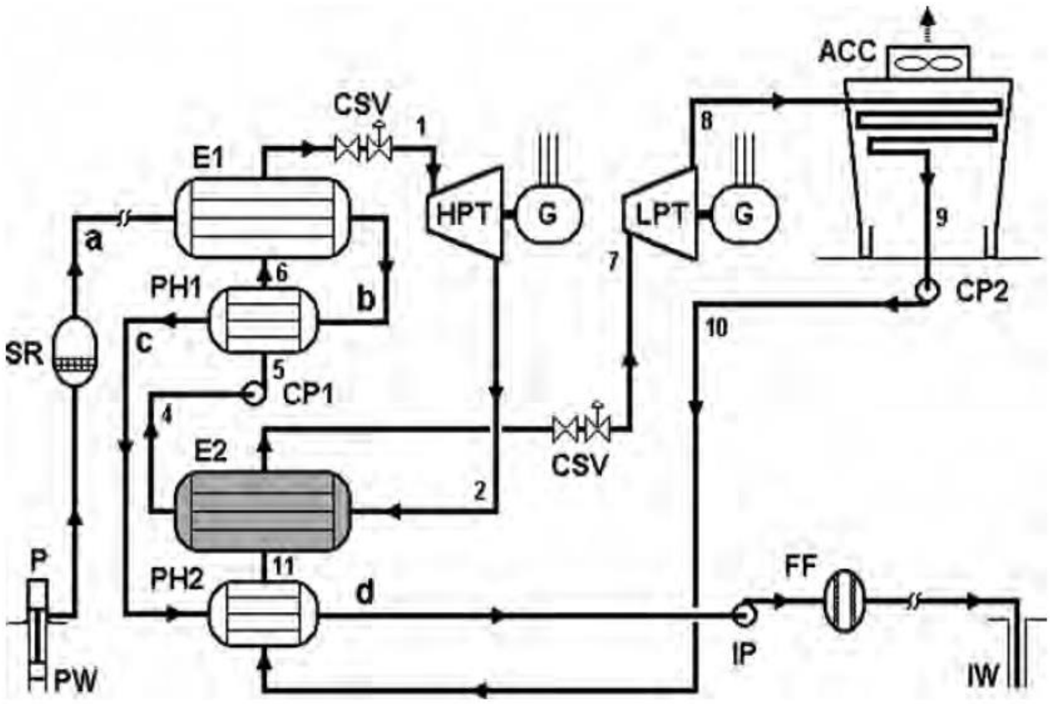

Figure 4-17 **Dual-fluid binary plant featuring a heat recuperator.**

- **Kalina binary cycles**: Figure 4.18 depicts a usual kalina cycle KCS-12. Distinct features of a Kalina cycle are as follows:

1. A binary mixture of water (H_2O) and Ammonia (NH_3) acting as a working fluid.
2. Evaporation and condensation take place at fluctuating temperature.
3. Recuperation of heat is included from turbine exhaust.
4. In some versions of Kalina cycle, mixture composition can be different during cycle.

Using the recuperative preheaters has one benefit, that the heat load on the cooling tower and the condenser is reduced. The lower capital expenditure for the smaller cooling tower and condenser must be compensated with the costly recuperators. Use of a distillation column for changing the mixture composition, makes this plant more complex than a basic binary plant. In the figure 4.19 a simple Kalina cycle with variable working fluid is shown. A saturated rich ammonia vapor flows through a turbine via a Separator S, this allows us to use smaller and economical turbine unlike in the case of hydrocarbon working fluid. A liquid which is rich in water (weak solution), is used in a preheater before being choked down to the turbine exhaust pressure. for the restoration of the primary composition, it is then mixed with the strong solution. Before the mixture can condense, it is used in a recuperative preheater RPH.

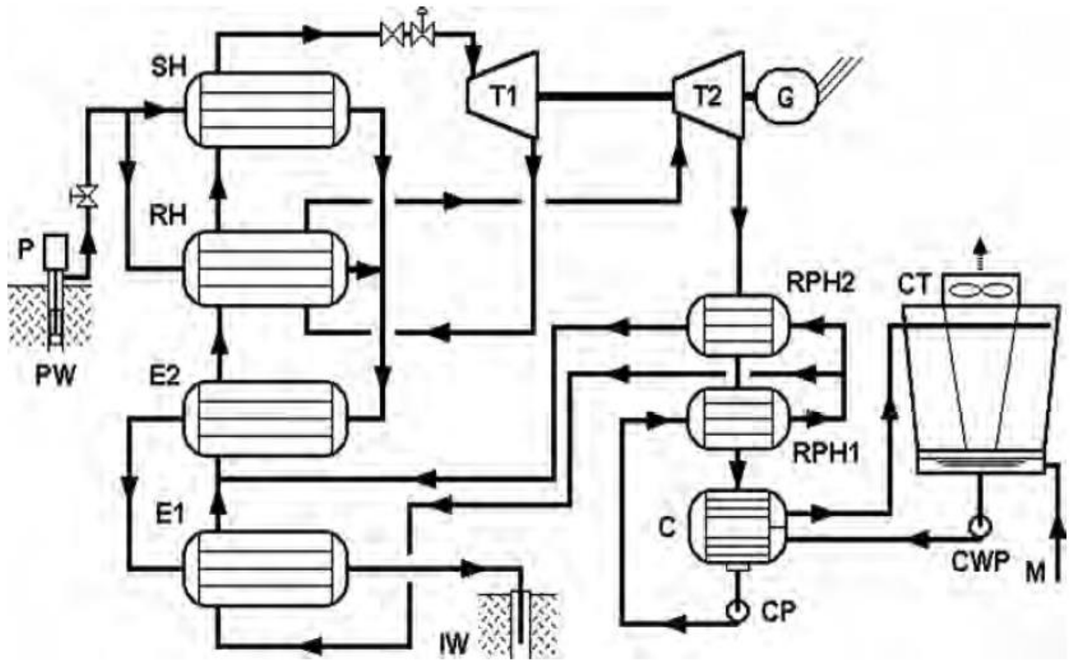

Figure 4-18 **Typical Kalina cycle employing a reheater and two recuperative pre-heaters.**

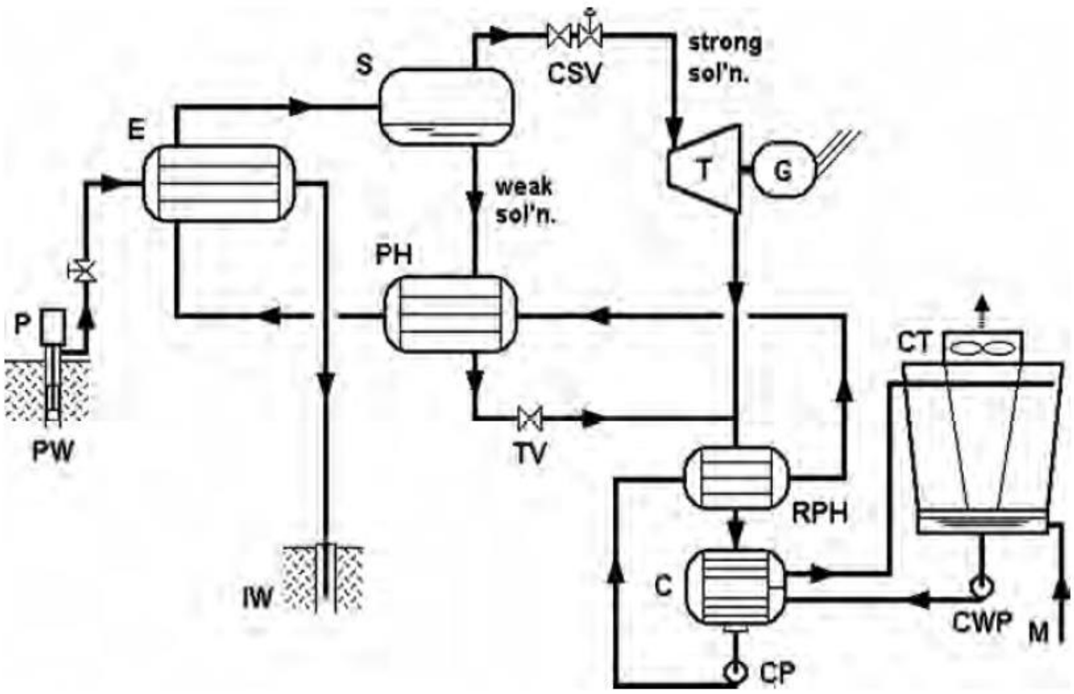

Figure 4-19 **Kalina cycle with a variable water-NH_3 working fluid composition.**

5. COMPARISON OF GEOTHERMAL SYSTEMS IN PAKISTAN AND ITALY

5.1 Pakistan's Energy background

80 % of the electricity produced by Pakistan comes from fossil fuels, namely: diesel oil, furnace oil, natural gas and gasoline. Additionally, 15 % of electricity generated is contributed by other resources like hydropower, nuclear and wind power. Imported fossil fuels play a huge part in Pakistan's economy which estimates the annual import bill to be more than USD 15 Billion per year.

Conventional sources of energy like mentioned above, have shared the energy burden for decades. Now, there is a dire need to shift the focus towards renewables and other alternative resources. One of the reasons being, at the present rate of fossil fuel consumption, they will not last very long because they are limited. Further reason being, that the greenhouse gas emissions (by burning fossil fuels) play a fundamental role in climate change, resulting in global warming. Additionally, considering the oil prices of today, many developing countries like Pakistan, cannot afford to import petroleum in excess to fulfil their energy needs. (Zaigham, Geothermal Energy Resources of Pakistan, 2005)

As for Geothermal energy, although no past governments, organization or individual has evaluated it's potential, Pakistan has vast geothermal energy resources. As of today, no official study has been carried out on any geothermal site in the country regarding geochemistry, geophysics, reservoir evaluation and water flowrate. Geothermal energy resources can be found in all the provinces of Pakistan, which can be exploited for electricity generation, district heating, hot water supply and other direct uses. This in turn will reduce the desperate dependence of the country on imported fossil fuels.

Source	Local (%)	Imported (%)
Coal	0.42	4.5
Crude oil	6.4	11.94
Petroleum products	-	18.81
Gas	41.60	-
Gas + LNG	-	0.66
LPG	-	0.22
Electricity	-	0.45
Nuclear electricity	1.92	-
Hydro electricity	10.75	-
Other renewables	0.27	-

Table 5-1 Energy supply sources in Pakistan source: HDIP 2016. (Farah, 2017)

5.2 Geography of Pakistan

Having a total land area of 800,000 km^2, Pakistan lies at 24°N to 37°N latitude and 61°E to 76°E longitudes. The country's length is 1700 km from north-east to south-west and its east to west width is 1000 km. the land features of Pakistan are diverse, and they vary from tall peaks of the Himalayas, Karakorum range, Hindukush and Pamirs in the north to the captivating shoreline of the Arabian sea in south. In the centre of these extreme northern and Southern features, we can find exceptional north-south oriented mountain ranges and fertile lands along the banks of 3000 km long river Indus. The other notable geographic landmarks include famous Thar desert that borders the India's Rajasthan region, vast tectonic depression of Kharan in west (part of Chagai volcanic arc). (Ahmad, 2014)

5.3 Geology and the potential Geothermal zones in Pakistan

Pakistan is a country with a long geological history involving tectonic events, that itself is a testimony that some large geothermal energy resources are available in different regions of the country.

Pakistan's geodynamic setup is majorly influenced by the tectonic plate motion theory which includes the north-northeast oriented compression motion by the Indian plate due to the upper mantle convection current; more easily known as the convergence of the Indian plate with the Eurasian plate. The interaction of Arabian, Indian and Eurasian plates in shown in figure 5.1. (Ahmad, 2014) Furthermore, a large-scale of fumaroles and various mineral alteration zones (especially found in the northern region near Himalayas), numerous hot springs found throughout the country, and evidence of quaternary volcanism in the Baluchistan province, strengthen the potential of geothermal energy in the country.

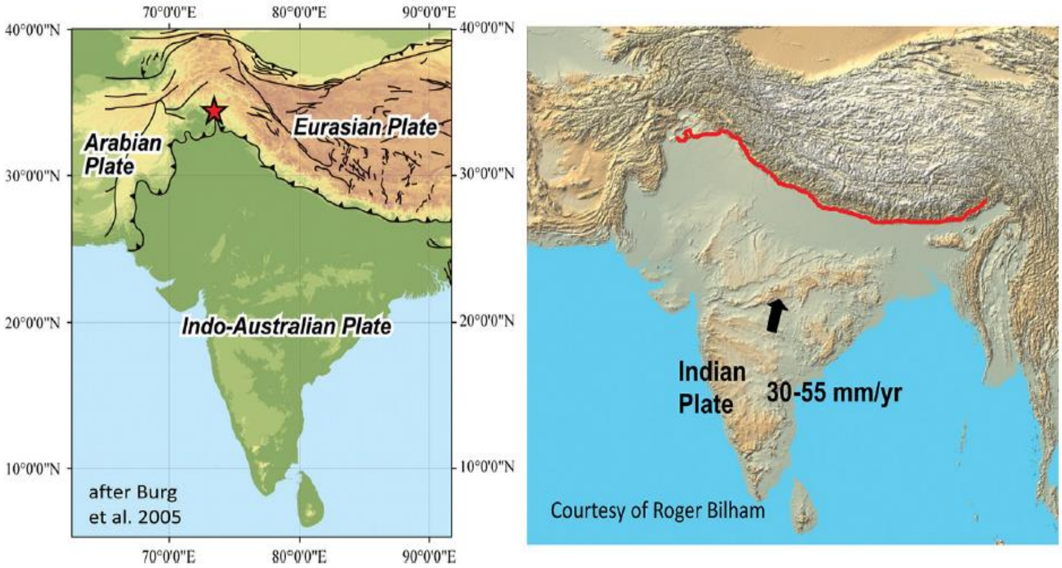

Figure 5-1 Due to the interaction of Arabian, Indian and Eurasian plates, Pakistan's seismic boundary was formed. The Indian plate has moving in northward direction at a rate of 40 mm/year. It collides and is forced beneath the Eurasian plate.

Based on these observations, Pakistan's geothermal energy resources can be classified and accredited to three zones:

1. The northern Himalayan region

2. The sedimentary basins of Pakistan

3. The Chagai volcanic Arc (Baluchistan)

1. **The northern Himalayan region:** this region is linked with the global geothermal belt. MKT (the Main Karakoram Thrust), which is related to this belt, stretches to Myanmar in east and to the Alps in the west. This area consists of hot springs and is a high temperature geothermal region. It is a plate tectonic zone extending to the North including some parts of the Kashmir region and is situated along the suture zone of Eurasia. The active secondary faults and volcanic consequence in the shallower Earth's crust act as the heat sources in this area. numerous thermal manifestations are found along this region. 50 kilometres northwest of Chitral, In Garam Chashma, thermal springs are found along the Ayun and Reshun Fault region. These springs are situated in an area of extremely high seismicity. Another hot spring is stated to be near Pechus glacier (105 kilometres northeast of Mastuj). This spring is near the contact of granite invaded in cretaceous sediments. A hot spring giving away sulphurous smell, is also reported about 3 kilometres north of Rawat village in Yasin district. This hot spring is emitted by the metasediments of Darkot group. (figure 5.2) 5 springs in a cluster are found near Murtazabad village (located near the MKT). (Zaigham, Geothermal Energy Resources of Pakistan, 2005) temperature range of these hot waters is 26°C to 91°C. range of reservoir temperature at this site is estimated to be 198°C to 212°C. In the district of Skardu (farther in south-east), three hot springs and two sulphur springs have been reported. The max temperature of these springs is estimated to be 71°C.

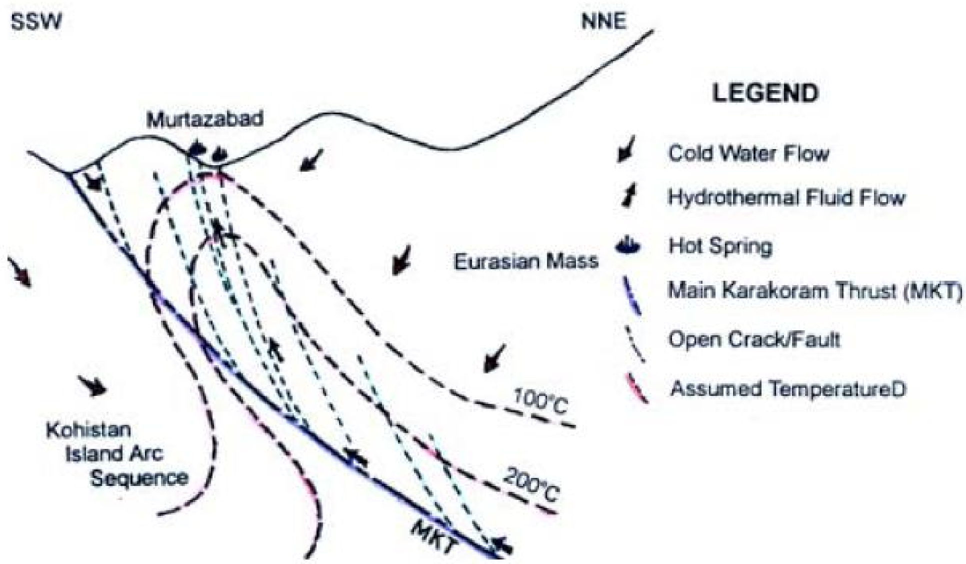

Figure 5-2 **Hot spring occurrences on Karakoram-Himalayan thrust zone.**

Several hot springs have been witnessed in the Tatta Pani area, which are situated on the both sides of Rakhiot bridge. These springs are spread over 8 kilometers. Along the Indus (western margin of Nanga Parbat and Haramosh Massif) a couple of Hot springs have been reported originating from the Raikot fault system. Water temperature at the surface was measured to be 54°C, whereas the range of reservoir temperature was estimated between 48°C to 152°C.

Figure 5-3 Heat flow values of potential Geothermal areas in North

2. **The sedimentary basins of Pakistan:** the interaction of Indian, Arabian and Eurasian Plates also resulted in Pakistan's large sedimentary basins. Bela-Chaman transform zone (which is a long 800km transform zone) separates the country's two major sedimentary basins, the Indus on the east side and Baluchistan on the west side.

2.1 The Indus Basin: regarded as a major sedimentary basin, the hot aquifers found here are linked with the hydrocarbons and linked with the secondary faults in the basin. Numerous geothermal springs have been reported here. The Indus basin can be subdivided into Upper, middle and lower Indus Basin.

- **Upper Indus Basin:** also known as the Northern Indus Basin, this part covers the entire Northern Punjab province and Kohat-Bannu areas of KPK province. This basin which consists of marine and continental fluviatile sediments (up to 7000m), dates to Pre-Cambrian to Pleistocene era. (Ahmad, 2014) The basin famous for hot sedimentary aquifers in the country is the Potwar-Kohat Basin (part of upper Indus Basin). This basin is considered the largest geothermal basin of Pakistan, consisting of many commercially producing oil and gas fields. There are a lot of wells in this area coproducing hot waters with temperatures estimated to be 80°C to 140°C. many dry wells were capped due to hot water and high pressure of the basin. Table 5.2 shows the temperatures recorded in the dry, producing and abandoned wells.

S.No	Depth	Temperature C°	Temperature F°
1	5734	160 c	
2	5840	139 c	
3	5000	116 c	
4	4618		222 F
5	4900		292 F
6	5319		291 F
7	4739	130 c	
8	4517		232 F
9	5367		292 F
10	3950		215 F
11	5175		257 F
12	4792		267 F
13	5119	142 c	
14	5300		284 F
15	3950		212 F
16	4784	114 c	
17	4601	114 c	
18	3711	99 c	
19	4940	136 c	
20	4814		265 F
21	4223	252F	

Table 5-2 Upper Indus sedimentary basin (temperature in oil and gas wells) source: Petroleum companies in Pakistan.

- **Middle Indus Basin:** consists of a fold and thrust in the west, a platform in the east and in the centre, it has a depression. Hydrocarbons formations related to Jurassic, Cretaceous, Palaeocene and Eocene periods have been found in this basin. Anticlines are the characteristic of this fold belt, with a thick sedimentary layer making it a major hydrocarbon generating spot. Fault traps, stratigraphic traps, salt produced traps and compressive faults are the characteristics of the platform, which is a west dipping monocline. Numerous hot water aquifers related to sedimentary basins and geothermal springs have been reported at different locations in the Middle Indus Basin. Throughout this basin, sedimentary rocks of Pre-Cambrian to Quaternary ages are present. Table 5.3 shows the temperature of geothermal waters recorded in dry and producing wells.

S.no	Depth	Temperature C°	Temperature F°
1	2226	105 c	
2	3601	116 c	
3	4406	125c	
4	4581		257 F78
5	4456	93 c	
6	2020		182 F
7	1062	65 c	
8	2100	60 c	
9	1646	74 c	
10	1645	79 c	
11	1590	167 F	

Table 5-3 Middle Indus basin (temperature in oil and gas wells) source: petroleum companies in Pakistan.

- **Lower Indus Basin:** this basin is filled with sedimentary rocks of Mesozoic to recent period, with thickness ranging from 5000m to 10000m. it also consists of a Platform in the east, few troughs and highs, and in the west, there is a major depression and a fold belt. Numerous hydrocarbon discoveries have been made in this region of Cretaceous, Palaeocene and Eocene formations. Hot sedimentary waters of 110°C to more than 150°C are produced in the fields situated in the upper section of the Lower Indus Basin. Geothermal gradient values above normal were encountered while exploratory drilling in the Lower Indus zone. The geothermal gradient of Damiri-1 well was 4°C/100m, while gradient of wells at Talhar and Khaskheli were in the range of 3-3.5°C/100m. one offshore well drilled at Dabbo Creek revealed a gradient value of 3.7°C/100m. (Ahmad, 2014) Table 5.4 shows the temperature of hot waters on the producing and abandoned wells in the upper Sindh geothermal area.

S.No	Depth	Temperature C°	Temperature F°
1	1679		143 F
2	1930		180 F
3	1470		168 F
4	1113		124 F
5	1830		188 F
6	1584		170 F
7	1615		176 F
8	2057		198 F
9	1168		54 F
10	1198		132 F
11	1189		130 F
12	1204		139 F
13	980	54 c	
14	2025	74 c	
15	911		128 F
16	2088		180 F
17	1712	75 c	
18	4100		320 F
19	2956		222 F
20	2848	109 c	
21	3500	126 c	
22	2743		225 F
23	3050		240 F

Table 5-4 Lower Indus basin Sindh province (temperature in oil and gas wells) source: petroleum companies in Pakistan.

2.2 Baluchistan Basin: this basin is around the subduction zone, created due to subduction of Arabian Plate beneath the Eurasian Plate. This basin consists of Tertiary and Quaternary thick clastic sediments and in the northern part there are some carbonate rocks Cretaceous, Palaeocene and Eocene periods. Some Mud volcanoes are found in the Makran coastal area along with some hot springs and fumaroles. (Zaigham, Geothermal Energy Resources of Pakistan, 2005) No surveys or related studies have been carried out on the mud volcanoes neither on the geothermal sites of the Baluchistan Basin.

3. **The Chagai Volcanic Arc (Baluchistan):** situated in the Chagai district of the Baluchistan province, this Volcanic arc is linked to active magmatic activity and some dormant volcanoes. Numerous geothermal springs have been reported in the cheken Dik area near Nokhundi town along with some fumaroles in the northwest. The origin of heat source is volcanic, with magma rising in the shallow part of Crust. The temperature of hot waters recorded in the Koh-i-Sultan area were from 120°C to 150°C. (Zaigham, Geothermal Energy Resources of Pakistan, 2005) apparently, this region has the maximum potential for exploiting geothermal energy economically in Pakistan, especially in the Southwest part of Koh-i-Sultan.

Hot spring Locality			Temperature °C	Flow Rate in l/min	pH	Electirc Cond. in µ/cm	Feature of hot water	Geology	Remark
NORTHERN PART OF PAKISTAN	Murtazabad	N1	42.3 (Ambient temp. 35.0)	33	7.5	1720	Colourless, odorless & taste less	Terrace deposit Garnet shist	Bathing & cloths washing
		N2	36.9°C (Ambient temp. 33.5)	6.7	7.8	-	Colourless, H_2S smell & sour taste	Surface Soil Terrace depost Garnet staurolite schist	Washing for prayer
		N3	30.0 (Ambient temp. 28.0)	500	9.21	2470	Colourless, H2S smell	Surface soil Terrace deposit Garnet staurolite schist	Boiling temp92°; $CaCO_3$ deposition
	BUDELAS	N8	46.0 (Ambient temp. 32.0)	100	7.85	1540	Colourless H_2S smell, salty taste	Talus/Garnet mica schist (Baltit Group)	Bathing
		N9	36.0 (Ambient temp. 17.0)	100	7.49	77.6	Colourless, H_2S smell	Talus/Garnet mica schist (Baltit Group)	
		N10	Near boiling temperature (91°C)	-	7.64	1160	Colourless, H_2S smell	Talus/Garnet mica schist (Baltit Group	
	TATA PANI	N4	83.0 (Ambient temp. 17.0)	> 621	8.83	1060	Colourless H_2S smell, salty taste	Terrace deposite or Fractured mphibolite	-
		N5	65.5 (Ambient temp. 36.5)	800	8.57	1540	Colourless, H_2 S smell salty teste	Terrace deposite/Fractured amphibolite	-
		N6	78.0 (Ambient temp.36.5)	More than 100	718	-	Colourless, H_2S smell salty taste	Terrace deposite Fractured amphibolite	-
		N7	80.0	34	8	-	Colourless, H_2S smell salty taste	Talus/Fractured amphibolites	-
	Mashkin		57 (Ambient temp. 34.4)	1	7.87	1070	Colour less, H_2S smell	Surface soil/Gneiss (Nanga Parbat Gneisses)	Cloth washing
	Sassi		54.0 (Ambient temp. 33.0)	-	7.87	1310	Colour less, Odorless	Talus/Gneiss (Kohistan Island Are sequerice)	$CaCO_3$ deposition
	Chu Tran		43.9	200	7.74	5090	Colour less, Odorless	Talus/ Limestone (Eurasian Mass)	$CaCO_3$ deposition

Table 5-5 Physical and chemical properties of hot springs in Northern Pakistan.

Hot spring Locality			Temperature °C	Flow Rate in L/min	pH	Electirc Cond. in µ/cm	Feature of hot water	Geology	Remark
CHAGAI VOLCANIC ARC	Chicken Dik		29.9 (Ambient temp: 40.9)	-	6.58	> 10,000	Colour less, odorless salty taste	Recent Deposits	$CaCO_3$ Deposition
	Koh-e-Sultan Volcanies	C2	29.5 (Ambient temp. 34.7)	< 1	7.44	1060	Colourless, ordorless salty taste	Basal agglomerate	Discharge from never bed
		C3	32.2 (Ambient temp. 38.6)	< 1	6.89	> 10,000	Colourless, odorless salty taste	Basal agglomerate	CO_2 gas bubbling $CaCO_3$ deposition Discharge from river
		C4	32.0 (Ambient temp. 36.9)	< 1	6-7	-	Colourless, odorless salty taste	Basal agglomerate	CO_2 gas bubbling $CaCO_3$ deposition Discharge from river
		C5	26.9 (Ambient temp. 31.1)	< 1	2.77	>10,000	Colourless, H_2S smell	Altered andesite	Sulphur & Salt deposition Discharge from river bed
		C6	25.5 (Ambient temp. 31.9)	-	2	-	Colourless H_2S small	Altered andesite	Sulphur & Salt deposition Discharge from river bed
		C7	27.5 (Ambient temp. 35.9)	10	7.13	> 10,000	Pale brown odorless salty taste	Basal agglomerate	Water contains Fe discharge from river bed

Table 5-6 Physical and chemical properties of hot springs in Chagai Volcanic arc.

5.4 Prospective types of Geothermal Energy that can be developed in Pakistan

- **Co-produced and Geo-Pressured Geothermal resources**: based on the different estimations viewing many depleted, abandoned and producing oil and gas wells, 40000 Megawatts of electricity can be added to the National grid by exploiting these co-produced and geo-pressured resources making the country less dependent on fossil fuels.

- **Hydrothermal Energy resources**: Hydrothermal energy resources usually resulting in several surface manifestations like hot springs (water or steam), geysers and fumaroles can be found distributed in Pakistan. Northern part of Pakistan including Gilgit-Baltistan, Kashmir and Chitral are well known for such manifestations with temperatures ranging from 80°C to 185°C. (Ahmad, 2014) it has been estimated that 30000 Megawatts of electricity can be added to the National power by exploiting such resources.

5.5 Pakistani Government initiatives and Policies

Like other developing countries of the World, Pakistan suffers from energy shortage on a consistent basis. (Farah, 2017) The reason of this shortage being constantly dependent on fossil fuels. according to a report presented by the Ministry of Petroleum and Natural Resources, due to the depletion of most of the large Oil and Gas reserves in the Country, Pakistan is set to face energy crisis for 12-15 years with conditions getting worse after 2025. (Zaigham, Geothermal Energy Resources of Pakistan, 2005) This danger of energy crisis is increasing year after year. As the country is more dependent on fossil fuels like coal and oil, producing energy from renewable resources like hydro or solar is very limited. The obvious reason being the negligence by the current as well as former Governments. To exploit these renewable resources, including Geothermal Energy, drastic measures are required to be taken by Government and Academia. Although not much research work has been done regarding Geothermal Energy can be an answer for Energy problems of the country.

In 2017, a proposal was made in the National Assembly of Pakistan (Parliament of Pakistan) to carry out feasibility study at Gurgur, Baluchistan. The director general of Geological Survey of Pakistan (GSP) briefed Standing Committee on Petroleum and Natural Resources in the National Assembly that in Gurgur, there is a potential of generating 5000 Megawatts of geothermal-generated electricity, while in the entire Pakistan the potential is 10000 Megawatts. He added that Pakistan can also control load shedding by developing its geothermal resources for power generation, He also mentioned examples of recent developments in Turkey and Philippines. He further mentioned that it will cost Rs991 billion for the development of Gurgur site. Besides, there is geothermal potential in Bhakkar and Zinda Pir area of Punjab. He was quoted, “We have nominated 50 sites for drilling and conducted drilling in 27 sites where we have discovered water resources. The water is hot on 500°C which can be used for electricity generation.” He also said that they required Rs140 million for 23 drilling. (The Nation, 2017)

5.6 Energy Background of Italy

Petroleum (for the most part utilized by the transport sector), natural gas (for producing electricity and heating purposes), coal and renewables are the resources mostly utilized by Italy. Most of electricity is imported, largely from Switzerland and France. Generation of Electricity is from natural gas mostly, which contributes to more than 50% the total final electricity produced. Hydroelectric power is another major source. practically, until 1960 it was the only source of electric energy. Italy being a net importer of electricity: statistics in 2014 show that it had imported 46,747.5 GWh and exported 3,031.1 GWh of energy. As nuclear power was banished in 1987 by referendum, Italy does not utilize it. Geothermal production stood at 5.92 TWh in 2014. (Wikipedia, n.d.)

5.6.1 Italy's latest status on Renewables

Statistical report mentioned in the issue of the "Energy from Renewable Sources in Italy – 2015" presents the current scenario on Italy's renewable sources, a constantly evolving and developing sector. As per this report, on the Italian energy landscape, renewables play an important role. Renewables are extensively used for electricity production (Electric sector) and heat production (Thermal sector). In 2015, renewable sources had powered some 697,506 installations in Italy (overall installed capacity of 51,475 MW), an 880 MW (+1.8%) improvement from 2014.

5.6.2 Production of electricity from renewable sources

From 2008 to 2014 production from the renewables had reached a new record, breaking records year after year. But in 2015, production totaled 108,904 GWh, which is a drop of approximately 12,000 GWh compared to the previous year (9.8%).

In 2015 too, hydropower was the sole largest contributor for electricity generation, although the production had decreased considerably against 2014 (-22%): with 45,537 GWh, hydropower contributed to 42% of the total production from renewables. Significance of renewable sources like solar, wind and bioenergy has increased in recent years, following in 2015, 58% of national electricity was produced from them. importantly, in 2015 renewable sources contributed to almost 38.5% to total gross national electricity production. although hydrocarbons, natural gas, still remains the major contributor for electricity generation in Italy.

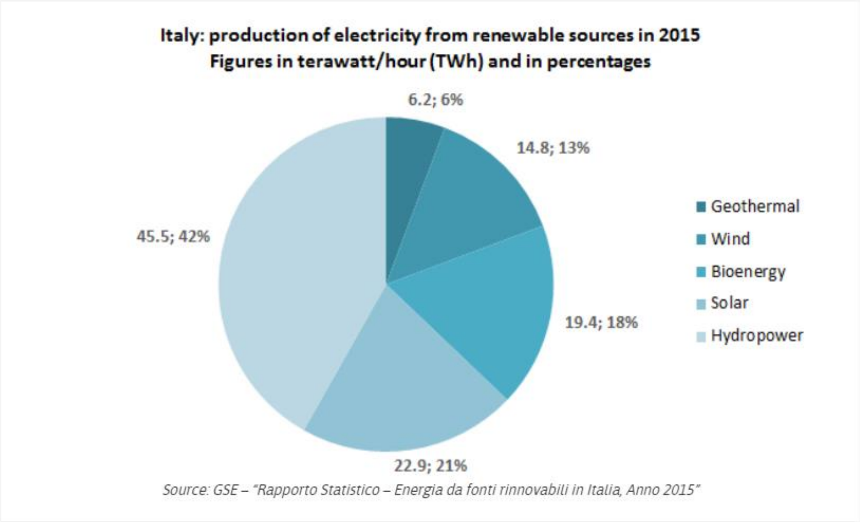

Figure 5-4 Electricity produced from renewables in 2015.

To better understand the development of wind, solar, geothermal and biomass sources from 2006 to 2015, hydroelectric power has been excluded from the chart above which shows the production from renewable sources in Italy.

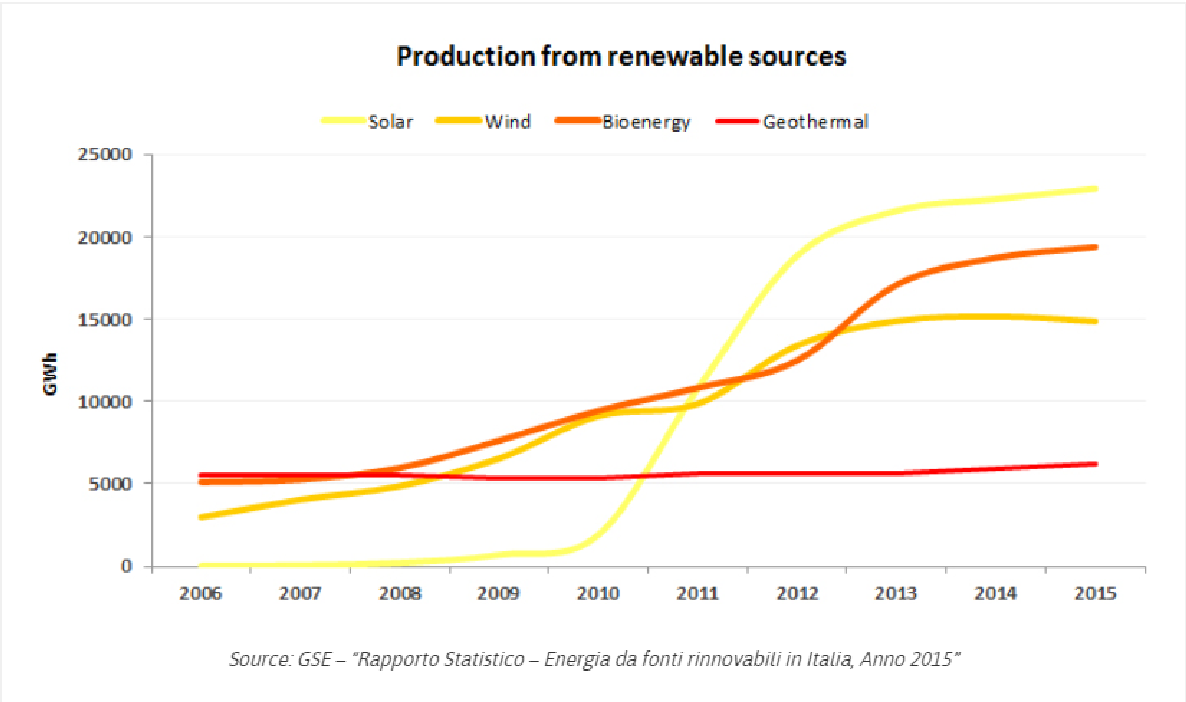

Figure 5-5 Production from renewables (with Hydropower deducted)

5.6.3 Power production from Geothermal energy

By the end of 2015, 34 geothermal power plants were installed in Italy, with combined installed capacity of 821 MW. All the 34 installations found in Italy are concentrated in Tuscany. In 2015, 6.185 GWh of electricity was produced at these installations. Also, in 2015, from all the renewable sources, geothermal power contributed to 5.6% of the electricity produced and 1.8% of the national production of electricity. The contribution of electricity from the geothermal energy to the electricity produced from other renewables has been variable over the years, increasing to the highest 12% in 2007 all the way from 9% in 2000, and in 2013-14 decreasing to a minimum 5%, because of the increased production from other renewables. The average contribution of the geothermal power to the total electricity produced (from all the sources) in Italy, has been almost constant at 1.6-2% during its timespan. (Palazzo, 2017)

5.7 Geography of Italy

Italian territory expands southward into the Mediterranean Sea as an extensive boot-molded promontory. The land area of Italy is 301,217 km^2 consisting of 20 regions. The country is 1330 km long. This expansion has helped to create individual waterways that are Tyrrhenian Sea, Ligurian Sea, Ionian Sea and the Adriatic Sea. Italy has contrasting climates with moderate in south (typical Mediterranean) and continental in north.

The Alps dominate the northern part of the Country, which is an extensive mountain range stretching all the way from France to Austria and along the Adriatic Sea in the Southern part. Mont Blanc or Monte Bianco (as it is called in Italian) is the highest peak of this range standing at 4748m. this mountain is shared by both France and Italy.

Several beautiful mountain lakes like Garda, Como and Maggiore can be found in northern Italy. The Po River flows from Turin to Venice and the valley is directly to the south of Alps. Rising in the Alps, the River Po is the longest river in Italy whereas the valley serves as the country's most fertile farmland.

The Apennines, considered as a range of the Alps, are an important part of the Italian Peninsula and they extend through south of Italy stretching towards Sicily. This range can be divided into northern (Liguria, Emilia Romagna, Tuscany and Marche), central (Latium, Umbria, Abruzzi and Molise) and southern Apennines (Campania, Basilicata, Calabria and Sicily). From the elevated areas of this range a lot of rivers flow including the Tiber and the Arno. Almost 30% of mainland Italy comprises of low areas specifically areas adjacent to the Adriatic Sea (from Ancona to Venice). Several gulfs and bays are featured by the diverse Italian coastline.

The Amalfi Coast, which is present in south of Naples, and Cinque Terre (5 villages) located north of Pisa provide some remarkable coastal spectacle as rocks sloping down the sea and colorful small houses on the cliffs.

Most islands in Italy are volcanic in origin. Sardinia and Sicily are notable large islands and the smaller islands include Capri, Elba, Ischia, and the cluster of Aeolian Islands. As mentioned above, most of Italy being volcanic in origin, a very few of its volcanoes are active today, including Mt. Etna in Sicily, Stomboli in the Aeolian Islands and Mt. Vesuvius adjacent to Naples. The latter being monitored by volcanologists on constant basis as it is potentially active. (htt2)

5.8 Geology of Italy

Italy consists of continental crust majorly except in the Tyrrhenian plain (a 10 km thick late Miocene-Pliocene oceanic crust) and in the Ionian Sea (where thick accumulation of sediments covers a Mesozoic oceanic crust). The Alpine belt has a thick crust (45-55 km) and gets thin (20-25 km) in western Tuscany and Latium.

Regarding the Lithosphere, in the western Alps it gets very thick (200 km), around 140 km thick in the central and eastern part. The lithosphere gets thinner (70 km) in areas near north Adriatic Sea and 110 km in the Southeast. Lithosphere thickness is depicted in figure 3. The lithosphere thins further to 20-30 km in the Tyrrhenian sea. evidence of it is the westward subduction of Adriatic continental and Ionian oceanic lithosphere underneath the Apennine range.

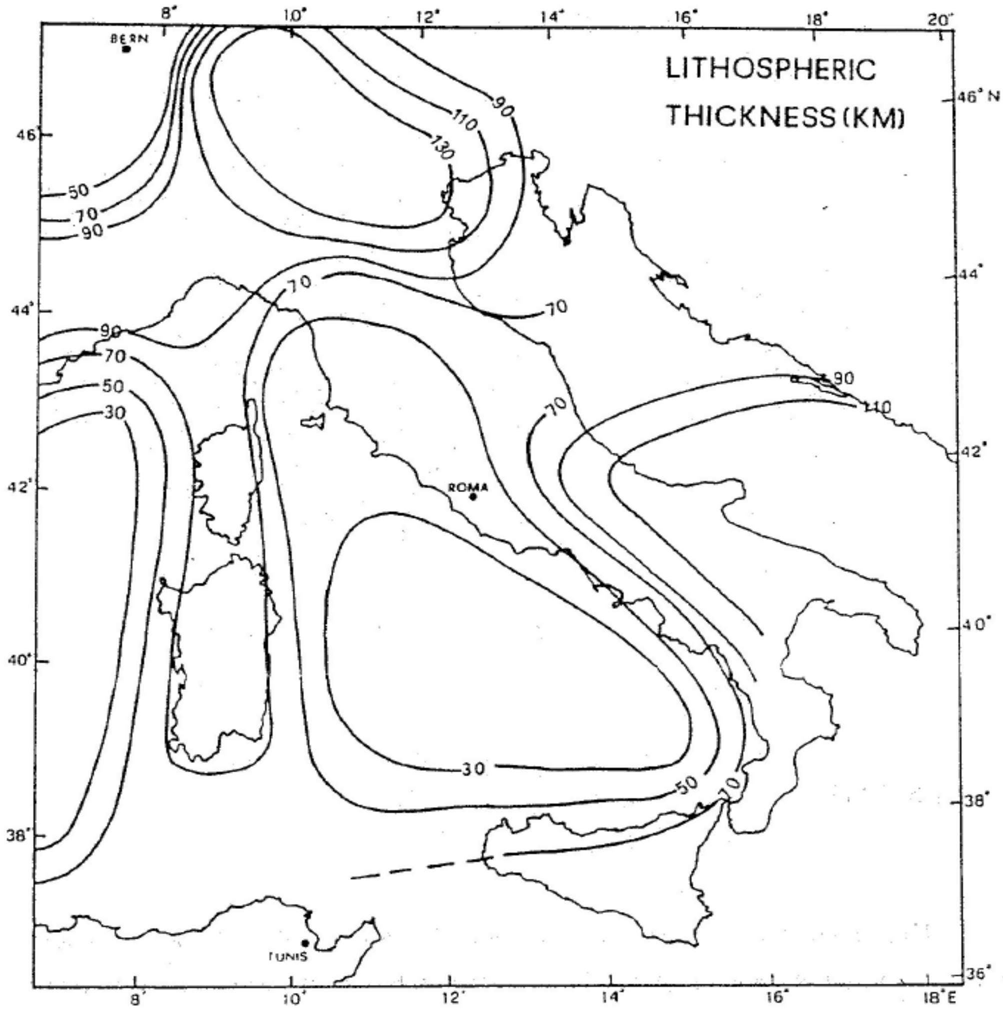

Figure 5-6 note the thickness around western Tuscany and Tyrrhenian sea.

In the Tyrrhenian sea and around the western Apennines, specifically in Tuscany we can witness very high heat flow values (200 mW/m^2) as shown in figure 5.9. While, in the foreland areas heat flow values decrease to 30-40 mW/m^2.

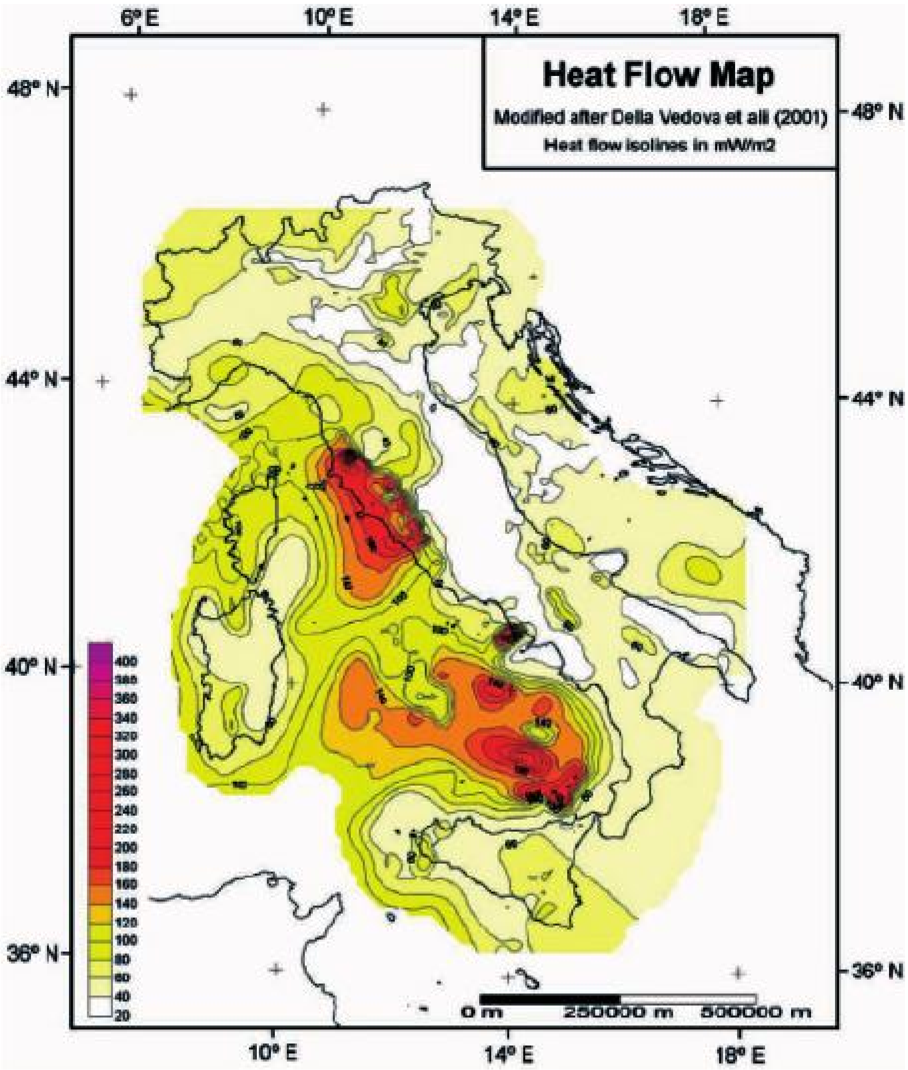

Figure 5-7 **Heat Flow Map of the Italian Territory.**

Presence of active subduction zones around the Adriatic plate, makes Italy very seismically active. Normal faults at a depth of 10 to 15 km play a main part in Apennine belt earthquakes. In the Alps and in the frontal Apennines Compressive mechanisms are present. In Giudicare, Friuli and in the Apennines strike slip mechanisms are present.

5.8.1 Tectonics

Two orogenic belts dominate the geology of Italy, the Alps (in the North) and the Apennines (running along the peninsula). The Alps were formed due to the west and northwest thrusting of the Adriatic plate over the European plate whereas, subduction of the Adriatic plate towards west was the reason behind the formation of the Apennines as depicted in figure 8. A back-arc basin can be seen to the west of the Apennines. (Doglioni & Flores, 1997)

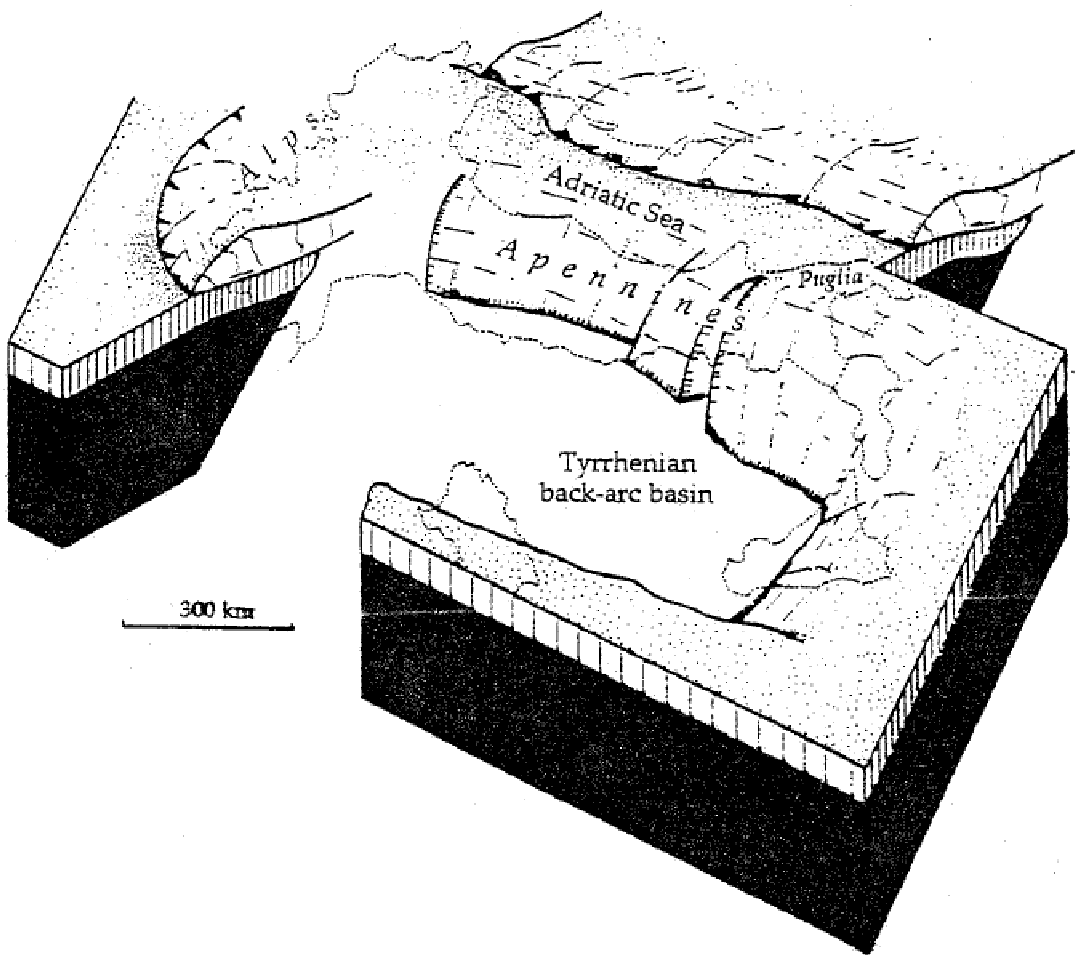

Figure 5-8 Formation of Apennines due to subduction of Adriatic Plate.

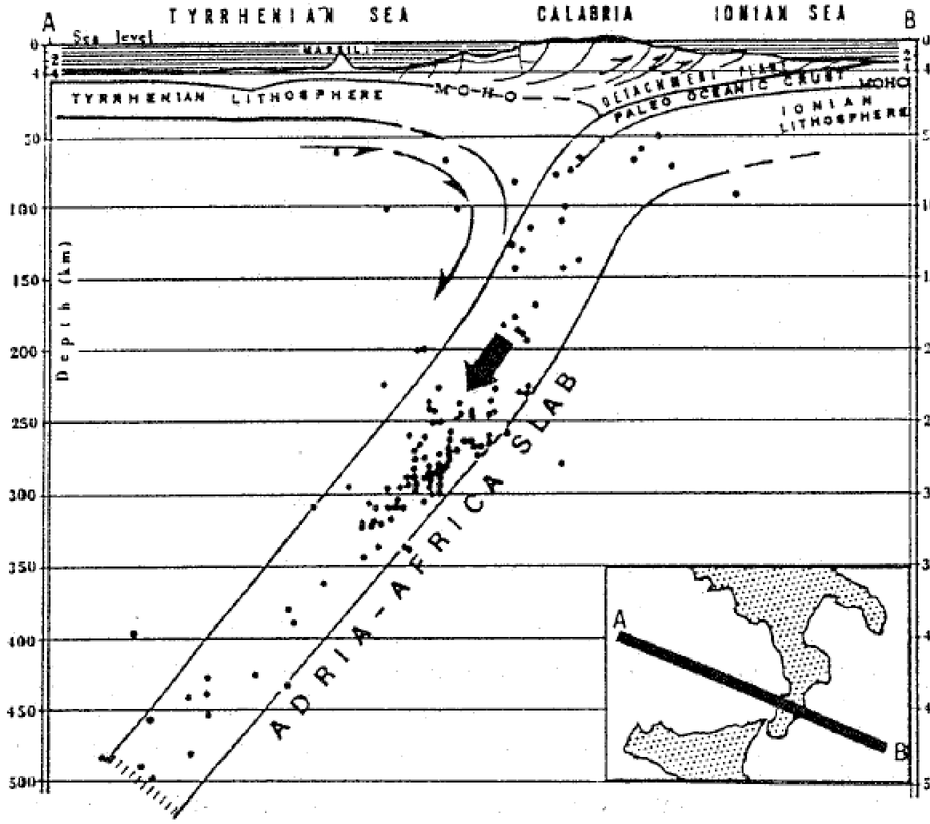

Figure 5-9 showing the cross section of Adriatic-African slab.

Arrangement and conformation is the first major difference between the Alps and the Apennines. The Alps have higher average altitude (1200-1300 m) as compared to the Apennines (400-600). Compression which resulted in the thickening of the crustal lithosphere is the main reason behind the uplift of the Alps whereas, extension or tension is the main mechanism behind the uplift of the Apennines. Being dissimilar, both the ranges have very different rates of evolution. The subduction of the Alpine belt started during early cretaceous and it continued until the Pliocene whereas, the formation of the Apennines is very recent (formed during the last 10-15 Ma).

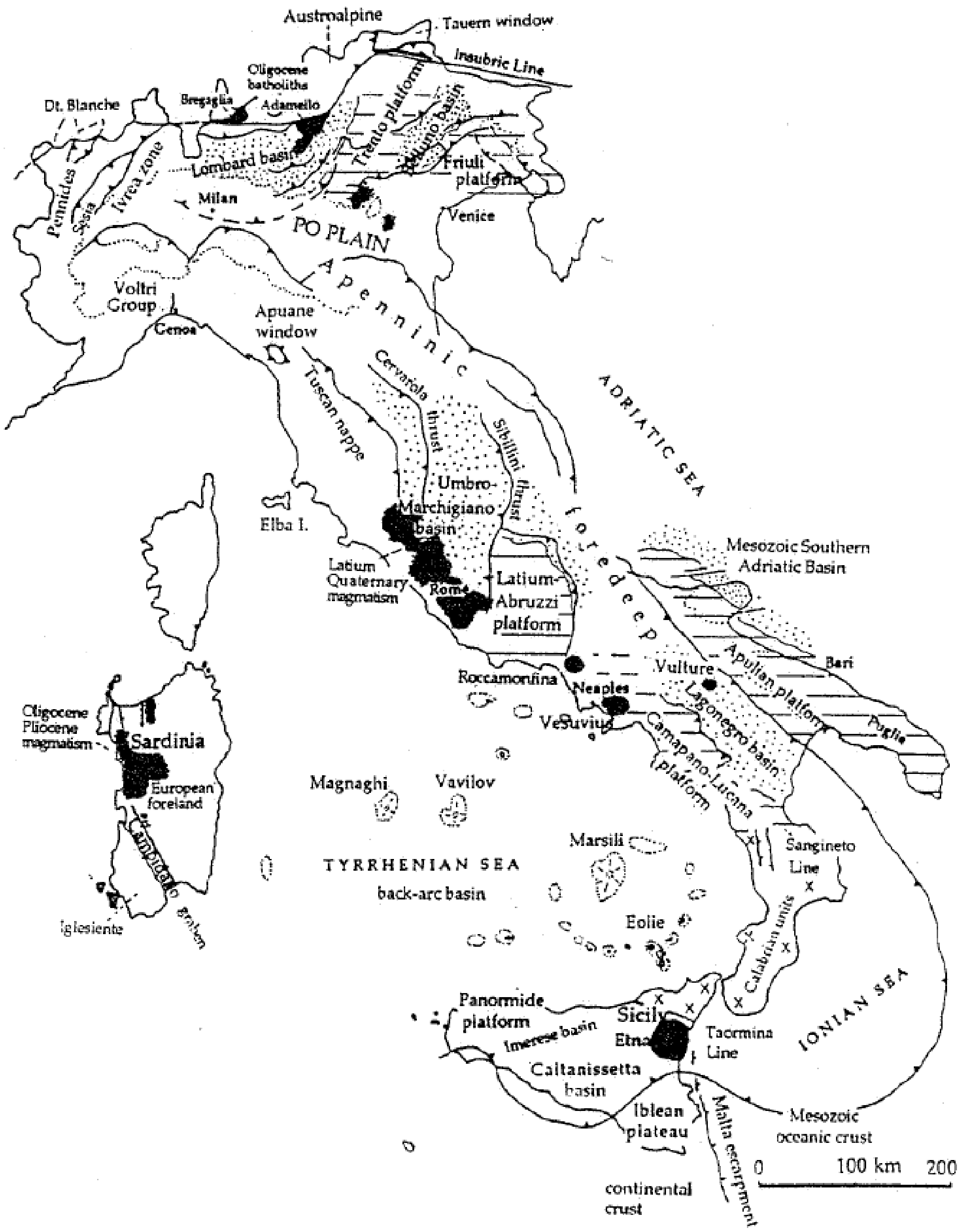

Figure 5-10 map of the main Paleogeographic and structural units in this region.

Beneath the west of Apennines and Tyrrhenian Sea a very strong thermal anomaly can be found using the heat flow map data. This strong thermal anomaly can be attributed to the large mantle diffusion (wedging in the subduction zone). (Doglioni & Flores, 1997)

5.9 GEOTHERMAL POWER PRODUCTION SCENARIO IN ITALY

The use of geothermal resources in Italy includes both for electricity generation and direct uses. All the power plants in the country are concentrated in Tuscany, in Larderello-Travale and Mt. Amiata.

As of today, the only company that produces geothermal electricity in Italy is Enel Green Power. In 2016, the gross generation of electricity reached figure of 5.9 billion kWh (installed capacity standing at 915 MWe), which is a new record regarding the geothermal electricity produced in the country. (Bertani & Romagnoli, 2017)

two new units were installed in 2010 and one unit in 2014 in addition to the six renovated units. Nuova Radicondoli GR2 (20MWe) and Chiusdino (20MWe) were installed in 2010 and Bagnore 4 (40MWe) was installed in 2014. Upgradation of the Cornia 2 power plant with a biomass-fired boiler was carried out in 2015. This upgradation allowed the superheating of the geothermal steam. These all account to 85 MWe of total capacity.

As for the direct uses, space heating (42% of the total geo energy) and balneology (accounting for 32% of the total geo energy) are the main sectors using it. Besides these two sectors, Major developments have been observed regarding ground-source heat pumps GSHPs (also known as geothermal heat pumps) and district heating systems DHs.

GSHPs are a chief contributor for the growth of direct uses, with their installed capacity doubling. Geothermal DHs are also expanding. In 2014, two district heating networks set up in Montieri and Monteverdi Marittimo started operation whereas, a new DHs network of Grado started operation in 2015. Two other networks are planned which will be set in the areas of Tuscany namely Radicondoli and Chiusdino.

Other sectors of application like Industrial uses are starting to expand again after the difficult time of economic crisis. A lot of expectations have been set on the improvement of geothermal direct uses due to the prospect of Italian economy improving.

Electricity (2016)		Direct Use (2015)	
Total Installed Capacity (MW_e)	915.8	Total Installed Capacity (MW_{th})	1,372
New Installed Capacity (MW_e)	40 MW in end of 2014	New Installed Capacity (MW_{th})	About 300
Total Running Capacity (MW_e)	761.2	Total Heat Used (PJ/yr)	10.5
Contribution to National Capacity (%)		Total Installed Capacity Heat Pumps (MW_{th})	531
Total Generation (GWh)	5,870	Total Net Heat Pump Use [GWh/yr]	906
Contribution to National Generation (%)	2.1%	Target (MW_{th})	2,500
Target (MW_e or % national generation)	1,080	Estimated Country Potential (MW_{th} or PJ/yr or GWh/yr)	
Estimated Country Potential (MW_e)	4,000		

(N/A = data not available)
(* indicates estimated values)

Table 5-7 Geothermal energy statistics regarding electricity generation and direct use.

5.9.1 GEOTHERMAL PROJECT DEVELOPMENT

Projects commissioned: no projects were set up in 2016. Nevertheless, approval was given to the 20 MW at Monterotondo. The process regarding the Environmental Approval has been given, and the incentive tariff according to the 2016 bid (will be further discussed in the Government incentives section) has been awarded. Drilling was started in 2017 with the project expected to start operations in 2019.

Projects operational: the trend of electricity generation in Italy over time from geothermal energy is shown in figure 5.13. Two sudden increasing phases can be seen in the figure. The first one was between 1930s and mid-1970s, due to the shallow carbonate reservoir development (with wells drilled down to about 1000 m). second phase was from the starting of 80s until now, due to the deep drilling activities and reinjection of water/condensed steam to artificially recharge the depleted reservoirs resulting in the increased production of geo fluids.

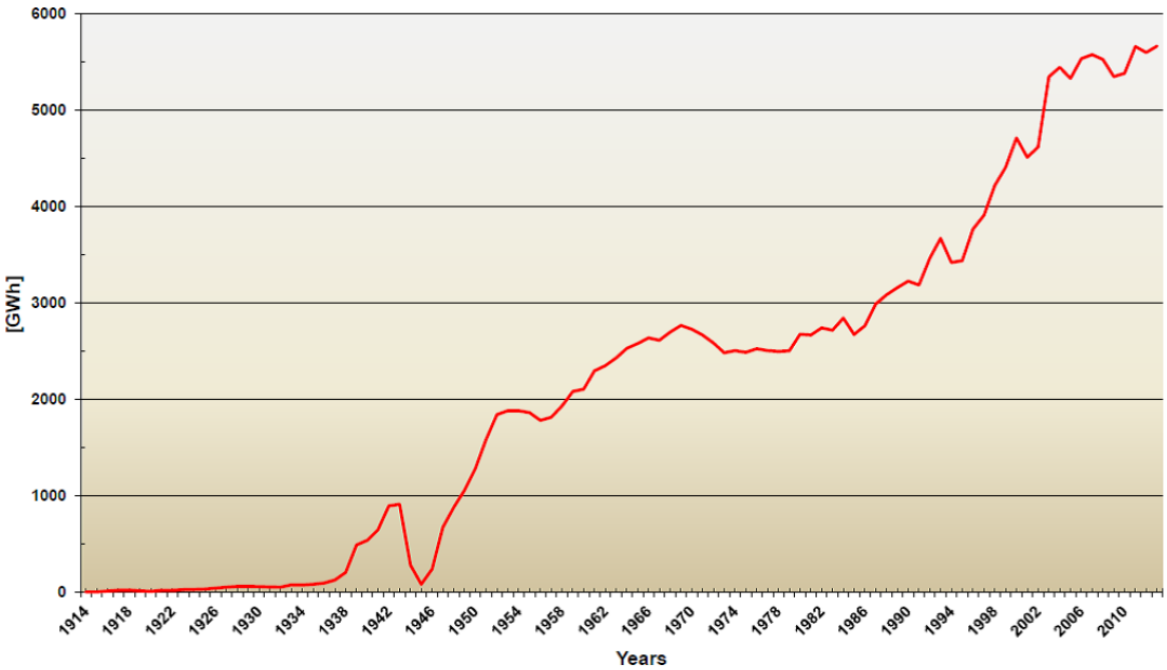

Figure 5-11 over the years trend of Electricity generation from geothermal energy in Italy.

All the geothermal power plants in Italy are located in Tuscany as shown in figure 3. Larderello, Travale/Radicondoli, Bagnore and Piancastagnaio (these last two are in Mt. Amiata area)

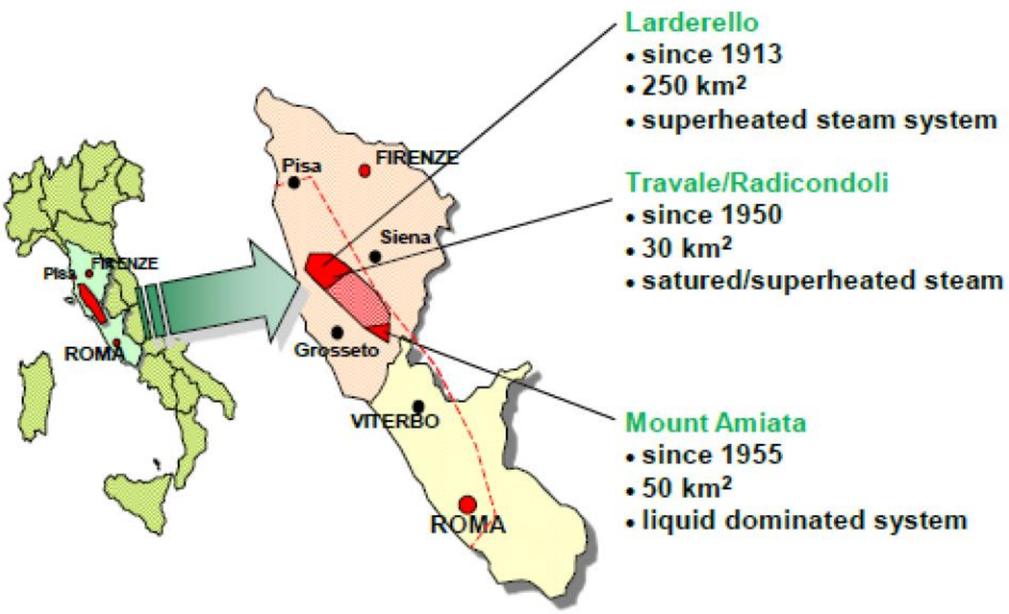

Figure 5-12 Geothermal fields in Italy.

The first Geothermal-Biomass hybrid power plant was set up in Italy, at the Cornia 2 plant in 2015. This resulted in an increased output (from 12 MWe to 17.2 MWe). (Bertani & Romagnoli,

2017) Overall plant efficiency also improved as a result. This hybrid power plant consists of superheater boiler for geothermal steam. Agriculture residues and local forest woodchip provide the combustion grate. This hybrid power plant in Italy is the first of its kind in the World (figure 5.15).

Figure 5-13 Bagnore (1 MWe) power plant.

5.9.1.1 Acquired leases

4 different exploration leases were acquired by ENEL since 2011 (figure 5.16). Area of acquired land is 1000km^2. Montebamboli and Montegemoli are in the Northwest of Larderello, Boccheggiano is in the south of Travale/Radicondoli and Murci is near the geothermal field of Piancastagnaio.

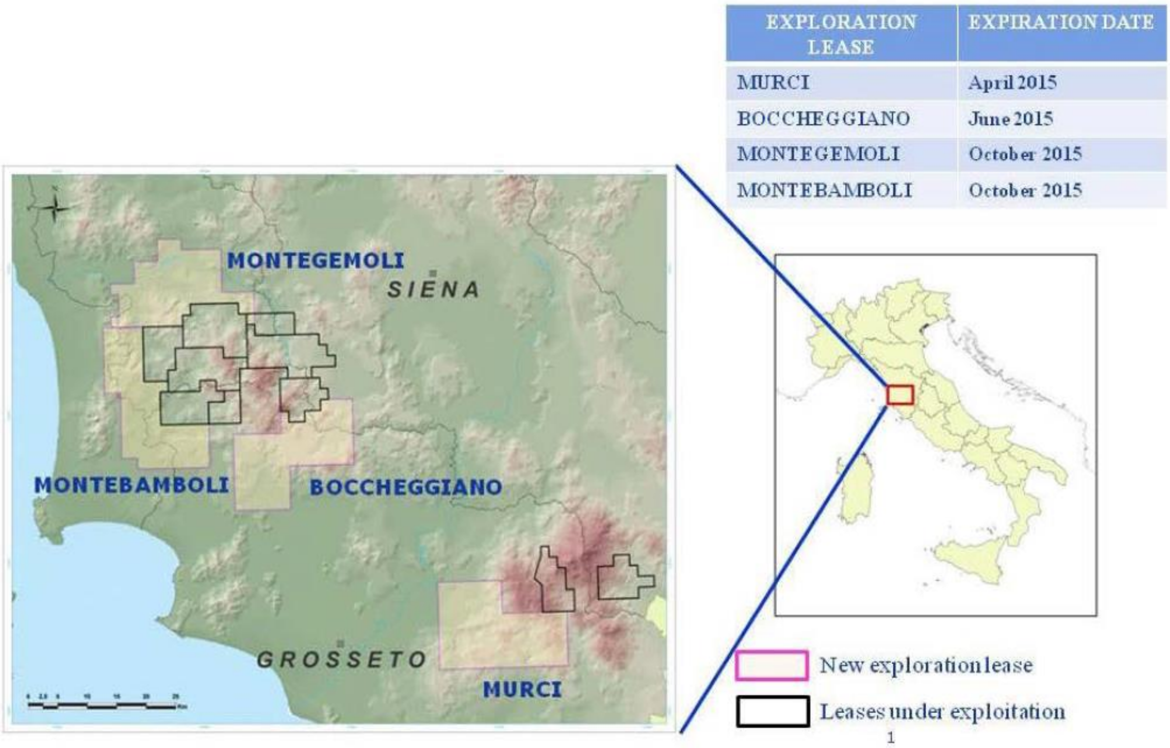

Figure 5-14 New exploration leases (EGP data)

The main purpose to acquire the exploration leases of these fields is to obtain better knowledge of the area which will help in finding fluid with medium to high enthalpy (greater than 150°C) suitable for electricity production. As of now, 2D seismic and magneto Telluric surveys have been carried out assisting in location of some slim holes and wells for the deep exploration phase. In the exploration lease of Boccheggiano three slim holes were drilled in 2015, positive results were obtained indicating possible future developments in that area. To complete the exploration phase 2 deep wells are planned along with some slim holes in near future. (Bertani & Romagnoli, 2017)

5.9.1.2 New Exploration Leases

The new exploration leases can be synthesized as:

- Released exploration leases 36
- Requested exploration leases 39
- Requested exploitation leases 2
- Pilot plant requested 10

The distribution of the lease regions is shown in figures 5.17-5.22 (indicated with their respective colors).

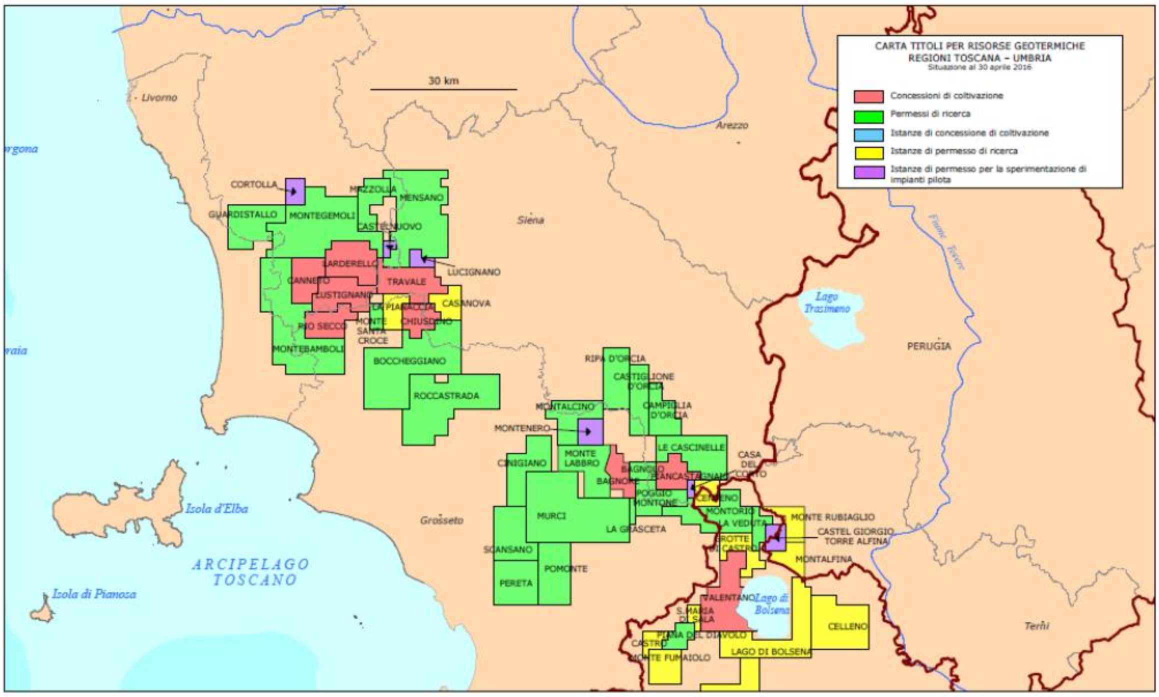

Figure 5-15 Tuscany and Umbria

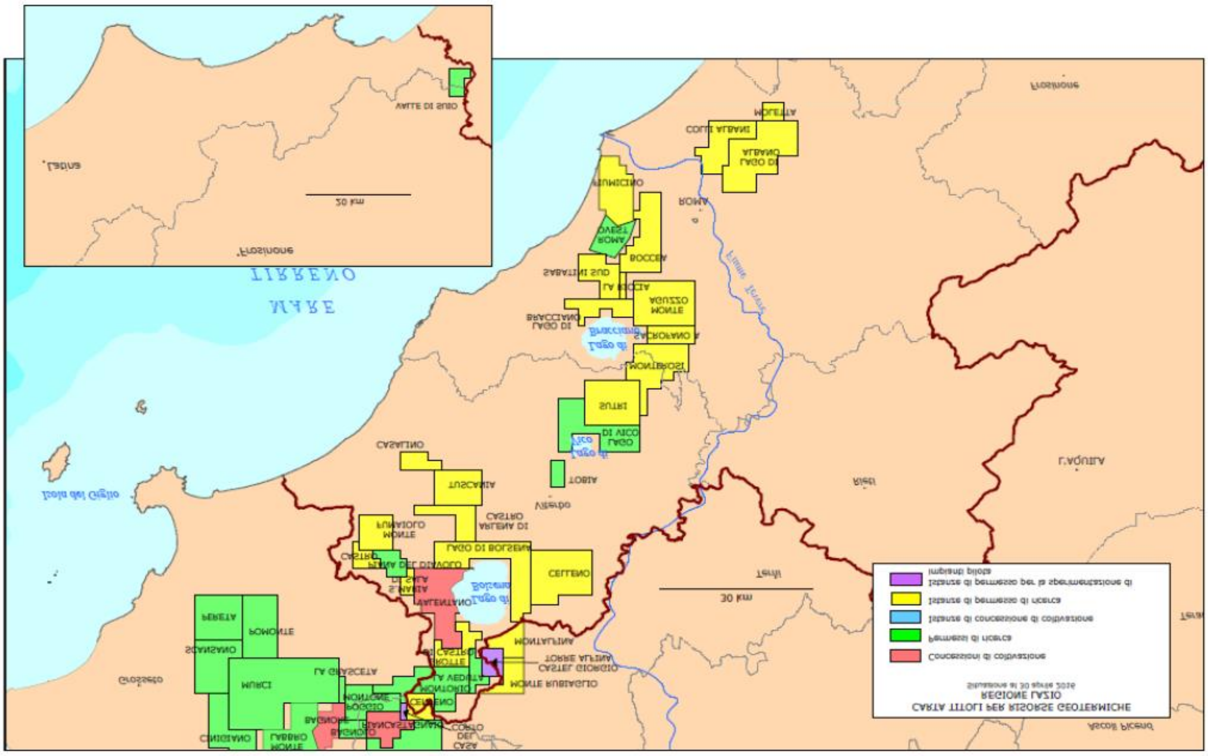

Figure 5-16 Latium

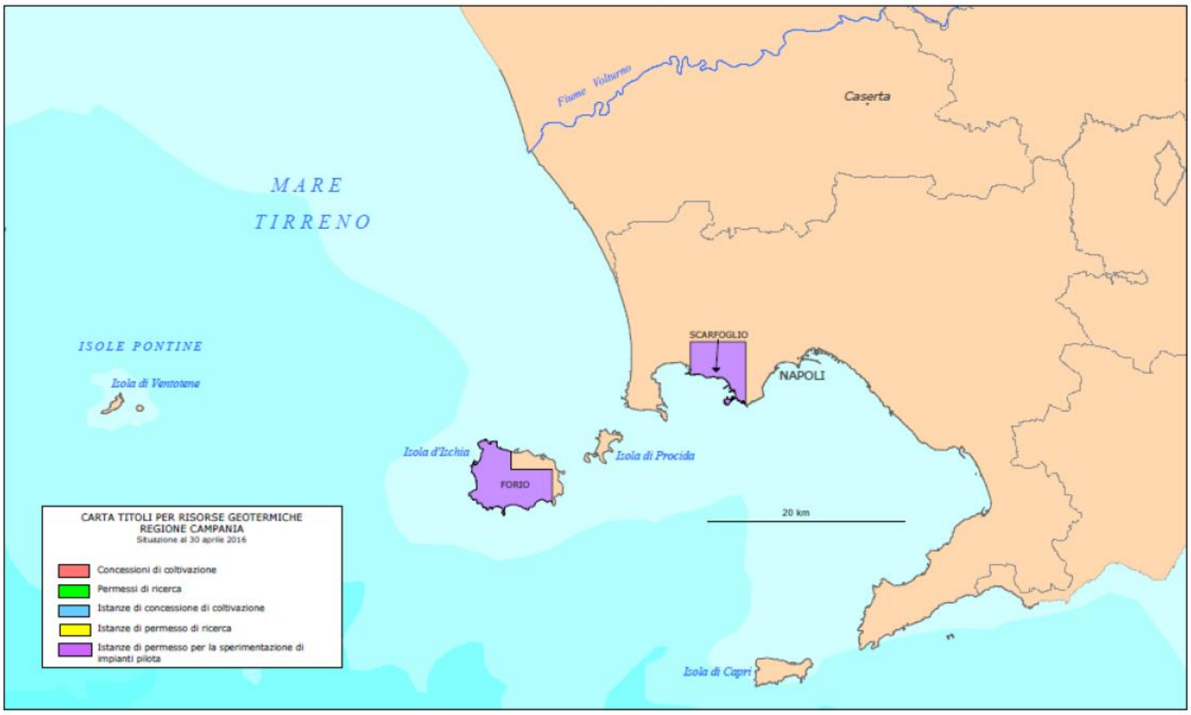

Figure 5-17 Campania

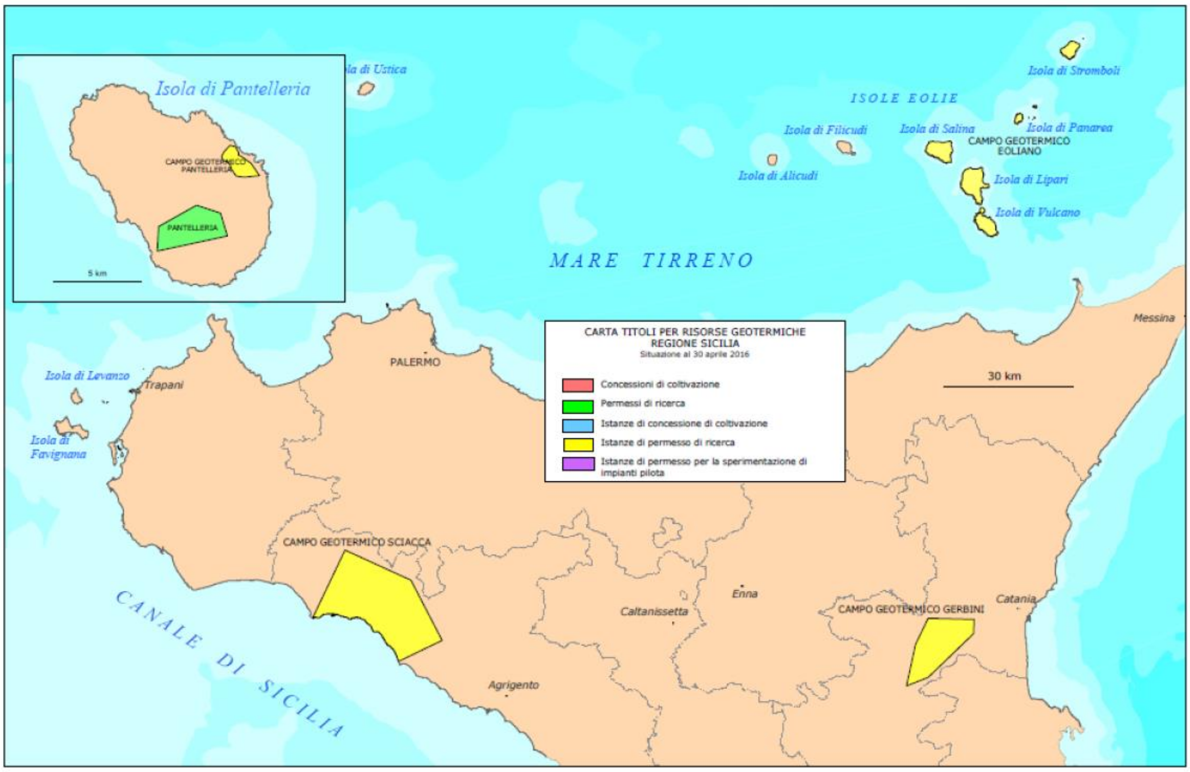

Figure 5-18 Sicily

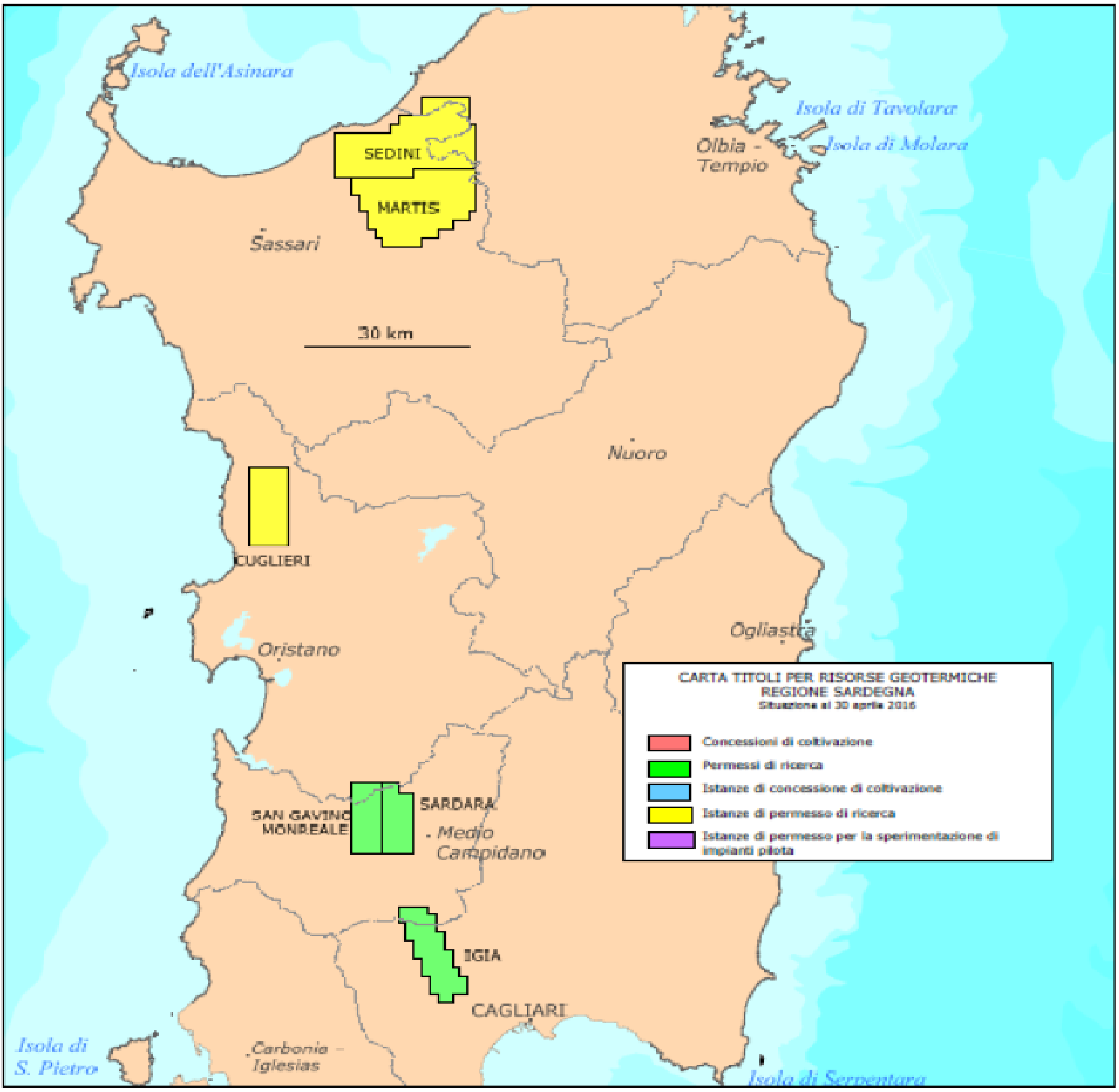

Figure 5-19 Sardinia

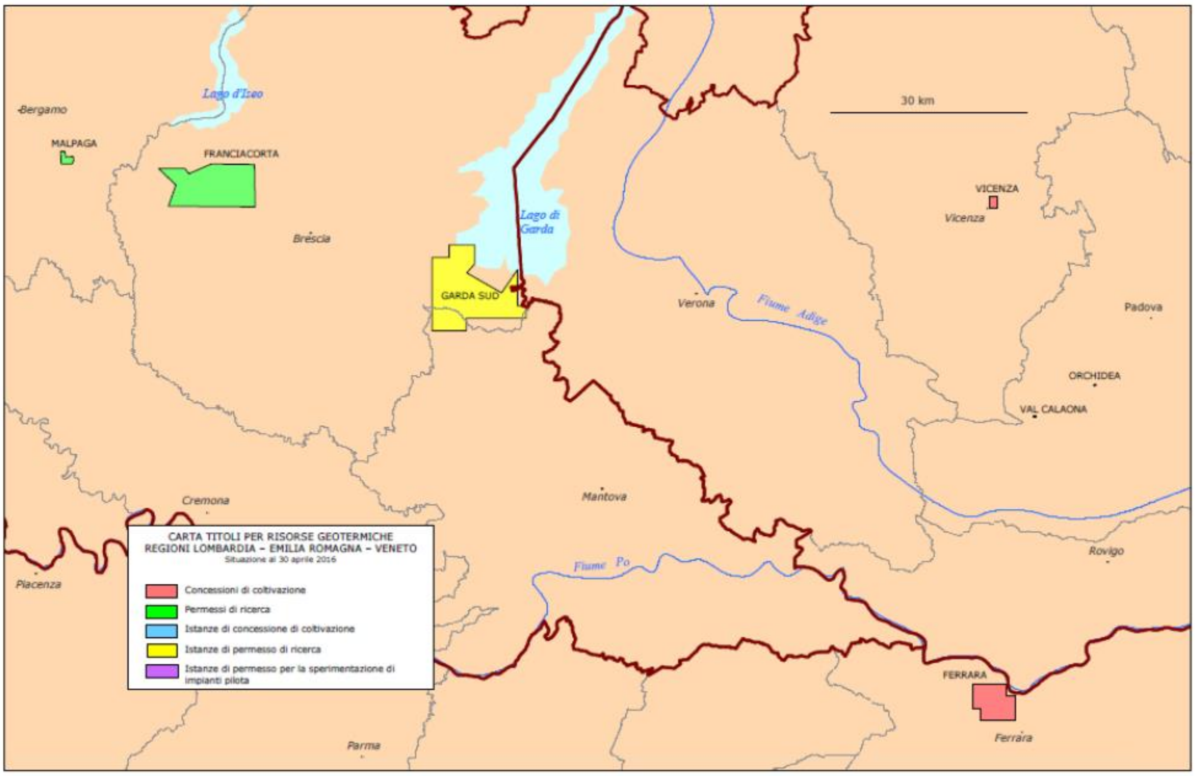

Figure 5-20 Lombardia, Emilia and Veneto

5.10 Government Policies and Incentives

In Italy, the electricity demand is about 323.5 billion kWh. 86.5% of this need is fulfilled using domestic supplies and the remaining 13.5% is imported.

Although only 2.1% of the total Italian generation is supplied by geothermal power, in Tuscany it contributes to 30% of the electricity needs.

A bill was issued in July 2012, which stated that from January 1st, 2013 no more "Green Certificates" will be granted to the any new power plants if their capacity would be exceeding 1 MWe instead an "incentive fee" will be granted to them. It is same as an all-inclusive fee which reduces by zonal energy price and additional premiums can be supplemented to them.

Average electricity market price in 2015, was almost 4.7 Eurocent/kWh. The value of electricity generated by plants having "Green Certificates" is approximately 13.7 Eurocent/kWh. Whereas, the new "incentive fee" mentioned before was 9.9 Eurocent/kWh (<20 MWe installed capacity) and 8.5 Eurocent/kWh (>20 MWe installed capacity)

The incentives scheme was amended by a new directive from the Economic Development Ministry in June 2016. However, these incentives will only be applicable on limited plants, to be officially shortlisted. If many plants demand for incentives, this process can be quite limiting. But it is expected to be smooth as the quota is high enough for planned geothermal development.

Three levels had been decided regarding standard tariff, for:

- Plants with capacity below 1 MW, tariff is 134 Euros/MWh.
- Plants having capacity between 1-5 MW, tariff is 98 Euros/MWh.
- > 5MW plants, tariff is 84 Euros/MWh.

Plants with special characteristics will be provided with an additional premium:

- A total reinjection plant (zero emission) will be provided a premium of 30 Euros/MWh.
- Installation of the first 10 MW in a new area having no prior plants will be provided a premium of 30 Euros/MWh.
- Plants with reduction of Mercury and H^2S reduction (at least 95% of the emission) will be provided a premium of 15 Euros/MWh.

Additionally, a plant using a non-commercial technology and considered fully innovative, will be provided an all-inclusive tariff of 200 Euros/MWh (with temperatures of fluid up to 150°C); this incentive will be reduced to 137 Euros/MWh at 235°C. (Bertani & Romagnoli, 2017)

6. ENVIRONMENTAL IMPACTS OF GEOTHERMAL ENERGY

Even though geothermal extraction is an important resource, it is not devoid of a big environmental impact caused by many discharges: gas is released to the atmosphere, chemicals contaminate watercourses and seas, and moreover it produces noise and it increases the seismic risk.

Geothermal fluids are two phase solutions (or a mixture) that can be separated in water and steam, or cooled in a heat exchanger, emitting gases into the air without causing adverse effects. The main gases dissolved in geothermal fluids are carbon dioxide (CO_2) and nitrogen (N_2) with small traces of hydrogen sulfide (H_2S) and ammonia (NH_3). The typical gas composition is reported in the table 6.1 below. Hydrogen sulfide is classified as a hazardous substance because of its flammability and high toxicity that can poison different systems of the body, especially the nervous one. Owing to this reason the emission of hydrogen sulfide is strictly regulated to limit its amount in the air. Many countries have adopted measures for reducing its level, for example scrubbers have been installed in the USA and Italy for cleansing the atmosphere of hydrogen sulfide emissions. (World Energy Resources , 2016)

	CO_2	H_2S	H_2	CH_4	NH_3	N_2	AR
Median	95.4	3.0	0.012	0.15	0.29	0.84	0.02
Maximum	99.8	21.2	2.2	1.7	1.8	3.0	0.04
Minimum	75.7	0.1	0.001	0.0045	0.005	0.17	0.004

Table 6-1 Composition of geothermal gas.

The environmental impact and its consequential damages depend on the intensity of emissions. The gases are present in low concentrations in the fluids that have low and moderate temperature, instead they are really concentrated in the high temperature geothermal fluids. The use of district heating systems implementing this geothermal resource at low temperature, coming from sedimentary basins allows to extract and inject fluids without any emissions of gas, and reduces the environmental impact.

One of the most important problem related to the environment regards the water pollution. The ancient and common practice of discharging the fluids to the waters or vaporizing them into ponds causing the contamination of potable water supplies has been abandoned, thanks to the community concerns about geothermal resources integrity and the obligatory inspections to the oil and gas wells, that recently are increased. Some shrewd steps also have been taken to avoid the poisoning of oceans and aquifers. For example, geothermal fluids can be conserved into specific reservoir located below the potable water level, where they are usually injected after cooling them down.

Some other regulations have been mandated to reduce the levels of noises and odors caused by the geothermal power plants. Their presence has a big impact to the community living near the geothermal stations, who complain not only about the annoying noise and odor but denounce also the lack of fresh groundwater and the ground subsidence.

The ground subsidence can be caused by the consumption of the shallow aquifers and brought to the deterioration of the surface facilities. In Steamboat Springs (USA) and Wairakei-Tauhara (New Zealand) have taken place two big cases of ground subsidence that have lead the authorities to an increased awareness of the necessity to monitor the surface to avoid other cases like the ones happened.

The last, but not least consequence of the geothermal operations is the increased seismic risk related to the practice of reinjection of the fluids in the geothermal reservoir. The EGS (Engineered Geothermal System) caused intentionally micro seismic tremors to intensify the permeability. Although this procedure has allowed the developments of the geothermal activities in the last 30 years the amounts of episodes related to it showing the induction of seismicity is increased. In the settlements of Coso (USA), Wairakei and Rotokawa (New Zealand), and Reykjanes (Iceland) micro earthquakes occurred probably because of the injections of geothermal fluids. The geothermal station of Basel (Switzerland, Europe) has blocked its geothermal activity to avoid seismic problems. Even if the community concerns regarding the risk of earthquakes is increased and has led the authorities of several countries (USA, New Zealand and Germany) to regulate and monitor this risk to understand what happens in the underground.

6.1 GREENHOUSE GAS EMISSIONS FROM GEOTHERMAL POWER PLANTS

Greenhouse gases, known as GHGs, are gases that absorb radiant energy and emit it within the thermal infrared range. They are naturally present in the geothermal resources and they are usually emitted by intermediate and high temperature fluids. They are released in the atmosphere without drilling or power production and this is probably the reason why they are not so concentrated in the outflows than the traditional fossil supply power generation units. The geothermal fluid contains non-condensable gas (NCG) in these percentages: around 95% of carbon dioxide (CO_2) and up to 1.5% in rare cases of methane (CH_4).

The increasing emergence and development of geothermal settlements and the exploitation of geothermal resources has caused the increment of gas released especially when the reservoir has a high amount of greenhouse gas. The emission of greenhouse gas is considered and regulated in different way in the world, the frameworks are various. There are some countries that not think that the discharges are a human responsibility and others that monitor it carefully every year, paying attention to the limits.

Most of the countries that have some big geothermal activities, such as the United States and New Zealand, have declared emissions corresponding to the global average in 2001, that for operational GHG emissions was 122 g CO_2/kWh. The United States has recorded a release of 106 g CO_2/kWh in 2002 and New Zealand a release of 123 g CO_2/kWh in 2012. The outflows reported in Iceland are lower than this range, 34 g CO_2/kWh, instead the one reported in Italy higher, 330 g CO_2/kWh. The values reported by the South West Turkey are excessively out of this range: between 900 g to 1.300 g CO_2/kWh. (World Energy Resources , 2016) These data are higher than the one of the fossil- fueled power plants which can increase until 1.030 g CO_2/kWh for a circulating coal plant and 580 g CO_2/kWh for open-cycle gas plant. These excessive emissions are caused by the fact that the geothermal reservoirs situated in carbonate rocks have a high temperature and increase the outflows. This situation does not happen so common, so the high emission is regulated.

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