Developing geothermal power in Puerto Rico:
Cost benefit analysis and barriers for development

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Abstract
Geothermal energy is a clean and renewable energy source. It is abundant but only a very small fraction can be converted commercially into electricity currently. The Earth's core reaches maximum temperatures of approximately 4000°C [44]. Occasionally geothermal heat is available at high temperatures in the subsurface and electrical production using turbines can be feasible [44]. The installed capacity for geothermal power has more than doubled and is due to engineering advances. Worldwide, 24 countries are generating electricity from geothermal resources (Italy USA, New Zealand, etc.)[5].

In order to determine which type of geothermal technology is suitable for an island like Puerto Rico, Enhanced Geothermal Systems for power production was studied to determine if they could be used as base load electricity. Technologies such as Dry Steam, Flash Steam and Binary cycle plants are also discussed in this report.

Other technologies such as Geothermal Heat Pumps are also discussed but briefly. Further studies have to be made Geothermal heat pumps is a fast growing application of renewables and can have a huge impact on energy efficiency and decreasing energy cost for cooling.

Acknowledgments
I would like to thank everyone who supported me during this research project. Special thanks to Jan Diederik van Wees and Ruben Contreras, who suggested this topic and provided me with feedback and new insights.

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Enhanced Geothermal Systems (EGS)

Geothermal Energy (GE)

Geothermal Power (GP)

Geothermal Heat Pump (GHP)

Green House Gas emissions (GHG emissions)

Hot Dry Rock (HDR)

Levelized cost of electricity (LCOE)

Puerto Rico (PR)

Cents/kWh (this unit refers to US dollar cents)

1.0 Introduction

The dependency for fossil fuels keeps growing world wide besides the negative effects it has on the global economy and energy and resource use. Caribbean islands, such as Puerto Rico, are facing crucial energy challenges, and have a huge need for energy efficiency and renewables due to the reliance and high dependence on imported oil for power production.

Oil prices have spiked due to increase in demand and global politics. The citizens of PR are heavily impacted by the variability of the oil prices. This has lead to high electricity rates that has an impact on the livelihood and economic resilience of the residents of the island.

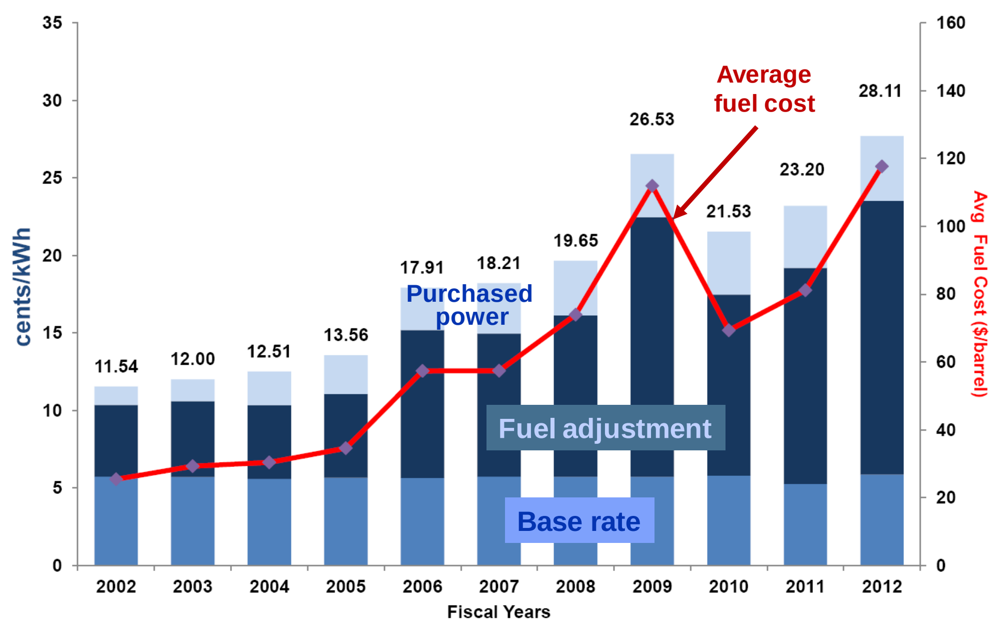

Figure 1 - PREPA average electricity and fuel cost[15]

Puerto Rico appears to have many residential energy efficiency problems that are associated with common everyday household appliances: air conditioning systems, kitchen appliances and other common items such as computers. Renewable residential energy practices such as wind power, solar, fluorescent lights can significantly improve energy efficiency, but there is still some dependency for oil.

1.1 Energy in Puerto Rico

Puerto Rico is a Commonwealth Territory of the U.S. in the Caribbean. Officially known as the Commonwealth of Puerto Rico, it is the smallest of the Greater Antilles (Cuba, Dominican Republic/Haiti, Jamaica Republic). The island of PR has land area of 13,790 square kilometers most of it mountains and also coastal plain belt in the north areas with a peak elevation of 1,338 meters above sea level (Cerro Punta) [10]. The island also has 2 populated islands to the east, Vieques and Culebra [10].

Approximately 71% of the population lives within urban communities; the remainder lives in rural areas. Continuing growth of these urban centers is pushing development onto surrounding steep slopes. According to the July 2013 census, population in Puerto Rico was 3,674,209 [10]. The overall population density of PR is 368 people per square kilometer; the density outside the four major urban areas, including the mountainous interior, is probably between 100 and 200 persons per square kilometer. The San Juan-Caguas-Guaynabo Combined Statistical Area, located in the northeastern part of the island, is the largest metropolitan area (by population) in PR.

Agriculture like coffee was once the main dominant economy in the island. During the 1950's, big American corporations invested heavily, shifting Puerto Rico's economy to an industrial sector. This industrial sector is now very diverse, which includes pharmaceuticals, food products, some electronics and apparel.

Puerto Rico has a lot of potential for developing renewables and other energy sources. In order to also tackle the reduction of CO_2, energy efficiency is essential. Figure 2 shows the CO_2 emission intensity for a period of approximately 31 years. As observed, emissions in the years 2005 and 2006 were the highest, above 37.5 million metric tones of CO_2.

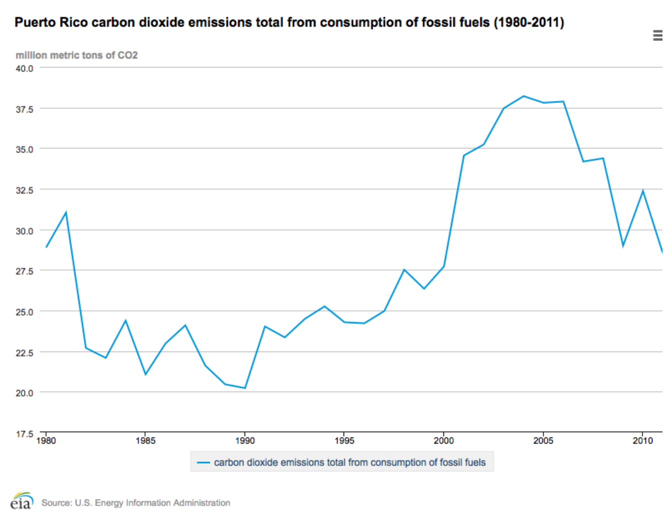

Figure 2 - CO2 emission from fossil fuels [50]

Puerto Rico enacted its first Renewable Energy Portfolio Standard in 2010. It is the first effort to support renewables and energy efficiency at the same time reducing the islands dependence on oil. The standard is to achieve a 20% renewables by 2035. In order to achieve this goal, renewable energy technologies as such geothermal power to achieve energy efficiency can benefit PR.

1.2 Electric Power Sector in Puerto Rico

The Puerto Rico Electric Power Authority (PREPA) is a government-owned corporation. It has complete dominion over the island's power production. Unlike other places in the world where there is an open electricity market to compete including one than one utility company, in PR there's only one public utility that provides electric service across the entire service territory of the island.

PREPA is largely self-regulated. Because there is no inter-state commerce of electricity, PREPA and the stakeholders in the Puerto Rican electric sector do not fall under the jurisdiction of the Federal Energy Regulatory Commission (FERC). For similar regional reasons, PREPA and other stakeholders also do not fall under the jurisdiction of the North American Electric Reliability Organization (NERC) and are therefore free to implement their own regional regulations and reliability standards.

2.0 Puerto Rico's Energy Sector

2.1 Puerto Rico Power Authority

PREPA is Puerto Rico's government-owned utility company. It is responsible for the production, transmission and distribution of electricity to approximately 1, 470,000 (June, 2010) residential, industrial and commercial customers across the island. PREPA is composed of a nine-member Governing Board. Puerto Rico's Governor appoints seven of these members after the senate approves. The Department of Consumer Affairs choses the remaining two members who represent the consumer sector via an election. The Governing Board appoints an executive director for utility operations, and divides PR into seven regions for administrative purposes.

2.2 Transmission Facilities

The Power Authority (PREPA) owns 2,416 miles of transmission lines of 230 kV and 115 kV. It also operates a 38kV sub transmission line with 175 transmission centers. The transmission system connects its power plants with different switching and load centers located throughout the island. It is composed of an integrated system, being able to provide electric power to the transmission and distribution system by each generating unit. The complete islands transmission system can be seen in Figure 3.

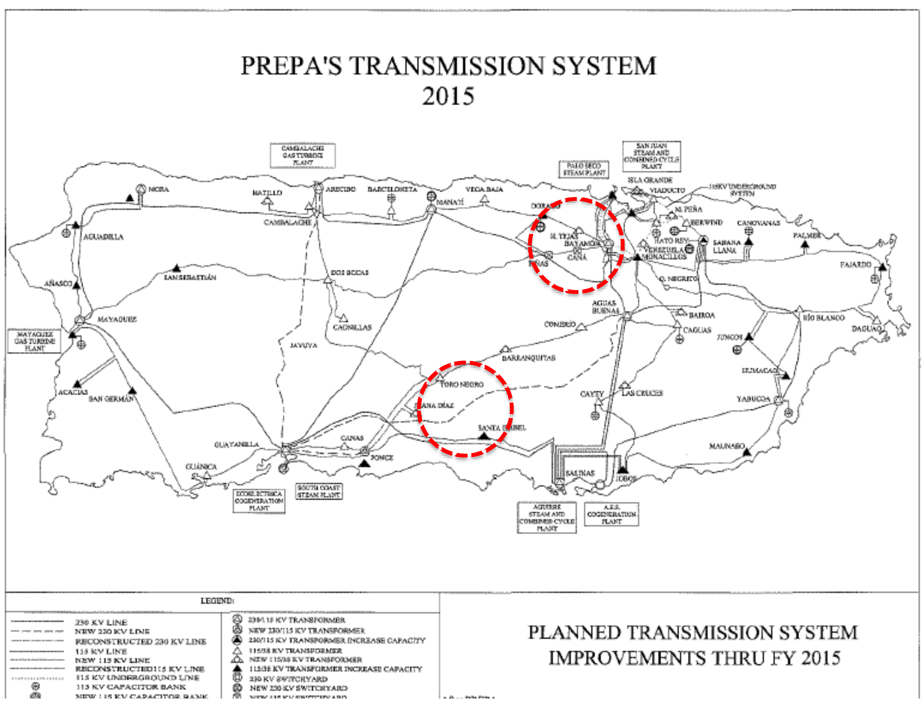

Figure 3 – Enhanced Geothermal System Locations Resource location should be close to existing power plants [15]

2.5 Existing Generating facilities prior to independent sellers

PREPA owns a generating 4,937 MW system with a total dependable generating capacity of 4,878 MW [9] The Authority also purchases power under long-term power purchase agreements from two cogeneration facilities: EcoEléctrica and AES-PR. As of October 2012, via a 20-year power purchase agreement with Pattern Energy, PREPA will purchase renewable energy from Finca de Viento Santa Isabel, a wind energy farm. Table 1 below shows the overall generation capacity of PR in MW.

	MW					
Generating Plants	**Total (82 Units)**	**Steam (16 Units)**	**Combined Cycle Power (13 Units)**	**Combustion Turbine (25 Units)**	**Hrydro Power (21 Units)**	**Other**
Aguirre	1,534	900(1)	592(2)	42(3)		
Costa Sur	1,032	900(1)	440(5)	42(3)		
Palo Seco	728	602		126		
San Juan	840	400				
Mayaguez	220			220(6)		
Arecibo	248			248(7)		
	277			168(8)	100	9(9)
Subtotal	4,878	2,892	1,032	846	100	9(9)
Peñuelas EcoElélctrica	507		507(10)			
Guayama AES-PR	454	454(11)				
Total	5,839	4,436	1,539	846	100	9

Table 1: PREPA's Power Generation Facilities: Energy mix is composed of several combined gas/steam units, steam units, diesel fuel units (MW) [15]

(1) Aguirre Unit 1/Unit 2, largest units, each dependable of generating capacity of 450 MW

(2) Two combined-cycle power blocks, each made up 450 MW combustion turbine units; 1 96 MW steam-turbine unit

(3) Two 21 MW units

(4) Six 21 MW units

(5) Two combined-cycle power block, each made up of 160 MW combustion turbines unit and one 60 MW steam-turbine unit

(6) Eight 27.5 MW dual fuel aero derivative combustion turbines

(7) Three 83 MW units

(8) Eight 21 MW units

(9) Five Diesel units in the Municipality of Culebra and two in the Municipality of Vieques with an aggregate dependable capacity of 8 MW held on standby reserve

(10) One combined cycle power block, made up of two 165 MW combustion turbine units a 177 MW steam turbine unit

(11) Two 227 MW units

3.0 Problem definition

Viewing Puerto Rico an energy efficiency perspective, decentralized power production and demand side management can be seen as key options to move towards a more sustainable energy system. Decentralized power production includes production from renewable sources such as geothermal power. Like many small islands in the Caribbean, PR is economically vulnerable to external factors such as energy price fluctuations, a consequence of the significant dependence on increasingly costly imported fuel. Securing supplies of cheap and reliable energy is a critical element for social and economic development. Most of PR's energy systems are old, based on fossil fuel technology, raising the cost of electricity and adding to national economic vulnerability.

Geothermal energy can have a huge potential in PR and is regarded and renewable energy. Geothermal technologies use renewable energy resources to generate electricity and/or heating and cooling. Geothermal power plants have many benefits such as providing base-load energy and it is a renewable clean source. A renewable resource like Geothermal Power (GP) can diversify the energy mix and also protect the country against volatile rising electricity prices, and can also provide economic. Geothermal energy can play an important role in decreasing cost of electricity, energy security and economic development in Puerto Rico.

Geothermal resources can be extracted and used to generate electricity and for cooling and heating in various ways (International Energy Angency). Conventional techniques deploying natural flow of hot water, Ground Source Heat pumps, as well as new emerging technologies such as Enhanced Geothermal Systems can benefit PR if feasible. A previous study conducted by the European Geothermal Energy Council, "*Towards more geothermal electricity generation in Europe" [19],* mentions that with technological improvements with EGS proven since 2007, in theory GP can be developed anywhere in Europe.

Electricity generation typically requires temperatures of above 100°C [50]. For heating or cooling a wider range of temperatures can be used depending on the application.

In the subsurface of the earth, the temperature of the rocks increases on average 1°C every 30 meters in depth [13].

The Earth's rigid outer shell of ca 100 km thick (lithosphere) is characterized by plate tectonics. There is an active convective thermal contact between the underlying "fluid" mantle (asthenosphere), which causes seismic activity, volcanoes, geysers, fumaroles, and hot springs [44]. Geothermal energy in regions with these characteristics has huge potential [44]. In certain part of the world this results in volcanic activity, where there is magma present at shallow depth level and consequently the geothermal gradient can be much higher than the average. An example of this is Laderello, Italy (increase 100°C every 100 meters). The precipitated water flows though the rocks close to the magma warm up increasingly in depth, and produce steam. This steam can be extracted and injected directly into a steam turbine to produce electricity.

Moderate increments in temperature gradient to approximately 50°C occur away from plate boundaries, and develop due to anomalies in crust composition and structure. Heat is released in these regions naturally by deep-water penetration in aquifers and convective water flow.

As mentioned before, PR has a population of approximately 3,674,209 people. This number is high, considering the size of the island; consequently the markets of the island are big. Because of PR's high dependency on oil, other forms of clean and renewable energy may have a future impact on the welfare of PR and its citizens. If the base load for energy can be replaced with an alternative source of energy, such as geothermal, it can have a huge impact on electricity prices, therefore improving the way of life in the island.

The aim of this study is to determine the feasibility of developing a project for the utilization of geothermal power to generate electricity as base load electricity in PR. In order to determine if the outcome is feasible, several factors will be measured, such as the Levelized cost of energy (LCOE) for geothermal electricity. The analysis is underpinned by a brief geological analysis of the tectonic setting of PR, resulting in scenarios for possible geothermal gradients in the earth's crust in PR, and the different available and future geothermal energy technologies.

4.0 Main Question

- ✓ How to improve base load energy and reduce cost of electricity in Puerto Rico using geothermal energy?

In order to answer the main question, several sub questions will also be answered to determine the feasibility of developing GE in Puerto Rico.

Sub-questions

1. What should be the ideal installed capacity for geothermal production in PR?
2. What would be the price of electricity (LCOE) using geothermal power?
3. How many wells should be used in order to supply the capacity?
4. What is the sustainability of the resource?

5.0 Outline

This report starts with a description of Puerto Rico’s energy situation and dependency on fossil fuels. A brief geothermal history is covered in section 6. Section 7 describes the available geothermal energy conversion technologies and also future developing technologies such as EGS. Section 9 and 10 cover Puerto Rico’s geothermal resource base (sub question 1- 4) for geothermal use for electricity production. Section 12 covers the drilling cost of geothermal energy. The Levelized cost of geothermal energy using EGS is covered in section 13 and also a sensitivity analysis is conducted to see the effects different variables have on the LCOE (sub question 2). The research is discussed and concluded in section 14.

6.0 Geothermal Energy

6.1 Introduction to GE

Geothermal energy is the thermal energy generated and stored as heat stored in the Earth's interior. It is considered a renewable energy source since there is a constant terrestrial heat flow to the surface, then to the atmosphere from the huge amount of stored heat within the Earth. Geothermal resources are basically thermal energy stored in the earth in trapped steam or liquid and rocks [5].

This internal Earth energy comes from two sources:

- Deep in the core and mantle, radioactive decay is occurring between such elements as uranium, thorium, and potassium. This interaction creates a heat flow that moves upward and outwards across the entire surface of the world [5].
- In places where there is magma movement into the Earth's crust, high heat flux and high temperatures may be present between the surfaces and approximately 10,000 ft. (3 km) below ground. If the requirements are optimal, geothermal can be developed for different purposes. Electric power generation can be produced with high sufficient high temperatures. This source of geothermal energy is the source of this research study [5].

6.2 Heat transfer within the Earth

Our planet had an internal structure and many physical and chemical processes are occurring there [5]. This heat is linked with all those processes occurring inside. Heat comes from inside the earth's structure, and it dissipates into the upper surface and into the atmosphere. Heat is transferred generally from depth to the subsurface firstly by conduction, then convection. Heat travel from the crust by (1) natural cooling and friction from the core, (2) radioactive decay of elements (uranium and thorium), and by (3) chemical reactions.

Heat spontaneously flows from a hotter to a colder body. There a three ways in which heat can be transferred: conduction, convection and radiation [20]. Conduction heat transfer can happen in all forms of matter (solids, liquids and gases), and can only happen within a material, between two or more objects that are in some contact with each other. Heat flow occurs within and through the material itself. Think of a frozen hotdog, when in contact with hot boiling water, heat is conducted though the whole hotdog, transferring the heat until it is ready to be served [20].

Convection heat transfer can be defined as the bulk movements of molecules within a fluid (liquids and gasses). An example of convection would be using forced air to transfer heat and dry something (hair dryer) [20].

Radiation is heat transferred by electromagnetic waves (generally infrared). Radiation is independent of conduction and convection heat transfer. This type of heat transfer can occur through water, air or a vacuum of space. Radiation heat can be felt if there is a sudden explosion for example. Heat will be felt and a moment, and then when it gone you don't feel the heat [20].

There is a constant heat interaction from the semi-fluid with the crust which maintains a temperature difference of 1000°C, and a mean temperature gradient of 30°C/km (Twidell and Weir). The crust has a mean density approximately ≈ 2700 kg/m^3, a specific heat capacity ≈ 1000 J/kg*K, thermal conductivity ≈ 2 W/m*K and an average geothermal flux of ≈ 0.06 W/m^2 [44].

The geothermal fluids act as the heat carriers to transfer this heat. These geothermal fluids are basically rainwater that has been transported and trapped in the Earth's crust. Water, due to its greater density is 24 times a better heat conductor than air [20]. Because of the materials and processes close to this water, it heat heated when in contact with hot rocks and has accumulated in aquifers. Deep aquifers can be drilled, and temperatures between 50°C to 200°C can be used for different purposes [44].

The water inside a reservoir moves by convection heat transfer. Heat is transferred from the lowest part of the reservoir to its upper part. This movement occurs because of the density variations. Via convection heat transfer water is transferred inside a reservoir due to density variations, transferring heat from the lowest part of the reservoir to its upper part.

6.3 *Geothermal history*

British chemist Robert Boyle, know for his gas law, constructed the first systematic measurements underground [12]. In 1671 he stated that temperature in the earth increases with depth. The use of hot springs has been known since ancient times, but it wasn't until the 19^{th} century that geothermal energy for electric power generation was first developed [12]. In Italy, Laderello (1904), Prince P.G. Conti was able to produce electricity using geothermal steam [12]. In 1914, a 250 kW turbo-alternator was connected to the grid at this same location [12].

6.4 *Worldwide geothermal power generation*

The current worldwide installed capacity for geothermal power is more than 10 GW [12]. In 2009, the global geothermal power capacity was 10.7 GW and generated approximately 67.2 TWh/yr of electricity (Bertani). Geothermal power has a significant share of total electricity demand in Iceland (25%), El Salvador (22%), Kenya (17%) and the Philippines (17%), Costa Rica (13%) [12].

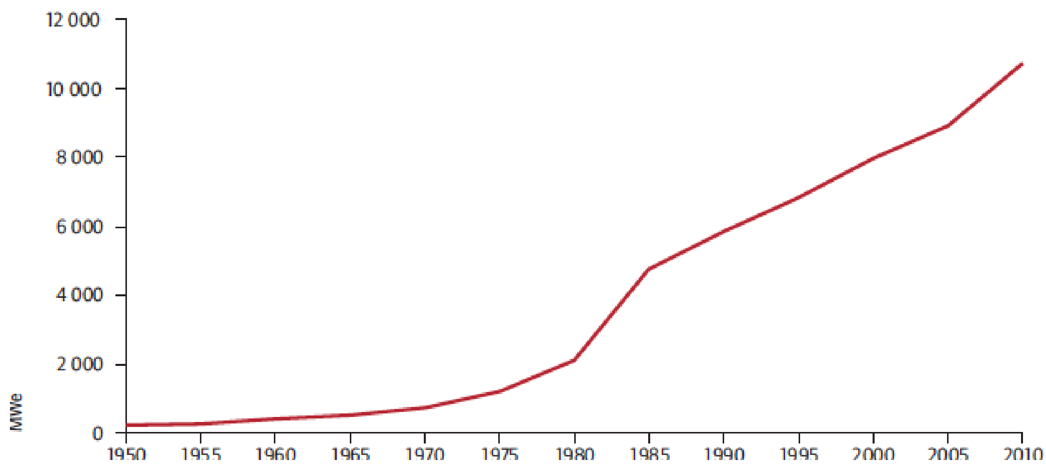

Figure 4 - Global development installed capacity geothermal Energy (MWe) [12]

Geothermal energy for electricity generation has been of great interest because of its high capacity factor [8]. The capacity factor for geothermal energy is the highest out of all the renewable energy technologies, and sometimes even higher than other power plants. The capacity factor can be defined, as the actual electricity that is generated for a period of time, divided by the energy the plant would have produced at full nominal capacity for the same time. Table 2 depicts typical values of different renewable energy technologies.

Technology	Capacity Factor
Geothermal Energy	90% or higher
Biomass	25-80%
Wind Power	20-30%
Solar Photovoltaic	8-20%
Solar-thermal Power	20-35%
Tidal Power	20-30%
Hydropower Energy	20-70%

Table 2: Common capacity factor values for different renewable energy technologies [44]

7.0 Type of geothermal resources

Geothermal systems can be classified in 4 categories: hydrothermal, hot dry rock, geo-pressured and magmatic. Only one of these methods is used currently at large scale, hydrothermal systems, the other methods are still developing [5].

Hot springs are an example of a discharge geothermal zone. There is a continuous circulation of heat and fluid in geothermal fields. The fluid typically enters a reservoir from the recharge zones, and needs a discharge area to dissipate this heat, as seen on hot springs.

In order to extract the geothermal heat, a large underground reservoir is needed with large permeable rocks at certain depth in order to have a productive resource of heat extraction.

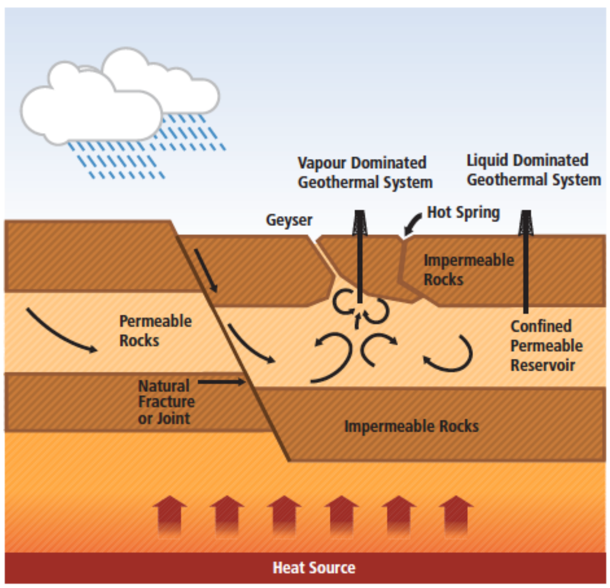

Figure 5 - Geothermal resource basin [27]

7.1 Reservoir Characteristics

The geological conditions permit a high temperature circulating fluid to transfer heat from the subsurface of the Earth to the surface through wells that discharge without any artificial lift (www.eia.gov). Hydrothermal systems (reservoirs) can be classified depending on its convective characteristics: water (liquid) dominated reservoir or a vapor-dominated reservoir.

Liquid dominated reservoirs

These reservoirs can produce temperatures between 40°C to 80°C. Temperature in the reservoir and also at the surface at atmospheric pressure remains below the boiling point of water. These reservoirs can be used for direct heat production (e.g. Kramers et al., 2012), and are used for green house heating and district heating.

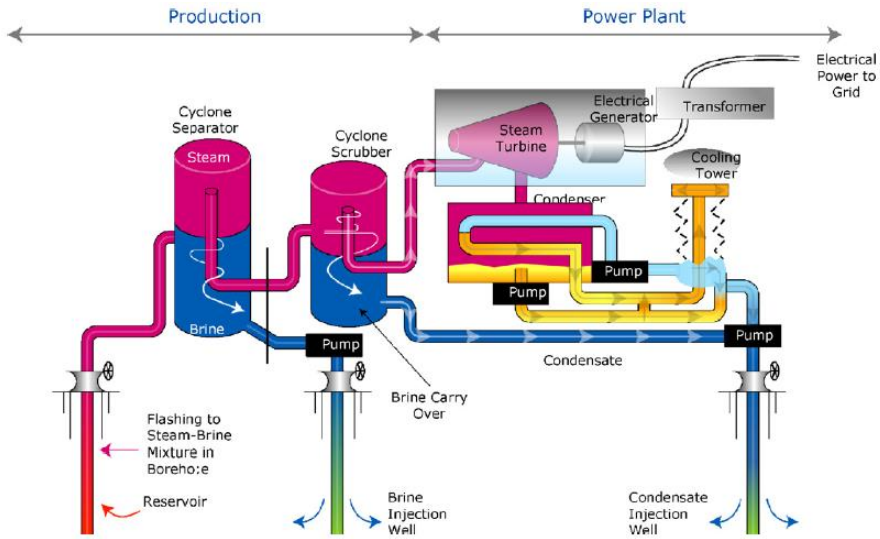

Figure 6 - Geothermal power generation system driven by liquid dominated reservoir [23]

Vapor dominated steam reservoirs

Vapor dominated reservoirs or wet steam reservoirs are made up of high-pressure water with temperatures above 100 °C. These regions are close to tectonic plate boundaries [44].

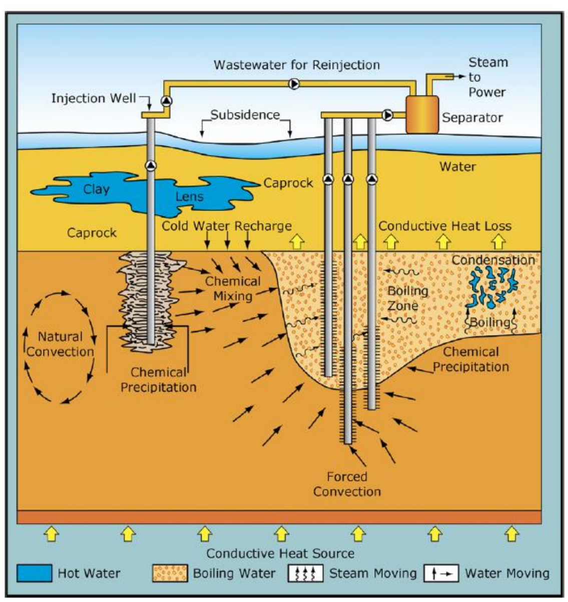

Figure 7 - Power generation system driven by vapor-dominated reservoir [23]

7.2 *Technologies for geothermal power and cooling*

Geothermal energy has been used for decades to generate electricity, for space heating or cooling, and industrial processes [5]. Geothermal energy has various types of applications. This research focuses on heat extraction for power generation and also GHPs for cooling. The section below describes in detail how each GE application works.

Currently today, there are 3 main types of high temperature technologies used for electricity production from a geothermal source. These commonly used technologies are Dry Steam, flash and binary plants. These technologies are explained in more detail in section 7.3.

Technologies such as hot dry rock (HRD) and enhanced geothermal systems (EGS) exist today, but are still not commercially viable. EGS is described in more detail section 13. The Levelized cost of electricity calculated in this report is assuming EGS is viable in different future scenarios.

7.3 Geothermal energy conversion technologies

As seen in Figure 9 (Líndal Diagram), geothermal sources vary in temperature. The source can be either steam, mixture of steam and water, or liquid water. Geothermal energy can be used in tree main ways: electricity production, direct heating, and indirect heating and cooling with the use of a heat pump. Each process uses high, medium and low temperatures. The temperature and the state at which the geo-fluid can be found will determine which type of technology can be applied. Below is a description of each of the available technologies for geothermal power.

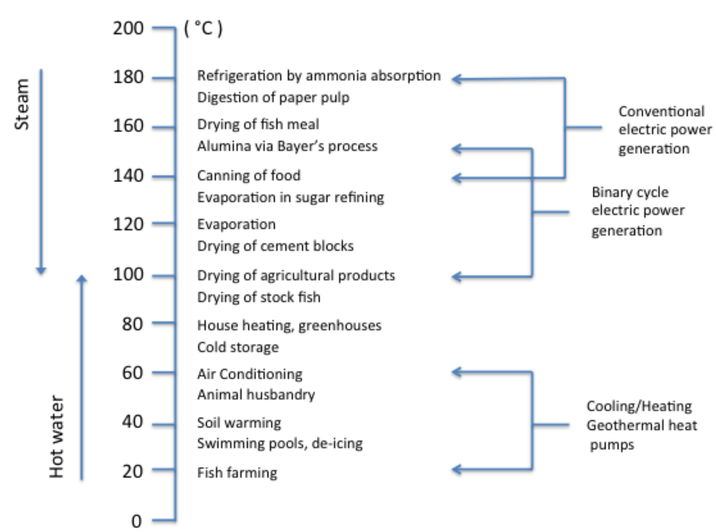

Figure 8 - Líndal Diagram: relation of geothermal use depending on temperature source [3]

Dry Steam Power Plants

Dry steam power plants use high temperatures, and vapor-dominant reservoirs produce dry steam. These types of power plants are the most suitable for commercial production of electricity [28].

This dry steam can go directly from the production well through a transport pipe, pass directly through a turbine of a power plant to produce electricity. The steam condensing the turbines can be used in [16] dry steam power plants that operate at high temperatures (more than 150 °C) [34]. The power capacity for this systems ranges from 20-110MW (DiPippo).

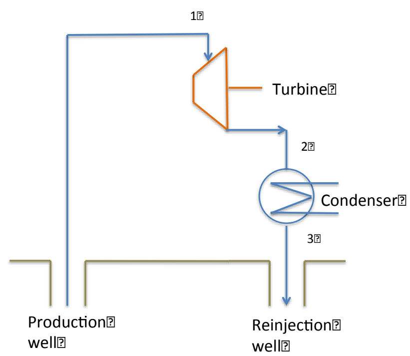

Figure 9 - Dry steam geothermal power plant cycle [16]

Flash Steam Power Plants

Flash steam power plants are the most common type of geothermal power plant in operation today [28]. This type of power plant can be used when the reservoir is a liquid-dominant reservoir and the fluid is not hot enough to flash in the well bore. In a flash system, hot water (180 °C) at very high pressure inside a reservoir and well bore is at surface suddenly released to a lower pressure [34]. This process allows some water to be converted into steam, and this steam is used to drive the turbine from the power plant [28]. Unlike dry steam power plants, after the well the fluid is sent into a separator, which allows a small part of the fluid (15-20%), to flash into steam [5]. The steam is then sent to the power plant, and what remains of the fluid (condensed) [24][4][43][48] steam and wastewater) is injected into the injection well.

Flash plants in high-temperature resources can be considered a mature technology with an average learning curve rate of 5% [30]. This means that a 5% decrease in investment per kW installed when cumulative installed capacities double. The cost of electricity production in flash plants can be considered in many cases competitive.

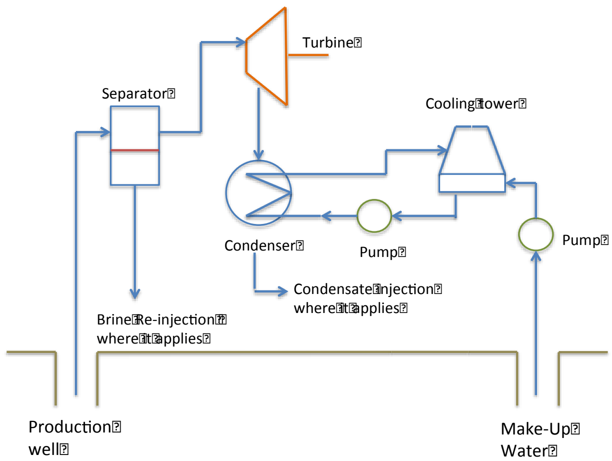

Figure 10 - Flash steam power plant cycle [16]

Single Flash Power Plants

For this type of power plant, a separation process is done in the mixture from the wellhead. This mixture is separated into different phases in a flash vessel. The remaining material is steam, which is sent to the turbine to produce electricity.

This type of technology can even more efficient if the mixture goes through an additional flash process producing even more steam. These types of power plants are called Double Flash power plants.

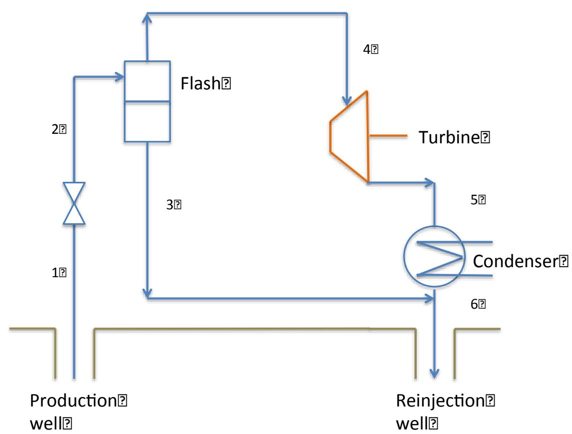

Figure 11 - Single-flash steam geothermal plant cycle [16]

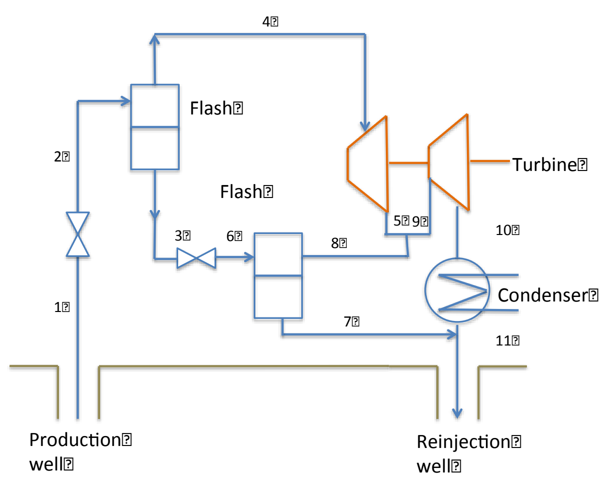

Figure 12 - Double-flash geothermal plant cycle [16]

Binary Cycle Power Plants

Binary cycle technology is used for temperatures from 100°C to 180°C [19]. This type of power plant differs from dry/flash steam system. Binary plants use geothermal brine from a liquid dominated reservoir at low temperature. They also operate with a binary working fluid (e.g. isobutene, R-114, isopentane, etc.) [16].

In these types of systems, heat from the water is transferred to a separate liquid (e.g. isobutene, R-114, isopentane) with a lower boiling temperature. The working fluid in side the heat exchanger transfers the heat when the geothermal is pumped from the underground.

The working fluid is completely vaporized and superheated by the geothermal heat and increasing pressure, expanding and passing trough a turbine. The working fluid and the geo-fluid are each in separated circulating loops, connected through a heat exchanger (Fig. 13), but never coming in contact with each other [16]. This means that neither the working fluid nor the geothermal water is exposed to the surface. The water is re-injected after heat exchange (European Geothermal Energy Council).

In the Rankine or Kalina cycles the working fluids can be adapted to surface temperature conditions and production temperature (e.g. ammonia, Freon, isobutene, etc.) (Chamorro, Mondéjar and Ramos). This working fluid evaporates and expands the turbine, then condenses and a pump returns it to the heat exchanger.

Binary plants are the most reliable technology to convert large amounts of low temperature geothermal resource into electricity power production but they are the most expensive power plants to build and are marked by low conversion efficiency of 7-20%, depending on production temperature (e.g. Tester et al., 1996).

According to the *Geothermal Roadmap Report [30][35],* binary plants working with low-temperatures resources are also considered to be a mature technology. Binary plants have small capacities currently, but the cost will decrease to competitive levels as capacity increases.

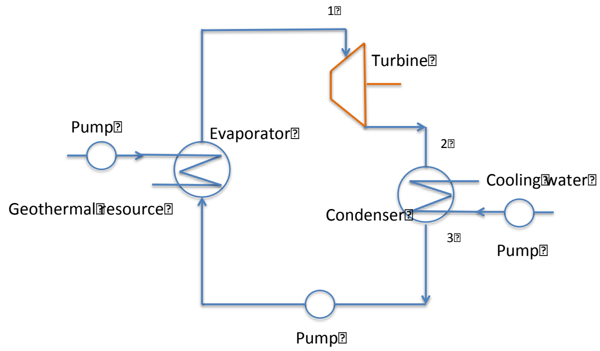

Figure 13 - Simple Rankine geothermal Cycle [16]

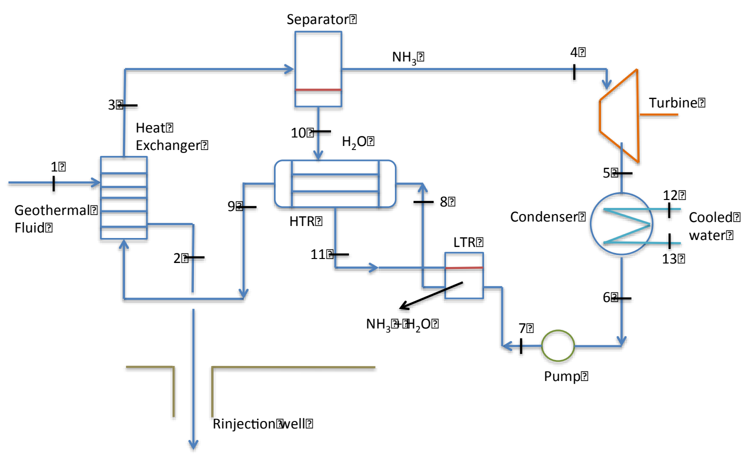

Figure 14 – Kalina geothermal Cycle [16]

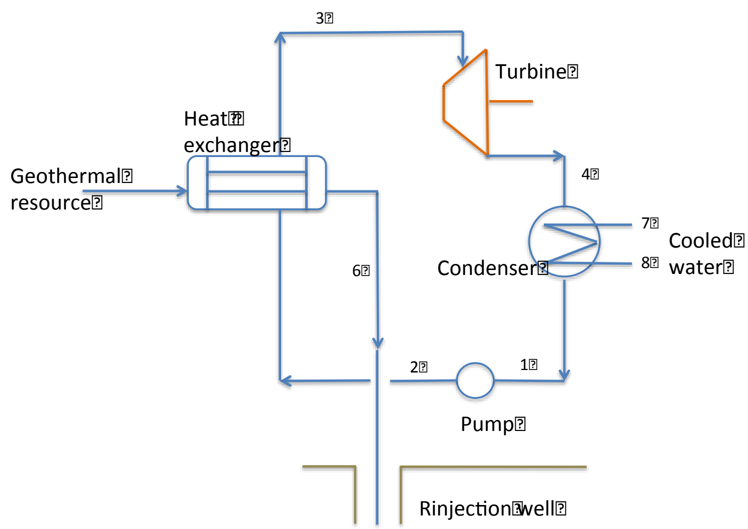

Figure 15 - Binary geothermal cycle [16]

Future Technologies: Enhanced Geothermal Systems (EGS)

Future GP technologies for electricity production could have a huge impact if developed in PR. An Enhanced Geothermal System (EGS) is a relatively new method of extracting heat from the subsurface. Experiments started in the early 1970s in USA, UK, France, Australia, Germany, Switzerland and Japan using Hot Dry Rock (HDR) [3].

Conventional geothermal resources for power production exist only in geological favored regions where there is a supply of hot rocks and hot water or steam. In 2006, the U.S. Department of Energy together with the Massachusetts Institute of Technology (MIT) worked on a report together with the US Department of Energy focusing on EGS in the USA (The Future of Geothermal Energy). Water can be pumped down an injection well to enhance the rocks permeability.

The concept comprises [9]:

- Using natural fractured systems in basement rocks
- Enlarging permeability through stimulation
- Installing a multiwall system
- Through pumping and lifting, forcing the water to go through the fractured system of enhanced permeability, using this heat to produce electricity

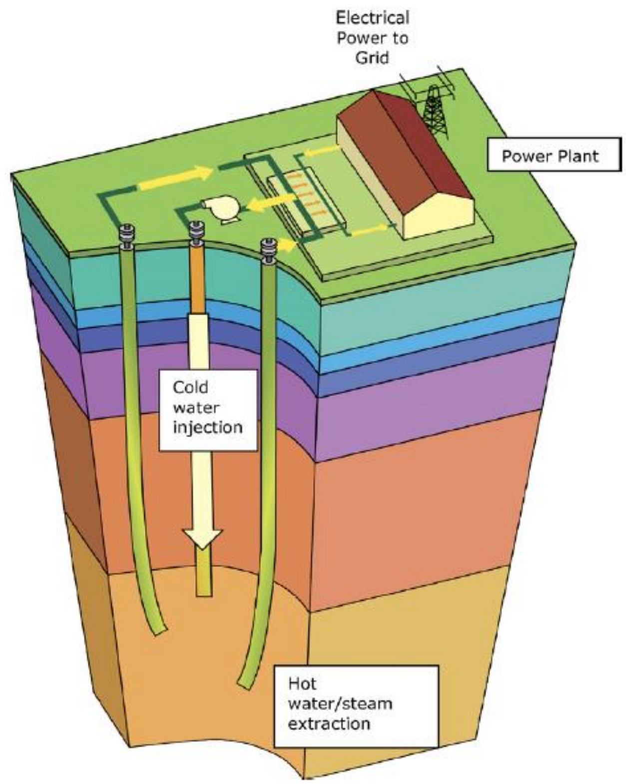

Figure 16 - Simplified representation of an EGS system (Geothermal Education Office)

To understand how EGS could works, imagine a HDR as depicted in Figure 17. The source is an element of thickness δ_z and depth *z*. Assuming it's a uniform material and no convection occurs, there is a linear increase of temperature with depth. At this depth the HDR has a greater temperature $T > T_1$, and heat available in the subsurface or heat in place (HIP) is calculated [9]:

$$HIP\ [PJ] = V * \boldsymbol{\rho}_{rock} * \mathbf{C}_{rock} * (T_x - T_s) * 10^{-15} \quad (6)$$

Where:

V = volume [m^3] of subsurface volume

$\boldsymbol{\rho}_{rock}$= Density = 2500 kg/m^3

$\mathbf{C}_{rock}$= Specific heat = 1000 J/kg*K
T_x = Temperature at depth in the sub-volume
T_s = temperature at surface

The theoretical capacity (TC) is a relation with the heat in place (HIT) multiplied by an electric conversion factor, which depends on the application [9].

$$H\ [PJ] = V\ \boldsymbol{\rho}_{rock} * \mathbf{C}_{rock} * (T_x - T_r) * 10^{-15}$$

Where:

T_r = 80°C (for binary systems above average surface temperature) [7]

After obtaining the values from the equations above, one can have an idea of how much potential a geothermal resource has. Still, many other tests and research has to be done for more accurate data.

EGS uses water as the heat transmission fluid. Supercritical CO_2 injection is also being researched to evaluate if it can be used as a transmission fluid [9]. The carbon dioxide is to be injected into a depleted or dry-geothermal system instead of water.

EGS consists of extracting heat from a man-made reservoir in rocks that have been artificially fractured because the rock's permeability is low [5][23]. Two wells are drilled into the rock for water injection and extraction. Water is pushed down the injection well down to the HDR reservoir where it gets heated. Steam then returns to the surface through the production well and is converted into electricity using a steam turbine.

Another technology being researched and developed is magma resources where heat is extracted directly from cooling magma [5]. Heat stored in magma can have a huge potential for developing GP. There are some limitations still since drilling has to reach the magma. Engineering materials need to be selected which can withstand very high temperatures and also heat extracting technologies.

Geo-pressured reservoirs have also been investigated for GE production [5]. This resource has been investigated by the USA in the Gulf Region. Geo-pressured reservoirs are deep reservoirs (4-6 km deep) that contain trapped hot water and excess of hydrostatic pressure. From these fields the produced water is used to drive a binary system, and any hydrocarbons from the produced water –e.g. methane can be sold.

EGS represents the new frontier of geothermal energy for power generation. Issues being addressed for these unconventional geothermal resources are: decreasing drilling cost, controlling water losses, and improving stimulation and mapping methods. In the long term, EGS holds the greatest promise. If developed for commercial use it would be ideal for PR and anywhere in the world.

Combined Heat and Power (CHP)

Geothermal power can also be used in a combined process to generate electricity and heat. With the production of electricity and heat then there is an optimization of the efficiency factor of energy production and upgrading cash flows [19].

8.0 Environmental characteristics of geothermal power

Geothermal energy is considered a renewable energy source but its development still has some environmental impacts. Serious environmental effects are the surface disturbances, effect of fluid extraction, heat effects and discharge of chemicals.

Geothermal energy and some other renewables emit a small portion of GHG emissions from electricity production compared to fossil fuel power plants [12]. If all fossil fuel power plants were replaced with geothermal power plants, GHG emission would be reduced by a minimum of 90% and even removed [26]. Figure 21 compares CO_2 emissions between coal, natural gas and geothermal. As it can be seen, the units are in ponds (lbs), but one can see how less CO_2 emissions are for GP.

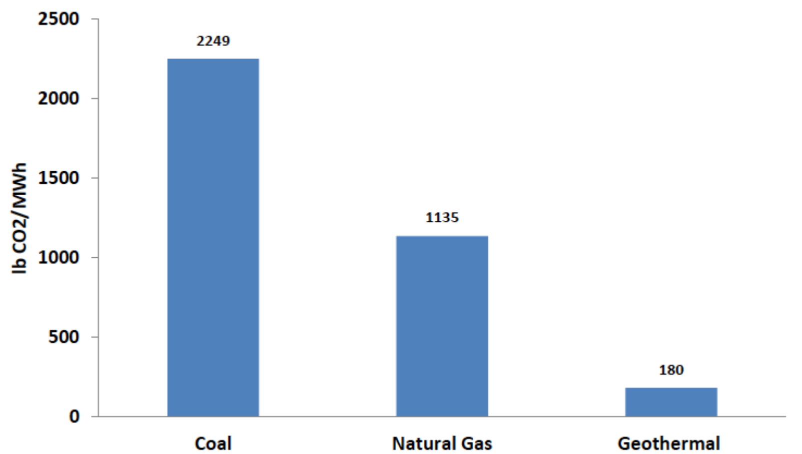

Figure 17 - Comparison of Coal Natural Gas and Geothermal CO_2 emissions [25]

Land subsidence is one of the negative effects GP can have in an area. Subsidence occurs when fluid extraction exceeds the natural inflow [32]. Beneath the subsurface, the weight of the rock on top of the reservoir keeps a certain pressure in the reservoir. As the geothermal source is extracted the pore pressure reduces, causing the ground on top to subside. Re-injection of the geothermal resource is a good method of preventing. The Wairakei power station in New Zealand was build during the 1950s. Due to the removal of hot water from the ground for power production caused subsidence, damaging the plant and some buildings [44].

Induced seismicity is another negative characteristic that a GE projects can have in the environment. Some geothermal reservoirs are located in unstable zones of the Earth's crust like volcanic areas. These zone have active deep earthquakes and the heat flow is higher than average [5]. The reduction of rock stress, stimulation of faults and tectonics may induce seismic activities [5].

In binary plants, the geothermal fluid passed through a closed system inside a heat exchanger and re-injected, without being exposed to the atmosphere. This can be seen in Figure 22 below. Emissions for binary plants are zero since it's a closed system. When comparing the other GP technologies such as Flash and Dry Steam plants, the difference is huge compared to coal and natural gas in Figure 21.

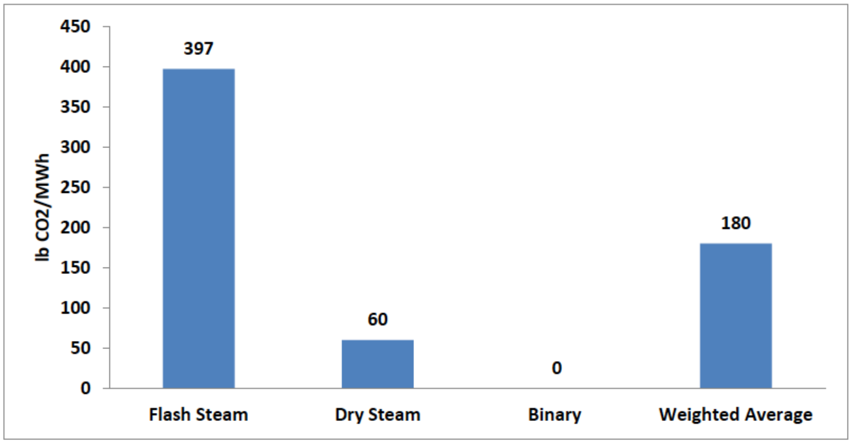

Figure 18 - Average 2010 geothermal conversion technology CO_2 emissions [25]

Considering GHP, there is no risk when being transported stored or operated like there is when transporting fuel. They are better also for groundwater, preventing contamination as it is with fuel tanks. GHP operate emission free therefore they can reduce GHG emissions.

General advantages of geothermal energy include:

- Limitless energy fuel
- Capable of supplying electricity base load 24 hours/day
- GHG emissions are only a fraction when compared to fossil resources
- It is easy to scale depending on the plant size and can have low capital cost
- It is obtainable almost everywhere

Little is know about the effects of developing GP and these effects have to be investigated full. Generally geothermal fields should be monitored for several years before developed in order to have the most efficient energy production and the impact it has on the environment. More research is needed in order to understand the complete picture on worldwide emission rates and its consequences. In 1997 the International Energy Association set up a Geothermal Implement agreement (GIA) in order to encourage sustainable development of GE resources in an environmental and economic manner [32]. Five years later, six countries were participating in the task: USA, Iceland, New Zealand, Japan, Greece, and Mexico [32].

9.0 Puerto Rico's geothermal resource base

Demand for electricity production is expected to keep rising all around the world. Figure 20, shows the projected demand growth in the island until the year 2030. Renewable energy technologies like geothermal energy; either for electricity production of for cooling using geothermal heat pumps may be developed.

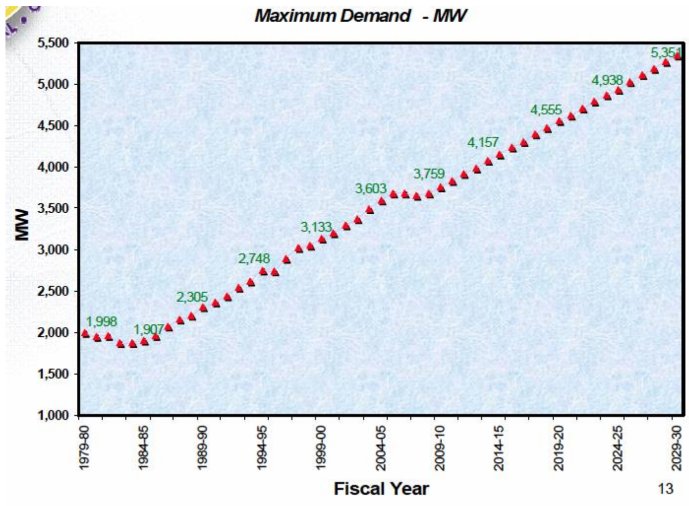

Figure 19 - Capacity expansion project in PR [15]

The use of geothermal energy in many countries has proved to be cost effective where geothermal systems are available [3]. The main factor for developing geothermal energy is the temperature at which we can find the resource.

Puerto Rico is composed of Jurassic to Ecocene volcanic and plutonic rocks, overlain by younger Oligocene to recent carbonates and additional sedimentary rocks [52]. The oldest rocks are located in the southwest part of the island and are approximately 190 million years old [52]. PR lies in the boundary between the North American plate and the Caribbean Plate (Puerto Rico Trench), and is currently being deformed by tectonic stresses caused by the interaction of the plates in a convergent intra-oceanic subduction system [52]. The Puerto Rico Trench is deepest trench in the Atlantic (800 km long) with a max depth of 8,000 meters [49][52].

Figure 18 depicts the three main Cenozoic basin phases along Puerto Rico. (A) Tectonic phase 1: Cretaceous to Ecocene formation and infilling of an east-west trending forearc basin with large normal faults along the southern edge of the basin and onlap of the forearc basin sediments into the outer ridge; (B) Tectonic phase 2: Oligocene to Pliocene period of tectonic quiescence and lack of large-scale folding or faulting on the 7 km wide extinct arc upon which the Puerto Rico-Virgin Island (PRVI) platform has been formed; (C) Tectonic phase 3: Pilocene to Holocene northward tilting of the platform along the northern margin of Puerto Rico, which has resulted in drowning of the platform to a depth of 4 km to the north and sub aerial exposure of the platform to an elevation of approximately 100-200 m in the north coast area of Puerto Rico [24].

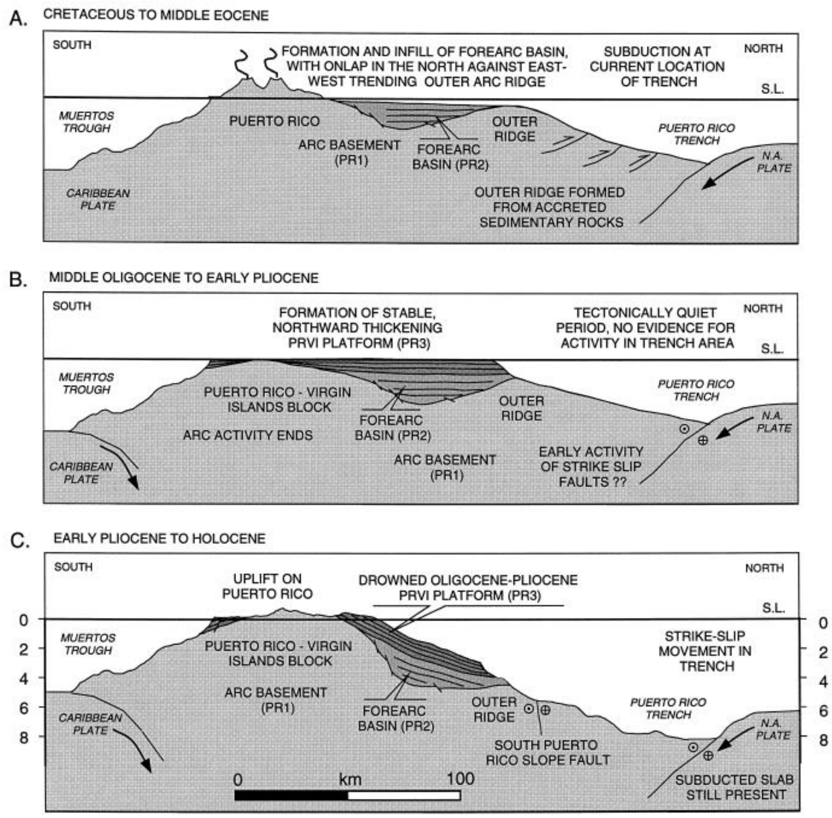

Figure 20 - Three main Cenozoic basin phases among the northern margin of Puerto Rico [24]

Information from seismic reflection, well, and outcrop data support the above three major tectonic phases, which characterize this region in the North-American plate boundary zone.

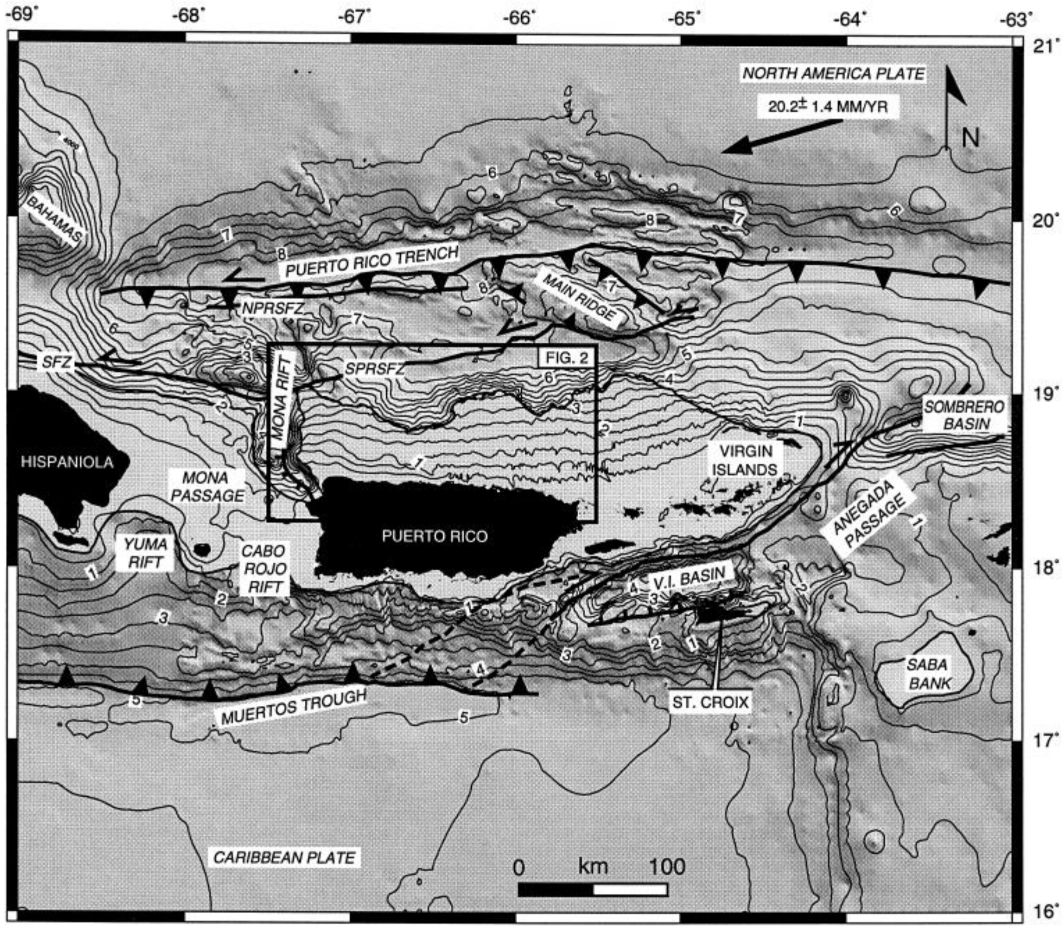

Figure 21 - Tectonic map of Puerto Rico [24]

10.0 (Subsurface) indicators for geothermal resources

Geothermal resources can be found deep beneath the surface and some reservoirs can also be found in regions where there is no volcanic activity. Deep penetrating faults allow ground water to flow deep several kilometers and become heated by the geothermal gradient [8].

Exploration is needed in order to locate these resources. Exploration consists of estimating the subsurface temperature, permeability of the rocks and the presence of a fluid, also the depth and thickness of the resource. All this can be achieved using geoscience methods and by drilling exploration wells. Exploration drilling has a huge financial risk since drilling is expensive and the resources are unknown in advance.

Important factors to be measured during exploration are: permeability at depth, reservoir temperature and volume. It is also important to determine what type of reservoir are we dealing with; weather it will produce hot water or steam.

Hot springs can be an excellent indicator for high temperature subsurface reservoirs. Hot springs consist of hot water rising from the underground, heated at layers in the earth that are at a high temperature, with a surface temperature greater than 5°C. Depending on their geological origin, there can be two types of hot springs: magmatic and telluric. Magmatic water always has very high temperatures and is born in volcanic areas. Telluric springs can appear anywhere where rainwater or river water gets penetrated and infiltrates this reservoir. This water penetrated deep into the crust, then gets warm, following the aquifer up to the surface.

10.1 Information from wells

Geothermal wells today are drilled typically up to 5 km deep [5]. After identifying the specific geothermal region, exploration techniques are then used to locate the best suitable spot for fluid production.

Puerto Rico happens to have already two onshore wells along the coast (CPR-4 well and Toa Baja well). They were both drilled for hydrocarbon explorations, but it was unsuccessful. CPR-4 well has a depth of 2144 m and was drilled by Kewanee International Oil (1960). The second well, Toa Baja well has a depth of 2704 m and was drilled by Henley Drilling in 1987. In the figure below one can observe the 2 well logs [1].

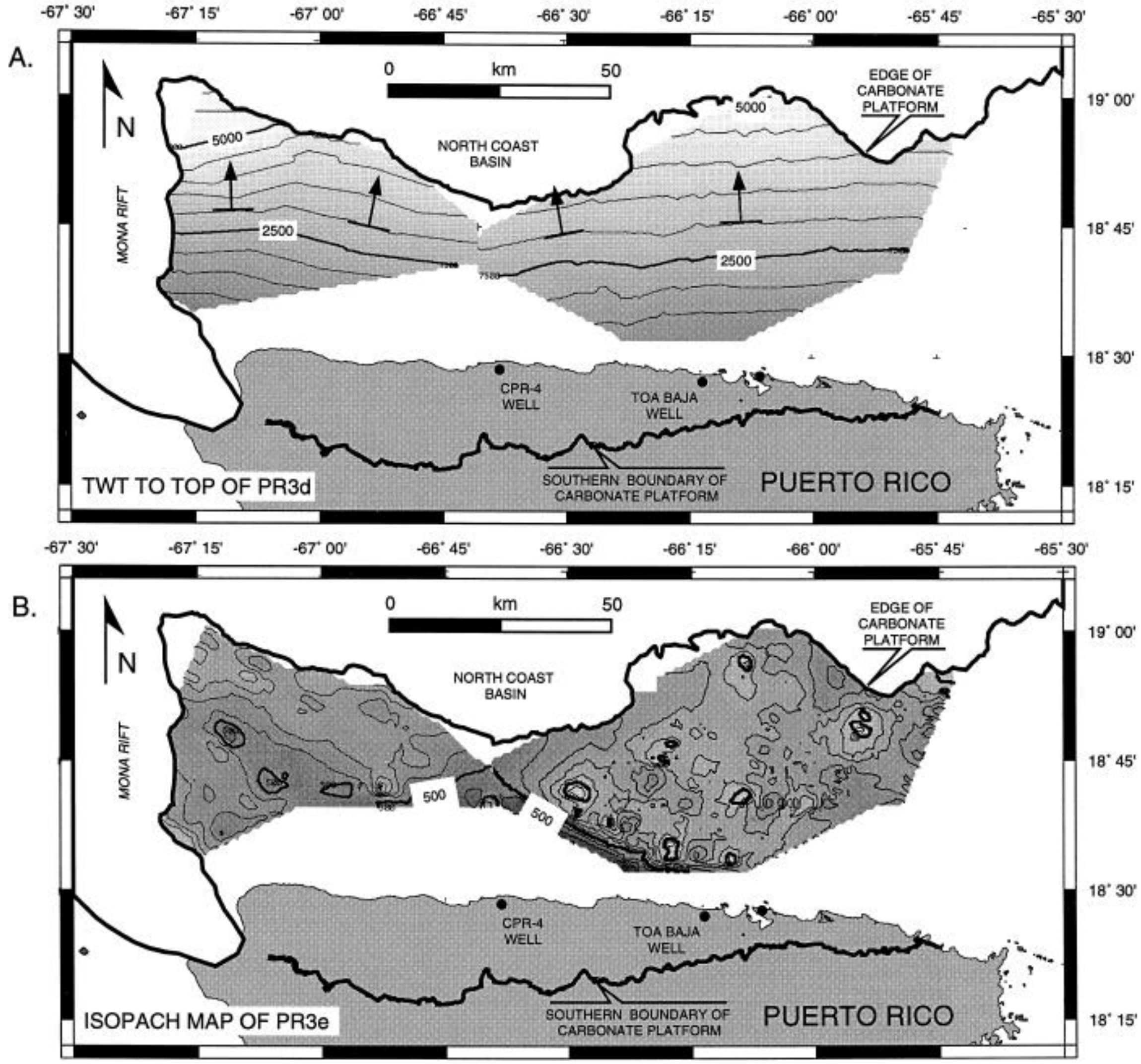

Figure 22 - Well locations in Puerto Rico [1]

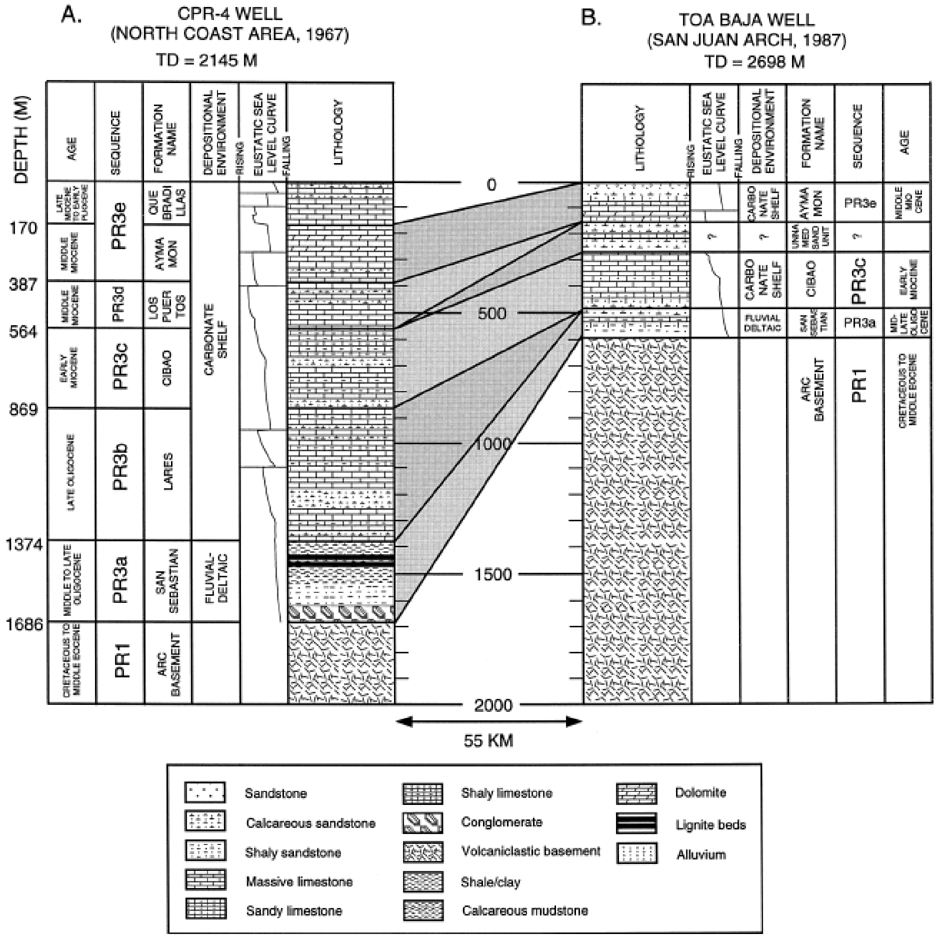

Figure 23 - Existing Well-logs [1]

From a previous study [1] done in PR using a scientific drillhole located in Toa Baja (North-Mideast), measurements such as thermal conductivity and heat-flows were obtained. Estimations of thermal conductivity range from 23 to 37 mW/m^2 from 800 to 2,500 m depth. At the base of the well an active hydrothermal system was found with a heat flow of up to 90 mW/m^2. This heat flow then dropped to 50 mW/m^2 beneath the hydrothermal system.

Due to uplift, erosion and cooling that occurred approximately between 30-40 million years ago, and also the reburial and deposition of Oligocene-Miocene Limestone produced a present day geothermal gradient of 15°C/km, with a heat flow of 30 to 50 mW/ m^2 [1]. Thermal gradients can be used in basins to determine the thermal state of the subsurface [1]. Heat flow is a function of thermal conductivity and thermal gradient. (Anderson and Larue). From another well in the west central Puerto Rico, a heat flow of 42 mW/m^2 and a geothermal gradient of 12.5°C/km were obtained for a

300 m drill hole [1]. Heat flow and geothermal gradients in Toa Baja are low, so more wells would be needed to define the geothermal system in PR.

In this study, the geological analysis and exploration surveys will only be covered superficial, not in real detail. Generally it is necessary to estimate factors such as reservoir volume, temperature, pressure and permeability at depth. It is also necessary to know if the well will produce hot water or steam. General geological exploration techniques for geothermal energy that could be used:

- Inventory of survey of thermal springs - This information can be obtained at low cost and is fundamental for exploration
- Geo/Hydrological surveys – These surveys provide information on the structural framework of the area, nature and size of the geothermal resource. They provide an idea of where faults, fractures and other tectonic features can be found. A pattern of the water circulation can be studied
- Geochemical surveys – This survey is used to calculate the age of the geothermal resource and temperature of the deep reservoirs
- Geophysical survey – This survey is used to study the behavior and nature of the rocks found at the targeted location
- Exploratory wells – This is the final stage of an exploration survey for geothermal energy. Wells usually have a diameter of 20 cm or less.

11.0 Economic feasibility for geothermal electricity production

Geothermal energy can be competitive with newly built power plants where high-temperature hydrothermal resources are available.

Investment cost for geothermal energy include surface cost, which includes construction, equipment and labor [12]. Additional to this is also the subsurface cost, which involves reservoir exploration and drilling. Once the reservoir is located, reservoir cost can be estimated. However, uncertainty is high with the subsurface cost, since the reservoir characteristics are not well known.

The cost for developing geothermal for electricity production varies depending on temperature and pressure, reservoir depth and permeability, fluid chemistry, location, drilling market, size of development, number and type of plants (dry steam, flash, binary or hybrid). Development costs are strongly affected by oil, steel and cement prices [30].

This section includes capital cost, operation and maintenance (O&M) cost, make up well drilling cost, well productivity/rate of decline, the recommended capacity, the years of drilling and the geothermal project's life.

Capital cost for GP plant is proportional to the power capacity. According to the International Energy Agency (IEA, 2010a), the capital cost of a geothermal electricity development ranged from 2000/kWe to 4000/kWe for flash plants and USD 2,400/kWe to USD 5,900/kWe for binary developments. The analysis done in this research was from a previous study done by S. Sanyal (Sanyal), which can be applied to geothermal power projects worldwide.

As seen in Figure 20 (capacity increase), Puerto Rico's energy demand is expected to increase up to the year 2030. For this reason this study will consider a power capacity range of 5 to 150 MW. The base case power cost capacity will be 50 MW, which covers capital cost with interest payments and financing cost, O&M cost, and make-up well drilling cost.

In order to compare different plant capacities independent of specific location characteristics, assumptions were made to estimate the unit capital cost of small and big scale projects. Factors that may affect the cost of geothermal power cost can be grouped in four categories:

1. <u>Economy of scale</u>

Allows both unit capital cost ($/kW installed) and O&M (cost $/kWh) to decline when capacity is increased. According to Entingh and McVeigh (2003) and Twidell and Weir (Renewable Energy Resources), the unit capital cost or surface cost today can be estimated $2,500/kW for small capacities and $1,600/kW for larger projects. From S. Sanyal's (2004) study, since an assumption is made that capital cost declines exponentially with plant capacity, the correlation below is used for surface cost in $/kW ($C_d$) and the plants capacity in MW (P):

$$C_d = \$\,2500e^{-0.003\,(Power-5\,MW)}$$ → For small scale projects

$$C_d = \$\,1600e^{-0.003\,(Power-5\,MW)}$$ →For large scale projects

Subsurface cost is hard to estimate since there is little data available to determine reservoir characteristics in PR. Technologies that can be applied to GP production were not evaluated in this study, but cost will also depend on it and its complexity and the surface cost. A previous study [12] considers unit capital cost for a single flash model plant, double flash model plant, triple flash model plant and a dry steam model plant. It also assumes that the surface cost for a single flash plant is 50% of its total initial cost, equaling the subsurface cost to the surface cost.

Proportional to the energy production is also operation and maintenance cost (O&M). O&M cost also have an exponential decline when plant capacity increases.

The Table 4 below includes the calculated values of unit capital cost (surface cost), O&M, total capital cost and price of electricity from 5-150 MW capacities. Table 5 has values for large-scale capacities from 150-600 MW.

Plant Capacity	Unit Capital Cost $= \$2{,}500e^{-0.003(Power-5MW)}$	Unit Cost O&M $= \$2e^{-0.0025(Power-5MW)}$	Total Capital Cost	Price of Electricity
MW	**$/kW**	**¢/kWh**	**Million $**	**¢/kWh**
5	2,500	2.00	12, 500,000	0.285
10	2,463	1.98	24,627,798	0.296
20	2,390	1.93	47,799,874	0.287
30	2,319	1.88	69,580,761	0.279
40	2,251	1.83	90,032,452	0.270
50	2,184	1.79	109,214,489	0.262
60	2,120	1.74	127,184,056	0.255
75	2,026	1.68	151,984,546	0.244
100	1,880	1.58	188,003,564	0.226
125	1,744	1.48	218,023,852	0.210
150	1,618	1.39	242,724,250	0.194

Table 3: Cost variance for small-scale capacity projects 5-150 MW [41]

Plant Capacity	Unit Capital Cost $= \$1{,}600e^{-0.003(Power-5MW)}$	Unit Cost O&M $= \$2e^{-0.0025(Power-5MW)}$	Total Capital Cost	Price of Electricity
MW	**$/kW**	**¢/kWh**	**Million $**	**¢/kWh**
150	1,036	1.39	155,343,520	0.124
200	891	1.23	178,273,876	0.107
300	660	0.96	198,102,803	0.079
400	489	0.75	195,677,555	0.059
500	362	0.58	181,201,873	0.044
600	268	0.45	161,085,179	0.032

Table 4: Cost variance for large-scale capacities projects (150-600 MW) [41]

As can be seen in Table 4 and 5 above, unit capital cost does decrease exponentially with an increase in installed power capacity. The price of electricity was also calculated using the equation below:

$$Price\ of\ electricity = \frac{Total\ capital\ cost}{Plant\ capacity * 8760\ (hours\ in\ a\ year)}$$

As one can see from the values, the price for electricity for a GP project in Puerto Rico is would be very competitive. From Figure 1, the price of electricity in 2012 was approximately 0.2811 ¢/kWh. For a small capacity power plant the price is not comparable, but 30 to 40 MW onwards, the price decreases exponentially as well.

2. Well productivity characteristics

A huge disadvantage of commercial geothermal to conventional fossil fuels is the need to drill enough wells to supply the plant capacity [23]. The analysis done here is only to have an idea of different cost factors for conventional geothermal resources. The only values used from the analysis to apply for EGS is the number of wells needed.

As S. Sanyal (2004) mentioned in his report, geothermal productivity characteristics can affect geothermal power cost in mainly two ways:

- Power cost is correlated with the number of wells needed. If productivity is higher, fewer well will be needed to supply a plant, so the power cost will reduce
- The more heat you extract from a well, the less productivity it will have in the future. In Sanyal's (1989) report, wells undergo a "harmonic decline rate" over a period of time. As the installed capacity increases, the decline rate increases. A higher rate of decline will require additional wells, increasing the power cost [41].

Geothermal reservoirs are dynamic systems that change to production load, changing their initial characteristics with time. These disadvantages are caused by pressure drop in the reservoir. The flow from the wells will decrease with time, often in a manner approaching and exponential decline [3]. To calculate the harmonic decline rate, the equation below can be used:

$$W = \frac{W_i}{1+D_{i*}t} \quad [41]$$

W_i = *Initial well productivity*
$D_i t$ = *Initial annual decline rate in productivity*
W = *Well productivity in year t*

In Sanyal's report, he mentions that the harmonic decline trend infers a decline rate that reduces with time. So to actually be able to calculate the annual decline rate in productivity, equation (5) is used. The values from the initial harmonic decline rate (D_i) were obtained from Sanyal's report.

$$D = \frac{D_i}{1+D_i t} \quad [41]$$

3. Development and operational options

If an independent power producer were to invest in geothermal power in Puerto Rico, he would have the option to choose the plant size. When the plant is in operation, the plant manager has to maintain the capacity equal to the demand. In order to maintain generation with out any shutdowns, operational option was contemplated by assuming stand-by wells with at least a 10% power capacity in stand-by. In this report, a range of 5MW to 150MW plant capacities is considered.

4. Macro-economic analysis for GP production

Power cost varies with plant capacity, harmonic decline rate, initial well productivity and the number of years the plant will be in operation. Table 6 below contains the number of wells that have to be drilled depending on the GP plant capacity.

Plant Capacity	Initial Harmonic Decline (D_i)	Initial Productivity per well (W_i)	Number of Wells $(\frac{P}{W_i}+W_i) * 10\%$	Years for well extraction
MW	**%**	**MW**		
5	0.20 %	5	2	30 >
10	0.60 %	5	3	30 >
20	1.50 %	5	5	9
30	2.60 %	5	7	3
50	5 %	5	11	1
75	8.30 %	5	17	0
100	11.80%	5	22	0
125	15.40 %	5	28	0
150	19.20 %	5	33	0

Table 5: Number of wells needed for installed capacity. In the number of wells, an additional well is considered with a 10% capacity in stand-by [41]

As seen in the table above, the initial harmonic decline rate increases as we increase capacity. This is a logical consequence because when you increase capacity; increase the amount of heat extraction in the well, depleting the hot source temperature.

The number of wells needed also increases as capacity increases. This well need increases the investment cost substantially, since drilling is very expensive. When looking at the number of years, which use each well, only a 5 and 10 MW capacity plant can be operated for at least 30 years. For a plant with a capacity of 20 MW its 9 year, and for greater capacities the time is too little.

12.0 Drilling cost for geothermal extraction

The most critical operation in the development of a geothermal project is the drilling and completion. Drilling cost account for 30% to 50% of hydrothermal geothermal project. EGS have a higher risk profile compared to other renewable energy technologies since the drilling depths are higher. Well cost for EGS accounts for about 70% of the total cost [19]. Research and development (R&D) can improve drilling techniques and the cost might reduce. Deep geothermal drilling cost data is very limited since the market conditions for deep drilling still needs to improve. Geothermal drilling often uses the same technology as the oil and gas industry, so insight into geothermal wells costs can be obtained from this industry.

Geothermal drilling is generally more complex than oil/gas methods because of the rocks being penetrated are harder rather than sedimentary. Also high temperatures in geothermal wells affect the circulation system; cementing procedure as well as the design of the drill string and casing are different. Figure below the behavior of geothermal drilling and it follows the same trend as the oil and gas industry. It represents the total dependence to crude oil prices.

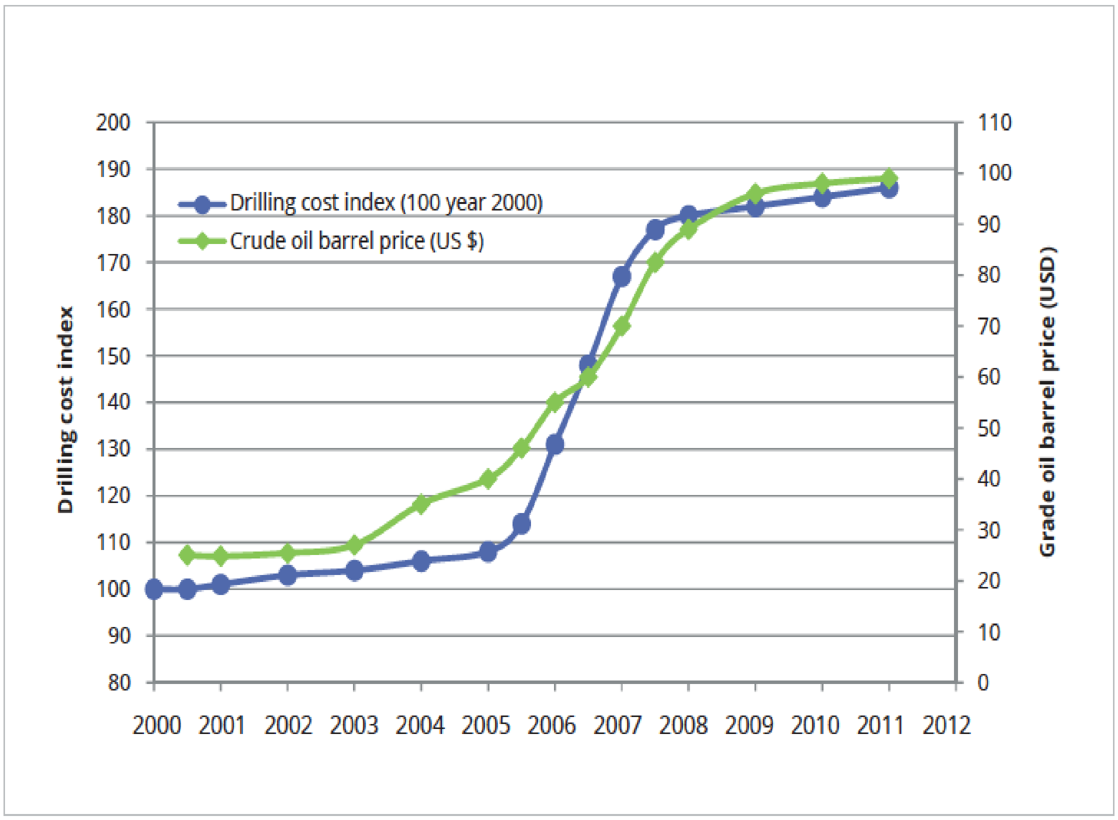

Figure 24 - Geothermal and Oil/Gas drilling cost trend [19]

Air and mud have been used as drilling fluid. Air drilling is faster and cheaper. Directional drilling can also be used in areas where the surface above the target is not accessible. Directional drilling has a slower penetration rate, making it more expensive (25% more) than vertical drilling. The hottest (500°C) well drilled so far is at a depth of 3729 meters in the Kakkoanda field, Japan [5].

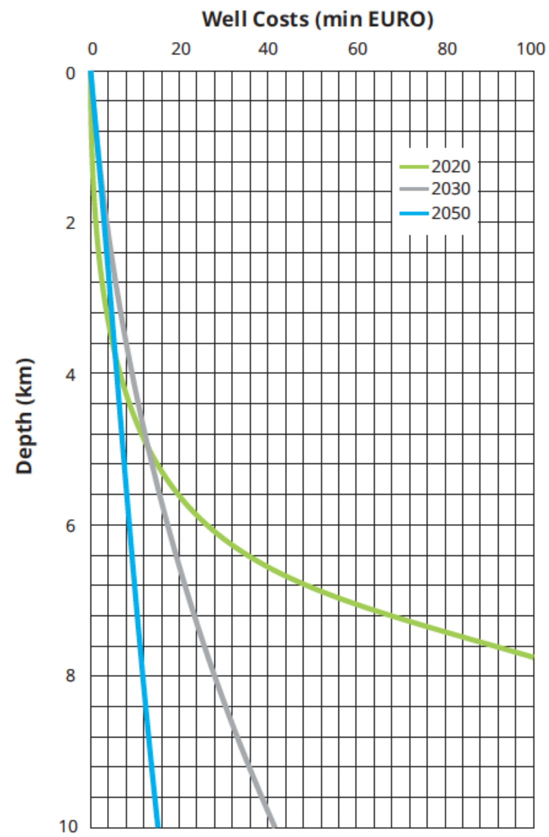

Figure 25 – EGS well cost with different scenarios [19]

R&D of current technologies and also new techniques can decrease drilling costs. Improvements in market conditions can develop competition; therefore decrease the cost of drilling. Equipment and methods such as drilling rigs, drilling services (drilling mud and directional drilling), drilling tools (high performance drill bits, novel drilling techniques, directional drilling (side tracks, horizontal multilaterals), and drilling completion (exploration wells, slim hole drilling, sustainable well completion) can also play a role in drilling cost reduction [19].

As mentioned in the GEOELEC report, some of the main problems of the drilling market in Europe are: rig manufacturing which take about 1 year and cost approximately 20 million Euros, the lack of experience and skilled drillers (3-4 months for training completion, deficit of geothermal workers and supervisors, business stream for the geothermal market is not consistent [19]. These problems can also apply in Puerto Rico, since geothermal development is completely absent though the regulatory aspects are different from Europe.

12.1 Well testing

After the well is drilled, the performance characteristics of the resource can be explored. The chemistry of the deep fluid can be determined. Testing also includes physical well measurement and chemical analysis of discharge and down-hole fluids. A log is developed to provide information on available fractures, temperature, depth, pressure and different points, type of rock, permeability, porosity and fluid content and production zones.

The hardest parameter to measure is the size of the reservoir and its energy potential. Long production test must be carried out carefully to determine if the investment is economically feasible or not in terms of flowrate and temperature.

13.0 Levelized cost of Energy for Geothermal Power

The Levelized cost of electricity (LCOE) is a constant unit cost (kWh or MWh) of a payment tributary that has the same present value as the total cost of a generating plant over its lifetime. The LCOE is a very useful tool used to compare technologies with different operating characteristics. Typically values for LCOE are calculated over 20 to 30 year life, and given in unit of currency per kWh or MWh. Because EGS is a new technology and still developing, it is difficult to evaluate the LCOE.

For potential GP investors it is important to see the economic potential based on investment cost know and capital expenditures (CAPEX) and operational expenditures (OPEX). CAPEX is the sum of all initial investment (I_t) needed for a geothermal plant in the year *t.* I_t include exploration costs, drilling costs per wells, power plant construction, grid connection, reservoir stimulation and power plant commissioning [38].

OPEX is the sum of all O&M expenses (M_t) that are made in year *t.* M_t
Includes cost of labor and equipment, maintenance, re-stimulation and additional wells if needed. E_t represents the amount of electricity produced in year *t.* Tax_t is the amount of tax that is paid in the year *t,* but they were not taken into account in this report. The LCOE can be calculated using (Limberger, Calcagno and Manzella):

$$LCOE = \frac{cumulative\ discounted\ yearly\ expenditures}{cumulative\ discounted\ yearly\ electricity\ production}\ [38]$$

$$LOCE = \frac{\sum_{t=1}^{T} \frac{I_t + M_t + Tax_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}\ [38]$$

The full list of the input parameters and default values can be found in *Assessing the prospective resource base of Enhanced Geothermal Systems in Europe [38].*

This analysis examines the impacts of various parameters to estimate the LCOE for developing EGS in Puerto Rico. The assumptions for this model where acquired from a recent report [38], regarding flow rates, plant lifetime, the conversion efficiency, and the recovery facto

The model used to perform the analysis is Excel (Limberger et al., 2014), and each model incorporates assumed values for different technical variables. By changing the values in each scenario one can alter the outcome of the prospects, to see which can be developed economically.

The model used in this research is based on a combination of models (Volumetric approach - Beardsmore; discounted cash flow model approach – Lako, van Wess) [38]. The main output of the model used is the minimum Levelized cost of electricity. The model used to perform the analysis is Excel, and each model incorporates assumed values for different technical variables.

Technical scenarios for 2020, 2030, and 2050 were used to estimate the different scenarios future EGS could have in Puerto Rico. By changing the values in each scenario one can alter the outcome of the prospects, to see which can be developed economically.

The depth in this report was not considered since it is hard to measure temperature and 7000-10,000 km. The well available to not reach this depths, so the cost per well were assumed (10,000 $/well) from different drilling reports for oil and gas industry. The total number of wells in this report is 2, one main well and 1 stand-by well. Well cost for 2030 decreasing slightly assuming drilling technology has improved. The following equation was used in the well-cost model:

Also since is hard to measure the flow rate of an EGS without information from a well, three-fixed flow rates were used to calculate the LCOE. Flow rates increase assuming permeability is enhanced through stimulation techniques.

The following table includes input variable that were kept fixed through the different scenarios:

Surface temperature	30 ° C
Economic lifetime	15 years
Variable O&M	5 $/MWhth
Power Load	8000 hours
Power plant investment costs	3 mln $/MWe
Power Distance to grid	5 km
Power grid investment	80 $/kWe
Power grid connection variable	100 $/m
Power fixed O&M rate	1%
Power fixed O&M	53 k$/MWe
Direct heat load hours	8000 hours
Direct heat plant investment cost	150 k$/MWth
Direct heat fixes O&M rate	1%
Direct heat fixes O&M	50 k$/MWth
Direct heat variable O&M	5 $/MWhth
Inflation	3%
Loan rate	7%
Required return on equity	15%
Equity share in investment	20%

Table 6: *Fixed variables for LCOE*

The input variables analyzed the analysis include:

Technical variables

- Flowrate of the geothermal resource
- Production temperature at which the water is produced
- Well costs (mln $)
- Stimulation costs
- COP (MWth/MWe) to drive the pumps
- Carnot efficiency
- Combined heat and power (CHP) that can be used to another process

	2020	2030	2050
Flowrate (L/S)	17	50	100
Production temperature (°C)	180	180	200
Well costs (mln $)	20	20	15
Stimulation Costs mln $)	5	5	3
COP	30	50	1000
Efficiency	60%	60%	70%
CHP (inlet temp) (°C)	30	30	30

Table 7: *Assumption Scenarios for LCOE [9]*

The depth at which the source is to be found is assumed to be 7 km depth. The fact that the radiogenic heat production in Puerto Rico is cero, there is a low heat flow. For electricity production the temperature source was calculated 180°C for the 2020 and 2030 scenario using a heat flow rate of 25 mW/m^2. The minimum production temperature set in the model was 100°C. With the assumption that drilling and stimulation techniques improve, for the 2050 scenario a temperature source of 200°C was calculated using a heat flow rate of approximately 28.5 mW/m^2. The equation used for the production temperature is:

*Tx = (depth-1000)*heat flow rate + Ts*

Where

Ts = Surface temperature

From a previous report [14], using a modeling approach, one can predict lithosphere dynamics in Puerto Rico. The temperature profile is a model of the thermal structure of the lithosphere. Assuming that the continental lithosphere is in equilibrium and steady state, the temperature gradient can be approximated using the surface heat flow. For a layer of the lithosphere, the steady state temperature is:

$$T\ (z) = T_{top} + q_{top} * {}^{z}/_{k} \text{ [14]}$$

Where;

T_{top} = 30°C
q_{top} = 20
z = 10,000 m
k = 2

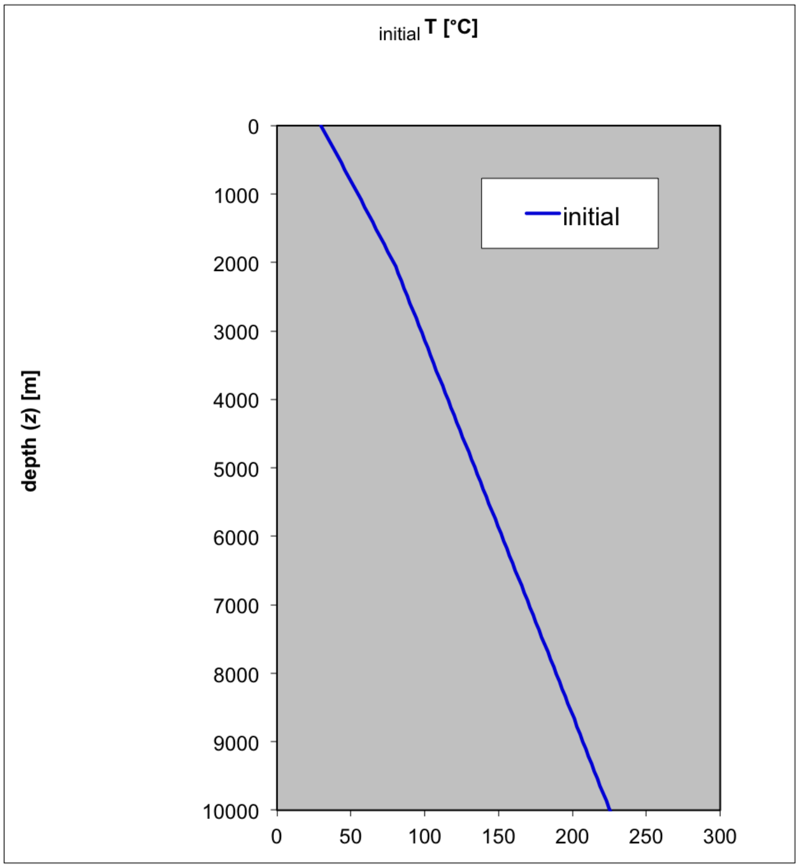

Figure 26 - Construction of continental lithosphere from a steady state relation between heat flow, conductivity and heat production [14]

For electricity production and combined heat and power (CHP), the same assumptions where used to 2020, 2030, and 2050. The CHP production temperature used was 30°C, but this temperature can increase or decrease depending on the application needed. Also, the heat (cold) efficiency was set to 50%, but it can be adjusted depending on how much heat is needed.

To give the best representation of the prospect for generating electricity from geothermal, it is important to choose the proper scenarios. These variables were selected for study because they are most likely to impact the LCOE, and must be carefully considered to develop a geothermal project.

Adjusting the scenarios can alter the outcome of a project. In these scenarios, we assume that with technological improvements the variables can change according to the outlook in Dumas et al., 2013. The following scenarios were chosen: 2020, 2030, and

2050. Table 7 above lists the assumptions chosen. When extracting geothermal fluids, the extraction rate should be kept at a constant rate over many years in order to recover the exploration and development costs. The flowrate increases to technological improvement and stimulation methods from 17 L/s in 2020 to 50 L/s in 2030 to 100 l/s in 2050. Stimulation costs remain the same for 2020 and 2030, but in 2050 it was assumed lower for the technological improvements. Well cost also remained the same for 2020 and 2030, but its lower in 2050 due to improvements in drilling methods.

The coefficient of performance increments from 30 in 2020, to 50 in 2030 and 1000 in 2050. The plant efficiency increases from 60% to 70% in the future. The use of CHP is more efficient and can be used for other processes. This CHP outlet temperature remains the same, but can be modified depending on the process needed but the LCOE will not remain the same.

13.1 Uncertainty and Sensitivity

Since most of the technical variables are dependent on technological improvements; there is a lot of uncertainty. The scenario for 2030 was considered as the base case reference point to measure the changes in the estimated LCOE from the individual variable sensitivities. In reality, variations and uncertainties can move a project away from the base case toward more or less cost-competitive geothermal projects. These variations are captured in the sensitivity analysis described below.

A maximum deviation of +-20% was assumed, to measure the effects on the technical variables. The sale price for CHP was assumed 11 $/GJ and the temperature for reinjection 30 °C. CHP can result in a reduction of the LCOE of 0.113 $/kWh. Increase in flow rates and production temperature on the other hand can reduce LCOE by 0.6-0.30 $/kWh. Adjusting the scenarios to the values assumed for the technological variables, the LCOE for EGS with CHP is 0.93 $/kWh for 2020, 0.28$/kWh for 2030, and 0.062 $/kWh for 2050.

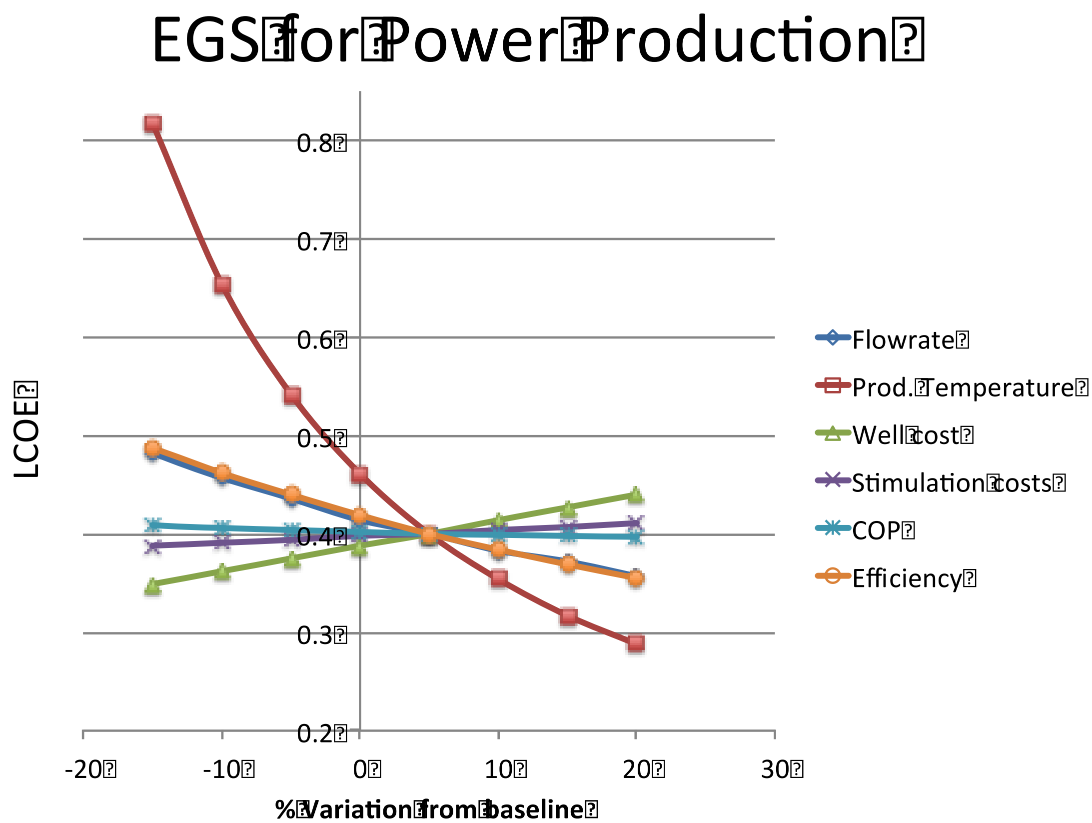

Figure 27 - LCOE sensitivities by input variables for geothermal energy

Figure 23 shows the LCOE sensitivity to the tested individual variables in all equity. As can be seen, production temperature has the largest impact on LCOE, even though the ranges tested were relatively small (+-20%, +-15%, +-10%, +-5%) in percentage terms from the base case input value. The LCOE decrease as production temperature increases, but the function is non-linear, so to a certain point the output is not proportional to the input anymore.

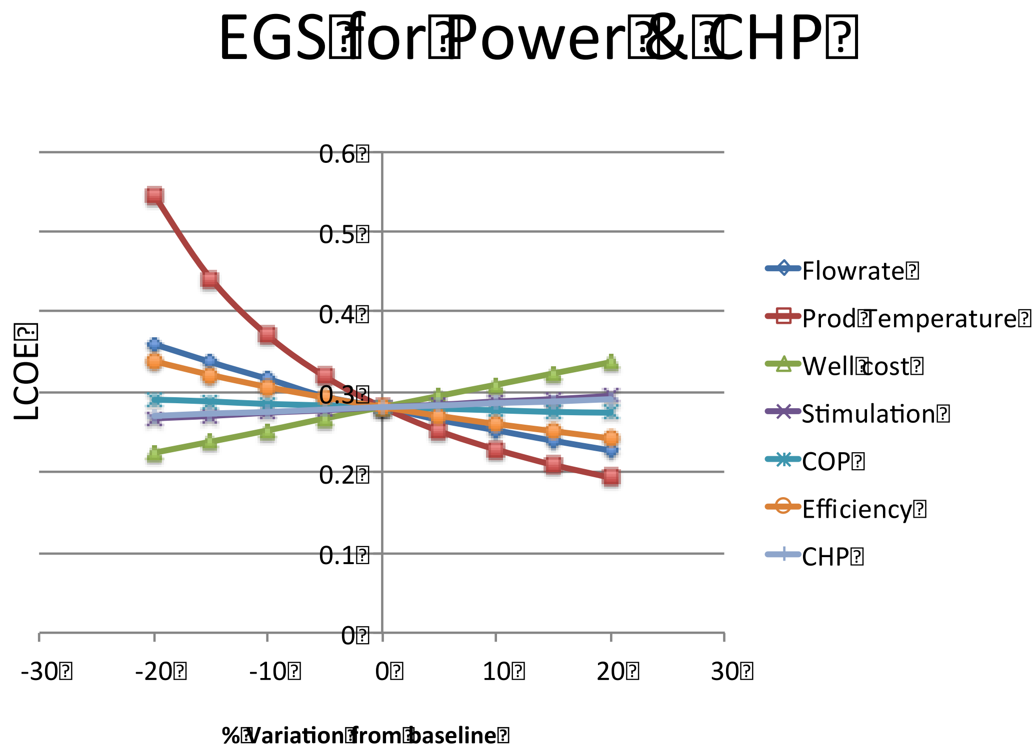

Figure 28 - LCOE sensitivities by input variables for geothermal energy and CHP

Figure 24 shows the LCOE sensitivity to individual variables but now CHP is included. As mentioned above, the production temperature has a huge impact in the development of geothermal energy. Most of the variables appear to have a mostly linear relationship to the estimated LCOE. This suggests that increasing flowrate and efficiency deceases the LCOE. Well cost and stimulation cost affect a project also, but as can be seen, if the well and stimulation cost increase, so does the LCOE.

14.0 Discussion and Conclusion

There is a huge need for cleaner and renewable energy sources such as geothermal energy. People in general are unaware of what GP is [5]. Geothermal energy has been used to produce electricity for some years now [12], and has a proven record of providing safe and reliable power at a competitive cost compared to conventional sources such as coal [44]. One of the best characteristics of GP is that it can provide power continuously without depending on intermittent sources of energy [44]. The area of this study for GP production is in the south of PR, in the town of Coamo. The main goal of this work is the evaluation of the potential feasibility of developing GP for electricity production or for cooling using GHP.

Conventional electricity production from geothermal energy can only be obtained when temperature from the geothermal resource is at least 150°C [44]. From 80°C till 150°C other conversion technologies such as binary cycle for power generation can be used. At higher temperatures, technologies such as Flash and Dry steam are the most extended GP technologies. Complete sketches for these conversion technologies were shown previously and can also be used to produce electricity from GP.

From the analysis done in Section 10.1, if a GP project were to be developed in PR, it should have a competitive price of electricity. From Figure 1, the price of electricity in 2012 was approximately 0.2811 ¢/kWh. For a small capacity power plant the price is not comparable, but 30 to 40 MW onwards, the price for electricity decreases exponentially. Despite the drawbacks, GP is generally cost competitive with conventional electricity generation in magmatic areas and is reliable and used to heat large municipal districts [5]. Big scale GP capacity projects if developed in the future could provide base-load electricity generation decreasing exponentially the price of electricity.

A well analysis was done in this study to determine the possible amount of wells needed to replace typical power producing units in PR. Most wells settle for a depth of 5 km [44]. A 10% stand-by well was considered since as mentioned above, each well goes though a harmonic decline rate with production and time. As time passes and production increases, the wells capacity decreases; therefore more wells will be needed in order to supply the electricity demand. The values obtained are comparable to the results on Sanyal's report.

If the resources for conventional GP were present in PR, small capacity projects would be ideal since stakeholders want to produce and supply energy from an available source with certainty and stable in price and time. This trend for long-time productivity may change over time. However, future developments such as EGS for electricity production hold the promise for GP development in PR. If EGS becomes economically viable, according to Bertani's report (Geothermal power generation in the world 2005-2010 update report), it is possible to have an installed capacity of 40 GW by 2050. Countries located in Africa, Central and South America and the Pacific could produce 100% of their power from GP.

However, future developments such as EGS for electricity production hold the promise for GP development in PR. If EGS becomes economically viable, according to Bertani's report (Geothermal power generation in the world 2005-2010 update report), it is possible to have an installed capacity of 40 GW by 2050. Countries located in Africa, Central and South America and the Pacific could produce 100% of their power from GP.

The uncertainty and sensitivity analysis suggest several insights for EGS development in Puerto Rico. As expected, changes in flow rate, production temperature, well cost, well stimulation, COP, efficiency and CHP have a significant impact on the LCOE, demonstrating that technological improvements can yield major benefits. Production temperature has the biggest impact on the LCOE. From Figure 23 and 24 we can see how the LCOE of electricity drops as the production temperature increases. As mentioned, the function is non-linear, so to a certain point the output is not proportional to the input anymore.

CHP can result in a reduction of the LCOE of 0.113 \$/kWh. Increase in flow rates and production temperature on the other hand can reduce LCOE by 0.6-0.30 \$/kWh. The LCOE for EGS with CHP is 0.93 \$/kWh for 2020, 0.28\$/kWh for 2030, and 0.062 \$/kWh for 2050. As can be seen, the price LCOE is quite competitive in the 2030 scenario. The price for fossil fuels is expected to keep getting higher, so in 2030 EGS could be a very feasible option for producing electricity.

Carnot efficiency is another variable that can decrease the LCOE. Well cost and stimulation cost are very costly also. EGS consists of drilling well at high subsurface depths, increasing the investment costs, and therefore the LCOE. Future drilling and stimulation techniques can make the price for drilling more competitive, therefore decreasing the LCOE as well.

Engineers are up to date in technology, but lack the knowledge of the Earth's interior. Geologists have vast knowledge of the Earth's heat and its uses but lack the technological side. Working together to find ways of extracting and producing GP can stimulate novel techniques for use and extraction and they can also improve efficiency.

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15.0 Appendix

Direct use geothermal application – Heat pumps

Geothermal heat pumps are an example of direct use technology for geothermal energy applications. They are one of the fastest growing renewable energy technologies. There has been an increase in 20% in 30 countries over the last 10 years (Laund, Sanner and Rybach). Geothermal heat pumps use normal ground or groundwater temperatures (between 5°C -30°C), which can be found all over the world (Laund, Sanner and Rybach). All year round, temperature at approximately three to five meters bellow remains between 10°C -16°C (Kreith and Goswami).

In the United States, present estimates for GHP systems installed are close to a million, mainly in the mid-western and eastern states (Lund, Gawell and Boyd). Figure 17 below illustrates the growth of geothermal heat pumps worldwide till the year 2050 (IPCC SSREN).

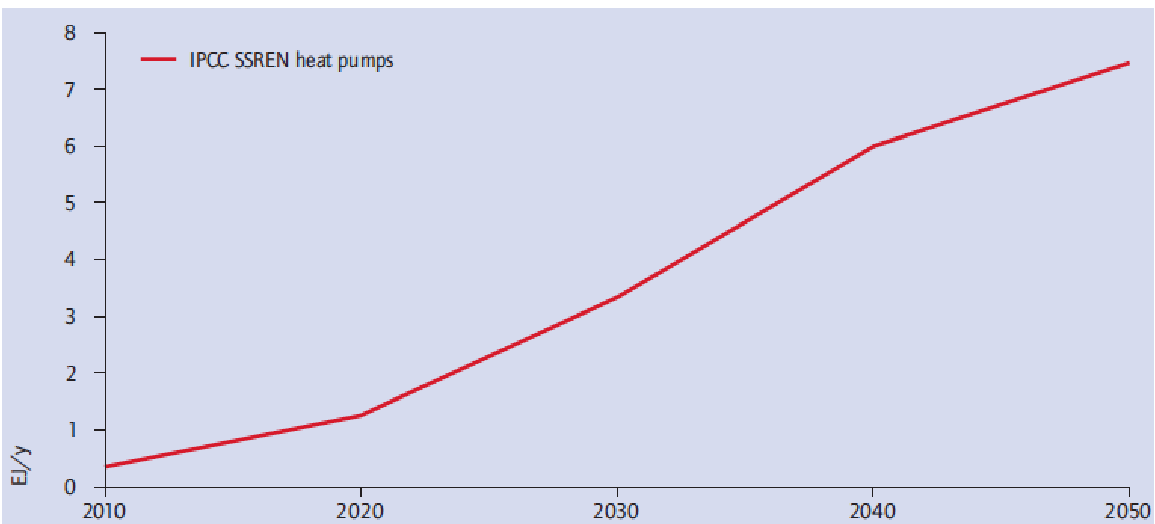

Figure 29 - Projected contribution of GHP **(International Energy Angency)**

Country	MW_{th}	GWh/yr	Number Installed
Austria	275	370	23,000
Canada	435	600	36,000
Germany	640	930	46,400
Sweden	2,300	9,200	230,000
Switzerland	525	780	30,000
USA	6,300	6,300	600,000

Table 8: Leading countries using Geothermal Heat Pumps as of 2004 (Lund, Gawell and Boyd)

Geothermal heat pumps operate similarly to a vapor-compression refrigeration cycle with heat rejected in the condenser for heating or extracted in the evaporator for cooling. The main difference between these two heat pump technologies is the investment in the ground loop for heat rejection or collection. The work done by the geothermal heat pump is described as "Pump", and "Lift" is the temperature difference. The greater the temperature difference (Lift), the higher the energy input; in other words the higher the temperature difference, more energy can go into the heat pump. Figure 18 demonstrates the two scenarios where geothermal heat pumps can be applied.

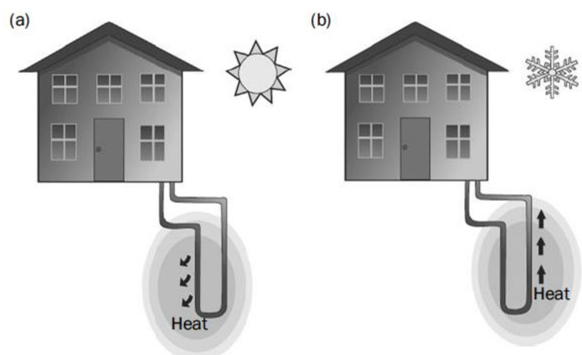

Figure 30 - GHP seasonal applications: (a) summer season (space cooling); (b) winter season (space heating) **(Self, Reddy and Rosen)**

Geothermal Heat Pump Systems

In a tropical weather Geothermal Heat Pumps (GHPs) are an application of geothermal energy. GHPs operate using electricity to move a compressor that will provide the necessary work to transport thermal energy between the earth and a space by controlling temperature and pressure by means of compression and expansion. It is based on the relative constant ground or groundwater temperature (ranging from 4°C to 30°C) to provide space cooling, heating and domestic hot water of all type of buildings.

A basic heat pump operates on a vapor-compression refrigeration cycle. Heat pumps and air conditioning systems operate on a reversed Carnot cycle: *Carnot Heat Pump and Carnot Refrigerator* (Cencel and Boles). The Carnot cycle is a totally reversible cycle that comprised of two reversible isothermal and two isentropic processes (Cencel and Boles). Because the cycle is reversible, all four processes in the Carnot cycle can be reversed also the flow direction.

A heat pump refrigeration cycle contains a refrigerant as its working fluid. The type of refrigerant will depend on the requirements of the GHP. The efficiency of GHP is described by a coefficient of performance (COP). The COP scales the heating or cooling output to the electrical energy input. COP for GHPs typically range between 3 and 4 (Lund, Gawell and Boyd).

$$COP = \frac{Output\ thermal\ energy}{Input\ energy\ of\ compressor\ for\ designated\ climate} = \frac{Heat\ removed}{Work\ done\ by\ GHP} \quad (1)$$

Any heat pump or air-conditioning system is made up of at least 4 major components as can be seen in Figure 19: compressor, condenser, expansion valve, evaporator. The additional components like the heat exchangers and the reverse pumps are additional components used for GHP. In this study, we are considering a GHP for cooling, since the weather conditions in PR are tropical, so the thermodynamic cycle is an ideal vapor-compression refrigeration cycle.

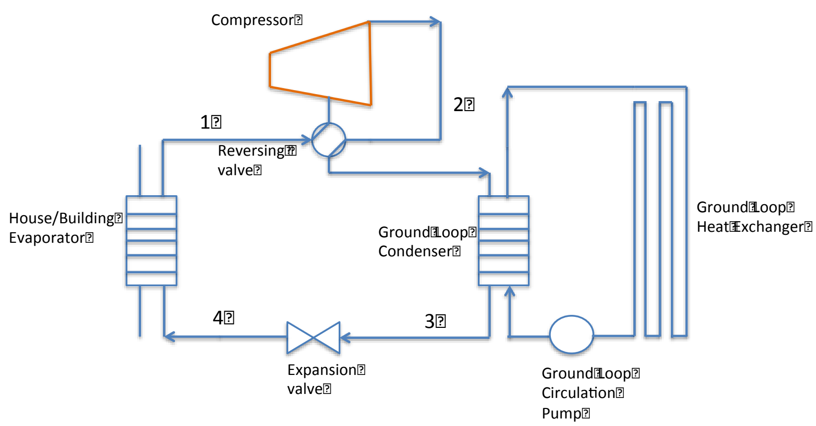

Figure 31 - Basic layout of a GHP **(Self, Reddy and Rosen)**

The vapor-compression refrigeration cycle is very common and is used all over the world for air conditioning systems and heat pumps (Cencel and Boles). In thermodynamic terms it consists of four processes.

Processes (Cencel and Boles):

1→2 *Isentropic compression in the compressor*

Refrigerant enters the compressor (state 1) as a saturated vapor and then is compressed isentropically to the condenser pressure. The refrigerants temperature increases due to the isentropic compression.

2→3 *Constant-pressure heat rejection in House/Building Heat Exchanger*
Refrigerant enters the condenser as superheated vapor at state 2, and leaves a saturated liquid at state 3 as a result of heat rejection in the ground loop heat exchanger.

3→4 *Throttling in an expansion Valve*
Saturated liquid refrigerant is throttled to the evaporator pressure as it passes through the expansion valve. The refrigerants temperature decreases below the temperature in the House/Building

4→1 *Constant-pressure heat absorption in evaporator*
The refrigerant enters the House/Building Heat Exchanger as a low quality saturated mixture and evaporates completely by absorbing heat from the house/building. The refrigerant leaves the heat exchanger as saturated vapor and reenters the compressor to complete the cycle, and then starting from step 1 again.

Calculation of LCOE of electricity
Geothermal Energy

Operational choice: Power

INPUTVARIABLES	used	Value	Unit	Comment
Flowrate	1	17	L/s	total flow rate which is achieved from the subsurface (measured at surface conditions)
along hole depth of a single well	1	7000	m	along hole depth (total length) of a single borehole in the subsurface
Surface temperature	1	30	C	average yearly surface temperature
production temperature (Tx)	1	180	C	production temperature (reservoir temperature, corrected for temperature losses)
Economic lifetime	1	15	Years	lifetime for cash flow calculations
subsurface				
well cost scaling factor	1	1.5	-	scaling factor for calculating well costs
well costs	1	20	mln euro/Well	calculated costs for drillling the wells
Stimulation and other Cost	1	5	mln euro/Well	additional well costs for stimulation (and other costs) of the reservoir
Pump investment	1	0	Mln euro/pump	pump investements. Workover is assumed every 5 years at installment costs
Number of wells	1	2	-	number of wells in the reservoir
subsurface capex	1	**50**	mln euro	calculated subsurface capex for wells, stimulation and pumps
subsurface parasitic				
pressure of water loop		0	bar	
electricity consumption		0	MWe	
COP	1	30	-	coefficient of performance (MWth/MWe) to drive the pumps. Ratio of thermal and electric power.
electricity price for driving the pumps	1	150	euro /MWhe	electricity price for the power consumed by the subsurface pumps
Variable O&M	1	5	euro/MWhth	calculated variable O&M per unit of heat produced (1MWhth=3.6GJ)
power temperature range used				
(co) heat relative starting temperature	0	0%	%	relative value (100%= Tx,0%=Tbase) for upper limit of temperature range for heat
outlet temperature power plant (Toutlet)	1	100	C	upper limit of Temperature for (co)heat use
power surface facilities				
thermal power for electricity	1	**6.231**	MWth	net power produced, taking into account the relative efficiency recorded by operating binary and flash plants
electric power		0.741	MWe	net power produced, taking into account the relative efficiency recorded by operating binary and flash plants
power Loadtime	1	8000	hours/year	effective load hours in a year for electricity production
power Plant investment costs	1	3.000	mln Euro/MWe	costs for power conversion system
power Distance to grid	1	5000	m	distance for the connection to the power grid
power Grid investment	1	80	Euro/kWe	grid connection cost per unit of power installed
power Grid Connection Variable	1	100	Euro/m	grid connection cost per unit of distance
power plant capex	1	**2.784**	mln Euro	calculated capex for power plant and grid connection
power Fixed O&M rate	1	1%	%	O&M costs as percentage of caclulated capex for (sub)surface facilities
power Fixed O&M	1	53	kEuro/MWe	calculated O&M costs per unit of power installed
power Variable O&M	1	42.01666667	Euro/MWhe	calculated variable O&M costs (dependent on COP, and efficiency of conversion)
(co)heat surface facilities				
direct heat reinjection temperature(Treinject)	0	30	C	reinjection temperature (effective temperature range is Toutlet..Treinject)
direct heat production	0	0.000	MWth	heat production
direct heat load hours	0	8000	hours/year	effective load hours in a year for heat production
direct heat plant investment costs	0	150.000	kEuro/MWth	heat surface installation costs per unit of heat production
direct heat capex	0	**0.00**	mln Euro	calculate capex for heat production surface facilities
direct heat Fixed O&M rate	0	1%	%	O&M costs as percentage of caclulated capex for (sub) surface facilities
direct heat Fixed O&M	0	50	kEuro/MWth	calculated O&M costs per unit of heat production installed
direct heat Variable O&M	0	5	Eur/MWHth	calculated variable O&M costs (dependent on COP)

Calculation of LCOE of electricity
Geothermal Energy

Operational choice: Power

complementary sales				
complementary electricity sales	1	0.00	Euro/MWh	complementary revenues from electricity sales
complementary heat sales	1	11	euro/GJ	complementary revennues from heat sales
fiscal stimulus				
fiscal stimulus on lowering EBT	1	**no**	yes/no	apply fiscal stimulus on lowering earnings before tax (EBT) of the project developer
percentage of CAPEX for fiscal stimulus	1	0%	%	percentage of CAPEX which can be deducted from EBT
legal max in allowed tax deduction	1	0	mln Euro	legal maximum in tax benefit
NPV of benefit to project	1	0.0	mln Euro	effective benefit to project
Inflation	1	3%	%	inflation for costs and benefits in project cash flow
loan rate	1	7.0%	%	interest rate on debt
Required return on equity	1	15%	%	required return on equity
Equity share in investment	1	20%	%	share of equity in the effective investment
Debt share in investment	1	80%	%	share of debt(the loan) in effective investment
Tax	1	25.0%	%	tax rate for company
Term Loan	1	15	Year	number of years for the loan
Depreciation period	1	15	Year	number of years for depreciation (linear per unit of production)

Rock, fluid properties and plant efficiency

parameter	Value	Unit
Cpwater	4250	J/kg K
ρwater	1078	kg/m3
Cprock	1000	J/kg K
ρrock	2700	kg/m3
power conversion		
relative efficiency	0.6	-
total conversion efficiency	0.1190	-
offset for Tbase	70	C
Tbase (minimum Tx for power)	100	C
heat (cold) conversion		
total efficiency	0.5	-
units		
Seconds per year	3.16E+07	s
seconds per 30 years	9.47E+08	s
Ultimate recovery		
subsurface area	4.5	km2
subsurface thickness	100	m
rock volume involved	4.50E+08	m3
UR for volume	6.07%	

Calculation of LCOE of electricity
Geothermal Energy

Operational choice: Power-CHP

INPUTVARIABLES	used	Value	Unit	Comment
Flowrate	1	17	L/s	total flow rate which is achieved from the subsurface (measured at surface conditions)
along hole depth of a single well	1	7000	m	along hole depth (total length) of a single borehole in the subsurface
Surface temperature	1	30	C	average yearly surface temperature
production temperature (Tx)	1	180	C	production temperature (reservoir temperature, corrected for temperature losses)
Economic lifetime	1	15	Years	lifetime for cash flow calculations
subsurface				
well cost scaling factor	1	1.5	-	scaling factor for calculating well costs
well costs	1	20	mln euro/Well	calculated costs for drillling the wells
Stimulation and other Cost	1	5	mln euro/Well	additional well costs for stimulation (and other costs) of the reservoir
Pump investment	1	0	Mln euro/pump	pump investements. Workover is assumed every 5 years at installment costs
Number of wells	1	2	-	number of wells in the reservoir
subsurface capex	1	**50**	mln euro	calculated subsurface capex for wells, stimulation and pumps
subsurface parasitic				
pressure of water loop		0	bar	
electricity consumption		0	MWe	
COP	1	30	-	coefficient of performance (MWth/MWe) to drive the pumps. Ratio of thermal and electric power.
electricity price for driving the pumps	1	150	euro /MWhe	electricity price for the power consumed by the subsurface pumps
Variable O&M	1	5	euro/MWhth	calculated variable O&M per unit of heat produced (1MWhth=3.6GJ)
power temperature range used				
(co) heat relative starting temperature	1	0%	%	relative value (100%= Tx,0%=Tbase) for upper limit of temperature range for heat
outlet temperature power plant (Toutlet)	1	100	C	upper limit of Temperature for (co)heat use
power surface facilities				
thermal power for electricity	1	**6.231**	MWth	net power produced, taking into account the relative efficiency recorded by operating binary and flash plants
electric power		0.741	MWe	net power produced, taking into account the relative efficiency recorded by operating binary and flash plants
power Loadtime	1	8000	hours/year	effective load hours in a year for electricity production
power Plant investment costs	1	3.000	mln Euro/MWe	costs for power conversion system
power Distance to grid	1	5000	m	distance for the connection to the power grid
power Grid investment	1	80	Euro/kWe	grid connection cost per unit of power installed
power Grid Connection Variable	1	100	Euro/m	grid connection cost per unit of distance
power plant capex	1	**2.784**	mln Euro	calculated capex for power plant and grid connection
power Fixed O&M rate	1	1%	%	O&M costs as percentage of caclulated capex for (sub)surface facilities
power Fixed O&M	1	53	kEuro/MWe	calculated O&M costs per unit of power installed
power Variable O&M	1	42.01666667	Euro/MWhe	calculated variable O&M costs (dependent on COP, and efficiency of conversion)
(co)heat surface facilities				
direct heat reinjection temperature(Treinject)	1	30	C	reinjection temperature (effective temperature range is Toutlet..Treinject)
direct heat production	1	2.726	MWth	heat production
direct heat load hours	1	8000	hours/year	effective load hours in a year for heat production
direct heat plant investment costs	1	150.000	kEuro/MWth	heat surface installation costs per unit of heat production
direct heat capex	1	**0.41**	mln Euro	calculate capex for heat production surface facilities
direct heat Fixed O&M rate	1	1%	%	O&M costs as percentage of caclulated capex for (sub) surface facilities
direct heat Fixed O&M	1	50	kEuro/MWth	calculated O&M costs per unit of heat production installed
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