University of Piraeus

School of Economics, Business and International Studies Department of International and European Studies

MSc in Energy: Strategy, Law and Economics

Geothermal Energy: Drilling Technologies, Electricity Production, and Global Geopolitics

Student: Angelcho Panov

Registration number: MEN19007

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Abstract

In this master's thesis, three different aspects of geothermal energy are presented. Digging, electricity generation, and policies of geothermal-rich countries. First, a general geological overview of the world is presented, followed by information on geothermal drilling techniques and available technology. It explains the basic elements of digging, such as drilling rigs, types of drilling bits, and types and performances of drilling pipes. It later explained the impacts of geothermal energy on the energy policies of states, i.e., the use of electricity as a diplomatic tool and as a substitute for fossil fuels; electricity production; as well as more sophisticated binary cycle variants and EGS systems. Here, a new geopolitical picture is presented, along with new international partnerships between geothermal-rich nations. Later, the inter-state relations related to geothermal energy were described to finally give the total world capacity of geothermal energy and the policies of the states towards it.

CHAPTER 1: INTRODUCTION

1.1 Introduction

The twentieth and twenty-first centuries were significantly impacted by energy geopolitics, which is the influence of nations on one another through the supply and demand of energy. The owners of fossil fuel resources are slowly losing ground to nations developing low-carbon sources of energy in the geopolitics of energy (Paltsev, 2016).

There is a great need to boost the development of innovative energy technologies in order to tackle the global challenges of clean energy, preventing climate change, and sustainable development (IEA, 2011). Increasing fossil fuel crises, rising oil price volatility, deteriorating environmental conditions, and the threat of climate change require a shift to a more sustainable energy system.

Renewable energy and its supporting technologies will be the foundation of such a future. Renewable energy is now just a minor contributor to global primary energy and electricity supply, although installed capacity and investment are fast increasing (Scholten & Bosman, 2016).

The geothermal energy has been used for millennia's. At the beginning of the 20th century, the first geothermal power plants were produced, and since then relatively slowly, but surely their share in the overall energy mix has been increasing (Massachusetts Institute of Technology, 2006).

Geothermal energy is stored in rock as well as trapped vapour or liquids such as water or brines; these geothermal resources may be used to create electricity as well as to provide heat (and cooling). Geothermal resources with a larger temperature range can be used to heat buildings and districts, spa and swimming pool heating, greenhouse and soil heating, aquaculture pond heating, industrial process heating, and snow melting. Geothermal technologies use renewable energy resources to generate power, as well as heating and cooling, while emitting relatively little greenhouse gas (GHG). As a result, they play a vital role in achieving aims for energy security, economic development, and climate change mitigation (IEA, 2011).

With that, geothermal energy is slowly but surely finding its place on the global energy map, and this master's thesis aims to describe the technological solutions for its exploitation, production of electricity, as well as to present the global geothermal map and the geopolitics related to that.

1.2 Overview

Geothermal energy as part of renewable energy sources is still at the beginning of its development. This master's thesis presented both technological and socioeconomic challenges associated with geothermal energy. Starting with the literature review in Chapter 2, the basics of geothermal drilling are laid out, so the production of electricity, the basics of energy security, the security of renewable energy sources, as well as the impact of geothermal energy are described. The results section later describes in detail the technologies currently used in the industry to later describe the geopolitical consequences of geothermal energy, as well as the new players in the global market and the countries' relations with each other, countries that use geothermal energy, countries that have active policies for the development of geothermal energy, and thus at the very end, the basic issues in the chapter methodology are explained. The thesis is finalized with the conclusions presented in Chapter 5.

CHAPTER 2: Literature review

2.1 Introduction

Geothermal energy is, in general, the thermal energy contained in the earth's crust at an accessible depth (USA Patent No. 6.742,603, 2003). The word geothermal is derived from the combination of the Greek words gê, which is earth, and "therm, which means heat (Barbier, 2002). Thermal energy from the interior of the Earth is contained in geothermal resources, which include trapped steam or liquid water as well as rock. Geothermal resources, as they are being exploited, are now occurring in a variety of geographical areas where the reservoirs have different temperatures and depths depending upon their geological conditions (Goldstein, 2011).

The location (depth and position) and quality (fluid chemicals and temperature) of a particular resource are determined by local and regional geological and tectonic phenomena. For instance, greater than average heat flow regions are typically correlated with tectonic plate boundaries and areas of recent volcanic explosions (Mock, Tester, & Wright, 1997), for instance, in Iceland, Indonesia, and parts of Italy. With a thermal gradient of between 5° and 70° per kilometer, the earth’s crust temperature rises steadily. The local heat flux and geothermal gradients can be slightly higher than the average in areas similar to those described above (Dumas, Antics, & Ungemach, 2013). Geothermal energy is known as a renewable resource because of the huge amount of heat held in the center of the earth. The heat tapped from an operating reservoir is constantly recovered by natural thermal regeneration (Goldstein, 2011).

2.2 Drilling technologies

2.2.1 Types of geothermal resources

According to (Goldstein, 2011), the technologies for geothermal resource utilization can be arranged under three types: direct use, electrical energy generation, and combined heat and power operation.

As claimed by (Mock, Tester, & Wright, 1997), geothermal resources are classified into four categories: hydrothermal, hot dry rock, magma, and geopressed.

Hydrothermal resources frequently occur at depths of 1-4 km and include steam or liquid water at temperatures of up to 350°C in a convectively active, porous rock area. These are the most common sources of geothermal energy and can be used for both direct use and electricity generation. The term "hot dry rock" has been used to characterize geothermal systems in which fluids are not created spontaneously. In many situations, these are really non-productive hydrothermal systems, and additional technologies must be implemented for the water to be injected into the well, there heated, and again brought to the surface. Hot dry rock systems are generally made available anywhere only by digging deep enough to achieve rock temperatures that are ideal for heat removal. In regions with recent volcanic activities, magma resources consist of partially or fully molded rock found at accessible depths (< 7 km), making them especially desirable for the efficient production of electric energy or industrial high-temperature heat applications. In fact, geopressed resources include the content of chemical energy contained in the dissolved methane and also the thermal and hydraulic energy. For these materials, the thermal energy is about 58%, the hydraulic component is around 10%, and the chemical energy stored in the hydrocarbon is around 32%.

2.2.2 Geothermal drilling

According to (Thorhallsson, 2008), about a century ago, drilling into geothermal reservoirs began, and it really took off in the second half of that century. A heavy chisel suspended from a wire rope was used in early drilling rigs to pound the earth in order to create the hole. Before the invention of the tri-cone bit in 1933, rotary drilling with hollow steel pipes was first conducted using drag bits and steel balls.

Early applications of rotary drilling with hollow steel pipes included drilling with steel balls and drag bits up until the creation of the tri-cone bit in 1933.There have been significant developments in depth and technologies, but the fundamental aspect is still the same: to create a hole by the application of rotating motion and to transfer energy and put weight on the bit. Very little has improved in recent decades.

The most expensive and crucial step in the exploration, production, and use of geothermal energy is drilling. (Huenges & Ledrt, 2010). As in the search for any natural resource, a geothermal energy exploration plan must be established and implemented. After identifying a geothermal zone, the next step is to use a specific discovery method to determine the most appropriate geothermal region and set production targets accordingly (Barbier, 2002). Geological mapping, a geochemical study of the geothermal water, and geographical techniques widely used by the mining industry are usually used while exploring geothermal resources (Barbier, 2002).

In the evolution of a geothermal project, drilling and production of wells are the most important operations. Geothermal fluid drilling is equivalent to rotary oil and gas drilling (Barbier, 2002). Although there are thousands of rigs operating around the world for oil and gas, only a few are operating at geothermal wells (Thorhallsson, 2008). Even then, the higher temperatures, the nature of the rocks being penetrated, and the corrosiveness of the fluids make geothermal drilling more complicated than in petroleum and gas operations (Barbier, 2002). Geothermal drilling technology was modified and widely integrated into these other types of drilling engineering. It uses the expertise, equipment, methods, materials, and experience that are gained from those types of drilling (Massachusetts Institute of Technology, 2006). Practically all this technology is derived from petroleum and gas exploration (Thorhallsson, 2008).

Geothermal exploration aims to reach the reservoir in the best and least costly way possible. The overall goal is to create a well in the safest manner possible while complying with normal protocols to economically extract the resource from the well (D, V, & R, 2013). Geothermal drilling cost reduction is indeed a big concern that should be addressed for the economic viability of geothermal energy (Huenges & Ledrt, 2010). Planning the well and engineering the well are two distinct but closely related aspects of planning for a drilling project. The term "planning" refers to the process of listing, defining, arranging, and budgeting for all of the individual tasks needed to drill the well, while "designing" refers to the layout of all of the physical parameters (depth, diameter, etc.) that create the well itself (Finger & Blankenship, 2012). The most critical aspect of an effective geothermal drilling operation, though, is understanding the dynamics of drilling a well from start to finish. Drilling involves the interaction of geology and mechanics, as well as the use of rock material and techniques. As a result, all fundamentally dynamic domains must be logically and functionally combined (Huenges & Ledrt, 2010).

Geothermal reservoirs commonly consist granite, quartzite, basalt, and volcanic tuff. Geothermal structures are naturally steaming (production ranges from 160°C to over 300°C) and often hard (240+ MPa of pressure), abrasive (quartz content over 50%), heavily fractured (fracture apertures of centimeters), and under-pressured in comparison to other oil and gas reservoir sedimentary formations (Finger & Blankenship, 2012).

Geothermal resources vary greatly in depth and temperature. Numerous power plants (for example, Nevada, California, Steamboat Hills, and Mammoth Lakes) run on lower-temperature fluid (below 200°C) created from depths of around 330 m, yet wells in The Geysers generate dry steam (higher than 240°C) and are usually 2500 to 3000 m deep. The hottest geothermal well drilled so far is located in the Kakkonda field, Japan, where more than 500°C were measured (Saito, Sakuma, & Uchida, 1998).

2.2.3 Drilling technology

The rig is the complete construction of the geothermal drilling platform; it consists of the drilling bit, drill pipe, motor or power source, drill line, mud tank crown block, and many other components. Oil well rigs with hook load capacities of 200–450 t and rotary table drives are used for geothermal drilling. In top-drive rigs, the drill string is directly connected to a hydraulic or electrical motor that is mounted high in the mast. (Thorhallsson, 2008). A production well can typically be drilled to a depth of 2,000 m in 35–45 days thanks to current technology. Drilling at 200-300 m/day is now extremely common, whereas 40-100 m/day was previously regarded as quite acceptable. (Thorhallsson, 2008).

The drill pipe and the bottom hole assembly (BHA), which includes drill collars, jars, stabilizers, and the bit, are the most essential drilling tools. The drill pipe serves as a route for drill mud and delivers surface torque to the bit. The drill collars' purpose is to add the needed bit weight and thus hold the drill pipe under stress. By centralizing the string inside the borehole, stabilizers improve directional control and decrease the risk of stuck pipe incidents. The string rotates the bit, and that can also be a hydraulic downhole motor that is driven by the drilling mud (D, V, & R, 2013).

The actual breaking of the earth is performed with the use of a rock bit. The bit is rotated when it is underweight from the drilling strings and the surface motors. Rotary speed, weight on bit (WOB), and hydraulics (combination of jet size and flow rate) are the three factors that can be easily modified for each bit/formation combination, and finding the correct integration of these values always needs some experimenting (Finger & Blankenship, 2012).

As it rotates, the bit both crashes and gouges the rock. The broken rock fragments from drilling are extracted from the bottom hole by floating them in a flowing drilling fluid. This procedure is repeated before the well is finished. (K.Ngugi., 2008). The most developed deep drilling technique is rotary drilling, which has been used since 1909 with the tri-cone rotary bit, replaced in the 1970s by the polycrystalline diamond bit, and used by diesel-electric drilling rigs to produce boreholes covered by steel casings, one inside the other. It is very important to follow the exact procedures of the drilling process to prolong the lifetime of the drilling equipment, especially the drilling bit. The lifespan of tri-cone drill bits has progressively improved, especially those with journal bearings and strong metal tungsten carbide inserts ("teeth") and "gauge protection". They are far more expensive, but they can drill up to 1000 meters and rotate over a million rounds before needing to be replaced. (Thorhallsson, 2008).

While the drill string is being lowered into a hot hole, water or mud is also pushed through it to prevent heat damage to the bit, mud motor, and down-hole instruments like Measurement While Drilling (MWD) tools. Such top drives can be installed to older rigs and are present on the majority of new ones. Nonetheless, because they are more affordable, durable, and have a good track record of performance, older, unmodified rotary rigs with rotary table drives are still utilized for geothermal drilling. (Thorhallsson, 2008). Even though this technology is relatively old and there has been little innovation during the past century, it is still used for almost all geothermal drilling today. Also, there are a wide variety of technologies among which rotary, preferably hydraulic, and electrically driven drilling are best suited to deep-seated targets (Dumas, Antics, & Ungemach, 2013). Projectile drilling, spallation drilling, laser drilling, and chemical drilling are examples of such techniques.

Projectile drilling involves firing steel balls at high speeds and using pressurized water to break and remove the rock surface. The projectiles are collected after being removed from the drilling mud and rock chips (Geddes & Curlett, 2005). High-temperature flames are used in spallation drilling to quickly heat the rock surface, allowing it to break, or "spall." A device like this may also be used to melt non-spillable rock. Laser drilling follows the same mechanism as conventional drilling but relies on laser pulses to heat the rock surface (Massachusetts Institute of Technology, 2006). Chemical drilling uses heavy acids to break down the rock, which can be used in combination with traditional drilling techniques (USA Patent No. 6.742,603, 2003). Such drilling solutions are only in the early stages of development and are not yet available commercially. However, the practical application of all of these technologies could result in a significant shift in drilling techniques, significantly lower drilling costs, and, more specifically, allow for deeper drilling performances (Massachusetts Institute of Technology, 2006).

2.2.4 Drilling costs

Exploration, production, and injection well drilling are all significant costs of any geothermal project. Geothermal exploration is costlier (in terms of cost per depth) than on-shore oil and gas drilling for three main reasons:

1. Technical reason: Because of the above-mentioned circumstances, special equipment and techniques are needed for the rough downhole conditions.

2. Large diameters: Since the generated fluid (hot water or steam) has a low real value, large flow rates are needed, as are large holes and casing. In certain situations, a geothermal well may also take more time and effort to reach a given depth than an oil well to the same depth.

3. Uniqueness: Since geothermal wells, even within the same field, differ more than oil and gas wells in the same field, the experience gained from the oil and gas wells is sometimes impractical in this case (Finger & Blankenship, 2012).

There are three major well cost generators of geothermal exploration. The most significant is the technological difficulty posed by the harsh underground conditions and the hard rock. The second driver is an appropriate (wider) borehole diameter to ensure the necessary mass flow. The wider the diameter of the borehole, the longer the drilling and completion rate. The third and smallest generator, but with the greatest possible savings, is the well's uniqueness and potential issues with machinery, the environment, and possible complications (D, V, & R, 2013).

2.2 Electricity production

2.2.1 Geothermal energy outlook

Geothermal resources have been utilized economically for more than a hundred years (Goldstein, 2011). Electricity has been generated commercially by geothermal steam since 1913 (Bertani, Geothermal Power Generation, 2012), when in 1904 at *Larderello, Tuscany* in Italy, Prince Piero Ginori Conti pioneered the use of geothermal steam to generate electricity (Fridleifsson, 2001). As energy affects all aspects of modern life, the geothermal industry currently has a diverse group of members, including global energy companies, private and public entities, equipment producers, retailers, and suppliers. As a general rule, demand is dictated by population increase, housing demand, and the energy intensity of activities in both the manufacturing and commercial sectors of the economy, (Massachusetts Institute of Technology, 2006) the geothermal-electric market appears to be accelerating compared to previous decades (Bertani, Geothermal Power Generation, 2012).

The estimated thermal energy present in the earth is vast, on the level of 12.6 x 1012 EJ, and that of the crust is on the order of 5.4 x 109 EJ to depths of up to 50 km (Dickson & Fanelli, 2015). It is assumed that geothermal energy could provide up to 8.3 percent of total global energy, supplying 17 percent of the world's population (Bertani, Geothermal Energy: An overview on resources and Potential, 2006). Over the past five decades, geothermal technology has been used on a large scale (hundreds of megawatts) for both power generation and direct use. During the last three decades, utilization has increased exponentially. Geothermal resources have been found in 90 countries, with measurable reports of geothermal utilization in 72 of them (Bertani, Geothermal Power Generation, 2012). Over 39 nations, predominantly in Africa, Central and South America, and the Pacific, will be able to obtain all of their energy needs from geothermal resources (Dauncey, 2001), though geothermal energy now contributes for more than 10% of electricity demand in six states and is used directly for heating and cooling in 78, producing 121.7 TWh/yr (0.44 EJ/yr) of thermal energy. (Goldstein, 2011). Geothermal energy is used for power generation in 24 countries, with five of them obtaining 15–22 percent of their national electricity supply from geothermal energy (Bertani, Geothermal Energy: An overview on resources and Potential, 2006).

2.2.2 Geothermal power generation

High-temperature geothermal reservoirs holding water and/or steam can supply steam to directly drive steam turbines in power facilities (Mburu, 2015). Here, the kinetic energy created by the pressure of steam or water with the help of the turbine will be converted into mechanical energy, and later, the electrical generator will convert that energy from mechanical to electrical energy with a very high current, which will later be connected with a transformer and after that, in the electrical grid. A power plant's usual components include pipelines, water-steam separators, vaporizers, de-misters, heat exchangers, turbine generators, cooling systems, and a step-up transformer. The power unit scale typically ranges from 20 to 110 MWe (DiPippo, Ronald, 2012). According to (Mburu, 2015), geothermal power plants are divided into three groups based on fluid temperature, pressure, and chemistry.

1. condensing power plants (dry steam, single or double flash systems),
2. back-pressure turbines (atmospheric release), and
3. binary plants (for lower temperatures or separated brine).

Direct steam plants are used with vapor-dominated resources (WHITE, 1973), These plants are also known as dry stream plants. The first geothermal power generation plants were designed using dry steam systems. They are the simplest of all systems, as they use steam from geothermal reservoirs as it flows from wells and routes it directly into turbine and generator systems to generate electricity. (Mburu, 2015)**.**

The most famous type of geothermal power plant is a flash steam power plant. When segregated from the water, the steam is piped to the turbine and used to turn the steam turbine. After leaving the engine, the steam is condensed, producing a vacuum pressure and enhancing the power provided by the turbine generator. Steam is usually condensed in a direct-contact condenser or a heat exchanger. m geothermal reservoirs as it flows from wells and routes it directly into turbine and generator systems to generate electricity (Mburu, 2015).

The most basic type of flash plant is a single-flash plant. Such plants are referred to as "single-flash" since only one flashing operation occurs between the reservoir and the power generation system (DiPippo, Ronald, 2012). Flash condensing geothermal power plants usually range in scale from 5 MW to more than 100 MW. Depending on the steam properties, gas content, temperatures, and power plant configuration, each MW of electrical power needs between 6000 kg and 9000 kg of steam per hour (Mburu, 2015).

By implementing a secondary flash operation, a major increase in resource usage over a single-flash steam plant can be realized (WHITE, 1973). Rather than being discharged, the liquid released from the separators is exposed to another pressure drop, resulting in the release of extra steam. At the appropriate stage, lower-pressure steam is admitted to the steam turbine, which produces additional power (DiPippo, 1991).

Small power plants (less than 10 MW) are often known as well-head units since they only use the steam from one well and are situated next to the well on the drilling pad to minimize pipeline costs. These well-head units are known as backpressure units because they do not have a condenser. Although they are inexpensive and simple to install, they are inefficient (usually using 10–20 tons of steam per hour for every MW of energy) and may have negative environmental effects (Mburu, 2015). Conventional electric power generation is limited to fluid temperatures over 150°C, but far lower temperatures can be used in binary cycle systems, often known as organic Rankine cycles (in this case, the outlet temperatures of the geothermal fluid are usually above 85°C) (Barbier, 2002).

More heat from the resource can be used for power generation thanks to newly evolved binary power plant technology. The use of a hybrid of traditional flash and binary cycle technologies is growing in popularity. (Mburu, 2015). A binary plant is used where geofluid cannot come into contact with electricity-producing devices, such as turbines or engines (DiPippo, 1991). Binary cycle plants are commonly used in reservoirs where temperatures are less than 220^o C but greater than 100^o C (Mburu, 2015). As opposed to steam, the binary plants use an auxiliary operating fuel, which is usually a natural liquid (typically n-pentane) with a high boiling point and high vapor pressure at low temperatures. (Dickson & Fanelli, 2015). In a basic binary system, the hot liquid enters a vapor generator, where it transfers heat to a secondary working fluid (hence the name 'binary' cycle) (DiPippo, 1991).

The efficiency of geothermal steam power production varies from 10% to 17%, which is about three times lower than fossil-fueled or nuclear plants. Due to the low temperature of the steam, geothermal plants have the lowest efficiency (Barbier, 2002).

In example, a kilogram of oil provides 10,000 kilocalories (41,800 kJ), a kilogram of the finest geothermal steam generates just 700 kcal (3000 kJ), and a kilogram of hot water operating between 80°C (production temperature) and 30°C (discharge temperature) delivers only 50 kcal (209 kJ) (Barbier, 2002).

The fluid requirements for geothermal power plants range from 6 kg/kWh (if dry steam is available) to 400 kg/kWh (if binary cycle plants use hot water) (Barbier, 2002). Carbon dioxide emissions from geothermal energy are in the range of 0.01–0.4 kg/kWh, compared to 0.5–1.1 kg/kWh from fossil fuels (Murphy & Niitsuma, 1999). Even after these disadvantages, geothermal kWh is generally cost-competitive with traditional sources and is generated using well-proven conventional technology. Geothermal energy is a trusted source of energy (Barbier, 2002), furthermore, geothermal resources are not dependent on climate factors, and climate change is not predicted to have a direct effect on the capacity of geothermal resources. (Goldstein, 2011). Geothermal energy is ideal for providing base-load electricity due to its natural thermal storage capability. (Goldstein, 2011)**.** Base-load requirements are usually achieved by acquiring the most cost-effective and high-capacity-factor energy available. Although this varies by area and time of day, the most efficient fuel/technology combinations available to meet this requirement include gas, hydroelectric, nuclear, and geothermal electricity. (Massachusetts Institute of Technology, 2006).

The power rating of geothermal turbine/generator units is usually lower than that of traditional thermal power plants. The most typical units are 55, 30, 15, and 5 MWe or less. One of the benefits of geothermal power plants is that they can be installed economically in far smaller units than, for instance, hydropower plants. In developing countries with a limited energy sector, geothermal power plants with units ranging from 15 to 30 MWe can therefore be more readily adapted to the annual rise in electricity demand than, say, hydropower plants with units ranging from 100 to 200 MWe (Barbier, 2002).

The long-term reliability of the resource and characteristic power curve are key aspects of sustainable hydrothermal geothermal power. Operators or grid managers consider this power curve for base-load conditions where load following or quickly shifting load operations are not needed. Except for upgrades or planned maintenance, geothermal plants work continuously throughout the year (Massachusetts Institute of Technology, 2006). Today, geothermal power is considered base-load capacity because it is fully available year-round, 24 hours a day.

2.2.3 Enhanced geothermal systems

The basic idea behind Enhanced Geothermal Systems (EGS) is simple: in the deep subsurface where temperatures are high enough for electricity generation (150–200 °C), an extensive fracture network is formed to serve as new routes. Water from deep wells, or surface cold water is distributed via this deep reservoir through an injection and production well and recovered as steam or hot water. The circulation system is completed by injection and production wells, as well as external surface systems. The heat collected can be used for district heating or electricity production (Bertani, Geothermal Energy: An overview on resources and Potential, 2006).
Geothermal configurations usually consider cascade applications that use geothermal fluid first to generate energy, and then the same fluid can be used for heating (Anderson, 1979), in this context, geothermal heat sources at temperatures greater than 150 °C can combine heat and power generation, so the condensing temperature, which is usually greater than 60 °C, is appropriate for district heating or other direct heat uses. (Lund, 2016).

2.2.4 Environmental concerns and capital

Climate change and energy security are critical aspects of energy policy, as are energy reliability, energy affordability, and market competitiveness for businesses, industries, and households (Stigka, Paravantis, & Mihalakakou, 2014). A single-flash plant needs approximately 1200 m2 per MW, while a coal-fired plant requires 40,000 m2 per MW, and a photovoltaic plant requires 66,000 m2 per MW. (DiPippo, Ronald, 2012), as a result, this is a cost-effective choice in terms of property. Geothermal energy is a highly capital-intensive and technologically reliant sector. (Massachusetts Institute of Technology, 2006). Approximately 50% of the overall costs of geothermal exploration for electricity generation are related to the discovery and characterization of reservoirs and, most notably, the drilling of production and re-injection wells. The amount is divided as follows: 40% goes to power plants and pipelines, and 10% goes to other operations (Barbier, 2002). There are other environmental concerns regarding geothermal power plants in general; water waste, noise and visual pollution, water and land use, greenhouse gas emissions, and a lack of natural beauty are only a few examples (Braun & McCluer, 1993). Governments must develop a legal and institutional basis, as well as fiscal instruments, to allow geothermal resources to compete with existing energy production systems. (Fridleifsson, 2001). Although, (Bayer, Rybach, Blum, & Brauchler, 2013) argues that there are many ways to mitigate these environmental problems, such as reinjection for surface water pollution, the use of silencers for reducing noise pollution, air-cooled condensers for water use, and restricting construction in national parks. On average, geothermal power plants have a smaller effect on the atmosphere and release fewer greenhouse gases than fossil-fuel-fired nuclear power plants.

2.3 Global geopolitics

2.3.1 Global renewable geopolitics

Geopolitics is a scientific research discipline that is part of both Political Geography and International Relations and studies the relationships (in three dimensions: physical, geographical, and spatial interactions) between politically acting groups and their territoriality (Criekemans, 2011), (Scholten D. C., 2020).

Energy problems have long been in the interest of geopolitics, as common energy sources such as oil, natural gas, and coal are physical-geographical factors of geopolitical significance. The energy regime of the global economy, as well as the energy ties between producer, transport, and user countries, are essential variables that can affect international relations (Scholten D. C., 2020).

Although there is an abundance of literature on energy geopolitics, renewable energy technology, and energy transformations, the geopolitics of renewables is a relatively recent field (Scholten & Bosman, 2016). The first efforts to merge the fields of geopolitics and renewable energy are increasingly taking shape (Criekemans, 2011). As an example, renewable energy sources are not as limited or restricted geographically as fossil fuels. Any nation has access to renewable energy in some way, whether it be wind, solar, or geothermal. (Scholten & Bosman, 2016). In contrast to the current fossil fuel scenario, which is characterized by resource shortages and geographic concentration, the availability of renewable energy sources and the ability to generate energy domestically drastically change the power balance between consumer and consumer nations (Scholten & Bosman, 2016). We have already shown that green energy is by far more decentralized, meaning that we can build robust energy mixes even in the renewable energy world (Scholten D. C., 2020).

Any energy source has unique characteristics that contribute to the formation of its own 'geotechnical ensemble,' which has an influence on macro-regional and international affairs (Scholten D. C., 2020). Some observers now claim that the transition to green energies would result in the reappearance of the resource curse in countries rich in basic materials with massive, exportable renewable energy surpluses. It is assumed that, like other oil producers in the past, their increasing prosperity would lead to a weakening rather than a strengthening of their role in the world (O'Sullivan, Overland, & Sandalow, 2017). Furthermore, countries that tend to invest in renewable sources of energy and technology today will be the dominant geopolitical players tomorrow (Scholten D. C., 2020).

Since renewable energy resources are more uniformly dispersed internationally than fossil and nuclear fuels, the economic and security advantages of access will be distributed much more evenly across nations, there will be fewer transportation issues, and competition for strategic places may be less vulnerable to attack (Overland I. , 2019). Another widely held assumption about the impact of the energy transition is that geopolitical competition in essential renewable energy technology materials would escalate (Barteková & Kemp, 2016) (Brown, et al., 2014) (O'Sullivan, Overland, & Sandalow, 2017). Theoretically, renewable energy for export will require long-term infrastructure maintenance, create more local jobs, and produce profits more stable than oil and gas (Garrett-Peltier, 2017).

2.3.2 Geothermal energy and electric grids

When it comes to geothermal energy, the most interesting thing that can be reviewed from the geopolitical aspect and the energy security aspect is the electricity and the electricity grids. There is little or almost nothing to mention for geothermal energy as it is from a geopolitical view, but the main product of geothermal energy—electricity—is the main interest among the countries.

Geothermal electricity production is a relatively recent phenomenon in Europe. Before 1990, only a few geothermal power plants were in operation in Europe, mainly in Iceland and Italy (Vonsée, Crijns-Graus, & Liu, 2019). A large number of projects have been built in the EU over the last five years, and geothermal power is on its way to becoming an important player in the EU energy mix. In Europe, 102 geothermal power plants were operational as of the end of 2016. The total capacity that was installed was 2.5 GWe, with the EU accounting for 1GWe. It should be taken into account that installed capacity in Iceland and Turkey accounted for more than half of total installed capacity in Europe. The total capacity of the plants in each field varies dramatically. In Iceland, total generation capacity per plant is approximately 83 MWe, whereas in the EU, it is approximately 19 MWe (Vonsée, Crijns-Graus, & Liu, 2019).

A common view is that renewables are more difficult to manage than fossil fuels because they are less dense and more evenly distributed around the world (Vakulchuk, Overland, & Scholten, 2020). Some assume that consumption of renewable energy at the point of generation would dominate large-scale regional production and delivery because it is seen as being much more reliable and cost-effective than long-distance distribution networks (Sovacool, 2016). (Overland I. B., 2019) Believes that expanded use of renewable energy would lead to increased electrification and cross-border electricity exchange. When countries produce power from national energy sources, energy imports are reduced, and countries' interdependence is reduced, which may minimize international tensions and threats. The participation of many suppliers makes it easier for consumer countries to change suppliers and restricts suppliers' ability to fix prices. As a result, energy exchange patterns among producers, consumers, and transit countries are very fluid. (Scholten & Bosman, 2016). States that the creation of new forms and ways of regional cooperation can contribute with regards to renewable energy. The availability of many renewable energy sources, as well as the interconnected and complex electrical grids, requires a strategic focus on the utilities and infrastructure of the associated countries (Scholten & Bosman, 2016).

Another concern is that the interstate shutdown could become an important instrument in foreign policy. This issue is often supported by past examples of the use of energy as a foreign policy instrument (O'Sullivan, Overland, & Sandalow, 2017) (Johansson, 2013) (Moore., 2017). Electricity flows through the grid at close to the speed of light, necessitating on-the-spot regulation of loads and voltage levels. Accidents can spread across the grid in a matter of seconds, affecting many sides (Scholten & Bosman, 2016). (Westphal K, 2015) Argue that more power interconnectors between nations would lead to increased interdependence, which may lead to a reduction in global security. (O'Sullivan, Overland, & Sandalow, 2017) claims that as renewable energy is widely implemented and cross-border electricity trading increases, the territorial regulation concept would be comparable to that used by oil and gas pipelines. Finally, the instability in renewable energy production is expected to result in more unpredictable electricity costs than fossil fuels, requiring the use of storage to maintain competitive energy markets (Scholten & Bosman, 2016). Most geothermal wells can be an important factor in inter-state relationships, and the factor "location"—where the energy resources are and how they can be transported to (potentially rival) market countries—is an important area of research within the field of Geopolitics (Scholten D. C., 2020).

As claimed by (Scholten & Bosman, 2016), the energy supply has absolutely no geopolitical consequences. Geopolitical issues have changed from energy input to material input in sustainable energy generation technologies as each nation now produces its electricity from renewable sources without needing to import.

In the continental context, the development will take place in countries with the strongest geothermal energy conditions. Given that countries favor productivity over stability, i.e., cheap imports over domestic production, centralized manufacturing and transportation infrastructures will prevail (Scholten & Bosman, 2016). In the national context, countries or even societies have the ability to internalize all functions (production, transport, and consumption) and become energy self-sufficient, at least to some degree. Energy-consuming countries in this so-called "prosumer country" model can have a significant stake in their energy mix.

When academics, businesses, and policymakers draw on one another's achievements, technology progresses more quickly. However, where a clean-energy investment is viewed as a zero-sum game clearly aimed at improving national productivity, states often build barriers. Rather than adopt approaches that accelerate cross-border cooperation, they follow economic and industrial strategies that prevent foreigners from engaging in their economies' clean-energy industries. As a result, experts, security think tanks, intelligence and security agencies, parliamentary committees, and consultants are concerned that terrorists or the intelligence services of conflicting countries might attack the computers that manage utilities and the grid (Månsson, 2015).

2.3.3 Geographical zones of the geothermal energy

According to (Scholten D. C., 2020), three geographical zones and three thematic playing fields will structure the emerging ‘geopolitics of green energy.' The European Union, with Germany as its main region, the United States of America, and Asia are the three geopolitical regions (with China, India, South Korea, and Japan as core countries). The three thematic playing fields are:

(1) Leverage over innovations that need to be further developed, as well as the division of the added value these technologies can produce,

(2) Reducing energy dependency, and

(3) The effect on national growth models in the post-2012 climate policy period.

Geothermal energy will also be part of this scenario, as the technological race, no matter what the renewable energy in question, is identical. So far, no significant international relations have been noted regarding geothermal energy because it is not a fundamental source of energy, but it is important to note the countries that are actively developing this technology and their capacities so that we can understand the overall geopolitical map when it comes to geothermal energy. As well as the relations between the countries that are mutually produced by the existence of geothermal energy.

CHAPTER 3: Methodology

3.1 Research questions

After talking about the technical and geopolitical aspects of geothermal energy more or less in general in the previous chapter, in the next chapter of the thesis I would like to investigate the technological, geopolitical, and aspects related to international relations.

In the technological part, I would like to work on the technical solutions of geothermal drilling as well as the technical solutions and challenges of electricity production. On the other side, I would like to work on the geopolitical aspects of geothermal energy as a promising alternative energy. Despite a significant number of studies on renewables, it isn't reported any work on socio-economical and geopolitical aspects of geothermal energy in one case. Therefore, the main objective of the second part of the thesis is to review the research on the technical and geopolitical aspects of geothermal energy. So, the main questions that will be discussed in the next chapter are:

- *What are the most commonly used geothermal well drilling technologies?*
- *What is the importance of geothermal energy in the terms of energy statecraft?*
- *What is the percentage of the geothermal energy worldwide?*

3.2 Methods

The methodology behind this thesis is mainly qualitative, which means it will be based on academic literature, which will be collected mainly from online libraries, as well as scientific journals in the field of energy but also in the fields of economics, econometrics, mechanical engineering, electrical engineering, architecture, geology, and geopolitics. During the research, more than 60 titles were analyzed and processed, including scientific papers, books, analyses, and textbooks. During the preparation of this thesis, information and books from official organizations related to the activity were used, such as IRENA, IEA, and GEOLEC.

This thesis, apart from the technical part, has its own geopolitical as well as statistical part, which expands the image of this branch of energy, as well as complements the existing scientific literature with one of my personal aspects of how I view this.

Among the most influential authors in this field are (Ruggero, 2016) and, (DiPippo, 1991) who have written thousands of pages in the field of geothermal energy, from the technical to the geopolitical and environmental aspects. Thus, their books and papers are an important part of the creation of this master thesis.

CHAPTER 4: Results

4.1 Introduction

Just like other forms of energy, geothermal energy has multiple aspects to analyze. Despite the fact that it is relatively new to the global energy mix, geothermal energy has its own set of challenges. Starting from the fact that the digging is taking place in temperatures of a few hundred degrees Celsius, this is a sign that it is a serious technological challenge to be part of such a project. The same is true for electricity generation. Over the last century, huge advances in technologies for producing electricity from geothermal energy have been made, and many countries now have very strong national knowledge in this area. The aspect of international relations and geopolitics is also present in the field of geothermal energy.

In this chapter, the technological solutions for digging geothermal wells will be covered, including the types of drillers and the descriptions of geothermal rigs, as well as the challenges associated with them. Later, the production of electricity will be added, as will the multifaceted utilization of geothermal energy. Also, the challenges related to electricity within the framework of international relations, in order to finally give a complete picture at the world level of geothermal energy, and what are the appropriate policies.

4.2 Contemporary technology of geothermal drilling

4.2.1 Drilling rigs

As mentioned above, the drilling process is the most complex and expensive segment of the whole project of creating a geothermal well.

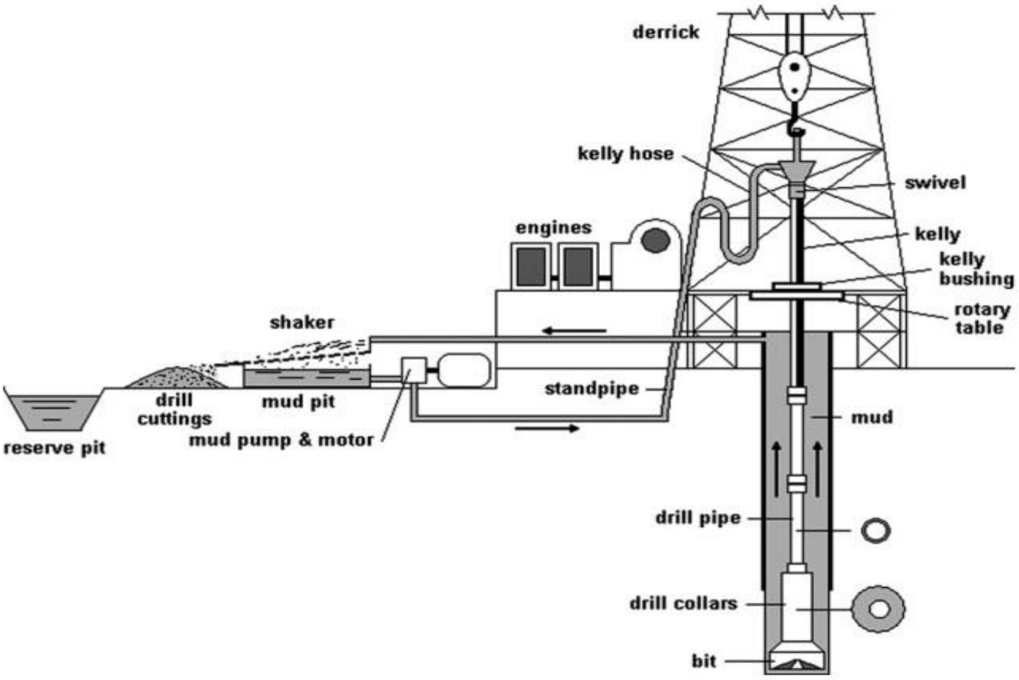


Figure 1. Drawing of simplified drilling rig *(DiPippo, Ronald, 2012)*

Figure 2: Drilling rig *(DiPippo, Ronald, 2012)*

In Figures 1 and 2, the whole geothermal rig is presented. Here are the main parts of the drilling rig, starting from the drilling bit. The drilling bit is the frontal object and the most exposed one; after that, the drill collars are also an important part of the drilling, supporting the bit, which is connected with a long series of drilling pipes, which are the connection with the rotary table, whose rotation comes from the main drilling engines. There are other engines whose job it is to pump the mud, after which there is a shaker for separating the cuttings, and many other electronic components for measurement, observation, and safety systems.

4.2.2 Drilling bits

-Drag bits

Rotary drilling is a standard method for geothermal drilling, and although new technologies are emerging, drilling with a rotary bit is still used for almost all the drilling projects. There are many different types of rotary bits, and their use depends on the rock formation, type of rock, temperature, and diameter of the well. The drag bits are the oldest type of bits; they are fixed, and no additional moving parts are on the bit. This bit was used only for soft formations. On Figure 3, the form of the drag bit is presented.

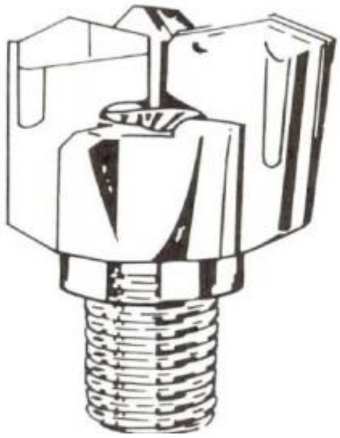


Figure 3. Drag bit *(K.Ngugi., 2008)*.

-PDC bits

The PDC bits are different from the others because of their long life and different configuration. Although they are static with no moving parts, they have special diamonds embedded, which increase their durability and their thermal resistance, as shown in Figure 4. They are not widely used because of their high price.

Figure 4. Polycrystalline diamond compacts (PDC) *(K.Ngugi., 2008)*.

-Tri-Cone roller drilling bits

Figure 5. Tri-cone roller drilling bits *(K.Ngugi., 2008)*.

The most commonly used drill bits are the tri-cone roller drill bits. They are specific because of their multiple rotating parts and their effectiveness. They come in various dimensions and shapes. Two main principles are used by rotary bits to drill the formation: 1) rock removal by exceeding its compressive strength, and 2) rock removal by exceeding its shear strength.

Scraping or hydraulic cleaning are used to get rid of the shattered rock pieces. Depending on the requirements of the drilling well, they are available in various sizes.

Figure 5 shows tri-cone roller drilling bits and several of their key components.

4.2.3 Drill string

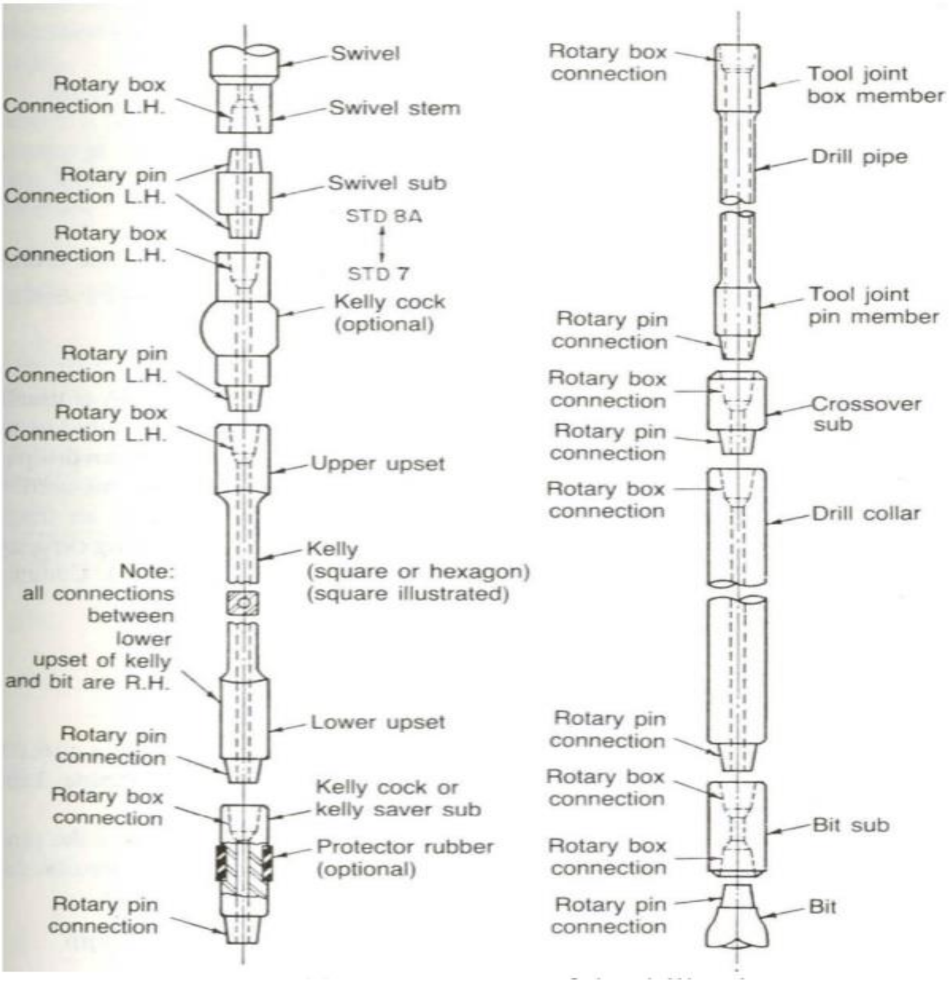
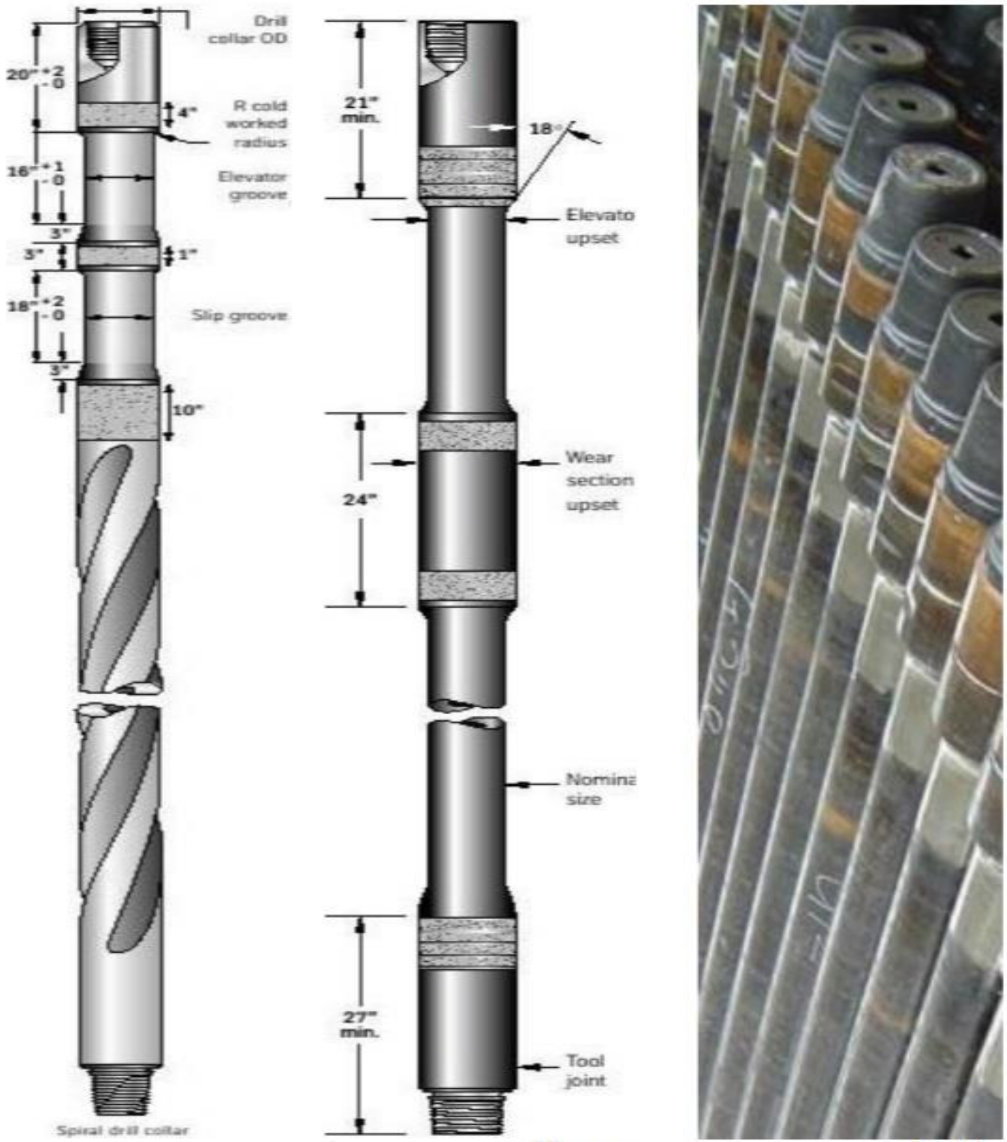


Figure 6. Components of drill string *(K.Ngugi., 2008).*

Another important part of the equipment is the drill string. For the bit to perform its duty, rotary motion is needed, as is a force from above, or weight, to crush the rocks and water, or drilling mud, for cleaning the broken rock particles. The drill string is an essential requirement for the bit to perform; it holds the whole assembly, gives the weight that is needed, and serves as a pipe for drilling mud. On Figures 6 and 7, the main parts of the drill string are presented. The drill string is the direct connection between the rig and the bit. The drill string is the longest construction that is underground. It consists of many parts, including drill pipes, drill tubes, drill collars, and the drilling bit.



Drill collar

Heavy weight drill pipe

Drill pipe

Figure 7. Drill collars and drill pipes *(K.Ngugi., 2008)*.

4.2.4 Drill sub

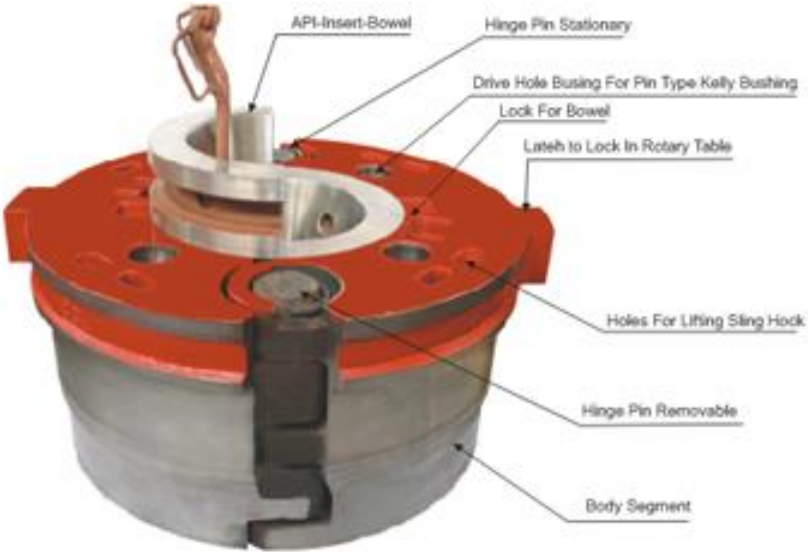
Right after the bit is the bit sub, which is a piece of metal with a dimension of a few decimeters to one meter and connects the drill bit to the drill collar. It also has a non-return valve, which ensures the fluid does not spill back down the string to the rig surface. This is crucial in geothermal exploration since the fluids can be incredibly hot for the workers operating on the field.

Drill collar

Another important part of the underground drilling equipment is the drill collar. The drill collar is placed right above the bit, after the drill sub. This piece of metal adds weight to the drilling bit, stabilizes its rotation, provides the strength required to run the process, and aids in shaping the walls inside the well. They can weigh up to a few tons.

4.2.5 Drill pipes

Figure 8 .*Kelly fitted into drive bushing. (Autobahn Industries, 2023)*



https://www.autobahnindustries.com/master-bushing-latch-type

Drill pipes are the longest section of the drill string; their main purpose is to connect the whole drill string and the connected parts, to transmit the water from and to the drilling bit. The drill pipes are connected on the surface to the kelly. Kelly is also an important part of the drill string; it is in a hexagonal or square shape, which allows the drive bushing to exert a force and generate rotary movement. The drive bushing is then connected to the rotary engine, which generates rotary movement and so rotates the whole drilling string underground. The whole assembly is a complex construction, the weight may go up to 150 t, and there are a lot of practical problems that can occur during the drilling, starting from string failure, failure among the joints, belling and thread, and tool joint shoulder damage. Figure 8 shows an illustration of drill pipes and the kelly.

4.3 Inter-State relations

4.3.1 Power equipment

The second most important part of the functioning of geothermal sources is the use of geothermal energy, which is the production of electrical energy. There are various solutions for electricity production, but generally, all are based on the most basic principle of transforming heat energy from a geothermal source into kinetic energy so that it can later be converted into electricity through electric generators. Geothermal energy can be used as a combination of both, i.e., the heat that is not fully used in the production of electricity is transferred to local areas as well as in the agricultural industry. Figure 9 shows a system for full utilization of the geothermal energy.

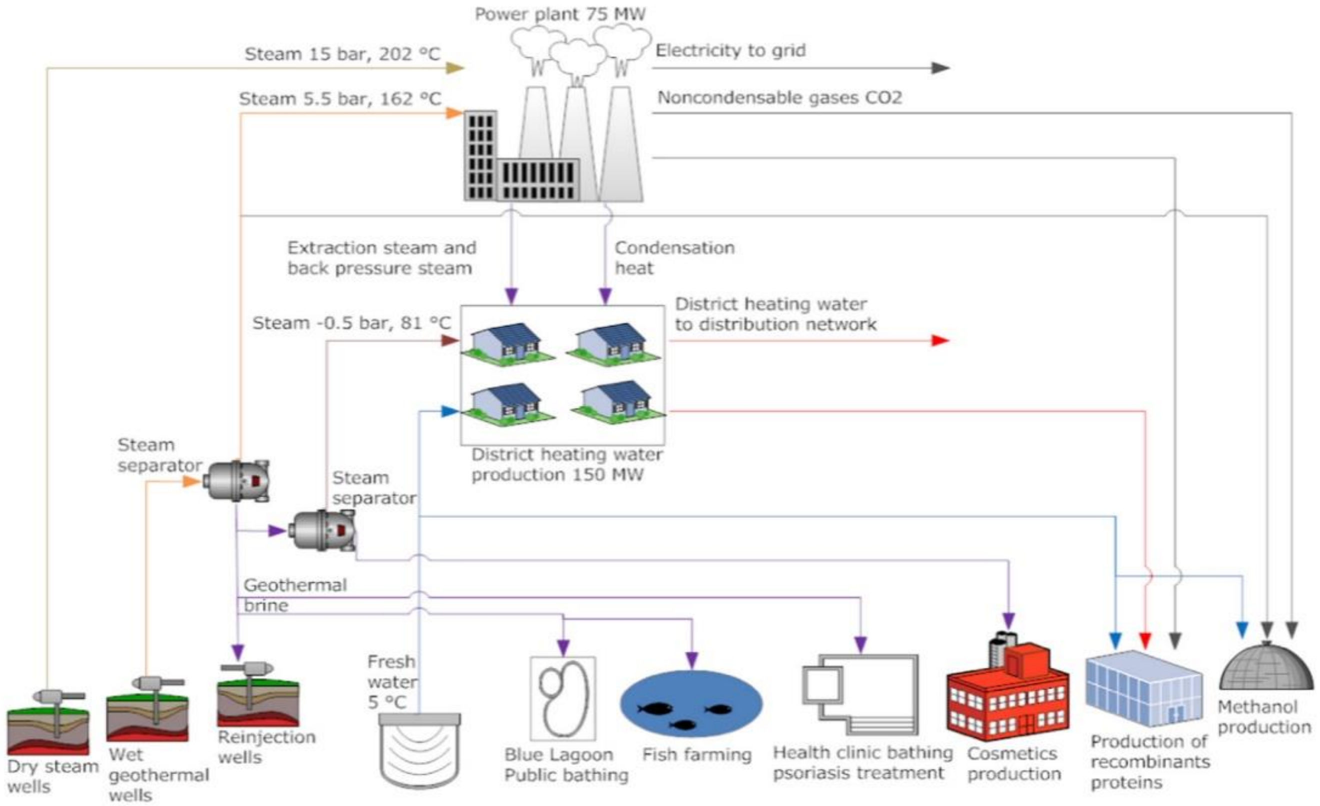


Figure 9. Geothermal systems and technologies. Geothermal communities (2021). [Slides].https://geothermalcommunities.eu/assets/presentation/6.Course_GT.pdf

4.3.2 Geothermal electricity production

Electricity contributes to 19% of overall energy consumption. It is the fastest-growing sector of the total energy mix, growing two-thirds faster than total energy consumption since 2000. After 2016, the power sector has drawn more investment than the offshore oil and gas markets, which have occupied electricity investment in the past, reflecting the global economy's continuing electrification. This major change will undoubtedly have an impact on geothermal energy. Geothermal energy differs from fossil resources and other renewables in several ways, and it has distinct strategic and security implications. The transition of energy will be one of the main components of geopolitics' restructuring in the 21st century, with geothermal energy being a valuable source for renewable energy.

Country	MWe Installed in 2020		Country	MWe Installed in 2020
1. USA	3.700		6. Mexico	1.105
2. Indonesia	2.289		7. New Zealand	1.064
3. Philippines	1.918		8. Italy	916
4. Turkey	1.549		9. Japan	550
5. Kenya	1.193		10. Iceland	755

Table 1. Ten nations having the most installed geothermal power generation in 2020 *(Ruggero, 2016)***.**

Today, many countries are actively involved in the development of geothermal technology, with many of them producing a large percentage of their electricity thanks to geothermal energy. The leading countries are the United States, Indonesia, the Philippines, and many others, as shown in Table 1 and Figure 10.

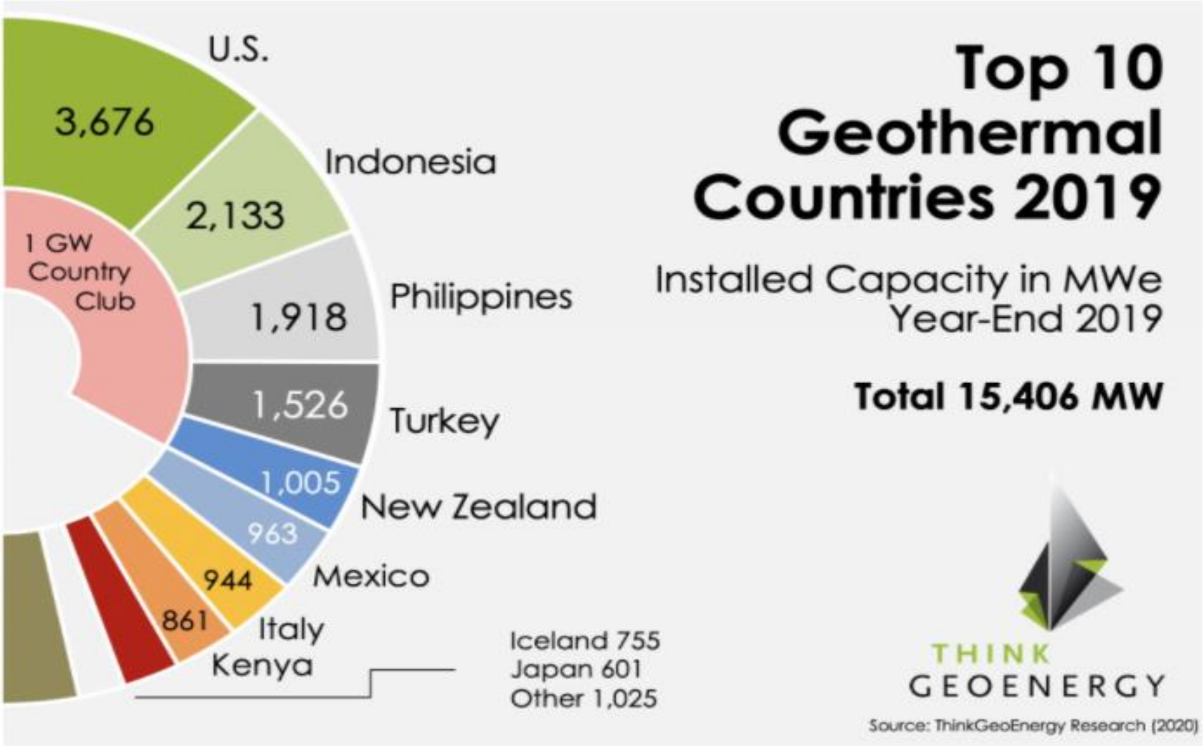


Figure 10. Top 10 geothermal countries. *(Think GEOENERGY, 2021)*

https://www.thinkgeoenergy.com/

4.3.3 Geothermal energy and energy statecraft

There are various characteristics that affect a state's status relative to the global community, including its GDP, demographics, size, natural resources, geostrategic position, military, and soft power. One of the major advantages, as it allows states to defend domestically critical national interests and exploit economic and political power, is access to and control over natural resources, with geothermal energy among them. For a long time, states have used natural resources as foreign policy instruments, a process called energy statecraft. Energy resources would lose much of their currency as diplomatic weapons in an era characterized mostly by renewables. Nowadays, the increase in installed capacity trends of geothermal energy is evident on a global scale, as shown on Figure 11.

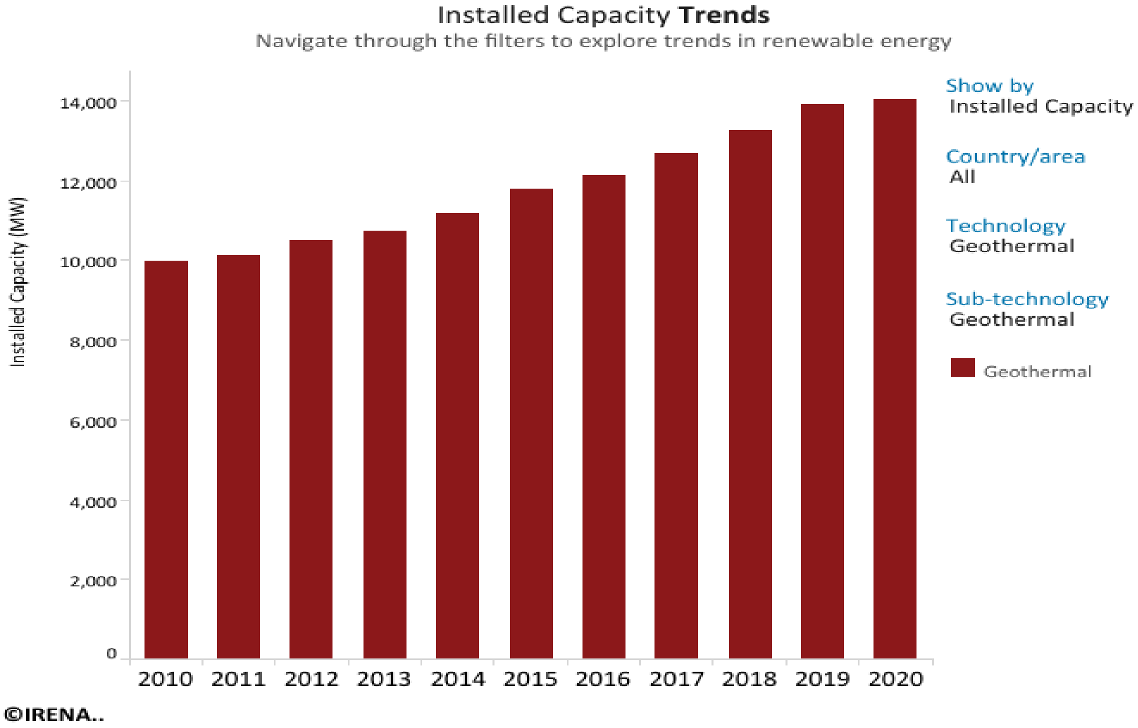


Figure 11. Installed capacity trends IRENA. (2021). https://irena.org/geothermal

4.3.4 Geothermal energy as a source of oil and gas reduction

The current nation-state and the economy of fossil fuels have developed side by side; nowadays, the electricity trade continues to be more competitive than the oil and gas trade. The partnership between electricity sellers and consumers is less exclusive than the trade of natural gas because, although oil and gas flow from one exporter to another in one direction, the electricity trade between countries flows in both directions.

Electricity is actually a regionally traded asset, as opposed to oil, LNG, and crude oil, which are traded internationally. In an increasingly electrified world, the decline in the fossil fuel era and the rise of a decentralized generation of electricity may have serious consequences for the nation state's role.

One potential outcome of this type of energy revolution would be a reduction in the geostrategic value of oil and gas as foreign policy instruments. The role of the state in the energy market will change, and many new players and business models will emerge.

States that already import oil from other parts of the world will aim to improve domestic technology and link their networks with those of neighboring countries; all this means that the influence of large energy exporters on smaller countries will be significantly reduced.

4.3.5 Electricity as diplomatic tool and security

It is expected that countries that regulate power grids will exert unfair control on their neighbors, with cross-state electricity cuts being a major foreign policy instrument strategically implemented in the same manner as petroleum and gas sanctions. Even then, as more countries generate geothermal energy and provide interconnections, such a situation is less likely, so they will tend to provide more local electricity.

Even if an electricity exporter assumes a superior role in relation to an importing country, asymmetry cannot easily be used as a diplomatic tool. Every energy exchange connection has a certain degree of asymmetry, whereby inequalities in the wealth of natural resources or energy production are the motive for trade between countries. Trans-border interconnection of energy is discouraged because of the concern that partnerships dependent on asymmetric dependence will be created and then used by one partner and the other. While dependence increases, the less dependent party will benefit from the dependent party's asymmetry. This is why nations will either generate energy for themselves. As a consequence, electricity exporters will still be part of a dynamic network of interrelationships in the market, which somehow helps to reduce the capacity for geopolitical use of geothermal energy.

4.3.6 Bringing energy independence

First, unlike fossil fuels, which are clustered in small geographic areas, geothermal energy reserves are available in many forms; they are almost everywhere, in any country; they only need to be dug deep enough. Geothermal energy can be used almost anywhere and is best used for heating and producing electricity.

This helps to restructure the economic and political power of the countries since geothermal energy helps to decentralize and democratize energy systems. Local production of energy will give industry and households more autonomy and choice than a centralized system. In brief, energy transformation is followed by power dispersion. In that case, the result will be a certain degree of change in the political situation in certain regions.

States that can benefit from emerging geothermal resources can hope to increase their energy independence, and that will bring new energy leaders. Of course, appropriate geothermal knowledge is absolutely necessary for that, as well as technological expertise and technological development. For example, Chile has some of the greatest geothermal and ocean energy resources in the world, but the remoteness of these areas and lack of expertise and technology are stalling any new potential.

On the other side, there are already several countries that are net exporters of geothermal energy, and many of them are actively developing programs for its use. Iceland is now a leading exporter of technologies and geothermal expertise; Indonesia and the Philippines are also important to mention; and the USA is also one of the first countries on the list.

4.3.7 Interconnection between geothermal resourceful states

The geothermal final product, the electrical energy, unlike the fossil fuels, which can be in the form of stocks, must be produced and consumed at almost the same time, thereby highlighting the need for interconnection between countries.

International grid interconnections increase electricity efficiency, and, as a result, social benefits are also increased. There are also financial, societal, and environmental benefits.

A typical example is the case of West African countries, where electricity grid interconnections are reducing electricity supply costs, improving system reliability, and reducing capital investments.

The next example is the case of Central America, where cross-border grids are increasing the availability, affordability, and dependability of power for residential and industrial consumers. These benefits are enhanced where energy prices are high.

Electrification would be increased by the spread of geothermal energy, stimulating cross-border energy trade. Integrated with other electricity sources, these geothermal power plants will produce flexible power networks that can meet demand and supply differences in real time. When energy is transmitted over long distances, part of it is lost; as a result, global energy markets are likely to become more localized; therefore, the need for flexibility will be effectively met by innovations in market structure, smart grids, and storage technologies, along with direct high-voltage electricity links between countries.

Geothermal energy would affect more than just the balance of power between nations. It would also reshape partnerships and exchange flows, resulting in fresh interdependencies based on the power grids. It can create new geographies of interconnections and reliance between countries and regions.

4.3.8 Global geothermal market

The issues of using electricity as a diplomatic tool between states, explained in the previous paragraphs, can nowadays be avoided. The emerging new technologies are very likely to change the situation of the geothermal electricity market. It is worth mentioning here the prospects for building ultrahigh-voltage (UHV) infrastructures.

An ultra-high-voltage transmission can transfer electrical energy over greater distances. Grid losses are significantly reduced as a result of the ultra-high voltage. This lessens the significance of existing energy choke points, such as the narrow channels on heavily used sea routes that are vital to the global oil supply.

With proof-of-concept demonstrated in different parts of China, UHV technology is aimed at transferring very large quantities of electrical energy right across continents. This "national grid" will use daytime (East-West) and seasonal variations (North-South) on earth in order to transport electricity from source to market.

The creation of such a network will allow energy flows to bypass certain countries or even regions, partially offsetting the indirect countries' geopolitical advantage by having the power to cut off connections. The global implementation of the UHV infrastructure will in turn pose numerous governance concerns. In the future, a large proportion of small geothermal producers will be able to connect their markets and increase the electricity market, which will reduce the price for the end-user. This will also help the large producers, such as Iceland and Indonesia, to sell their electricity and, thus, bring the energy trading liquidity to a higher level.

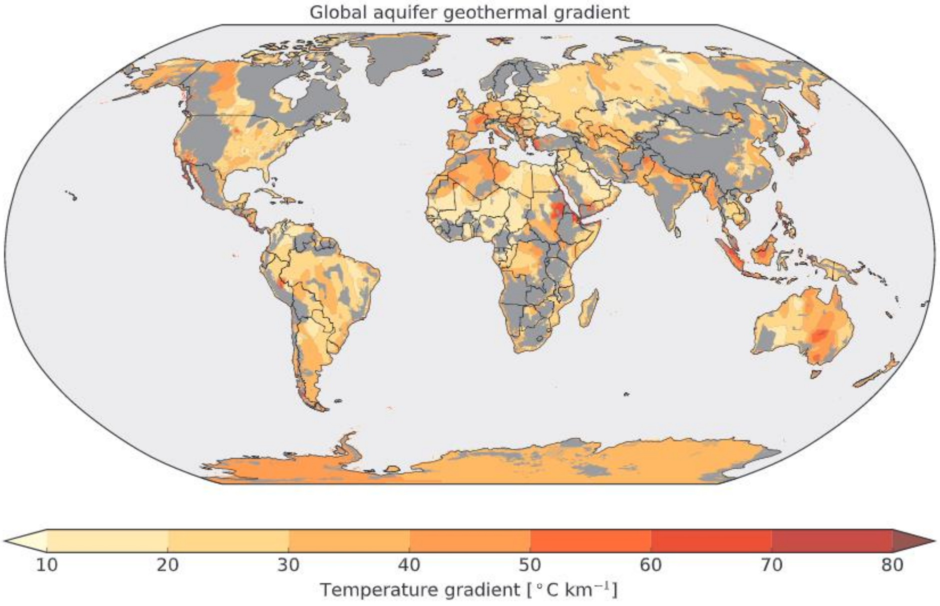


Figure 12. Global geothermal gradient *(Limberger, et al., 2018)*

4.4 Global energy geopolitics

4.4.1 Global geothermal geopolitics

When it comes to energy security, as well as geopolitics in energy, things get more complicated. In order to fully understand energy, it is undoubtedly necessary to take into account the geopolitical situations in the world. It is most pronounced in conventional energy resources such as oil and natural gas, but it often spills over into renewable energy sources as well as electricity.

In this thesis, a special section is given to the state of the geothermal image worldwide.

As a relatively young field of geopolitics, energy geopolitics adds another thread to the whole picture, but when it comes to global geopolitics in the context of geothermal energy, nowadays with a relatively smaller impact on the global energy mix, geothermal energy is not an extremely important point in relations between countries.

From a geopolitical standpoint, geothermal energy can only be seen through its product - electricity. Electricity has so far been used as a geopolitical weapon among the countries among themselves, but that alone does not allow us to classify geothermal energy as an essential part of the energy mix of countries. On figures 13 and 14, the geothermal power plants around the globe are shown, as is the capacity of the electricity production.

Figure 13. Geothermal power plants *(Think GEOENERGY, 2021)*

https://www.thinkgeoenergy.com/

Judging by the above, geothermal energy is not a huge challenge from a geopolitical point of view. Only in this thesis will the production capacities of countries in the world be indicated, which can indirectly give a picture of the situation of producing countries and their potentials. Undoubtedly, in the future, when renewable energy sources will create greater inertia, the countries' need for them will be of greater significance, and this will contribute to geothermal energy's growing importance worldwide. In the following pages, a detailed analysis of the capacities of the countries as well as their potentials will be made.

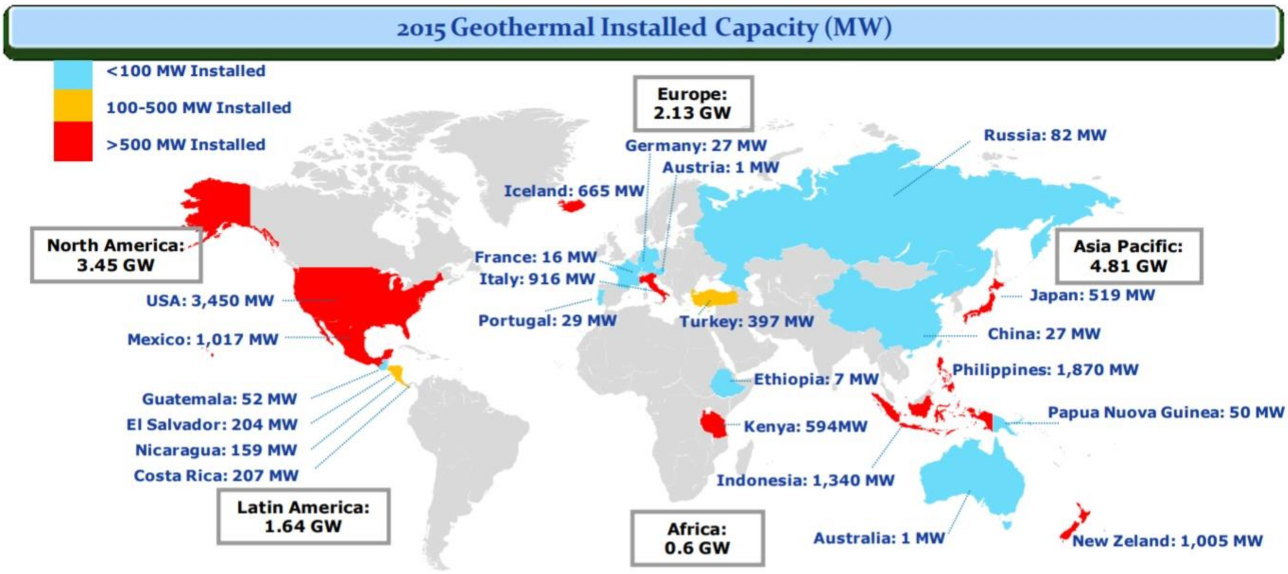


Figure 14. Global installed capacity in 2015. *(Bertani, Geothermal Power Generation in the world 2010–2014 update report, 2016)*

4.4.2 Global Overview

Argentina

Few discoveries have been made in recent years in most geothermal fields aimed at power generation. A future assessment of the geothermal area of Copahue demonstrated that electricity can be generated using current geothermal steam. Around 1200 m deep with a 30 MWe capacity. In the province of Neuquén, a public bid was also requested for private contracts. Investors in future 30 MWe electricity generation projects with an investment of US$100 million participated in construction and operational activities. Other regions are currently under assessment (Domuyo, Los Despoblados, Tuzgle-Tocomar, Peteroa, and Los Angeles).

Chile

In recent years, Chile's geothermal exploration by about 14 private companies operating in 76 geothermal fields has been very active. Based on the results of these studies, in Apacheta and Tolhuaca, eight concessions were given for exploitation.

Carribean

The eleven volcanic islands of the East Caribbean have significant thermal capabilities. There's a crustal Atlantic plate below the Caribbean plate. In certain situations, the temperature of the subsurface recorded in the region exceeds 290°C. The Dominican Government launched exploratory holes with Icelandic Drilling Inc. to validate the existence of an economically feasible resource at temperatures up to approximately 240 °C and a 10 MWe power plant of up to 100 MWe to be exported to Guadeloupe and Martinique via undersea cables. In St. Lucia, the government has signed a memorandum of agreement to explore and produce sulfur springs with UNEC Company. In 2013, Montserrat successfully drilled two wells with temperatures of up to 298 °C at 2.347 m depth.

Canada

For several years, geothermal power generation in Canada has been studied, but any significant developments into a sustainable industry have been postponed because of policy constraints and insufficient financing. It is estimated that over 5000 MWe will be available for an additional 10,000 MWe using current techniques from low geothermal reservoirs, including hot sedimentary aquifers.

Costa Rica

Since the last decade, geothermal growth and research have seen great progress in the region. The production facilities of Miravalles Geothermal Field (165 MWe) remain in operation with the initial Las Pailas Geothermal Field Unit (42 MWe) in 2011 and the planning for the second one, as well as in Borinquen and Pocosol.

Ecuador

The nation started its geothermal program in 2010. The pre-feasibility phase included 11 targets for studies: Chachimbiro, Chalpatán, Chacana-Jamanco, Chalupas, Guapán, Chacana-Cachiyacu, Tufio, Chimborazo, Chacana-Oyacachi, Baos de Cuenca, and Alcedo. At this point, geological, geochemical, and geochemical surveys have been undertaken.

El Salvador

Geothermal energy has been one of the main sources of electrical energy in the area since the mid-1970s, and the total geo-capacity deployed in the country now is 204 MWe (Ahuachapán 95 MWe, Berlin 109 MWe), around 24% of electricity needs and 13% of installed capacity, generating 1,442 GWh of electricity per annum.

Guatemala

Guatemala has roughly 1,000 MWe of available geothermal resources, with 14 promising areas in the volcanic belt. There are currently two geothermal fields owned by INDE and Ormat through the controlled companies Orzunil, Zunil, and Amatitán (28 and 24 MWe respectively).

Mexico

In Mexico, the installed geothermal power is 1 017 MWe (839 MW operating) in four active areas, owned and managed by the state CFE (Comisión Federal de Electricidad), which is located in four geothermal areas (Cerro Prieto, 720 MWe; Los Humeros, 94 MWe; Los Azufres, 194 MWe; and Las Tres Virgenes, 10 MWe). Two more geothermal schemes are currently being implemented. 50 MWe Los Azufres III and 27 MWe Los Humeros III-A are under construction. Production was approximately 6,100 GWh, accounting for 2.4 percent of all electricity production in the region.

Nicaragua

The geothermal research began in Nicaragua in the 1960s, and an incredible geothermal potential (about 1,100 MWe) was estimated, but only a limited proportion, covering approximately 10% of the country's electricity demand, has been utilized. There are five geothermal areas, of which only two have power plants.

Peru

Peru has massive geothermal potential. Six geothermal regions have been found in Peru. The Eje Volcánico Sur, which contains all of the active volcanoes, is the most important. The Japanese government provided funding for pre-feasibility studies in two regions, Calientes and Borateras, worth $150. As a result of the new geothermal law, many private companies have expressed an interest in investing in Peru as there is a strong chance for the growth of geothermal resources in over 30 countries, most of them in southern Peru.

USA

The entire installed capacity in the USA is 3,450 MWe, producing roughly 16,600 GWh per year. Alaska, Idaho, New Mexico, Oregon, and Wyoming have recently seen the building of geothermal power plants, in addition to California, Nevada, Utah, and Hawaii.

More than 350 MWe have been installed in the past five years. Of the two main active sites, the Geysers and the Imperial Valley, California is the most significant. the binary cycle's lowest temperature is 74°C.

For geothermal fluids, Chena Hot Springs in Alaska holds the record. There, three units are producing around 730 kWe. The first solar PV and thermal hybrid facilities were implemented in Nevada, in Stillwater, where the geothermal power plant is fully integrated with a capacity of 48 MWe.

Africa

Kenya

A very aggressively developed process is underway with the building of several new projects in a variety of regions, due to the immense geothermal potential of about 10 GWe. The Kenya Rift Valley has all kinds of high-temperature opportunities. The most significant development area is the Olkaria Geothermal Area (591 MWe), which has recently expanded to 300 MWe over the past two years after the first units were operational in 1985. It is operated by the Kenya Power Generation Company (KenGen) and Orpower.

Asia

China

The average geothermal temperature in China is highly sufficient for a direct geothermal application, although the production of electricity is developing. Research called 'Guidelines for the Promotion of Geothermal Energy Production and Use,' which has recently been launched by several agencies, has been increasingly investigational and has included geothermal surveys for state-owned as well as private firms. At present, 28 MWe is the installed power capacity, and around 155 GW is the annual electricity production.

Philippines

The new legislation provides fiscal and non-fiscal stimuli to promote and speed up the finding, generation, and exploitation of clean energy options, including geothermal energy.

Consequently, 43 geothermal contracts have been made, with 20 MW in Maibarara and additional power of 30 MW in Nasulo planned for commissioning by 2014. Geothermal supplies 14% of the energy needs for seven production poles with a current installed capacity of 1,870 MWe. Bacon-Manito/Sorsogon/Albay: 131 MWe; Mak-Ban/Lagoon: 458 MWe; Mindanao/Mount Apo: 108 MWe; Palinpinon/Negros Oriental: 192 MWe; Tiwi/Albay: 234 MWe; Maibarara: 20 MWe; and Tongonan: 726 MWe.) The total installed capacity is 1870 MWe, and the annual geothermal electricity production is 9646 GWh/y.

Europe

France

France has set high goals for its confined to foreign nations (Guadalupe, Caribbean Sea) geothermal electricity generation, which mixes heat and power.

The 1.5 MWe EGS pilot plant at Soultz-sous-Forêts is now fully operational.

Germany

Due to a shortage of high-enthalpy resources at low depth, only organic Rankine and Kalina cycle processes are applied in Germany, mostly in combination with district heating systems.

In Germany, a total of several new 5 MWe power plants with a combined installed capacity of 27.1 MWe have been commissioned. The Federal Government is assisting geothermal development to attain €0.25 per kWh by funding R&D initiatives and new feed-in tariffs. Rhineland-Palatinate (7 MW) and Bavaria (20 MWE), respectively.

Iceland

The country's geographical characteristics (its location in the Mid-Atlantic Ridge) favor Iceland's broad use of geothermal energy. Iceland's main electricity source accounts for about 68% of its share of geothermal energy, representing 90% of all domestic energy consumption. The electricity produced from geothermal started 45 years ago and has now reached 29% of overall energy requirements. The full installed capacity now consists of 650 MWe, and the annual production of the following fields is roughly 5250 GWh: Namaphyll (3 MWe), Hellisheidi (303 MWe), Husavk (2 MWe), Krafla (60 MWe), and Nesjavellir (120 MWe).

Italy

Geothermal resources for electricity generation can be found in Tuscany, specifically in the historical regions of Larderello-Travale (795 MWe) and Mount Amiata (121 MWe). Gross electricity output has surpassed 5,700 GWh, setting a new milestone for geothermal energy generation in Italy. Italy now has 916 MWe of installed capacity.

Turkey

Over the last five years, Turkey has made significant progress in the generation and direct use of geothermal energy (district, greenhouse, and thermal tourism), owing in part to the current geothermal law, its rules, and tariff feeds. In Turkey, approximately 225 geothermal fields have been found, and electricity production has now reached nearly 400 MWe.

Oceania

New Zealand

Due to the abundance of high-temperature, reliable geothermal supplies and the lowest cost of electricity generation facilities in comparison to other clean energy sources, New Zealand is experiencing rapid growth in geothermal electricity output. In an electricity grid dominated by renewable energies, geothermal electricity production capability contributes about 16% of national electricity generation (75 percent of its electricity comes from renewable energy sources). Wairakei 399 MWe, Kawerau 140 MWe, Reporoa 57 MWe, Rotokawa 167 MWe, Ngawha 25 MWe, Mokai 111 MWe, Tauhara 24 MWe, and Ngatamariki 82 MWe are the active areas in the Taupo volcanic zone.

4.4.3 Future projections of the geothermal energy

It is encouraging to note that there are new countries in the this category, even though the number of countries using geothermal energy to generate electricity is still small in comparison to the number of countries using their thermal capacity for district or space heating, agriculture, aquaculture, and/or light industrial purposes. Despite the fact that these first attempts into geothermal power may be relatively small (less than 20 MWe), this renewable energy may represent a sizable portion of the national electricity market and help to meet the rising demand for energy as shown in Figure 15.

The United States, Indonesia, the Philippines, Turkey, New Zealand, Mexico, Italy, Kenya, Japan, and Costa Rica have the most installed geothermal power. Indonesia is home to four of the world's largest power plants, the largest of which is Gunung Salak at 375 MWe. At the rate at which Indonesia has stated that it intends to exploit more of its vast geothermal resources, it is possible that it will overtake the United States and become the global market leader by 2030.

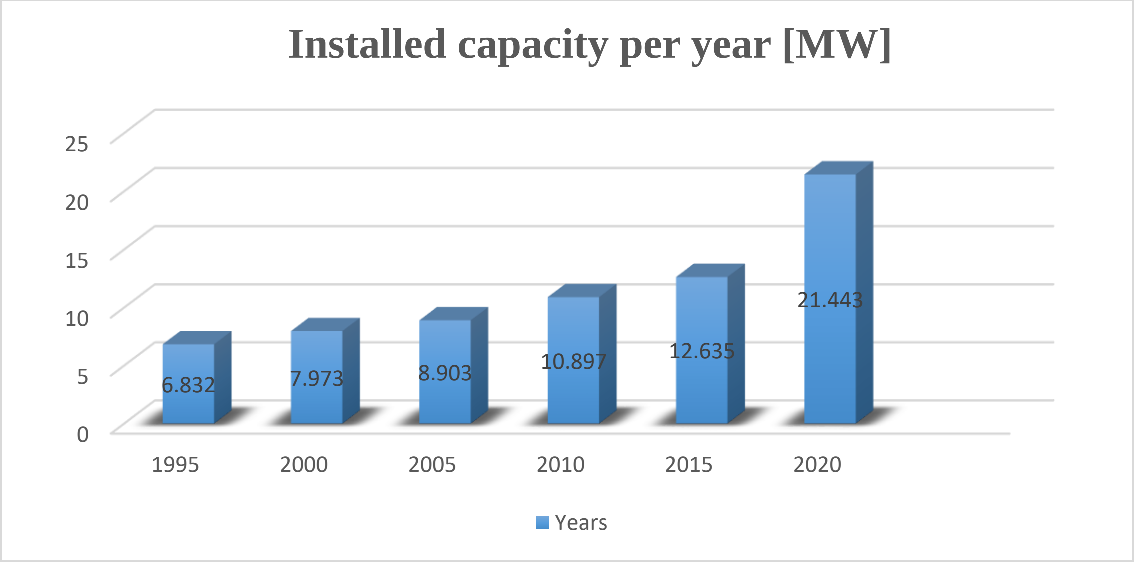


Figure 15. Installed capacity per year *(Bertani, Geothermal Power Generation in the world 2010–2014 update report, 2016)*

And then, it is evident that the projections of a more than 18% rise in geothermal-generated electrical power between 2020 and 2025 are below the 25% growth trend reported in the last 10 years. It is suspected that this drastic downturn is largely due to competition from other renewables, such as wind, solar, and fracking-produced natural gas-powered installations, with lower potential risks, shorter pay-out times, and lower prices per kWh. Also contributing are the continued slow pace of acceptance of geothermal-specific legislation, rules, and regulations in some countries and, at the end, bureaucratic delays that significantly increase the time, expense, and risk required: access to land, mitigation of local property, cultural, moral, and other objections or barriers, securing all the requisite approvals, and, ultimately, exploring, designing, building, and commissioning all elements of the project.

Finally, the hope that geothermal energy will continue its course remains, and all countries of the world should find the strength to overcome all barriers in this regard in order to maintain the set goal.

CHAPTER 5: Conclusion

5.1 Summary and conclusion

This master thesis described the whole process, from finding and digging geothermal springs, through their use, energy production, to the analysis of world capacities. Undoubtedly, the aim of the thesis was to describe geothermal energy, not only from a technological but also from a geopolitical and statistical point of view, thus providing the reader with a broader picture.

The research resulted in the following findings:

- Geothermal energy discovery, production, and technology are extremely challenging and expensive undertakings.
- In essence, not much has changed in the technology of machine drilling as such. Only the elements themselves have been improved by newer technology and materials. Still, the classic drilling with rigs and drilling bits continue to be prevalent technologies.
- Geothermal energy plays significant role in terms of energy statecraft of some countries, such as Iceland, Sweden, and Norway. However, these natural treasures are restricted to specific areas of the world.
- Due to a lack of technical know-how, many nations with proven geothermal energy deposits do not fully utilize them.
- Geothermal energy has not yet been shown to play an essential part in the world's energy mix, despite the fact that it offers some degree of energy independence.
- The potential of geothermal energy has not yet been fully realized, and it’s utilization is predicted to increase in the coming decades, anyhow, significant global trend toward the use of it has been noticed over the past ten years.

5.2 Limitations and recommendations for further research

There are currently a small number of nations engaged in geothermal energy research as compared to other energy sources. Another drawback is the large number of studies conducted in foreign countries that are not English-speaking.

Finding resources on the geopolitics of geothermal energy and international relations related to geothermal energy was the largest challenge in the writing of this thesis.

The limitations of this research refer to future subjects for investigation. Geothermal energy will continue to expand globally, and researchers working on this topic should seek to improve on what has already been found.

Future research areas suggest the following:

- *Which additional technologies can be employed to improve the drilling project?*
- *How can geothermal energy be made more efficient for both power generation and heating?*
- *Which way will international relations evolve in response to greater usage of geothermal energy?*

To summarize, geothermal energy is still in its early stages, and given the rising need for green energy, governments' interest in exploiting it will only expand over the coming years. With the further development of renewable energy sources, as well as the search for more environmentally friendly alternatives, it will certainly find its place on the world map.

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