Potential of Geothermal Energy in China

by

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

This thesis provides an overview of geothermal power generation and the potential for geothermal energy utilization in China. Geothermal energy is thermal energy stored in the earth's crust and currently the only ubiquitously available form of renewable energy that does not require a fuel or present intermittency concerns when used for power generation. In China, geothermal fields were first studied in the 1970s, but commercial development for power generation has been limited to 25MW, which is insignificant when compared to 1978MW of geothermal power plant capacity in the neighboring and much smaller Philippines. The barriers to geothermal development in China are common and can be narrowed down to uncertainties in commercial viability, lack of technical knowledge, and poor oversight of geothermal projects. This thesis finds several ways in which the federal and local Chinese government can encourage the development of geothermal energy. In light of increasing CO_2 emissions and its effects on climate change, the development of renewable energy such as geothermal energy remains critical.

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Chapter 1

Introduction

Catastrophic natural disasters in the past several years have fueled public interest in conserving our natural environment. A major contributor to global pollution is power generation for electricity, so clean energy has become a hot topic as of late. One country that has attracted a lot of attention for its pollutions level is China, which has surpassed the United States as the biggest emitter of CO_2 as of 2008 (Edwards, 2008). Air pollution is specifically of concern in China because 83% of electricity was generated by conventional thermal sources such as coal and natural gas. The result of this heavy reliance on the burning of fossil fuels has led to China's particulate matter (PM10), a measurement used for air pollution, to be several times higher than the World Health Organization guideline levels. Although the level of air pollution in China has improved as a result of efforts made for the 2008 Beijing Olympics, there is a consensus that China needs to continue to reduce its pollutions level (BBC, 2008).

Today, most people have likely heard or read about wind, hydro, and solar power, and understand that those are clean energy resources. Each technology these its limitations – wind and hydro power require favorable geographic locations, and current methods for harnessing solar power are too inefficient to use solar energy as a primary source for generating electricity for commercial use. One natural and clean renewable energy resource that is not often discussed is geothermal heat.

Geothermal power generation uses heat from inside the earth. Heat is pumped out from a drilled hole several kilometers deep in the form of natural steam or liquid, and is used to drive a turbine to generate power. Unlike other forms of renewable energy, geothermal heat is not necessarily limited by location and can generate sufficient power to be used as a primary source of energy in prime locations. It has virtually no downtime – another advantage over most other sources of renewable energy. Furthermore, geothermal plants can be modular so they are suitable for growing communities.

Geothermal energy has been embraced by few countries and more can benefit from using geothermal energy. One such country is China. With the world's largest population and energy demand and pollution levels growing at an alarming pace, geothermal energy could be a solution to both its energy supply and pollution mitigation needs.

The stories of geothermal energy development in countries such as the Philippines and Mexico are useful in understanding how geothermal power generation could be deployed in China. The availability of local energy resources, economic resources, and energy consumption levels will help us realize how effective geothermal energy might be in China as a solution to growing energy needs and pollution.

1.1 Current State of Energy Use and Pollution

In the year 2007, the world's total energy consumption was 483 Quadrillion BTUs (10^{15} BTU). Of this total, the US was responsible for using 21%, while China was responsible for

16%. Back track this data 16 years and we can see why China's economic growth is so alarming from an energy standpoint. In the year 1980, the world used 284 Quadrillion BTUs. 28% was used by the US, while only 6% was used by China. Simply put, the world's energy use has increased by 70% between 1980 and 2007, and approximately 30% of that increase has been due to China alone. Explained another way, China's energy use has increased almost 4.5 times in a period of 27 years and there are no signs of slowing down (EIA, n.d.).

Year	1980	2007
US	78.1	101.6
	28%	21%
China	17.3	77.9
	6%	16%
World Total	283.2	483.6

Table 1: Energy consumption in 1980 and 2007 in quadrillion BTUs and in % of world total (EIA, n.d.)

In the same time period, worldwide carbon emissions from the consumption and flaring of fossil fuels increased by 61%. Of this increase, the United States was responsible for approximately 11%. Comparatively, China's alone has been responsible for 42% of worldwide carbon emissions increase between 1980 and 2007 (EIA, n.d.).

Year	1980	2007
US	4,789	6,003
	26%	20%
China	1,460	6,247
	8%	21%
World Total	18,503	29,873

Table 2: CO_2 emissions from the consumption of fossil fuels in 1980 and 2007 in million metric tons and in % of world total (EIA, n.d.)

What is more alarming than these figures is the accelerating trend of energy use in China. A popular method for determining energy demand projections is *income elasticity of energy demand*, which is the growth rate of energy consumption divided by the growth rate of GDP. Whereas most developing countries have an income elasticity of energy demand of 1.0 or greater, that number has been around 0.5 for China until recently. This means that China's energy demand had been growing at a relatively slower pace compared to its peers. However, recent studies show that in 2004 China's income elasticity of energy demand has grown past 1.5. This sharp increase in energy demand can be attributed to the growth of manufacturing industries as well as improvements in living standards. (Austin, 2005).

Year	2000	2001	2002	2003	2004	2005	2006
CO_2 in million metric tons	2967	3108	3441	4062	4847	5429	6018
Year-over-year change	-25.6	141.5	332.6	621	785.7	582	588.4
Year-over-year % change	0.86%	4.77%	10.7%	18.05%	19.34%	12.01%	10.83%

Table 3: CO_2 emissions from the consumption of fossil fuels in 1980 and 2006 in million metric tons (EIA, n.d.)

This acceleration in energy demand is reflected in the acceleration of CO_2 emissions as well, as the above table indicates. Up until 2002, China's year-over-year CO_2 emissions increase hovered around 5% with some exceptional years with small decreases in CO_2 emissions. However, between 2002 and 2003 alone, China's CO_2 emissions increased by 18% and then again the next year by over 19%. The growth rate of carbon emissions from China from the burning of fossil fuels has decreased to around 11% in 2005 and 2006, but this is still an alarming number. It is difficult to say how much of this is accurate for numbers prior to 2002, but it is clear that a country's energy consumption increases with economic growth, and China's economy is growing for sure. In fact, according to the MIT Coal Study completed in 2007, China is completing the equivalent of two 500MW coal-fired power plants every week, each of which produces approximately 3 million metric tons of CO_2 every year (Katzer, 2007). We can also see China's role in the rise in world-wide CO_2 emissions from the following graph.

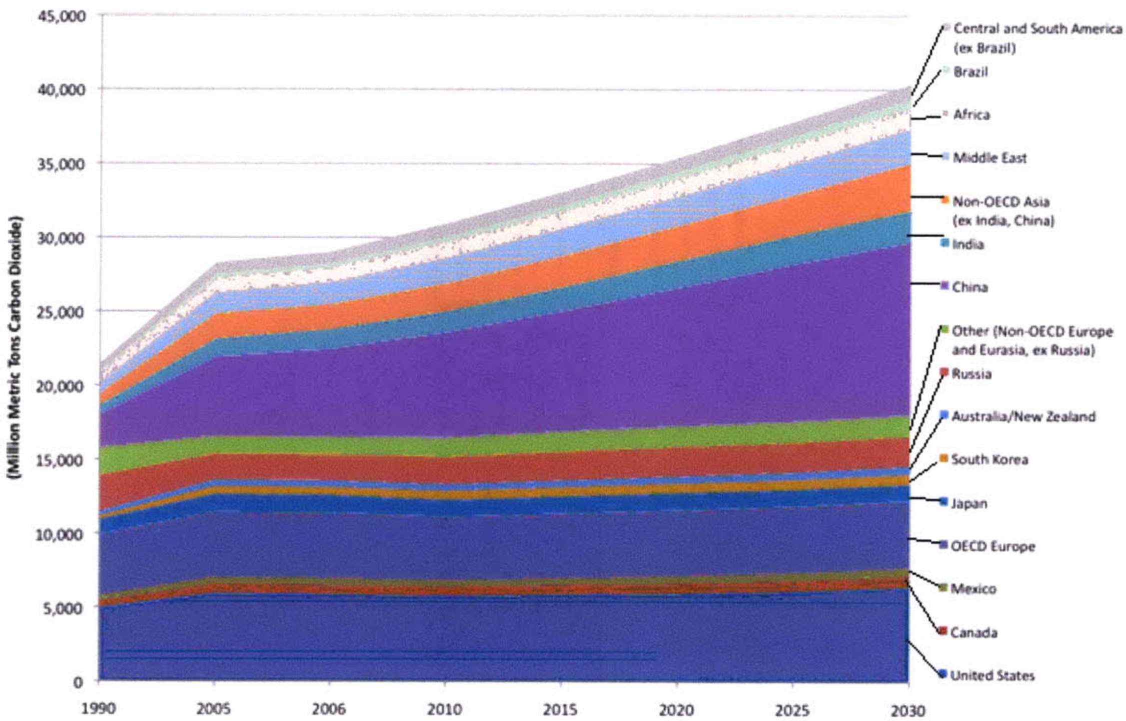


Figure 1: World carbon dioxide emissions by region, reference cast, 1990-2030 (EIA, 2009)

1.2 Current State of Geothermal Energy Use

Renewable electricity generation has grown worldwide at a steady pace in the past decade and now accounts for 18% of all global electricity generation. However, world consumption of electricity has grown at an even faster rate so the percentage use of renewable energy has been decreasing in the past few years (EIA, 2008). In light of increasing carbon emissions and its effects on global warming, it is essential that renewable energy is used at an even greater rate. Of the different renewable energy resources – hydro, wind, geothermal, biomass, solar – only solar and wind energy have seen a steady and significant growth in use between 2000 and 2006 (EERE, 2008). Despite having a relatively low price range, geothermal energy utilization has only seen a compounded annual growth rate of 3.1% between 2000 and 2006, and still only accounts for 0.3% of worldwide electricity generation.

	Hydro	Solar PV	Biomass	Wind	Geothermal
2000	15.9%	0.0%	1.1%	0.3%	0.3%
2001	16.5%	0.0%	1.2%	0.4%	0.3%
2002	16.2%	0.0%	1.2%	0.5%	0.3%
2003	17.1%	0.0%	1.1%	0.6%	0.3%
2004	16.4%	0.0%	1.0%	0.7%	0.3%
2005	16.0%	0.0%	1.1%	0.8%	0.3%
2006	15.8%	0.1%	1.2%	1.0%	0.3%

Table 4: Worldwide renewable electricity generation as a % of total generation (EERE, 2008)

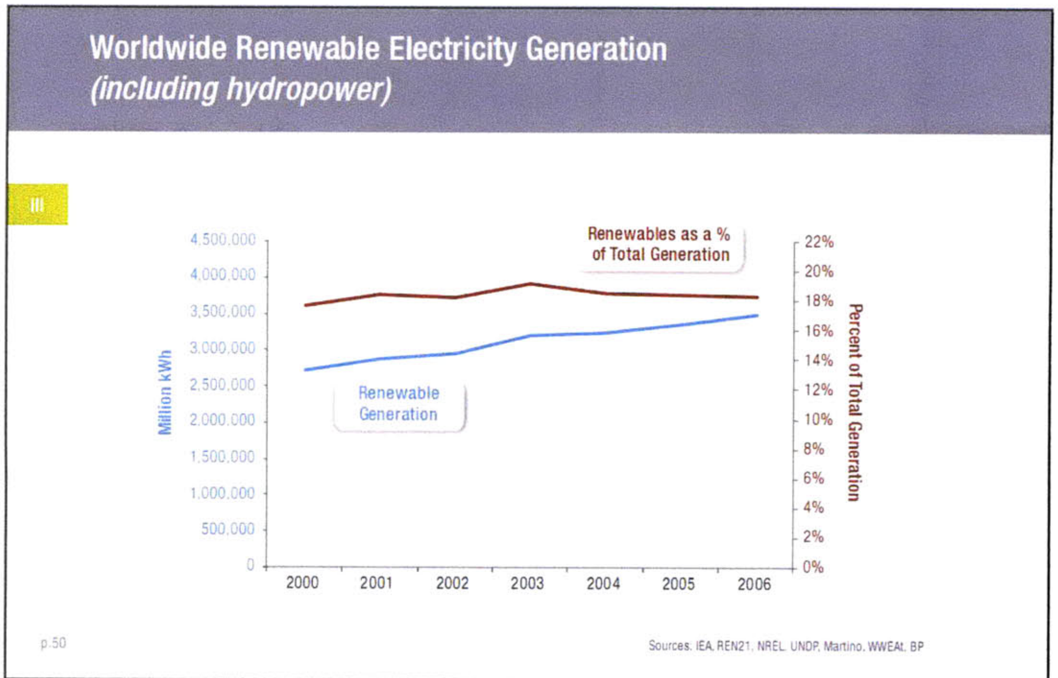


Figure 2: Worldwide renewable electricity generation 2000-2005 (EERE, 2008)

A projection of world energy consumption by the US Department of Energy shows an increase in the use of renewable energy in the future. However, world consumption of energy is projected to grow faster than the rate of renewable energy used, so the percentage use of renewable energy will actually decrease. Of the five categories in the study – oil, natural gas, coal, nuclear, and renewable – only natural gas and coal will take up a bigger proportion of the world energy consumption than now, and the other three sources of energy will decline in relative use. While it is true that we are harnessing more and more energy from renewable resources, it is also true that the world's energy demands are growing at a faster pace.

Since the general public has become aware of the effects of carbon-energy pollution and its effects on the earth, there are been record investments going into the green industry. In fact, the green industry, including renewable energy and energy conservation, is now seen by many developed nations as being the next driver for economic growth. While investments in renewable energy continue to reach a record level every year, geothermal power has been seeing a very thin slice of this investment.

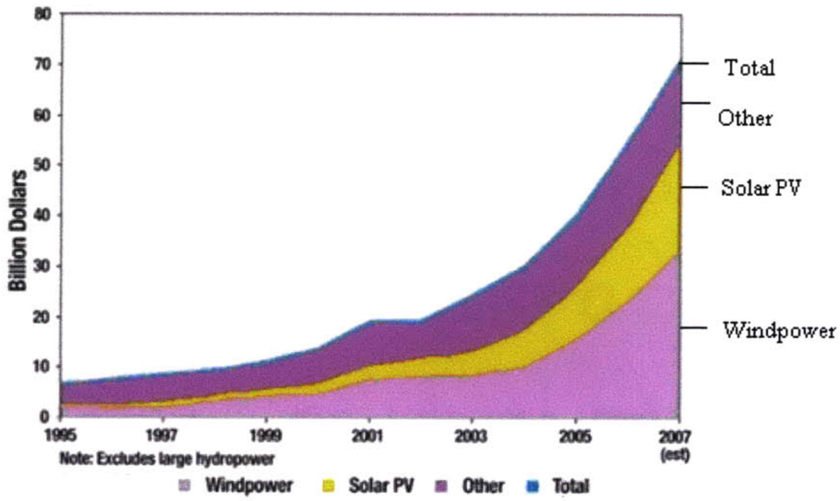


Figure 3: Growth in global renewable energy investments (REN21, 2007)

Chapter 2

Introduction to Geothermal Energy

This chapter provides an introduction to geothermal power production. A basic explanation of the source and types of geothermal resources is presented, followed by a more detailed discussion of favorable criteria common to high potential geothermal locations. Finally, the process of developing geothermal resources for power generation is presented.

2.1 Geothermal Power Production

Geothermal energy is thermal energy stored in the Earth's crust. Heat that radiates from the crust is the product of convection and conduction of heat from the Earth's core and the decay of radioactive elements in the crust. There are two types of geothermal resources that are considered for power generation today – hydrothermal and hot dry rock (HDR). Hydrothermal resources have naturally occurring steam within the system that act as the heat transfer medium. These resources are often noticeable by visual manifestations in the form geysers and hot springs. Conversely, HDR resources do not have sufficient naturally occurring steam in the system so liquid from an outside source is needed as a heat transfer medium. Traditionally, hydrothermal resources have been exploited for geothermal power generation because good quality hydrothermal resources are easier to notice by sight and also because they pose less stringent requirements on providing a heat transferring liquid. The technology for using HDR as a source for commercial power generation is still being developed and refined, but HDR resources are seen as having more potential than traditional hydrothermal resources. This is because the number of geographical candidates for HDR far outnumbers that of hydrothermal resources. The technology used for mining heat from HDR resources is called Enhanced Geothermal Systems (EGS), sometimes also known as Engineered Geothermal Systems. Other types of geothermal resources are geopressure and magma energy, but geopressure resources are limited to the Gulf Coast and magma energy is not yet fully obtainable with today's drilling technology (DiPippo, 2005).

In general, tectonic plate boundaries and recent igneous/volcanic areas tend to exhibit higher than normal heat flow at its crust. It is for this reason that many people associate geothermal energy with places where we see such geological/tectonic activity. It is also for this reason that geothermal projects in other areas have simply been overlooked (Tester, 2006).

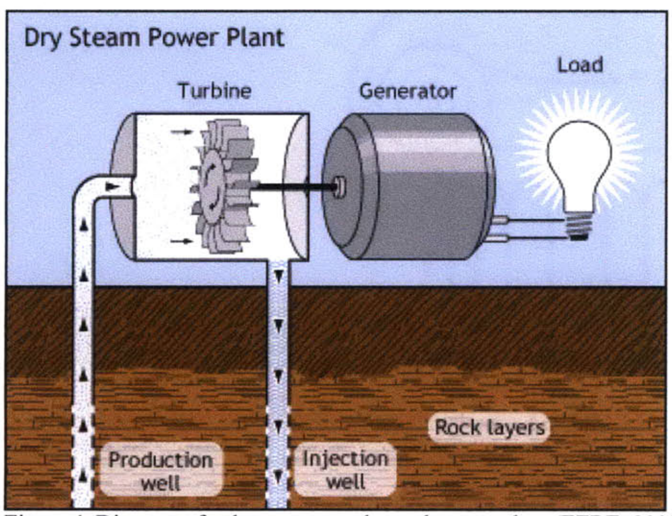


Figure 4: Diagram of a dry steam geothermal power plant (EERE, 2008)

Geothermal energy offers advantages similar to what other renewable energy resources offer such as minimal chemical waste, lack of fuel needed, and low operating costs. One major advantage of geothermal systems is that the energy output is fairly constant over time. Therefore, it does not have intermittency problems posed by other forms of renewable energy such as solar or wind energy. Also, unlike solar, wind, or hydro energy, there are no topological or meteorological limitations because geothermal heat is accessible, although at different levels, all over the world. Geothermal energy's reliability and accessibility make it a great candidate as a renewable energy source in generating power for mainstream use.

2.2 Geothermal Resource Requirements

There are several criteria for assessing whether a specific region is fit for harnessing geothermal energy. In '*Geothermal Power Plants – Principles, Applications and Case Studies*', Ronald DiPippo outlines the features of a successful environment for geothermal development.

For both hydrothermal and HDR geothermal plants, the most important feature is the existence of a large heat source. Without a high grade heat source, the temperature of the geofluid, the fluid used to carry thermal energy to the surface, will likely be too low to make any project economically viable. Along with a sufficient heat reservoir, there must also be an overlaying impermeable rock lying over the reservoir. This is to ensure that the formation does not lose pressure due to geofluids escaping through the surface. Below is an image depicting the geological features that must be taken into account when developing a field for geothermal power production.

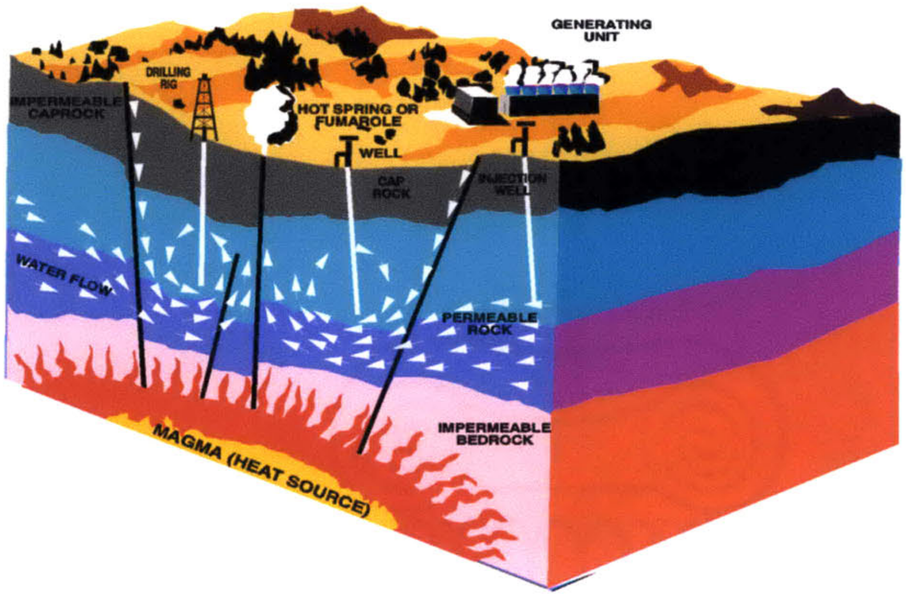


Figure 5: Geothermal energy methods (Tester, 2006)

There are also several other factors that determine how heat will be extracted from the ground. For any type of geothermal resource, it is useful to have a permeable reservoir through which the heat-transferring geofluid can pass though. However, heat can still be extracted from impermeable rocks using techniques such as fracturing, a method in which a high-pressure liquid is used at the surface to induce stress cracking. For both hydrothermal and HDR resources, it is also useful to have a sufficient supply of water. Fluid is needed as a heat transfer medium, and a reliable mechanism is needed to replenish the reservoir even in hydrothermal resources in order to keep it from becoming depleted of geofluids. To reduce the amount of water needed for replenishment, geofluids can be re-inserted into the reservoir and fluids can be brought to the site externally.

The system of inducing fractures and replenishing reservoir fluids is referred to as Enhanced Geothermal Systems (EGS) and is often regarded as having the most potential for widespread use of geothermal energy. By definition, Enhanced Geothermal Systems are engineered reservoirs that use low permeability and/or porosity geothermal resources. Enhanced Geothermal Systems exclude high-grade hydrothermal formations, but include low-grade hydrothermal, conduction-dominated, geo-pressured, and magma formations. (DiPippo, 2006).

2.3 Resource Assessment and Development

Assessing a specific location for geothermal accessibility is a difficult and time consuming process, but it is also the most important step in developing an economically viable project. Assessment is difficult because much of the essential sub-terrain information has to be deduced from measurements taken above-ground, giving room for errors in calculations and assumptions. As such, a geothermal field surveyor makes use of all information gathered throughout exploratory surveys, drilling, and reservoir engineering. As more information becomes available from each process, scientists are able to accurately model the site and make predictions for economic viability for a geothermal plant at a specific location.

The overall process begins with an exploration program that narrows down potential locations for geothermal development. A series of surveys take place in order to estimate the size and quality of the reservoir, as well as the properties of the fluid to be produced from the reservoir. Although high quality geothermal fields are often recognizable by plain sight or by higher than normal ground temperatures, it is important to note that as technology improves we will be able to drill deeper and use lower grade resources for commercial development. Surveys for this process include a literature survey, airborne survey, geologic survey, hydrologic survey, geochemical survey, and a geophysical survey. The results from all these surveys are used to make initial assessments of the geothermal reservoir.

After an extensive exploration effort, it is time to drill wells to test specific sites. Considering the high cost of drilling, it is important to go through the exploration process thoroughly so that the best spots are chosen for drilling.

In this drilling phase, usually three deep wells are drilled in a triangular formation to help delineate a productive area in the field. Safety precautions are important in drilling a geothermal well. If the drilling reaches an unexpected high-pressure zone, a blowout can happen. There are also toxic gases such as hydrogen sulfide that are present in deep wells and leaks may exist in well walls that can lead to high accumulations of hydrogen sulfide and carbon dioxide within the well cellar. There are strict regulations enforcing these safety precautions in most countries. These precautions should be in place wherever geothermal drilling is to be carried out.

After the drilling phase, a quantitative model of the fluid movement in the rock formation is generated through a process called reservoir engineering. The goal of this process is to use computer simulation to forecast outcomes from varying production and injection scenarios. An accurate and complete simulation is crucial in forecasting the economic viability and longevity of the project. However, this is a difficult task because nobody can be certain of the underground fracture patterns and also because the formations evolve over time.

Since the model is based on incomplete information, it is important to continue to modify the model as more information from the field becomes available. The model is tested by matching the evolution of early wells to the projected forecast based on the model. Many commercial geothermal reservoir simulators are available today.

Once a location has been deemed fit for a geothermal power plant, it is time to choose what type of plant should be built. Four types of geothermal power plants are widely used commercially – flash, dry steam, binary, and flash/binary combined cycle. In a flash power plant, steam is separated from the well fluid and delivered to the turbine, which powers a generator. In dry steam power plants, steam from the well is delivered directly to the turbine. Dry steam power plants can only be used with wells that only produce steam. In binary power plants, the fluid that powers the turbine is heated by the well fluid via a heat exchanger. This allows liquids with boiling temperatures lower than that of water to be used, which makes it possible to economically produce electricity from lower-temperature geothermal fields. Finally, a flash/binary power plant makes use to both flash and binary technologies, using flashed steam to power the turbine and using the exiting low-pressure fluid in a binary system to make the overall process more efficient. The quality and nature of the geothermal reservoir in question helps determine which type of plant should be used (DiPippo, 2006).

Chapter 3

China's Economy and Energy Portfolio

This chapter takes a look at key developments in China and its effects on the domestic energy industry. It is followed by a discussion of China's current energy portfolio and the availability, distribution, and usage of energy resources in China. Finally, China's history of geothermal resource development is summarized to conclude the chapter.

3.1 China's Recent Growth

In 1978, China began to implement reforms to open up to the rest of the world. As a result, the Chinese economy has seen rapid growth over the past few decades, achieving the objective of quadrupling economic output in 20 years earlier than planned. Much of this growth has been export-driven, but almost 50% of China's total export value in 2008 originated from using external components and the processing of external materials. For example, China imported 70% of its copper-making raw materials in 2008. Raw materials and heavy processing industries have been China's strength due to relatively cheap labor, land, and resource inputs, but the manufacturing of end-use products have surged in the past decade as well. An event that heavily affected this development was China's entry into the World Trade Organization in November 2001. With its inception, the Chinese government made commitments to open the Chinese economy to foreign firms and in 2008, 55% of China's total export value was invested by foreign companies. Economic growth gained from opening up to foreign investment has led to higher quality of life for most Chinese people and as a result, a historic level of infrastructure development is taking place. As quality of life improves, energy demand of end-users increases, which in turn increases demand for infrastructure development. As infrastructure development surges, even more raw materials need to be processed. The combination of increased consumer and industrial energy consumption has led to the power sector increasing its capacity by a staggering 12 percent annually for the past decade. Between the year 2000 and 2008, installed capacity has increased from 319GW to 792 GW (Zhou, 2009). Despite this rate of growth in power generation, China has been experiencing a nationwide power shortage since 2001. Estimates indicate that current Chinese electricity shortfall is 80 billion kWh a year out of a total demand of 2456 billion kWh, with demand continuing to outpace supply (EIA, 2009).

3.2 China's Energy Portfolio

Coal makes up 69% of China's total energy consumption and China is both the largest producer and consumer of coal in the world. In 2007, China's installed electricity generation capacity was 624 GW with 83% of it coming from the burning of fossil fuels.

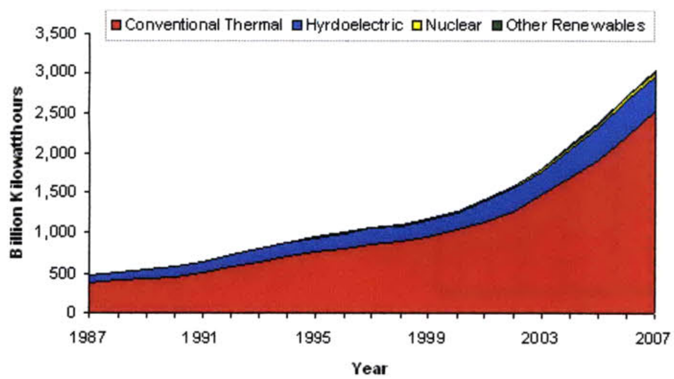


Figure 6: China's electricity generation by type, 1987-2007 (EIA, 2009)

China's extensive reliance on coal poses a major pollution problem not only for itself but for the rest of the world. At 126.2 billion metric tons of coal, China has the third largest coal reserves in the world, most of which is readily accessible in the North. Coal is also found in the South but southern reserves tend to contain high levels of sulfur and ash, making it unsuitable for many applications (EIA, 2009). Looking forward, China is likely to continue relying on domestic energy supply, which currently account for more than 90% of the primary energy supply. Outlook on China's coal production are diverse. While some believe that China could still double its coal production to 5 billion metric tons per year, the Chinese government recognizes that constraints in environmental preservation, land availability, water resources, and labor efficiency already make China's coal production unsustainable especially when China's large population and high-energy consumption trend is considered (Zhou, 2009). In fact, recent government stimulus programs to revitalize the economy have led to a sharp increase in demand for power, which has led China to sign a USD$60 billion contract with an Australian firm to supply coal to Chinese power stations (BBC, 2010).

Although the recent economic stimulus plan is causing China to burn more coal for power generation, US$45 billion of that same stimulus plan was earmarked for renewable energy projects for 2009 alone. With the semiconductor market growing at a slower place and having gained valuable experience in heavy manufacturing in the past couple of decades, China is focusing its renewable energy projects on solar and wind power. As it is the case in other countries' renewable energy policy, China has ignored geothermal energy development for the most part. Furthermore, although China has shown a level of commitment to developing its renewable energy industry, it is not clear if China is looking to offset pollutions emissions or if this new renewable policy was signed for purely economic reasons. One indication that China might be more concerned about economic is its mass production and dumping of solar cells and wind turbines at a low price, which has destabilized the entire solar and wind power industry across the whole value chain (Bradsher, 2010).

3.3 China's Geothermal History

China has rich geothermal resources throughout the country. Most of the resource is utilized as direct heat due to low source temperature, but there are high temperature resources in Tibet and Yunnan. Facing a worldwide petroleum crisis in the 1970s, China made an effort to utilize alternative energy resources by conducting geothermal survey and exploration throughout the country. Nine small hydrothermal plants of 50-300kW capacity were installed in various locations, but lower temperatures and inefficiencies led to seven of these plants to close quickly. Meanwhile in 1977, a 1MW high temperature hydrothermal power plant was built in Yangbajing, Tibet, 90km away from Tibetan capital Lhasa. Further development of geothermal fields in China was concentrated in Tibet, where 25MW of capacity was installed between 1977 and 1991. This amount covers approximately 88% of China's total power generation capacity from geothermal resources. In 1992, a new surge of geothermal development began throughout the world with the United Nations Global Congress of Environment and Development's call for sustainable developments in 'The Agenda of the 21st Century'. Developing nations such as the Philippines, Indonesia, and countries in South America have seen a rapid growth since 1992, but geothermal power generation in China has only increased with a 1MW unit in Nagqu, Tibet.

Figure 7: Chinese provinces map (SACU)

Although the capacity of these plants is fairly low, they have combined to provide over 40% of the total power output of the Lhasa grid. Generally the geothermal development and utilization of China is represented by Tibet's high geothermal potential, but there were many problems in the initial stages of geothermal development in the area. These problems were, but not limited to;

- Corrosion of plant parts
- Lack of cooling water
- Poor maintenance
- Ineffective field monitoring
- Lack of funds to fix problems

Moving forward, Tibet province has potential future development locations in the Yangbajing deep reservoir and the Yangyi geothermal field. In Yunnan province, the Tengchong geothermal field is believed to be very valuable and is seen as the next location for geothermal development (Liu, 2005). Through these initial efforts, China has determined that development of the Yangbajing geothermal field would be most effective.

Several barriers to further development of geothermal resources in China have been noted over the years. The first barrier is the nature of geothermal heat source. Whereas in most high temperature geothermal systems in the world are of young acidic magma intrusion at shallow depth at the crust of the earth, Tibet is a collision zone of two continental plates (not continental/marine) and the fields in Yunnan are related to neo-volcanic activity and pose high risk for development. Both locations have a low geothermal fluid yield, which means fluids have to be imported for reinjection, increasing operational costs (Liu, 2005). By comparison, geothermal fields in the Philippines and Indonesia have been easier to develop because they are hydrothermal resources that originate from continental and marine plate collisions. Furthermore, the cost of exploration and drilling has been extremely high in both Tibet and Yunnan due to the disadvantage of being located at high altitudes. Economically, China has cancelled national fund input for geothermal exploration while restructuring its economy from a socialist to market economy, and the Tibet and Yunnan areas are relatively poor and unable to locally fund geothermal projects.

Chapter 4

Potential for Geothermal Energy in China

Geothermal power generation can be useful in China today as well as in the future. Today, technological improvements made since the 1970s can help expand existing operations in high geothermal potential provinces such as Tibet while avoiding the problems of the past. Geothermal technology has improved to such an extent that this can be done right now, even if only locally because of geothermal resource quality constraints. Although the effect of these local projects on China's pollution problems will be marginal, the experience gained in handling current technology can help China on a national scale in the future when EGS technologies become commercially mature. Because developing and managing an EGS is very similar to managing a hydrothermal geothermal system, experience with hydrothermal systems will help pave the way for a smooth and less capitally expensive deployment of EGS all over the country in the future.

4.1 Using Improved Geothermal Technology Locally

Using technological improvements, geothermal energy becomes more attractive in high potential regions such as Tibet and Yunnan. While there are already some geothermal plants running in those areas, not much has been done since the 1970s. Improvements in geothermal technology that apply to geothermal projects in China can be divided into two parts; drilling for access to the geothermal system and management of the geothermal reservoir.

4.11 Improvements in Drilling

Exploration, production, and drilling is capitally intensive in geothermal projects and can account for 30% of the total capital investment for high grade resources and up to 60% for lower grade resources. Investments in geothermal technology research is miniscule when compared to investments made for mainstream energy sources such as oil, natural gas, and even renewable energy sources such as solar energy. Fortunately, the process and technology used in drilling geothermal wells is similar to those of oil and gas well (Tester, 2006). Therefore, improvements in oil and gas well drilling can be applied to drilling geothermal wells.

In the past, problems faced while drilling included instrument and casing failure in high temperatures, bit failure in hard crystalline or granitic formations, corrosion of various parts, and loss of circulation. All of these problems were faced in China in the 1970s to such an extent that some projects had to be halted (Liu, 2005).

Solutions to Drilling at High Temperatures

Dealing with high temperatures in geothermal drilling primarily affects electronics, seals, and casing. Advances in materials engineering have improved the performance of elastomeric materials, which are used as seals and insulators. Currently, electronics used in geothermal well drilling tend to fail at temperatures above 150°C and elastomeric insulators and seals that help shield electronics from heat fail at temperatures above 190°C. High temperature electronics is applicable to a variety of industries and ongoing research continues to push the limit. For example, NASA is developing silicon carbide (SiC) as a semiconducting material for electronics. When research completes, silicon carbide-based electronics could operate at up to 600°C.

In deep well drilling, casing is needed along the entire length of the well to seal off the well from surrounding water aquifers and to prevent the collapsing of the well. Casing in high temperature has been a problem in geothermal well drilling because thermal expansion can cause the casing to buckle and collapse. Even worse, the casing can collapse while cooling as well because it is subject to tensile pressure. In order to provide stability to the casing, cement is poured into the space between the outside of the casing and the wall of the well bore. Current methods of casing used safely for temperatures below 260°C. The same process can be used for temperatures above 260°C, but extra care must be taken. Many promising casing technologies are under development. One such technology is the use of expandable tubular casing, which essentially increases the diameter of the casing after it has been run down-hole. This technology is helpful because by design it eliminates unwanted effects of thermal expansion. Furthermore, it reduces the initial diameter of the well bore because the diameter of the casing does not have to decrease with depth, which means that less cement has to be used for filling in the empty space between the casing and the well bore. Being that casing and cementing is expensive for deep wells, this technology reduces the overall cost of preparation for drilling. Other promising emerging technologies include drilling-with-casing, which saves costs by allowing the use of fewer strings (Tester, 2006).

Solutions to Drill Bit Failure and Corrosion

Drilling geothermal wells can be harder than drilling wells for oil or gas because fractured crystalline or granitic formations are present in geothermal well sites. Even as recently as the 1990s, geothermal well drilling in China has faced problems of rapid bit wear and breaking. These problems led to increased downtime in drilling, maintenance of hole diameter, as well as added cost for replacing drill parts. Today, wear-resistant tungsten carbide is used and past problems with bit bearing and cutting wear has been fully overcome. When facing severe cases of abrasive formations, polycrystalline diamond compact (PDC) also known as man-made diamond can be used. The use of advanced materials and corrosion inhibiting fluids has eliminated much of the corrosion problem as well. Below is an image of a PDC bit.

Figure 8: Schlumberger PDC drill bit

Solutions to Lost Circulation While Drilling

When drilling for deep wells, drilling fluid is used to return cuttings from the well. Lost circulation occurs when the fluid circulation cycle is interrupted and well cuttings fail to return to the surface. When this happens, the cuttings may become suspended or fall down the well and clog up the drill pipe. To fix this problem, the drilling fluid must be pumped fast enough to maintain flow in order to keep the drill bit clear of cuttings. To do this, work is interrupted and the pumping of drilling fluid is an extra cost to drilling. The use of aerated drilling fluids is a widely used solution and projects in the 1970s in China already used this solution. However, lost circulation was still a major problem that reduced effective drilling time and increased drilling costs. Today, greater use of aerated drilling fluids and air drilling can be used to reduce the overall density of the drilling fluid, which allows for better circulation of cuttings and fluids back to the surface. In a new process, air is injected using a dual-tube system and the stuck portion of fluids and cuttings is essentially airlifted to the surface. Lost circulation is still a problem in deep well drilling today, but its frequency and severity has been greatly reduced in the past several decades (Tester, 2006).

Directional Drilling

Directional drilling enables wells to cover a greater area of a geothermal field and have been used since the 1960s. However, high temperatures, the lack of real-time steering, and inadequate directional and steering tools prohibited the technology from being used for geothermal purposes until after the 1970s. Today, directional drilling is commonly used for geothermal drilling, even though some limitations on operating in high temperatures still exist. With this new technology, drilling a single well has become much more effective than it was in the 1970s when geothermal fields were being developed in China (Tester, 2006).

4.12 Improvements in Reservoir Management

Reservoir management is crucial in maintaining productivity in the long run. Many geothermal projects in China have been abandoned simply because production declined so much over time that running the plant was no longer economically feasible. Factors that determine the continued productivity of a well are production temperature, fluid availability, well pressure, and the evolution of geology. These factors must be monitored carefully and production has to occur at an optimal rate for the longevity of the power plant. Furthermore, the careful management of geothermal reservoirs is important in minimizing induced seismicity. Reservoir management problems specific to geothermal projects in China have been loss of production temperature, pressure, and the lack of locally available water to replenish reservoir fluids (DiPippo, 2005).

Management of geothermal reservoirs is done through an understanding of the properties of the geothermal resource. Since each geothermal system is unique in nature, there is no easy way to cut and paste production scenarios from other projects. Several methods for analyzing geothermal systems have been developed that can be used to improve the success rate of geothermal power plants in China.

Well testing is a process in which well productivity, field permeability, reservoir volume, and the nature of boundaries are determined through measurement of pressure response to the extraction of geothermal fluid from a well. Because all of the useful sub terrain information is deduced from measurements taken above ground, the pressure response model becomes more accurate with longer and frequent testing.

Dynamic simulation models are also being used to assess geothermal reservoirs. Dynamic simulation uses the conceptual model of the geothermal system gained from processes such as well testing and helps define reservoir requirements, plan reservoir operation, and determine injection strategies. On the most basic level, dynamic simulation models try to predict heat and mass transfers and pressure changes. As the model becomes more refined through feedback by testing the estimations of what the system response would be, modeling can expand to include geochemical, geological, and stress modeling. While adding new models helps further define the nature of the geothermal system in question, findings from these additional models can be difficult to interpret. There is limited field data available at the scale at which geothermal modeling takes place and the dynamic interactions between each model is not always taken into consideration. For example, thermal elastic effects on fractures are not included in stress models and the thermal properties of local rock may be insufficient as well (Tester, 2006). Even with these limitations, vast improvements made in geothermal system simulation since the 1970s will help improve the long-term performance of geothermal projects in China. It is important to understand that these new methods of modeling will become more useful in determining production scenarios when extensive testing of geothermal systems is done locally.

4.2 Potential of EGS in the Future

Engineered geothermal systems (EGS) are different from conventional hydrothermal geothermal systems in that sufficient water and rock porosity are not required. Because most of the geothermal energy accessible with today's drilling technology is present in dry and non-porous rock, EGS has the potential to be used in a much larger capacity anywhere in the world than geographically selective hydrothermal systems. Since geothermal energy can be accessed almost anywhere with EGS, the amount of recoverable energy through EGS is much greater than that of conventional hydrothermal geothermal systems, which are not very cost effective. A 2006 MIT study on EGS calculated that in the United States alone, resources from depths of 3-10km would be sufficient to provide the world's energy demand for several thousand years. Although EGS technology for commercial use is still years away, the MIT study finds that through research and development EGS can have a bright future. While cost estimates are heavily influenced by the nature of resource, drilling costs, material costs, and power conversion efficiency, the report finds that within the next 50 years, EGS can produce electricity for cost-competitive prices across a wide area of the US. The good news for China is that its national geothermal potential is just as good as the US for EGS while perhaps having more of an incentive to switch to clean energy (Tester, 2006).

Economics of EGS

No matter how environmentally friendly or widely available an energy resource is, only the economic viability of its use will determine how widely it will be used. Like any other energy resource, minimizing the levelized cost of power over the entire life of the project is the key to optimizing geothermal resource economics. Generally, the cost of developing a power plant can be divided into the capital cost of development in $/kW installed, and the cost of operations and management (O&M) in ¢/kWh generated. The simplified method of calculating the levelized cost of electricity is taking the sum of fixed charge rate to invested capital and annualized operating and management cost and dividing it by annual electric generation. The more complex method uses a full financial cash-flow model and takes into account various cost parameters that may change over time. Since there are so many variables that determine the cost of developing and maintaining a geothermal field, the more complex method of calculation is used. Even then, the O&M cost of a geothermal plant is somewhat unpredictable because of its sensitivity to resource characteristics that may only be discovered sometime after the project is underway. There are several computer programs and databases available for economic analysis of geothermal systems. One such program is an MIT-released computer program called "EGS for Windows" that takes in various user-defined inputs and presents results. Another tool widely used is called the Geothermal Electric Technologies Evaluation Model which is an excel spreadsheet that presents results based on about 80 user-defined inputs. As all aspects of geothermal technology improve, relevant parameters of these economic models are updated (Tester, 2006).

Currently the cost of electricity generated with EGS is far from being economically competitive. Whereas electricity generated from more commonly used sources of energy such as coal and nuclear energy cost around 5 cents/kWh, using EGS costs more than 10 cents/kWh today even in optimal locations. Below is a graph showing the different costs of commonly used sources of energy for electricity generation.

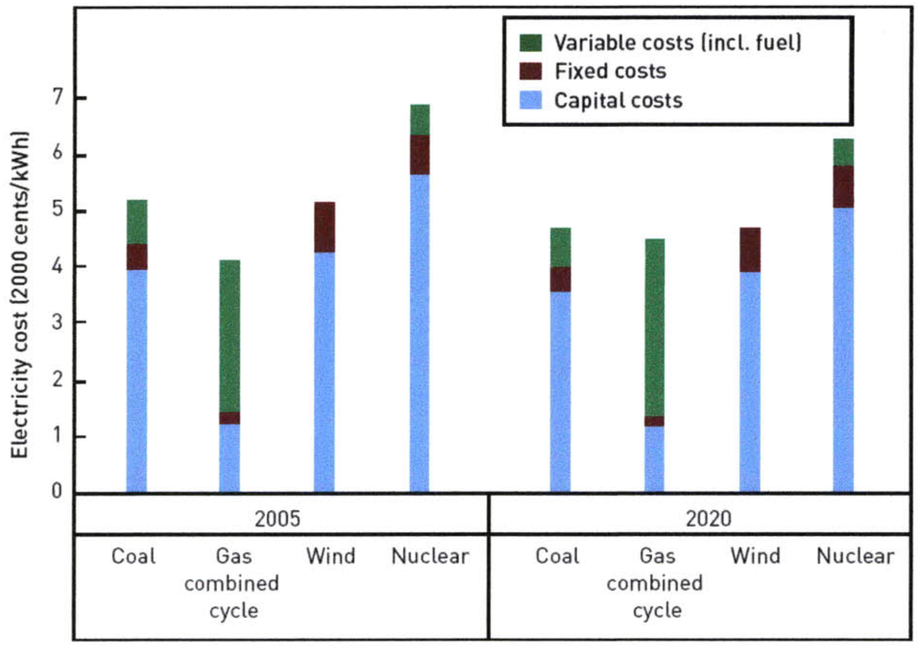


Figure 9: Projected levelized electricity generating costs, 2005 and 2020 (Tester, 2006)

Because at the moment the cost of EGS varies greatly with location, it is difficult to give a definitive cost of electricity generated with EGS. However, the table below shows the base case (today) and optimized (future) cost of electricity generated with EGS in seven sites in the US. From the table we see that EGS is currently not economically viable, but can become competitive in the future when EGS technology improves.

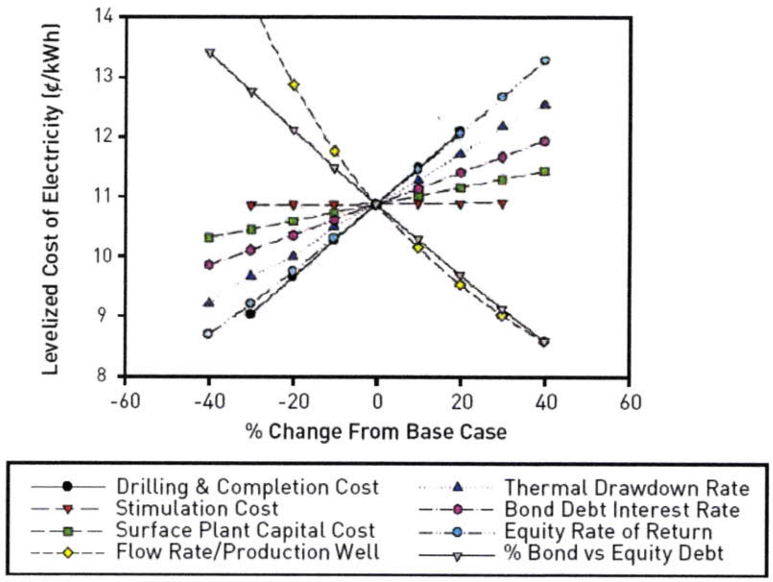
Site Name	∂T/∂z (°C/km)	Depth to Granite (km)	Completion Depth l(km)	Fracture Costs ($K)		LCOE Using Initial Values for Base Case (¢/kWh)		Optimized LCOE Using Commercially Mature Values (¢/kWh)		
				@ 93 l/s	@ 180 l/s	MIT EGS	GETEM	MIT EGS	GETEM	Depth (km)
East Texas Basin	40	5	5	145	171	29.5	21.7	6.2	5.8	7.1
Nampa	43	4.5	5	260	356	24.5	19.5	5.9	5.5	6.6
Three Sisters Area	50	3.5	5	348	450	17.5	15.7	5.2	4.9	5.1
Poplar Dome a	55	4	2.2	152	179	74.7	104.9	5.9	4.1	4.0
Poplar Dome b	37	4	6.5	152	179	26.9	22.3	5.9	4.1	4.0
Clear Lake	67	3	5	450	491	10.3	12.7	3.6	4.1	5.1
Conway Granite	26	0	7	502	580	68.0	34.0	9.2	8.3	10*

***10 km limit put on drilling depth – MITEGS LCOE reaches 7.3 ¢/kWh at 12.7 km and 350°C geofluid temperature.**

Table 5: Levelized cost of electricity for selected US sites for development (Tester, 2006)

As mentioned earlier, electricity generated with EGS even at the best location (Clear Lake) currently costs more than twice as much as coal generated electricity. This high cost can be reduced through improvements on many fronts, such as gaining better access to high quality resources, better reservoir management, and using more efficient drilling methods. Below are graphs illustrating the sensitivity of electricity cost for base case and commercially mature EGS for two of the above locations, Clear Lake and Conway Granite.

Initial Base-Case Values for Clear Lake (11cents/kWh)



Commercially Mature Values for Clear Lake (3.5cents/kWh)

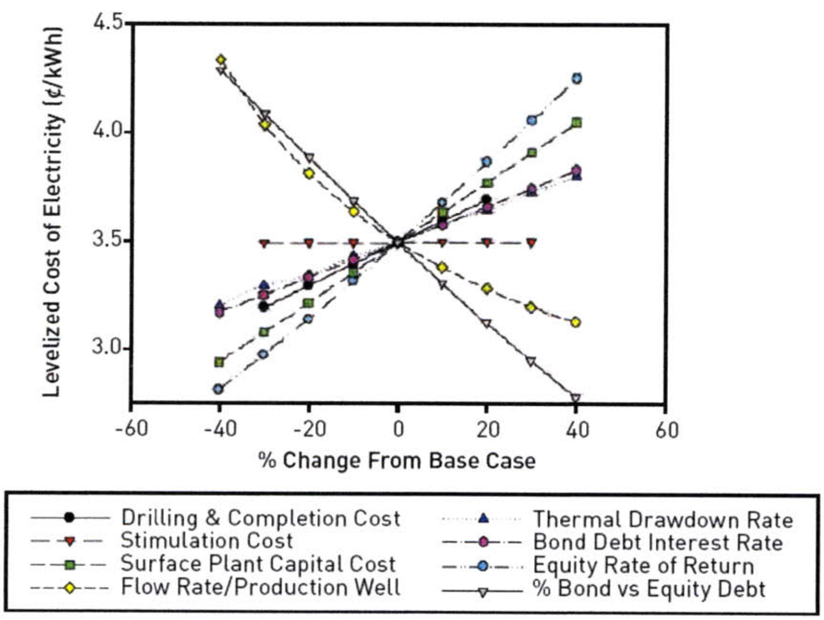
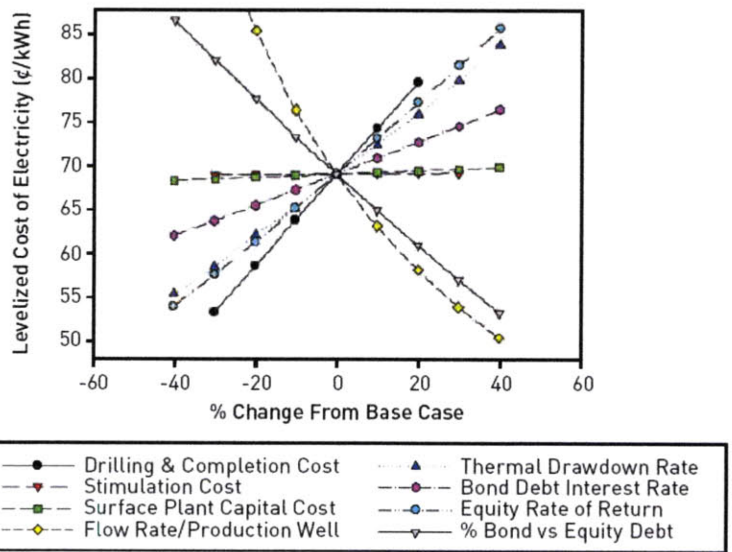


Figure 10: Sensitivity of EGS levelized cost of electricity for Clear Lake (Tester, 2006)

Initial Base-Case Values for Conway (69cents/kWh)



Commercially Mature Values for Conway (8.5cents/kWh)

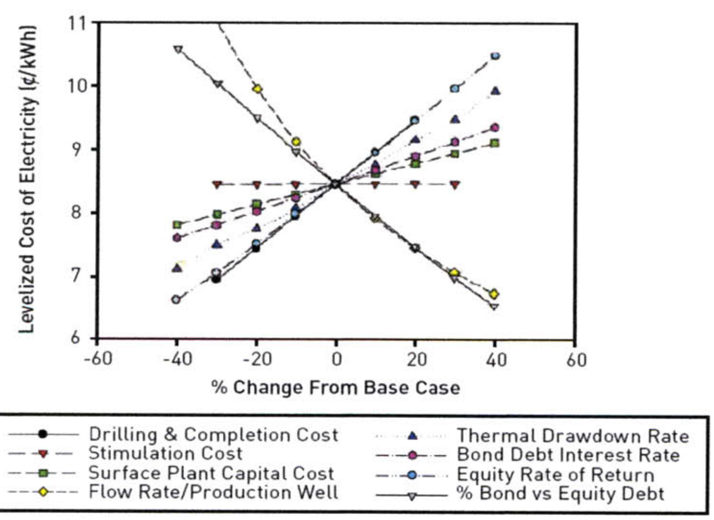


Figure 11: Sensitivity of EGS levelized cost of electricity for Conway (Tester, 2006)

The first set of sensitivity graphs is for Clear Lake, which exhibits the lowest levelized cost of electricity amongst the seven locations analyzed in table 2. On the other hand, the second set of graphs is for Conway, which exhibits the highest cost from table 2. From table 2 we can see that the levelized cost of electricity with current technology at Conway is 3-6 times that of Clear Lake at 34-68 cents/kWh and 10.3-12.7 cents/kWh, respectively. Despite these differences, sensitivity analysis for both these locations shows the same order of sensitivity to a range of parameters.

The 8 sensitivity parameters can be divided into three groups. The first group is influenced by technology– drilling and completion cost, stimulation cost, and surface plant capital cost. The second group is influenced by resource characteristics – flow rate/production and thermal drawdown rate. Finally, the third group is influenced by financing - bond debt interest rate, equity rate of return, and % bond vs equity debt.

As expected, cost sensitivity of geothermal power generation to resource characteristics and financing options remain virtually unchanged between the current base-case scenario and commercially mature future scenario. Although the cost of financing may change from one year to the next, for the purpose of this sensitivity analysis the fluctuations in the economy are treated as an externality. Similarly, resource characteristics vary from one location to another but do not change much in the relevant timescale of this analysis.

With these other factors fixed, the shift in the cost of geothermal power generation can only come from the technology group, as exhibited in both sensitivity analysis. In the current case, drilling and completion cost heavily influence the levelized cost of electricity of EGS. Surface plant capital cost is a factor but not as big of a factor as drilling and completion cost, and stimulation cost seems to be non-factor. However, at commercially mature values, the order of sensitivity changes as drilling and completion cost becomes less of a factor than surface plant capital cost. Therefore, while today's EGS drilling and completion cost heavily affects the final levelized cost of electricity generated from that project, it is expected to become a smaller and/or more stable source of cost in EGS projects in the future.

There are a few ways in which EGS drilling cost can be reduced and made more stable from project to project. One way to achieve drilling cost reduction is through technological refinements and breakthroughs that would make drilling deep into the earth for EGS easier that it is today. Improvements in drilling are expected to continue to happen because as mentioned earlier, geothermal drilling technologies improve in tandem with deep sea oil drilling because of their similarities. To further reduce and stabilize the cost of drilling for EGS, it is important to research and practice the application of deep sea drilling technologies to EGS drilling. Furthermore, it is important to compile an extensive database on potential EGS sites in order to make optimal plans for EGS drilling when the time comes. With extensive knowledge of the resource characteristics, accurate drilling plans can be made, which leads to reductions in time spent drilling and problems faced.

Chapter 5

Factors Affecting Geothermal Investment

This chapter briefly examines the major factors that affect geothermal investment both globally and locally. These factors are defined in order to formulate a successful plan for developing geothermal resources.

5.1 Global Geothermal Investment

Globally, three key factors determine the level of investment in geothermal projects. The first factor is the price of oil. When oil becomes expensive, there is more of an incentive to explore alternative options for generating power.

The second factor is the development of drilling technologies. Fortunately, well-drilling for geothermal field development is similar to deep-sea drilling for oil, which is heavily funded by energy companies. How fast these new technologies develop will be also affected by the price of oil. For example, as the price of oil rises, the US government and energy companies are likely to spend more on developing new drilling technologies to be used in the Gulf of Mexico in order to tap previously inaccessible local resources.

Finally, because developing geothermal fields is very capitally intensive initially, global economic climate plays a big role as well, just as in the case of any large-scale project. A study by the California Energy Commission concluded that 65% of the cost of geothermal power can be attributed to capital reimbursement and interest charges compared to only 22%

for combined-cycle natural gas plants (Tester, 2006). Therefore, ability to borrow capital at a low rate is extremely important.

5.2 Local Geothermal Investment

There are also three factors that will determine the level of investment in geothermal projects locally. The first is how much geologic, hydrologic, and other field information can be readily available to investors. In one sense, it is important to survey potential locations over a period of time in order to gain an accurate and refined model of the sub terrain system. In another sense, how much effort local governments put into researching their land can be noted by investors as an indication of how committed the region is to developing geothermal plants (Deloitte, 2008).

The second factor that will determine the level of investment locally is the availability of financial and operational incentives for investors. What kind of incentives should be given will depend on the type of role geothermal plants is to have in that region. If the government wants to encourage the development of small-scale plants and tackle intermittency problems posed by other technologies, it can promote down-stream incentives such as discounted distribution and transmission fees. If the government wants to develop large-scale plants, it can allow foreign investors to bid for rights to a field. Because the development of commercial geothermal plants is highly technical and costly, there can be a lot of synergy to be gained by less developed countries partnering up with global corporations or developed countries. If two partners share a border, like the US and Mexico, power generated in one country may also be used in the other. Other than those already discussed earlier in this paper, several countries offer significant incentives for developing and/or operating geothermal plants. Below is a table with the list of those countries and details of their incentives program. Governments that are interested in harnessing geothermal energy should use these incentives for reference in generating their own incentives programs.

Canada	Certain expenditures are 100% tax deductable for the year incurred or for future years.
China	Possible income tax incentives, tax exemption on import of equipment, electricity price sharing mechanism, subsidy from a fund, priority to go on the grid.
France	Reduced local tax and depreciation of constructed or acquired equipment over 1 year.
Germany	Minimum price feed program for renewable energy resources, guaranteeing a level of income from those resources.
India	10-year tax holiday
Japan	7% tax credit for acquisition costs (limited to 20% of the tax) or initial depreciation of 30%
US	10-year federal production tax credit of US$ 2cents per kilowatt hour produced, adjusted for yearly inflation

Table 6: Incentives for geothermal development (KPMG, 2007)

Finally, the stability of local governments is an important factor in attracting investors. This factor can be noted in the case of Indonesia's development of geothermal plants and is applicable to countries in Africa, Eastern Europe, and Southeast Asia. Investment is unlikely in countries where government stability is in question. Amidst growing world-wide energy problems, these global and local factors can be used as a guideline for future development of geothermal energy.

Chapter 6

Case Studies

In this section, we look at the utilization of geothermal resources in the Philippines and Mexico. Lessons learned from these success stories should be adopted to fit China's unique characteristics.

6.1 The Philippines

While geothermal energy supplies less than 1% of the world's energy, 27% of electricity production in the Philippines comes from geothermal power plants. Endowed with excellent geothermal resources, the Philippines has taken key steps to actively harness its resources, most notably through Presidential Decree No. 1442 (1978), also known as "An Act to Promote the Exploration and Development of Geothermal Resources". The main goals of this decree are to draw in foreign investors and to create financial incentives for geothermal operations. Drawing foreign investment is important for the Philippines because the country is relatively poor and there are insufficient financial resources for domestic companies, especially for high initial cost investments like geothermal field development. The two geothermal companies in the Philippines have made good use of foreign investment. The PNOC-EDC, the larger geothermal energy development company with 60% of the country's capacity, has been drawing from the World Bank and allowing foreign private firms to bid for ownership of planned plants in the Philippines. Following the Philippines' footsteps, China should also open up its geothermal investment and operations to foreign parties. As it did with the Philippines, opening up to foreign parties would help more geothermal fields to be developed than previously allowed and also helped to parse financial risk. As building geothermal power plants have high initial cost, financial incentives for their operation allows for a quicker return on investment and therefore a more attractive investment opportunity (Gawell, 2007). Because of China's interesting economic status - as a whole a giant in world economy, but still having a low standard of living and mostly poor locally – incentives may be provided most usefully at the federal level.

6.2 Mexico

Similar to the Philippines, Mexico has been promoting the use of geothermal resources since the 1970s. Also like the Philippines, Mexico has done this with financial incentives for developing and operating geothermal power plants. However, unlike in the Philippines, incentives in Mexico seem to be focused on developing smaller, independent facilities that can be used in the national grid not only for a 'green' purpose, but as a fix for frequent black-outs. In this sense, geothermal energy is being used to supplement existing, unreliable energy infrastructure. Another way that Mexico expedited the development of its geothermal resources was through technology transfer by geothermal-related scientists and engineers from the US (Baker, 2003). By contrast, China's efforts to utilize its geothermal resources in the 1970s failed in part because of the engineers' lack of expertise and knowledge of geothermal resource development. China needs to follow Mexico's example and not repeat a mistake of the past. Recently as nations are starting to get involved in the green energy market, China has shown signs of cutting out foreign parties from benefitting from its green energy incentives program. Because of the complexity of geothermal projects and the level of risk involved, the success of geothermal projects is heavily dependent on the expertise of its scientists and engineers. Considering this, China should open up its borders and perhaps give foreign experts incentives to work on geothermal projects in China.

Chapter 7

Conclusion

This thesis provided an overview of geothermal power generation and its potential in China. Geothermal resources have been used by humans for thousands of years for heating and despite decades of experience in commercial development of geothermal power plants, economic viability still remains a problem for most parts of the world. Following the oil crisis of 1973, China funded several geothermal resource development projects in the 1970s, but most of these projects failed due to inferior technologies and poor reservoir management, and insufficient funds to fix these problems even when the technology had improved. Since then, there have been no significant developments in this market in China.

Today, with the global spotlight on utilizing renewable energy, geothermal energy is primed for a second wave of development. This is especially true in China where a significant portion of the world's pollution originates. Learning from its previous experiences, China can invest in geothermal development in three ways; resource investment, technology investment, and monetary investment.

At the initial stages of geothermal resource development in China, investments must be made to learn about the resource that they will be using. Such investment can help refine existing geothermal models and is also a great way to prepare for EGS in the future. Considering the importance of accurate geothermal resource assessment and the time it takes to do this, China would be placing itself in a favorable position to deploy EGS in the future by learning about its geothermal resources now.

Monetary investment is needed to encourage geothermal projects until grid parity is achieved. As this thesis found, high initial costs and risks associated with exploring and developing a field are a major barrier to geothermal field development across the globe. With future benefits of experience and capability in mind, China needs to provide monetary incentives until geothermal power can be economically competitive. Such monetary incentives can be in the form of federally funded geothermal projects, tax incentives for private investors, or funding for locally developed geothermal projects. In providing these incentives, China should not limit eligibility to local parties as it has with other renewable energy plans such as solar cell development. Considering the complexity involved in developing geothermal systems, China will need outside participation for technological knowledge, just as Mexico has successfully.

Technologically, there have been many improvements that China can use to update and add to its existing infrastructure. Many more technological improvements must be made for the commercial deployment of EGS across China, but there are numerous corporation and nations developing technology crucial for future EGS. China has the economic scale to make an impact in technology research, but investment priority should go to monetary and resource investment because even the existing technologies will be useless without proper resource and monetary investment.

China already regards the renewable energy market as one of the drivers of future economic growth and the government has recently pledged to produce 15% of its energy with non-carbon sources by 2020. Due to its size, China can make a big positive impact on global pollution even with a small change in its energy portfolio. If China replaces 1% of its electricity generating capacity of 624GW with geothermal power, it will be replacing over twelve 500MW coal-fired power plants, which in turn results in a reduction of 40-plus million tons of CO_2 emissions per year. To maximize future benefits, one has to act today with that future in mind even though it may not maximize today's benefits. In the same way, investing in geothermal projects might not be economically profitable today, but it is a low price to pay for a potential windfall to come in the next few decades.

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