EVALUATION OF LEVELISED COST OF ELECTRICITY GENERATED FROM HOT SPRING GEOTHERMAL RESOURCES IN NIGERIA: A CASE STUDY OF RAFIN REEWA HOT SPRING, LERE LOCAL GOVERNMENT OF KADUNA STATE

BY

ALIYU KOFA MUSA

DEPARTMENT OF MECHANICAL ENGINEERING
FACULTY OF ENGINEERING
AHMADU BELLO UNIVERSITY, ZARIA
NIGERIA

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BY

Aliyu Kofa MUSA, B.ENG (A.B.U) 2009,
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DEPARTMENT OF MECHANICAL ENGINEERING,
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DECLARATION

I declare that the work in this dissertation entitled "*Evaluation of Levelised Cost of Electricity Generated from Hot Spring Geothermal Resources in Nigeria A Case Study Of Rafin Reewa Hot spring in a case study of Rafin Reewa hot spring, Lere local government of Kaduna state*" has been carried out by me in the Department of Mechanical Engineering. The information derived from the literature has been duly acknowledged in the text and list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other Institution.

....	....	....
Aliyu Kofa MUSA	Signature	Date

CERTIFICATION

This dissertation entitled "*EVALUATION OF LEVELISED COST OF ELECTRICITY GENERATED FROM HOT SPRING GEOTHERMAL RESOURCES IN NIGERIA, A CASE STUDY OF RAFIN REEWA HOT SPRING, LERE LOCAL GOVERNMENT OF KADUNA STATE*" by Aliyu Kofa MUSA, meets the regulations governing the award of the degree of Master of Science of the Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

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Prof. C.O Folayan Chairman Supervisory Committee	Signature	Date
……………………......................	....	....
Dr. D.M Kulla Member Supervisory Committee	Signature	Date
……………………......................	....	....
Dr. M. Dauda Head of Department	Signature	Date
……………………......................	....	....
Prof. Kabiru Bala Dean, School of Postgraduate Studies	Signature	Date

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ABSTRACT

This study work, *Evaluation of Levelised Cost of Electricity Generated From Hot Spring Geothermal Resources in Nigeria* aims to investigate the economical and technical prerequisites for electricity generation from Rafin Reewa hot spring located at Lere local government of Kaduna state; a potential development sites.

Geothermal energy is thought to have great potential in Nigeria due to the high abundance of sedimentary rocks and numerous hot springs. However, it is still a relatively new technology that has not yet been proved to be economically viable at commercial scale in Nigeria.

The study investigated both the technical and economical aspects of geothermal energy as a resource for electricity production. The technical investigation is based mainly on identifying the resource temperature at Rafin Reewa hot spring and subsequently which technology is suitable for use in the study area. In the economical section of the study, the impact of resource flow rate and resource depth (variables) on factors that determine the geothermal power plant construction costs are analyzed. Within each variable, geothermal power plant cost factors are calculated, and subsequently the levelised cost of electricity (LCOE) at power sales of 50MW was evaluated.

The result of the study shows that the temperature of the geofluid at the study sites (Rafin Reewa) is 122.14^{o}C, and hence this shows that Rafin Reewa hot spring is a hydrothermal geothermal resource suitable for air-cooled binary power plant. Consequently, the results of the study show electricity generation from geofluid of Rafin Reewa hot spring is viable.

On the economic aspect of the study, the result shows that the total plant cost, exclusive of wells, for an air-cooled binary is $663,609,961 (N132, 721,992,200) for 50MW plant capacity at study site. The Levelised Cost of Electricity *(*LCOE) in cent/kWh is calculated using Geothermal Electricity Technology Model (GETEM). To evaluate the LCOE of the geothermal power plant, the impact of production flow rate and resource depth on the cost factors that influence LCOE were evaluated. The result of the study shows that the LCOE at a flow rate of 100kg/s and a resource depth of 1000m is 43.010cent/kWh (N86.02/kWh). Although both variable parameters influence the LCOE, the study shows that the LCOE is more sensitive to the production flow rate than the depth of the resources.

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LIST OF ABBREVIATIONS

ATP: Available Thermal Power

BHT: Bottom Hole Temperature

CC: Capital Cost

COE: Cost of Electricity

DCF: Discounted Cash Flow

EC: Energy Conversion

EERE: Energy Efficiency and Renewable Energy

EGS: Engineered (or Enhanced) Geothermal Systems

FCR: Fixed Charge Rate

GETEM: Geothermal Energy Technology Evaluation Model

GHP: Geothermal Heat Pump

HDR: Hot Dry Rock

HFR: Hot Fractured Rock

HFU: Heat Flow Unit

LCOR: Levelised Cost of Electricity

NE: Northeast

NEP: Net Generated Electric Power

NPV: Net Present Value

O&M: Operation and Maintenance

ORC: Organic Rankine Cycle

P: Project’s power capacity

PPA: Power Purchase Agreement

RE: Renewable Energy

RPS: Renewable Portfolio Standard

SE: Southeast

SW: Southwest

USD: United States of America Dollar

LIST OF SYMBOLS

~: Approximately

<: Less than

>: Greater than

±: Plus or minus

≤: Less than or equal to

≥: Greater than or equal to

α: Capacity factor

β: Correction factor for the cation geothermometer

$: United State of America Dollar

As: Arsenic

B: Boron

Ca: Calcium

Cd: Cadmium

CH_4: Methane

CO_2: Carbon dioxide

Cp: Specific heat capacity of water

Ct: Cash Flow in year t

Fe: Iron

H_2: Hydrogen

H_2S: Hydrogen sulphide

Hg: Mercury

K: Kelvin

K: Potassium

K: Thermal conductivity (W/mK)

K-Ar: Potassium-Argon

Li: Lithium

Mg: Magnesium

Mn: Manganese

N: Nigeria Naira

N_2: Nitrogen

Na: Sodium

Na-K-Ca: Sodium-Potassium-Calcium (cation)

NH_3: Ammonia

Pb: Lead

SiO_2: Silica

T: Temperature (°C or K)

T: Temperature gradient (°C/km)

Zn: Zinc

Q: Heat flow (mW/m^2)

LIST OF UNITS

cents/kWh: Cents per kilowatt hour (US cent)

^{o}C: Degrees Celsius

^{o}F: Degrees Fahrenheit

kg/s: Kilogramme per second

km: Kilometre

m: Meter

mg/L: Milligrams per Litre

mW/m^{2}: Milliwatts per square meter

kWh: Kilowatt hour

EJ: Exa Joule

MW: Megawatt

MWe: Megawatt electric

MWt: Megawatt thermal

g/kg: Grams per kilogram

GWh: Gigawatt hours

CHAPTER ONE

INTRODUCTION

1.0 BACKGROUND

Energy is fundamental to development in all facets of life: economical, technological, industrial, ecological, educational and standard of living (Alozie et al., 2011). Energy is a multifarious entity, which may transform into highly diverse aspects. Despite the abundance of energy resources in Nigeria, the country is in short supply of electrical power. Only about 40% of the nation's over 170 million has access to grid electricity and at the rural level, where about 70% of the population live, the availability of electricity drops to 15% of the domestic and industrial demands (http://odinakadotnet.wordpress.com/). Nigeria requires per capital power capacity of 1000 Watts per person or power generating/handling capacity of 170,000 MW as against the current capacity of 3,920 MW. This will put Nigeria slightly below South Africa with per capita power capacity of 1047 Watts, UK with per capita power capacity of 1266 Watts and above Brazil with per capita power capacity of 480 Watts, China with per capita power capacity of 260 Watts (http://odinakadotnet.wordpress.com/). Currently Nigeria has per capita power capacity of 28.57 Watts and this is grossly inadequate even for domestic consumption (http://odinakadotnet.wordpress.com/).

To achieve the goals of development, a strong energy sector is essential. However, in Nigeria energy supply has been epileptic in nature causing the socio-economic status of the country to be low. In a quest to realize a sustainable energy supply, Nigeria has turned to different sources of energy some of which are renewable. Currently a high proportion of the Nigeria's total energy output is generated from fossil fuels such as oil and coal.

Nigeria as a nation has started feeling the impact of climate change, especially those climate conditions caused by greenhouse gases produced by thermal power plants, manufacturing industries, oil spillages following the activities of oil prospecting firms as a result of the country's dependence on crude oil and gas.

Renewable energy (RE) has been identified as the only alternative of addressing these problems. RE is energy derived from an energy source that can regenerate itself through natural processes within a relatively short period; unlike fossil type resource that takes millions of years to form and which is non-regenerative. Such energy sources generally include solar, wind, biomass, hydropower, tidal wave, ocean thermal and geothermal (Chinyere, 2011). Amongst these renewable energy sources, geothermal offers a clean base load source of power; it also provides a consistent electricity production nearly 24 hours a day with little to or emissions.

Geothermal energy is present everywhere in Earth because temperature increases with depth. Existing technologies can extract heat from deep layers and utilize it to produce electricity. Geothermal energy is one of the few renewable energy resources that can provide continuous power with minimal visual and other environmental impacts. Geothermal systems have a small footprint of carbon dioxide emissions (Eyal et al., 2008).

Geothermal power development consists of successive development phases that aim to locate the resources (exploration), confirm the power generating capacity of the reservoir (confirmation) and build the power plant and associated structures (site development). Various kinds of parameters will influence the length, difficulty and materials required for these phases thereby affecting their cost (Hance, 2005).

Geothermal energy provides a robust, long-lasting option with attributes that would complement other important contributions from clean coal, nuclear, solar, wind, hydropower, and biomass (Jefferson et al, 2006). When compared to other energy sources (both renewable and non-renewable), geothermal energy has many benefits, including: extremely low emissions, low environmental impact, high capacity factor, base-load, low surface footprint, and low levelized energy cost (Kimball, 2010).

The geothermal energy is one of the sources of renewable energy available for exploitation in Nigeria. Some African countries like Kenya have already started harnessing this clean source of energy (Uyigue et al., 2009). Nigeria also has the potential to harness energy from this source of renewable energy. There are geothermal resource areas in Nigeria with the potential for power generation: Ikogosi warm spring in Ondo state, Rafin Reewa in Kaduna state and the Wikki warm spring in Bauchi state etc. Within sedimentary areas, high geothermal gradient trends are indentified in the Lagos sub-basin, the Okitiputa ridge and the Abakaliki Anticlinoruim. The deeper cretaceous and tertiary sequences of the Niger delta are pressured geothermal horizons (Babalola, 1984). Bauchi state, Plateau state, and the Adamawa areas, have experienced Cenozoic volcanism and magmatism. Geothermal gradients (rate of increasing temperature with respect to increasing depth in the earth’s interior) indicate that hot steam would be encountered at a depth of about 4,250 ft (1,300 m) in the Abakaliki area and of about 6,000 ft (1,800 m) in the Lagos and Auchi-Agbede areas (Babalola, 1984).

In spite of its immense potential, geothermal remains an underutilized resource and represents zero fraction of the Nigerian renewable energy portfolio. Exploiting the geothermal energy potential in Nigeria has been limited by several factors which include poor policy and regulations, financial, technological barriers, minimal public awareness and low investment (Federal ministry of Power and Steel, 2006). Improved access to resource data, more efficient drilling processes, increased understanding about the industry’s potential, and improving access to finance are driving expanding interest in the sector.

There is basically one primary prerequisite for any energy resource to be commercially exploitable, and that is for it to be economically competitive with other energy resources. Hence, the unit cost of producing and utilizing the energy resource is the most sought after for a viable energy project.

The levelised cost of power is a very useful tool for alternative power options. It is on the levelized cost that geothermal projects are evaluated for investment, approval and financing by prospective investors, governments, consumers or regulators and bankers or credit providers. The levelized cost is premised on the net present value of cash flows arising from a power project. Investors engage in power projects to increase their wealth. The application that considers tax and depreciation provides better basis for investment decision. The levelised cost of power is project specific and must therefore be established for each individual project.

1.1 STATEMENT OF THE PROBLEM

Geothermal technology is heat mining from sedimentary rock which has been successfully used around the world but is ignored in Nigeria despite our energy needs.

Consequently, this has led to undervaluing the long-term potential of geothermal energy available from large volumes of accessible sedimentary rock in Nigeria.

Geothermal power is sometimes misconstrued to be an expensive source of electricity. While it is true geothermal power plants require a significant amount of start-up capital and some government assistance in the earliest phases of exploration, the overall capital costs and operating costs of geothermal power are significantly lower than many other technologies. To ascertain its competitiveness and viability among other renewable energy sources, it levelised cost of power must be evaluated.

1.2 PRESENT RESEARCH WORK.

Considering the need for additional energy sources due to the growing Nigeria energy demand couple with the environmental effects of fossil fuels and the opportunity for utilisation of geothermal energy; it is clear this resource should be further studied and developed.

The present study examines the competitiveness of geothermal energy in contributing to Nigeria energy-mix by establishing the levelised cost of generating power using this abundant resource.

1.3 OBJECTIVE OF THE STUDY

The main aim of this research work is to establish the levelised cost of electricity generation by using “low temperature” geothermal resource from Rafin Reewa hot springs.

The cost of geothermal power is, obviously, dependent upon the technology employed in bringing geothermal energy to the surface and converting it to electricity. Consequently, the specific objectives of this research work are as follows:

i. To determine the reservoir temperature.

ii. To select energy conversion (EC) systems appropriate for Rafin Reewa hot spring needed to demonstrate feasibility of geothermal power plant at a commercial-scale.

iii. To determine the effects of mass flow rate as well as resource depth on the levelised cost of power generated using geofluid from Rafin Reewa hot spring.

iv. To estimate the Levelised Cost of power generation from Rafin Reewa geothermal resource.

1.4 SCOPE OF THE STUDY

It is recognized that the cost of geothermal power will depend upon the choice of variables associated with the subsurface and surface design of the production system, construction and operation of the power plant, and the economic model used in the cost analysis. In this study, primary attention will be focused on the levelised cost of power generated from low geothermal resources. Hence, it is beyond the scope of this study to project the cost of geothermal power using high grade geothermal resources. Also, the detailed design of the power plant is not considered in the course of this work.

CHAPTER TWO

LITERATURE REVIEW

2.0 INTRODUCTION

This section will describe the basic concept of geothermal energy and its conversion technologies. The section also x-rays the Nigeria geological setting as well as that of the study. The various geothermometers used to determine the temperature of the study area were reviewed. The economics and technological factors that influences the calculations of levelised cost of electricity (LCOE) will also be describes in this chapter, followed by an explanation of how the software used in the study work generate the LCOE.

2.1 GEOTHERMAL ENERGY

In a simple term, geothermal energy is “energy from the Earth”. Geothermal energy, the natural heat within the earth, arises from the ancient heat remaining in the Earth's core, from friction where continental plates slide beneath each other, and from the decay of radioactive elements that occur naturally in small amounts in all rocks (Antonia et al., 2012). The Earth’s core is molten with an average temperature of ~4000^{o}C, and this heat is continuously being lost at the surface to the atmosphere creating an increase in temperature with depth called the geothermal gradient. The transfer of heat from the core occurs primarily through solid rock by conduction and secondly through convection in areas with fluid interaction (i.e. water, magma, salt diapers) (Kimball, 2010). The Earth’s interior heat energy is estimated to be equivalent to 42 million megawatts (MW) of power, and is expected to remain so for billions of years to come, ensuring an inexhaustible supply of energy (Alyssa, 2007).

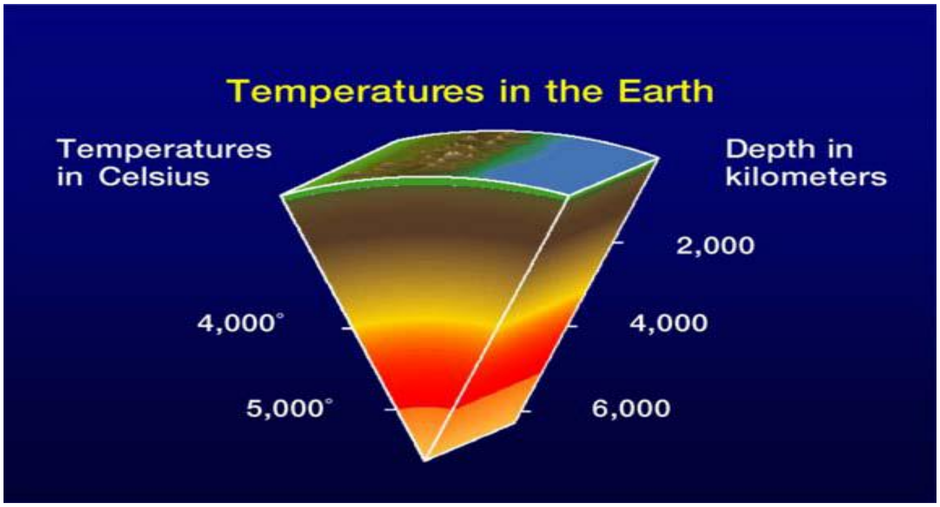


Figure 2.1: Earth’s Temperatures (Leslie & Kara 2009)

Heat energy is in all material on the earth, since the only matter without heat is at a temperature of absolute zero. The temperature of the earth's surface is controlled by the level of radiation from the sun, the filtering and insulating effects of the atmosphere, the local vegetation cover and the annual cycle of seasons (Jessop, 2008). The annual average temperature of the surface of the earth normally lies between -15^{O}C, in regions near the poles, and 30^{O}C, in equatorial regions. Apart from perturbations of up to 4^{O}C near the surface, due to rapid surface warming in the last 100 to 200 years, temperature in the solid earth increases with depth (Jessop, 2008).

Thermal energy in the earth is distributed between the constituent host rock and the natural fluid that is contained in its fractures and pores at temperatures above ambient levels. These fluids are mostly water with varying amounts of dissoblved salts; typically, in their natural *in situ* state, they are present as a liquid phase but sometimes may consist of a saturated, liquid-vapor mixture or superheated steam vapor phase. The amounts of hot rock and contained fluids are substantially larger and more widely distributed in comparison to hydrocarbon (oil and gas) fluids contained in sedimentary rock formations underlying the earth. (The NEED Project, 2011)

A geothermal system requires heat, permeability, and water. The heat from the earth's core continuously flows outward. Sometimes the heat, as magma, reaches the surface as lava, but it usually remains below the earth's crust, heating nearby rock and water, sometimes to levels as hot as 700°F. When water is heated by the earth's heat, hot water or steam can be trapped in permeable and porous rocks under a layer of impermeable rock and a geothermal reservoir can form. This hot geothermal water can manifest itself on the surface as hot springs or geysers, but most of it stays deep underground, trapped in cracks and porous rock. This natural collection of hot water is called a geothermal reservoir (Kimball, 2010).

Geologic processes, specifically plate tectonics, control the concentration of the earth's heat. Volcanic activity and the presence of magma near the surface occurs at tectonic plate boundaries and over mantle hot spots of volcanism which explains the concentration of geothermal energy production in regions such as the Pacific Ring of Fire as shown in figure 2.2 (Kimball, 2010).

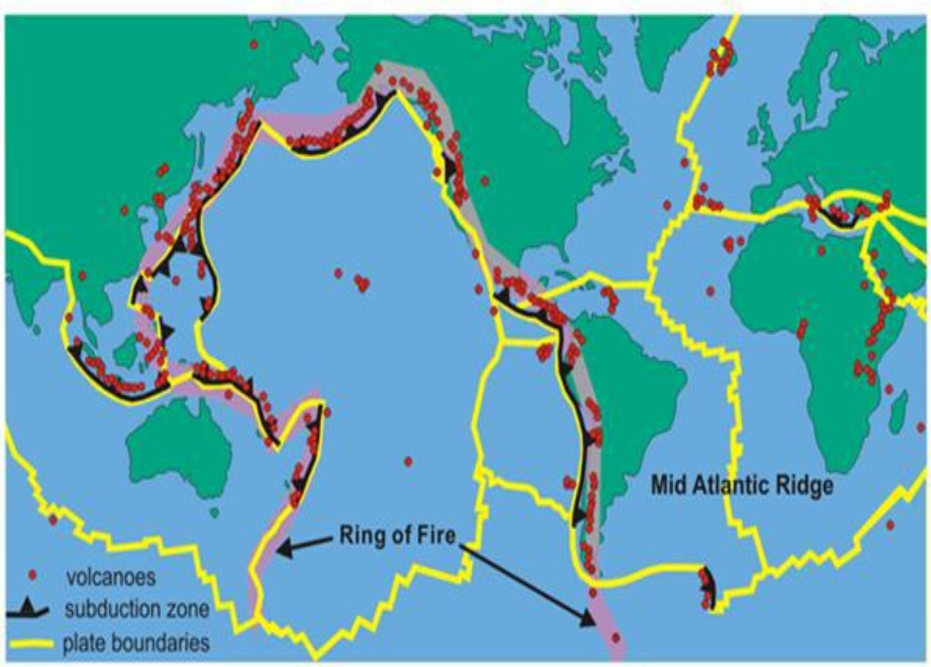


Figure 2.2: Volcanoes, subduction zones, and plate boundaries of the world showing the Ring of Fire (Kimball, 2010).

2.2 HEAT FLOW AND HEAT GENERATION

Heat flow is the factor that best describes the thermal state of the earth's crust at any location. Heat flow, when purely conductive, is an indicator of the nature of the crust as a whole and its radioactive content, of the depth to the mantle beneath it, and of the nature of mantle (Jessop, 2008).

Heat flow is the product of the geothermal gradient and the thermal conductivity of the rock. Thus geothermal gradient can vary within areas of uniform heat flow, depending inversely on the conductivity of the rock through which the heat must pass. Heat flow is measured by observing temperature gradients in boreholes and thermal conductivity of the rocks penetrated and by combining the two observations by the equation 2.1(Jessop, 2008) .

$$Q = -K \frac{dt}{dz} \qquad 2.1$$

Where is Q terrestrial flow, K is thermal conductivity, t is temperature, and dz is depth. The minus sign indicates that heat flows down the thermal gradient, or from the hotter zone to the cooler. Conductivity is not usually uniform in any rock, and may vary substantially between different rock layers, so the combination of temperature gradient and conductivity is not always a simple multiplication (Jessop, 2008).

For exploration into geothermal energy, the temperature and temperature gradient are more important than the heat flow. At any one site geothermal gradient may vary vertically as the conductivity of the rocks varies, or it may also be distorted by water flow (Jessop, 2008).

Heat generation is caused by the decay of uranium-238 and thorium-235. These two isotopes are found in amounts of a few parts per million in most rocks. There is also a contribution from potassium-40, which comprises only about 0.01% of natural potassium. The heat generated by these three isotopes is usually in the range zero to 10 $\mu W/m^3$ (microWatts per cubic metre). This seems like a small amount but, in a layer of thickness 10 km, it is sufficient to provide more than half of the total heat flow at the surface (Jessop, 2008).

The relation between heat flow and heat generation is of the form:

$$Q = Q_O + bA_O \qquad 2.2$$

where is Q surface heat flow, Q_o is “reduced” heat flow at the base of the layer of variable heat generation, A_o is the thickness of the layer of variable heat generation, and b is the heat generation observed at the surface, measured from surface samples or diamond drill cores (Jessop, 2008). This equation is satisfied by a layer of thickness of uniform heat generation, or by a deeper layer of exponentially declining heat generation given by:

$$A(z) = A_O \exp^{-(\frac{z}{b})} \qquad 2.3$$

Temperature deep in the crust below the depth of measurement may be calculated from the formula:

$$v = v_0 - Qz - \frac{Az^2}{2K} \qquad 2.4$$

2.3 GEOTHERMAL RESOURCE POTENTIAL

While the earth's subsurface heat is ubiquitous and essentially inexhaustible, the ability to produce geothermal energy requires unique circumstances. Firstly, there must be a concentration of the Earth's heat which most commonly exists in areas near cooling magma bodies. Secondly, this heat must be located at depths shallow enough (< 5 km but generally ~3 km with economic constraints) to be accessed by drilling. Finally, there must be a demand for geothermal energy such that the economic expenditures in developing the project can be justified (Kimball, 2010).

The total thermal energy contained in the earth is of the order of 12.6 x 10^{12} EJ and that of the crust of the order of 5.4 x 10^{9} EJ to the depths of up to 50 km (Goldstein et al., 2011). As mentioned above, the main sources of this energy are due to the heat flow from the earth's core and mantle, and that generated by the continuous decay of radioactive isotopes in the crust itself. Heat is transferred from the interior towards the surface, mostly by conduction, at an average of 65mW/m^2 on continents and 101mW/m^2 through the ocean floor. The result is a global terrestrial heat flow rate of around 1,400 EJ/yr. Continents cover 30% of the Earth's surface and their terrestrial heat flow has been estimated at 315 EJ/yr (Goldstein et al., 2011). Stored thermal energy down to 3 km depth on continents was estimated to be 42.67 x 10^6 EJ (Goldstein et al, 2011), consisting of 34.14 x 10^6 EJ (80%) from hot dry rocks or Engineered Geothermal System (EGS) resources and 8.53 x 10^6 EJ (20%) from hydrothermal resources. Within 10 km depth, Rowley (1982) estimated the continental stored heat to be 403 x 10^6 EJ with no distinction between hot dry rock and hydrothermal resources, and Tester et al. (2005) estimated it to be 110.4 x 10^6 EJ from hot dry rocks and only 0.14 x 10^6 EJ from hydrothermal resources (Goldstein et al., 2011). A linear interpolation between the EPRI (1978) values for 3 km depth and the values from Rowley (1982) results in 139.5 x 10^6 EJ down to 5 km depth, while linear interpolation between the EPRI (1978) values and those from Tester et al. (2005) only for EGS resources results in 55.9 x 10^6 EJ down to 5 km depth (Goldstein et al 2011). Based on these estimates, the theoretical potential is clearly not a limiting factor for global geothermal deployment. In practice geothermal plants can only utilize a portion of the stored thermal energy due to limitations in drilling technology and rock permeability. Commercial utilization to date has concentrated on areas in which geological conditions create convective hydrothermal reservoirs where drilling to depths up to 4 km can access fluids at temperatures of 180°C to more than 350°C (Goldstein et al 2011).

2.4 GEOTHERMAL RESERVOIRS

The areas of the earth can be classified into three groups: non-thermal areas with temperature gradient of 10°C to 40° C per km of depth, semi-thermal areas with temperature more than 70° C per km of depth and hyper-thermal areas with temperature gradient much higher than non-thermal areas. Among these three areas semi-thermal and hyper-thermal areas are suitable for power generation. Not all thermal areas are appropriate for utilization, due to impermeable rocks that prevent drilling and exploration of those resources. Thermal areas with permeable rocks that allow drilling and utilization of resources are called thermal field (US DOE, 2006). Four types of geothermal reservoirs are commonly found in thermal fields.

1**. Dry Steam**: These reservoirs contain dry steam with high temperature and relatively low pressure compared to other types of reservoirs. Temperature of these types of reservoirs is higher than 230°C. The degree of superheat is about 0°C to 50°C. This type of resource contains high amount of enthalpy and exergy. Also they are most suitable for power generation (US DOE, 2006).

2. **Wet Steam**: These reservoirs are made of wet steam that is mixture of steam and water, or steam that contains water droplets. These are the most common types of economically exploitable geothermal fields. The enthalpy and exergy of this type of geofluid is fairly high, which is suitable for flashing type of geothermal power plant (US DOE, 2006).

3. **Hot water**: This type of reservoirs contains hot water of temperature ranging between 70°C and 160°C. The enthalpy and exergy of this geofluid is low, where it is used for both electricity generation and direct heating. This type of reservoirs is found in most parts of the world. Binary power plant uses an organic or synthetic fluid to generate electricity from this low temperature geofluid. Geopressured reservoirs also fall in this type of reservoir. These reservoirs, having significantly higher pressure, are normally found much deeper in the ground (US DOE, 2006).

4. **Hot Dry Rock**: There are many geothermal zones containing high temperature but without the presence of any fluid and aquifer. To exploit this energy, wells can be drilled

to inject water or any suitable fluid to make an artificial geothermal reservoir. Similarly, a second well can be drilled to carry out the hot fluid to surface for utilization (US DOE, 2006).

2.4.1 Resource Variables

The uses of geothermal energy include a broad range of technology options from geothermal heat pumps, GHPs, which takes advantage of the more uniform temperature of the ground just a few feet below the surface, to electrical generation obtained from heat miles below the surface (US DOE, 2006). As a resource for today's electricity generation, the reservoirs being tapped are primarily found in tectonic areas where the characteristics of these resources allow for their ready use.

1. **Temperature Ranges*:*** Current technologies allow the use of geothermal resources (heat) greater than or equal to 100°C (212°F). Geothermal resources needed to generate electricity with existing technology typically require temperatures greater than 93°C (200°F). Recent developments in technology, though, indicate that successful electricity production from low-temperature resources is possible. Electricity production temperature ranges have dropped to include resources as low as 74°C (165°F) (US DOE, 2006)

2. **Drilling Depths*:*** The temperature ranges affect the necessary drilling depths, which in turn, determine the commercial viability of a given project. Access to geothermal resources suitable for electricity generation often requires drilling to depths of several kilometers. Geothermal-produced electricity has historically come from reservoirs drilled to a depth of 3 km (~1.9 miles). But current drilling technologies can reach depths greater than 10 km (~6.2 miles), gaining access to temperatures for geothermal electrical production at 74^{o}C and higher throughout the country ((US DOE, 2006).

3. **Permeability*:*** While temperature is usually the primary factor in determining the suitability of geothermal resources for electricity production, other important factors have to be taken into consideration. Key among these is the reservoir's connectivity (permeability). This refers to the ability of material, usually rock, to transmit fluid.

In order to establish geothermal as a major contributor to electricity generation, research has focused on ways to increase the number of viable reservoirs by enhancing their characteristics of permeability and fluid content (including the introduction of water where none is present). Recent geothermal assessments have begun to include reservoirs of low-permeability, expanding the definition of recoverable reserve as the promise of EGS technologies makes these resources exploitable (US DOE, 2006).

2.3.2 Types of Geothermal Resources

1. Hydrothermal

A hydrothermal system is defined as a subterranean geothermal reservoir that transfers heat energy upward by vertical circulation of fluids driven by differences in fluid density that correspond to differences in temperature (Bruce and Gerald, 2006).

The carrier fluid of a hydrothermal system can be either water or vapour, the latter however are relatively rare and only found in geothermal reservoirs of very high temperatures (250 to 320^{o}C), well in excess of the boiling point of water (Goldstein et al., 2011). The hot water or steam is referred to as a hydrothermal resource. Such resources are used today for the commercial production of geothermal power. They benefit from continuous recharge of energy as heat flows into the reservoir from greater depths.

2. Engineered Geothermal Systems

Engineered or Enhanced Geothermal Systems (EGS) have been heralded as the future of geothermal energy (Goldstein et al., 2011). Terminology used to describe these systems has evolved from Hot Dry Rock (HDR), Hot Fractured Rock (HFR), and more recently, Engineered or Enhanced Geothermal Systems (EGS). EGS more accurately describes systems in which water is present in the formation, but other elements such as permeability are absent. In principle, EGS resources extend the geothermal resource base to the entire world. Economically favourable EGS projects are located in areas that are easily accessible, with elevated heat flow and sufficient water resources for project operations (Goldstein et al., 2011). The resource temperature can be enhanced by drilling to greater depths (>5 km). Hydraulic fracturing of the reservoir or chemical stimulation (in carbonate formations) can enhance permeability. And, a carrier fluid (water) can be injected into the reservoir to carry the heat to surface. The enhancement of these factors allow for wider-scale application of geothermal technology (Kimball, 2010).

In general, EGS involves pumping high-pressure water down an injection well to stimulate a fracture network, creating artificial permeability. While traveling through the fracture network, the water captures heat from the surrounding formation and is pumped back to surface where the heat is extracted and converted to energy (Kimball, 2010).

3. Geopressured Resources

The geopressured resource consists of deeply buried reservoirs of hot brine, under abnormally high pressure, that contain dissolved methane. The resource contains three forms of energy: methane, heat, and hydraulic pressure. (Bruce and Gerald, 2006). Geopressured deposits are found in conjunction with oil and gas reserves. They are limited in availability and economical for electricity production only in combination with existing fossil fuel extraction infrastructure (EPRI, 2010).

Geopressured fluids are located in sedimentary basins at a depth of ~4 to 6 km where hot water has been trapped at the time of deposition and is now at pressures greater than hydrostatic. These fields could potentially produce energy from the pressurized hot water, hydraulic energy from the high pressure, and energy from associated methane gas (Barbier, 1997).

4. Co-Produced Geothermal Fluids

Sometimes referred to as the ‘produced water cut’ or ‘produced water’ from oil and gas wells, co-produced geothermal fluids are hot and are often found in water flood fields in a number of oil and gas production regions. This water is typically considered a nuisance to the oil and gas industry (and industry is accountable for proper disposal), but could be used to produce electricity for internal use or sale to the grid. Like geopressured resources, co-produced geothermal resources can deliver near-term energy savings, diminish greenhouse gas emissions, and extend the economical use of an oil or gas field. New low-temperature electric generation technology may greatly expand the geothermal resources that can be developed economically today. (Bruce and Gerald, 2006).

5 Other Resources: Magma and Off-shore

The high temperature of magma makes it an attractive target for geothermal power generation. The challenges are: identifying the location of magma bodies within the crust more accurately to allow for better drill targeting, developing drilling equipment able to operate at extreme temperatures (currently limited to ~250^{o}C), and providing a heat extraction technology that justifies the significant development costs (Barbier, 1997). The Iceland Deep Drilling Project drilled into rhyolitic magma at a depth of 2,104 m

(Fridleifsson, et al., 2001) and dacitic magma but geothermal production was not pursued due to issues of well control.

Hydrothermal vents located along oceanic ridges emit temperatures of about 300^{O}C. If only 1% of known hydrothermal vents were exploited using a binary cycle power plant housed inside a submarine it is estimated that 130,000 MW of power could be generated (Goldstein et al 2011). However, hydrothermal vents are located 100s of kilometers off-shore where transmission development would be extremely costly (Kimba, 2010).

Deep-sea geothermal resources accessed by drilling have also been postulated as a future geothermal resource. Shnell (2009) suggests power could be generated at the ocean floor by a self-contained, submersible, remote-controlled, geothermal powered electric generating station.

In petroleum wells that have been abandoned, or that have a large water fraction, there is the opportunity to generate power from the hot water. Additional drilling would not be required for co-production, however because of the smaller diameter and lower flow rates of typical oil and gas wells, the heat losses from the bottom to the top of the well and in the un-insulated surface equipment are un-suitable for geothermal production in many cases. This technology is being implemented in Swan Hills, Alberta where 75^{o}C water from mature oil wells will be used to generate geothermal electricity (Kimball, 2010).

Geothermal resources are also classified according to their fluid temperature, Table 1 below shows how these resources are classified by various researchers.

Table 2.1. Classification of the geothermal resources depending on temperature [°C] (Alessandro and Vaccaro, 2012).

	Muffler & Caltadi	***Hochstein***	***Benderitter & Cormy***	***Nicholson***	***Axelsson & Guulaugsson***

Low enthalpy	<90^{o}C	<125^{o}C	<100^{o}C	≤ 100^{o}C	≤ 190^{o}C
Medium enthalpy	90 – 150^{o}C	125 – 225^{o}C	100 - 200^{o}C	-	-
High enthalpy	>150^{o}C	>225^{o}C	>200^{o}C	>150^{o}C	>190^{o}C

2.5 APPLICATIONS OF GEOTHERMAL RESOURCES

The application of a geothermal resource is mainly a function of temperature as shown in figure 3; however site-specific factors (climate, economics, and technology) can shift the temperature boundaries of each type in either direction. Cascaded geothermal resources that utilize geothermal fluids for multiple applications are becoming more common and greatly enhance the economics of a project (Kimball, 2010).

Hot water from geothermal resources is used directly to provide heat for buildings, crop and lumber drying, industrial process heat needs, aquaculture, horticulture, ice melting on sidewalks, roads, and bridges, and district heating systems. (Bruce and Gerald, 2006). In direct use applications, a well (or series of wells) brings hot water to the surface; a mechanical system— piping, heat exchanger, pumps, and controls—delivers the heat to the space or process. Often, direct use applications use geothermal fluids not hot enough for electricity generation. To improve efficiencies, used water from geothermal power plants can be ‘cascaded’ down for lower temperature uses, such as in greenhouses or aquaculture. Flowers, vegetables, and various fish species and alligators are examples of products from greenhouse and aquaculture systems. (Bruce and Gerald, 2006).

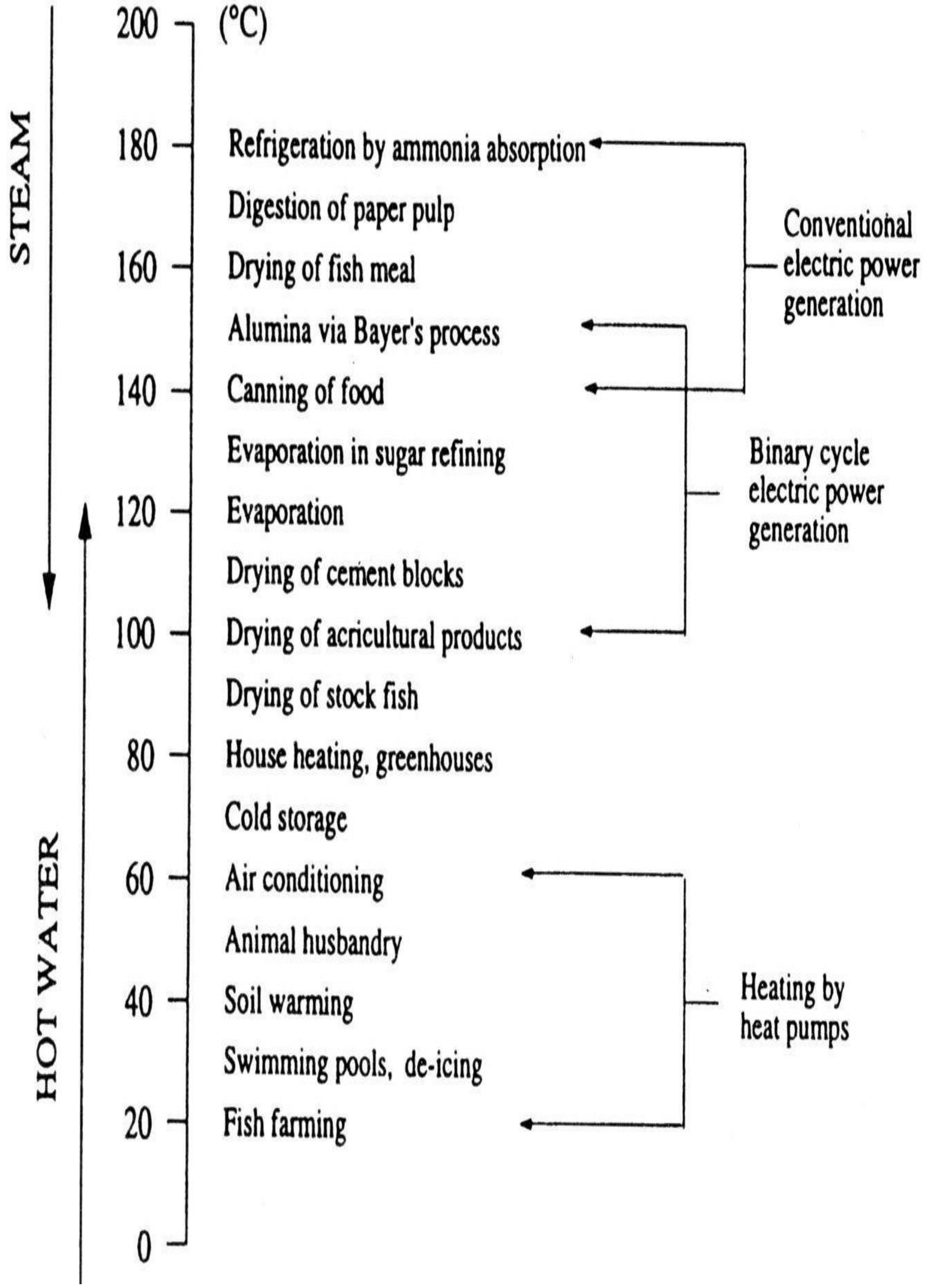


Figure 2.3: Lindal diagram depicting the use of geothermal water and steam in relation to temperature (ESMAP, 2012)

2.5 ENVIRONMENTAL IMPACTS OF GEOTHERMAL ENERGY

The environmental impacts of geothermal energy are minimal compared to other sources, particularly fossil fuel types. The main environmental effects occur from the discharge of gas and water that contains high concentrations of elements (metals and salts) leading to chemical pollution and possible biological effects. Less common impacts include physical effects due to water extraction, thermal changes, and noise.

Both natural geothermal features (e.g. fumaroles) and geothermal wells emit CO_2, H_2S, NH_3, N_2, H_2, and CH_4 gases that are generally found at concentrations of 3 to 47 g/kg as non-condensable gases in steam (Barbier, 1997). These gases may be emitted to the atmosphere in flash or dry steam power plants.

Geothermal waters often contain high concentrations of elements and are sometimes referred to as brines. The composition of fluids varies significantly depending on the geologic and meteorological setting; however common pollutants in geothermal liquids are H_2S, B, As, Hg, Pb, Cd, Fe, Zn, and Mn (Kimball, 2010).

Using binary cycle power plants reduces the amount of chemical pollution from geothermal power by eliminating the venting of gases into the atmosphere as well as surface discharge of liquids (Kimball, 2010).

In comparison to other energy sources, the emissions of CO_2 from geothermal power plants are minute (Table 2.2) so this choice of energy supply is a leading alternative to assist in addressing Climate Change issues.

Table 2.2: CO_2 emissions by energy source (Reed & Renner, 1995)

Energy Source	CO_2 emissions (kg/MWh)
Coal	990
Petroleum	839
Natural Gas	540
Geothermal	0.48

Withdrawing fluids from a geothermal reservoir at rates higher than natural recharge, may cause physical effects such as changes in surface manifestations such as hot springs, lowering of the groundwater table, land subsidence, and induced seismicity (Kimball, 2010). While the fluid is typically recycled back into the resource, drawdown of the water table is likely because of volume changes in the fluid after heat extraction.

2.7 GEOTHERMAL ENERGY CONVERSION TECHNOLOGIES.

There are several options for utilizing the thermal energy produced from geothermal systems. The most common is base-load electric power generation, followed by direct use in process and space heating applications. In addition, combined heat and power in cogeneration and hybrid systems, and as a heat source and sink for heat pump applications, are options that offer improved energy savings.

For base-load electric power generation, there are many different ways to produce power from geothermal energy; in general this may be accomplished by a dry steam, flash steam or binary plant.

2.7.1 Direct-Steam Power Plants

Direct-steam power plants utilize naturally occurring resources of pressurized steam, which are quite rare. In a dry steam plant, the temperature of the steam is over 235°C and is directly fed into the turbine to produce electricity as shown in figure 2.4. (EPRI, 2010)

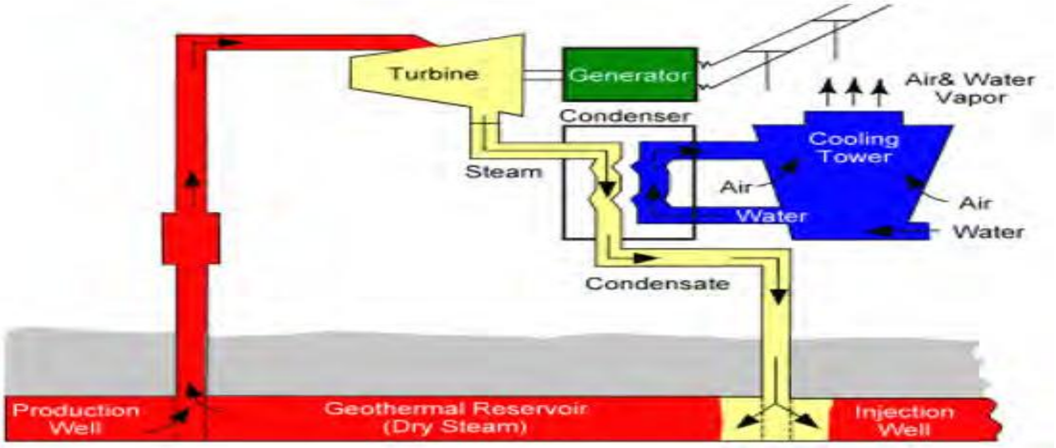


Figure 2.4: Schematic Direct Steam Power Plant (source: EPRI Technology Innovation White Paper 2010)

2.7.2 Flash Steam Plant

In a flash steam plant, the temperature is above 180 °C. The geothermal fluid is saturated liquid which is first flashed to a lower pressure and then part of the working fluid is converted to steam which is then fed into the turbine. (EPRI, 2010) The working fluid may be flashed multiple times.

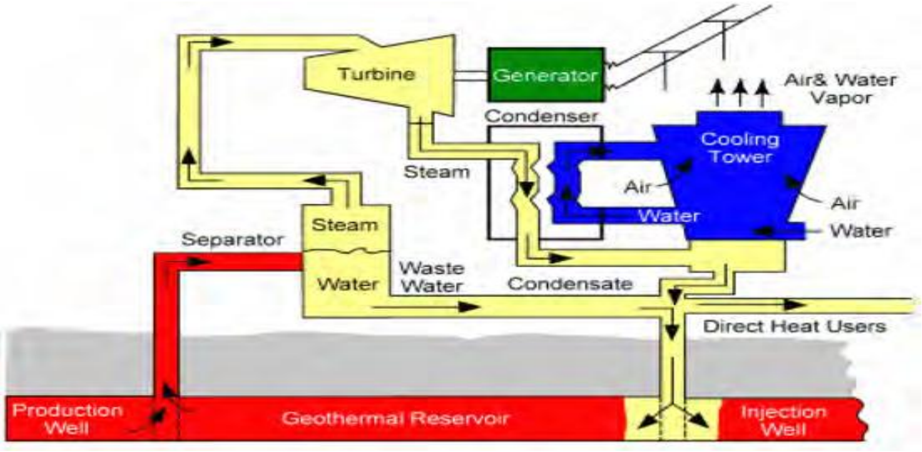


Figure 2.5: Schematic of Flash Steam Power Plant (Source: EPRI Technology Innovation White Paper 2010)

As shown in Figure 2.5, pressurized fluid is partially vaporized inside one or more flash tanks, which are large vessels allowing a portion of the liquid to expand to steam. Steam is piped from the top of a tank into the turbine, while the unflashed liquid, also known as brine, is drawn off from the bottom before being combined with condensate and reinjected underground.

2.7.3 Binary Power Plant

A binary plant is used when the temperature of geothermal fluid is between 100-180°C. The geothermal fluid is never fed into the turbine in a binary system. (EPRI, 2010) In contrast, it is used to heat up and evaporate a secondary working fluid, usually a refrigerant, which in turn is expanded into a turbine. Figure 2.6 gives the schematic diagram of Binary-Cycle Power Plant.

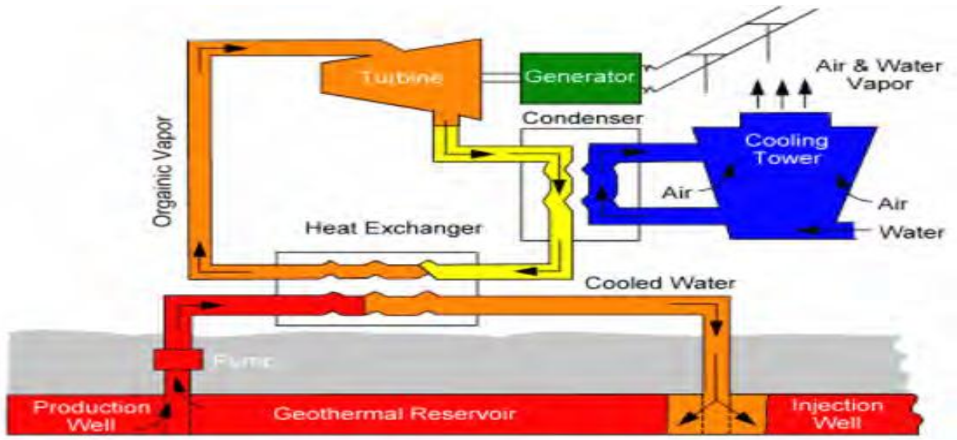
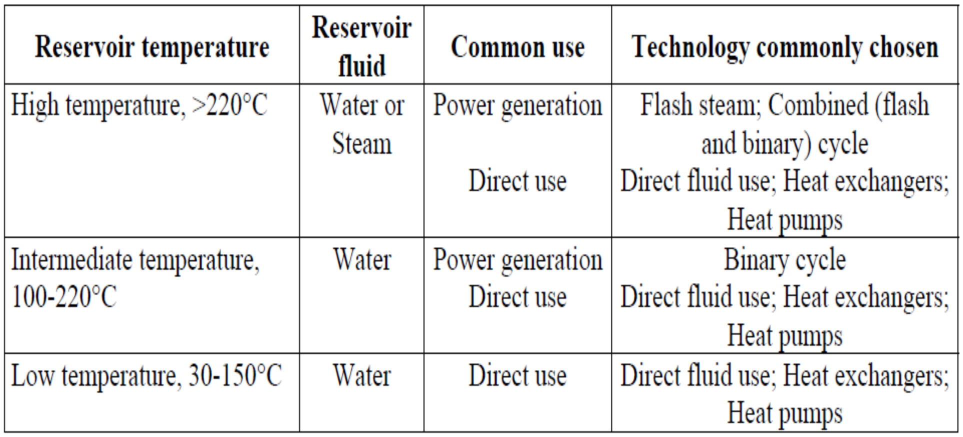


Figure 2.6: Schematic of Binary-Cycle Power Plant (source: EPRI Technology Innovation White Paper 2010)

Table 2.3: Basic Technology Commonly Used for Geothermal Energy (Mburu, 2009)



Reservoir temperature	Reservoir fluid	Common use	Technology commonly chosen
High temperature, >220°C	Water or Steam	Power generation Direct use	Flash steam; Combined (flash and binary) cycle Direct fluid use; Heat exchangers; Heat pumps
Intermediate temperature, 100-220°C	Water	Power generation Direct use	Binary cycle Direct fluid use; Heat exchangers; Heat pumps
Low temperature, 30-150°C	Water	Direct use	Direct fluid use; Heat exchangers; Heat pumps

2.8 LOW-TEMPERATURE GEOTHERMAL TECHNOLOGY AND BINARY CYCLE POWER PLANTS

Medium to low temperature geothermal resources are largely diffused, so that they have become very attractive for electrical power production in the last years (Alessandro and Vaccaro, 2012).

By selecting the appropriate working fluid, the binary system can be designed to operate with inlet temperatures in the range 85 to 170 ºC. The upper temperature limit is restricted by the thermal stability of the organic binary fluids (working fluid). The lower temperature limit is primarily restricted by practical and economic considerations, as the required heat exchanger size for a given capacity becomes impractical (Caixia, 2008).

Binary cycle geothermal power plants are close in thermodynamic principle to conventional fossil or nuclear plants in that the working fluid is in a closed cycle. The cycle is developed for medium to low-temperature geothermal resources. Generally there are two main types of binary cycles, the Organic Rankine Cycle (ORC) and the Kalina Cycle (Nazif, 2011). In binary cycle power plant, the working fluid is contained completely within pipes, heat exchangers and the turbine, so that it never comes in chemical or physical contact with the environment. The power cycles consists of preheater, an evaporator, a set of controls valves, a turbine-generator set, a condenser and a feed pump (Nazif, 2011). The cycle can be either water or air cooling system depending on the site condition.

In a binary cycle geothermal power, the thermal energy of the geofluid is transferred via a heat exchanger to a secondary working fluid for use in a fairly conventional Rankine cycle (Nazif, 2011). A secondary working fluid that has a low boiling point and a high vapor pressure at low temperatures when compared to steam is the fluid that the binary system utilizes. This secondary fluid is operated through a conventional Rankine cycle (Maghiar and Antal, 2001). Temperatures in the range of 85 to 180°C (185 to 348°F) are the values at which the binary system can be designed to operate through the selection of appropriate working fluid. The upper temperature limit is restricted by the thermal stability of the organic binary fluids. The lower temperature limit is restricted by practical and economic considerations, as the heat exchanger size for a given capacity becomes impractical and the parasitic loads (from well and circulating pumps for example) require a large percentage of the output.

If the geothermal fluid temperature is below 180°C, the ORC system becomes more economical than flash cycles, commonly using hydrocarbons as the appropriate working fluid. Meanwhile, a mixture of water-ammonia is used as the working fluid in a Kalina cycle, normally for geothermal fluid temperatures of 150-160°C (Nazif, 2011).

A binary system has two cycles: first is the heat exchange cycle of geothermal fluid where the working fluid absorbs heat from the geothermal fluid via the heat exchanger; second is the ORC working cycle as seen in Figure 6 above. These two cycles are separated so only the heat transfer takes place through the heat exchangers; normally, shell-and-tube heat exchangers are applied. (Nazif, 2011)

For a power plant that uses binary cycle, it has a number of advantages over other geothermal power cycles. These advantages are:

1. Maintaining the water under pressure prevents the escape of gases and salt precipitation, thus reducing if not completely eliminating the problem of production well plugging;
2. The temperature of the geothermal water at the heat exchanger inlet can be maintained at a much higher value than is in the case when steam is flashed before reaching the power plant inlet;
3. A gas removal system is not required;
4. Since oxygen cannot enter the system, one of the potential causes of corrosion is thus eliminated;
5. Water pipes from the well to the power plant are smaller in diameter than steam pipes would be in a flashing plant design. This reduces the cost of the gathering system;
6. The thermal efficiency of the pressurized water power plant is higher than the flashed steam plant. This reduces the number of geothermal wells required for given size power plant (Ashok 1974).

The size of the power plant (kilowatt (kW) rating) refers to the net generating capacity of the plant and is dependent on the amount of thermal energy available in a given location (Fitzgerald, 2003). Net generating capacity for binary cycle power plants can be calculated using resource temperature and flow rate.

Attainable flow rates within a reservoir depend on the resource productivity level. Resource productivity is a function of the underground matrix at a given location and controls the amount of fluid (flow rate) that can be used in the heat transfer process. Resource productivity is driven by the ease with which water can move through the underground matrix and is controlled by hydraulic parameters such as permeability, hydraulic conductivity, and hydraulic gradient (Fitzgerald, 2003).

Resource productivity also influences the well diameter selected during design. Well diameters are sized to provide the maximum amount of geothermal fluid (flow rate) to the generating equipment within the limits of the resource productivity level. For binary power plants, where pumps are used to move the geothermal fluid from the resource to the surface, pump type also controls the flow rate. According to Fitzgerald (2003), well diameters between 75mm and 300mm (inside diameter) submersible pumps provide the best attainable flow rates.

2.9 GEOTHERMOMETRY

Geothermal fluids have diverse chemistries, which largely reflect their geological setting. Many of these chemical differences largely depend on the source of recharge waters and the contribution of gases from magmatic or metamorphic sources. The constituents may be solutes gases or isotopes (Karingithi, 2009).

Most geothermometers are based on specific chemical equilibrium reactions. Geothermometers can be applied to both natural spring discharges and well fluids. They provide valuable insight as to the nature of the system (Karingithi, 2009).

Chemical and isotope geothermometers probably constitute the most important geochemical tool for the exploration and development of geothermal resources. They are also very important during exploitation in monitoring the response of geothermal reservoirs to the production load (Karingithi, 2009).

Geothermometers take advantage of specific mineral –solute reactions, which are slow to re-equilibrate at cooler temperatures, especially under conditions where the fluid is effectively separated from the minerals which controlled the equilibria. The result is that hot equilibrium temperature is“frozen in” to the fluid as reflected by solute concentration or solute ratios (Karingithi, 2009).

Geothermal reservoir temperatures can be determined from in situ measurements in exploration and production wells where available. In order to characterize the thermal state of a geothermal reservoir when in situ temperature measurements are not available, chemical geothermometers can be applied as proxies (Williams, et al., 2008).

The calculation of chemical geothermometers rests on the assumption that some relationship between chemical or isotopic constituents in the water was established at higher temperatures and this relationship has persisted when the water cools as it flows to the surface. The calculation of subsurface temperatures from chemical analyses of water and steam collected at hot springs, fumaroles, geysers, and shallow water wells (Williams, et al., 2008) is a standard tool of geothermal exploration and fills the need to estimate the subsurface temperature of a geothermal prospect area before any deep wells are drilled.

Chemical analyses of spring and well waters may be used to estimate subsurface temperatures by applying chemical geothermometers. These thermometers assumed that the chemical composition of the water reflects the last temperature of equilibration between the thermal fluid with the surrounding rock (Michael et al., 1980). This temperature is generally assigned to represent the reservoir temperature of the thermal system.

Note that some geothermometers are empirical (e.g. Na-K-Ca, D’Amore and Panichi (1980) gas geothermometer), whereas others are based on thermodynamic properties (e.g. Na-K, K-Mg). As the factors controlling empirical geothermometers are not completely known, theoretical geothermometers may in some cases be more reliable (Karingithi, 2009).

Geothermometers have been classified into three groups:

1. Water or solute geothermometers;
2. Steam or gas geothermometers;
3. Isotope geothermometers;

2.9.1 Water Geothermometers

The most important water geothermometers are silica (quartz and chalcedony), Na/K ratio and Na-K-Ca geothermometers. Others are based on cation ratio and any uncharged aqueous species as long as equilibrium prevails (Karingithi, 2009). A temperature equation for a geothermometer is a temperature equation for a specific equilibrium constant referring to a specific mineral-solution reaction.

2.9.1.1 Silica Geothermometers

Silica geothermometer is based on experimentally determined variations in the solubility of different silica species in water, as a function of temperature and pressure (Karingithi, 2009). The silica geothermometer is one of the most widely applied and reliable geothermometers because it is little affected by precipitation, base-exchange, salinity, and pressure (Michael et al., 1980).

However, interpretation of the silica geothermometer requires an assumption of the silica phase that controls the dissolved silica content of the thermal water, i.e., amorphous (chalcedony) or crystalline (quartz) (Michael et al., 1980). The quartz and the Chalcedony geothermometers are given by the equations 2.5 and 2.6 respectively.

$$Quartz, (T^0C) = \frac{1309}{5.19 - logS} - 273.14 \qquad 2.5$$

$$Chalcedony, (T^oC) = \frac{1112}{4.91 - logS} - 273.15 \qquad 2.6$$

2.9.1.2 Na-K Geothermometer

Waters from high temperature reservoirs (180°C) of chloride waters are suitable for this geothermometer. For lower temperature reservoirs where fluids have long residence times, the Na-K geothermometer may in some cases be applicable (Karingithi, 2009).

Na-K geothermometer may give indications regarding the deeper part of the system in comparison to the silica – quartz geothermometer, depending on the system's hydrology. A slow rising fluid can, however, re-equilibrate at shallower levels and cooler temperatures (Karingithi, 2009).

The Na-K geothermometer gives poor results below 100°C. It is also unsuitable if the waters contain high concentration of calcium (Ca) as is the case for springs depositing travertine. The following general rules apply;

1) Use for waters indicating reservoir temperatures >100

2) Use if the water contain low Ca; i.e. the value of (log ($Ca^{1/2}$/Na) + 2.06) is negative

3) Use for water near neutral pH chloride waters.

Na-K Geothermometer Equations are:

i. Fournier (1979):

$$T^{O}C = \frac{1217}{1.438 + \log\left(\frac{Na}{K}\right)} - 273.15 \qquad 2.7$$

ii. Arnorsson et al (1983):

$$T^{O}C = \frac{1319}{1.470 + \log\left(\frac{Na}{K}\right)} - 273.15 \qquad 2.8$$

iii. Giggenbach et al (1988):

$$T^{O}C = \frac{1390}{1.750 + \log\left(\frac{Na}{K}\right)} - 273.15 \qquad 2.9$$

iv. Arnorsson et al (1998):

$$T^{O}C = 733.6 - 770.55Y + 387.189Y^2 - 95.753Y^3 + 9.544Y^4 \qquad 2.10$$

Where Y designates the logarithm of the ratio of Na/K

Fournier's geothermometer is an empirical calibration whereas that of Giggenbach (1988) is based on thermodynamic data on low albite and K feldspar presented by Bowers et al. (1984). Hence, it is considered that their data are less reliable than the calorimetric data selected by Arnorsson et al (1998) which are therefore preferred.

2.9.1.3 Na-K-Ca Geothermometer

The Na-K-Ca geothermometer was developed for application to waters with high concentrations of calcium. This is an empirical geothermometer and theoretical constraints include equilibrium between Na-K feldspars plus conversion of calcium alumino silicate minerals (e.g. Plagioclase) to calcite. The main advantage of the Na-K-Ca geothermometer in comparison with the quartz geothermometer, and especially the

Na/K geothermometer, is that it does not give high and misleading results for cold and slightly thermal, non-equilibrated waters (Karingithi, 2009).

Na-K-Ca Geothermometer Equation:

$$T^{O}C = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \log\left(\frac{Ca^{0.5}}{Na}\right) + 2.24} - 273.15 \qquad 2.11$$

The following considerations apply in application of this geothermometer:

1) Calculate {log ($Ca^{1/2}$/Na) + 2.06}; if its value is positive, the use β = 4/3 in the formula in determining the temperature. If that calculated temperature is <100°C, then this temperature is appropriate.

2) If the β=4/3 calculated temperature is >100°C, or {log ($Ca^{1/2}$/Na) + 2.06} is negative, then use β=1/3 to calculate the temperature (Karingithi, 2009).

2.10 HOT SPRINGS

Hot or thermal springs, are defined as springs where the temperature of water lies significantly above the mean annual air temperature of the region. A hot spring or a hydrothermal spring is a place where warm or hot groundwater issues from the earth on a regular basis for at least a predictable part of the year, and is significantly above the ambient ground temperature (which is usually around 32–54 °C in the Nigerian Benue trough). The water issuing from a hot spring is heated by geothermal heat, essentially heat from the earth's interior. In general, the temperature of rocks within the Earth increases with depth. The rate of temperature increase with depth is known as the “geothermal gradient”. If water percolates deeply enough into the crust, it will be heated as it comes into contact with hot rocks. The water from hot springs in non-volcanic areas is heated in this manner. In volcanic zones, water may be heated by coming into contact with magma (molten rock). The high temperature gradient near magma may cause water to be heated enough that it boils or becomes superheated. If the water becomes so hot that it builds steam pressure and erupts in a jet above the surface of the earth, it is called a geyser; if the water only reaches the surface in the form of steam, it is called a fumarole; and if the water is mixed with mud and clay, it is called a mud pot. Warm springs are sometimes the result of hot and cold springs mixing but may also occur outside of geothermal areas.

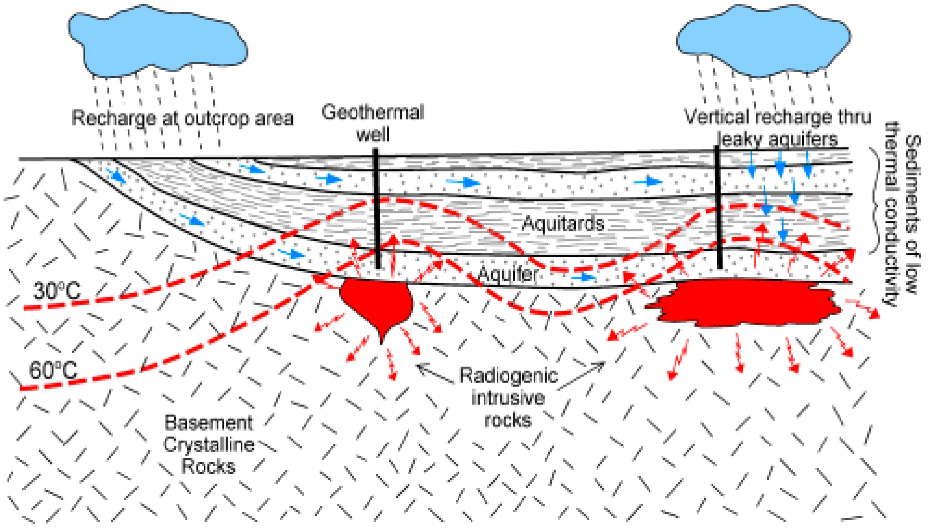


Figure 2.7: Radiogenic Geothermal System (Lund, 2007)

2.10.1 Hot Springs Characteristics

Hot springs do provide a surface indication of anomalous heat flow that may be linked to a high-temperature geothermal system at depth and hot springs are commonly used in geothermal exploration (Kimball, 2010). Active hot springs and geysers are dramatic examples of hydrothermal processes at work. There are thousands of active hot springs around the world (Kruse, 1997), occurring predominantly in association with volcanically active areas along spreading mid-oceanic ridges, convergent plate margins (subduction zones) and intraplate melting anomalies (Kruse, 1997). Because these areas exhibit high variability in rock permeability, composition, structure, and available surface water, a wide range of surface materials and their related morphologic features occur.

Hot springs are merely surface manifestations of much larger subsurface hydrothermal systems. Critical geologic questions which may need to be answered before using water from a hot spring or hydrothermal system include: the real extent of the system; the maximum temperature of the system; hydrologic information about the system; geochemistry of the water; and the heat source for the system (Henry, 1985).

Employed in geothermal exploration, hot springs provide a useful glimpse of the buried reservoir of hot water and/or steam.

Thermal springs may form siliceous sinter, travertine, or other types of deposits at the surface, or they may not form any significant surface deposit at all (Garba et al., 2012). Active hot springs systems (and by inference, inactive and fossil systems), can simplistically be genetically divided into three general types based on water chemistry and the types of mineral deposits formed. These are 1) alkaline, siliceous-sinter-dominated systems, 2) travertine carbonate dominated systems, and 3) acid sulfate systems (Garba et al., 2012). Mixed types are also common within individual hot springs systems with both sinter-travertine and alkaline-sulfate transitional types indicating subsurface mixtures of the two types of water.

The siliceous sinters commonly associated with the alkaline systems are initially deposited as opaline silica and subsequently converted to chalcedony at depth (Garba et al., 2012.). Other alteration minerals that may form at depth in hot springs systems include kaolinite, alunite, adularia, montmorillonite, illite, sericite, chlorite, pyrite, calcite, zeolites, and sodic plagioclase, as well as Ag, Au, Hg, Mn, W, Sb, Pb, Zn, Cu, As, Sn, and Fe ore minerals (Garba et al., 2012).

The travertine areas are the result of carbon dioxide-rich waters dissolving carbonate rocks at depth and then depositing calcium carbonate as pressure and CO_2 decrease at the surface (Garba et al., 2012). The presence of travertine-type deposits depends on spatial relationships to limestones, however, these deposits may also occur in non-limestone areas as calcium is leached from andesites and basalts. Acid-sulfate systems are dominated by sulfate minerals such as alunite and free sulfuric acid as well as clay minerals like kaolinite and are commonly associated with ridge and slope areas with poor surface water supply (Garba et al., 2012). Only small volumes of siliceous sinter are deposited. These areas are typically barren ground characterized by low flow, abundances of sulfurous gases, and silt/mud-laden waters which often form mudpots and mud volcanoes. Waters from these areas are low in chloride and silica, and high in sulfates. Sulfate areas often occur on the fringes of the basins, perhaps representing gas-dominated systems (Garba et al., 2012). Epithermal precious metal ore deposits appear to be the fossil equivalents of high-temperature geothermal systems (Garba et al., 2012). Convincing criteria supporting this idea include: 1) ore components (Au, Ag, and other metals) have been found in active hydrothermal systems and these systems are known to transport metals (Garba et al., 2012) 2) ore components are often concentrated in unconsolidated Quaternary rocks from which hot springs emerge, 3) there are significant spatial associations between mineralized veins and hot springs, 4) some deposits are related to the present topographic surface, 5) deep alteration of hot springs that have been drilled shows zoning with depth similar to zones observed in epithermal deposits.

Table 2.4: Some Noticeable Hot Springs in Nigeria

Hot spring	Local Government	State	Fluid Temperature (^oC)
Akiri	Awe	Nasarawa	54.0
Ruwan Zafi	Lamurde	Adamawa	54.0
Ikogosi	Ekiti West	Ekiti	37.0
Rafin Reewa	Lere	Kaduna	42.0
Wikki	Alkaleri	Bauchi	32.0

2.10.2 Hot Springs Flow Rates

Hot springs range in flow rate from the tiniest "seeps" to veritable rivers of hot water. Sometimes there is enough pressure that the water shoots upward in a geyser, or fountain (www.self.gutenberg.org).

Spring discharge, or resurgence, is determined by the spring's recharge basin. Factors that affect the recharge include the size of the area in which groundwater is captured, the amount of precipitation, the size of capture points, and the size of the spring outlet. Water may leak into the underground system from many sources including permeable earth, sinkholes, and losing streams. In some cases entire creeks seemingly disappear as the water sinks into the ground via the stream bed (en.mwikipedia.org).

2.10.3 Classification of Hot Springs

Springs are often classified by the volume of the water they discharge. The largest springs are called "first-magnitude," defined as springs that discharge water at a rate of at least 2800 liters (2.8 m^3) of water per second (en.mwikipedia.org). The scale for spring flow is shown is table 2.5.

Table 2.5: classification of hot springs according to flow rates (source: en.mwikipedia.org).

Magnitude	Flow rate(liter/sec)	Flow rate (kg/sec)
1st magnitude	2800	2800
2nd magnitude	280 to 2800	280 to 2800
3rd magnitude	28 to 280	28 to 280
4th magnitude	6.3 to 28	6.3 to 28
5th magnitude	0.63 to 6.3	0.63 to 6.3
6th magnitude	63×10^{-3} to 630×10^{-3}	63×10^{-3} to 630×10^{-3}
7th magnitude	8×10^{-3} to 63×10^{-3}	8×10^{-3} to 63×10^{-3}
8th magnitude	8×10^{-3}	8×10^{-3}

It should be noted that there are many more very high flow non-thermal springs than geothermal springs. For example, there are 33 recognized "magnitude one springs" (having a flow in excess of 2,800 liters/second) in Florida alone. Silver Springs, Florida has a flow of more than 21,000 liters/second (www.self.gutenberg.org). Some of the springs with their respective flow rates include:

1. The Excelsior Geyser Crater in Yellowstone National Park yields about 4,000 gallons per minute (about 252 liters/second) (www.self.gutenberg.org).

2. Evans Plunge in Hot Springs, South Dakota has a flow rate of 5,000 gallons-per-minute of 87 degree spring water. The Plunge, built in 1890, is the world's largest natural warm water indoor swimming pool (www.self.gutenberg.org).
3. The combined flow of the 47 hot springs in Hot Springs, Arkansas is 35 liters/second.
4. The hot spring of Saturnia in Italy with around 500 liters a second.
5. The combined flow of the hot springs complex in Truth or Consequences, New Mexico is estimated at 99 liters/second (www.self.gutenberg.org).
6. Lava Hot Springs in Idaho has a flow of 130 liters/second.
7. Glenwood Springs in Colorado has a flow of 143 liters/second.
8. Elizabeth Springs in western Queensland, Australia might have had a flow of 158 liters/second in the late 19th century, but now has a flow of about 5 liters/second (www.self.gutenberg.org).
9. Deildartunguhver in Iceland has a flow of 180 liters/second (www.self.gutenberg.org).
10. The hot springs of Brazil Caldas Novas are tapped by 86 wells, from which 333 liters/second are pumped for 14 hours per day. This corresponds to a peak average flow rate of 3.89 liters/second per well (www.self.gutenberg.org).
11. The 2,850 hot springs of Beppu in Japan are the highest flow hot spring complex in Japan. Together the Beppu hot springs produce about 1,592 liters/second, or corresponding to an average hot spring flow of 0.56 liters/second (www.self.gutenberg.org).

12. The 303 hot springs of Kokonoe in Japan produce 1,028 liters/second, which gives the average hot spring a flow of 3.39 liters/second (www.self.gutenberg.org).
13. The Oita Prefecture has 4,762 hot springs, with a total flow of 4,437 liters/second, so the average hot spring flow is 0.93 liters/second. The highest flow rate hot spring in Japan is the Tamagawa Hot Spring in Akita Prefecture, which has a flow rate of 150 liters/second. The Tamagawa Hot Spring feeds a 3 m (9.8 ft) wide stream with a temperature of 98 °C (208 °F) (www.self.gutenberg.org).
14. There are at least three hot springs in the Nage region 8 km (8000m) south west of Bajawa in Indonesia that collectively produced more than 453.6 liters/second (www.self.gutenberg.org).
15. There are another three large hot springs (Mengeruda, Wae Bana and Piga) 18 km (11 mi) north east of Bajawa, Indonesia that together produce more than 450 liters/second of hot water (www.self.gutenberg.org).
16. The Dalhousie Springs complex in Australia had a peak total flow of more than 23,000 liters/second in 1915, giving the average spring in the complex an output of more than 325 liters/second. This has been reduced now to a peak total flow of 17,370 liters/second so the average spring has a peak output of about 250 liters/second (www.self.gutenberg.org).
17. In Yukon’s Boreal Forest, 25 minutes north-west of Whitehorse in northern Canada, Takhini Hot Springs flows out of the earth’s interior at 385 litres (86 gallons) per minute and 47º Celsius (118º Fahrenheit) year-round (www.self.gutenberg.org).

Table 2.6 gives the summary of the above stated hot springs with their respective flow rates.

Table 2.6: Some Hot Springs Around the World With Their Respective Flow Rates

Hot spring	Country	Flow rate (liter/sec)	Flow rate (kg/sec)
Yellowstone national park	U.S.A	252	252
South Dakota	U.S.A	320	320
Saturnia	Italy	500	500
Lava Hot Springs	U.S.A	130	130
Glenwood Springs	U.S.A	143	143
Elizabeth Springs	Australia	158	158
Deildartunguhver	Iceland	180	180
Beppu	Japan	0.56	0.56
Kokonoe	Japan	3.39	3.39
Oita Prefecture	Japan	0.93	0.93
Akita Prefecture	Japan	150	150
Nage	Indonesia	453.6	453.6
Dalhousie Springs	Australia	250	250
Takhini Hot Springs	Canada	6.42	6.42

2.11 GEOLOGICAL SETTING OF NIGERIA

The Nigerian Precambrian basement complex is exposed on the earth surface within about 48% of total land area of the country and remaining 52% of the land is covered by Cretaceous to recent sediments deposited in several basins (Fig. 8). The basement complex of the central shield, south-western part, south-eastern and eastern margin of the country consist of three major groups of rocks: 1) migmatite and gneiss dominated (Liberian to Pan-African age), 2) schists (metasediments) with quartzites and other minor lithologies forming long, narrow, north-south trending belts, mainly in the western part of Nigeria and 3) intrusive granitic rocks – Older Granites (Late Precambrian to Early Palaeozoic age) and Jurassic Younger Granites (Kurowska and Schoeneich, 2010).

The major and deepest sedimentary zone filled mainly with different kinds of clastics of marine as well as continental origin is about 1 200 km long, rending from Niger Delta in SS through Benue Trough, towards NE to Borno (Chad) Basin. That belt, consisting of several sub-basins, together with its branches is related to the crustal stretching and opening-up of the Atlantic Ocean (Gulf of Guinea) and Gondwana break-up during the lower Cretaceous time.

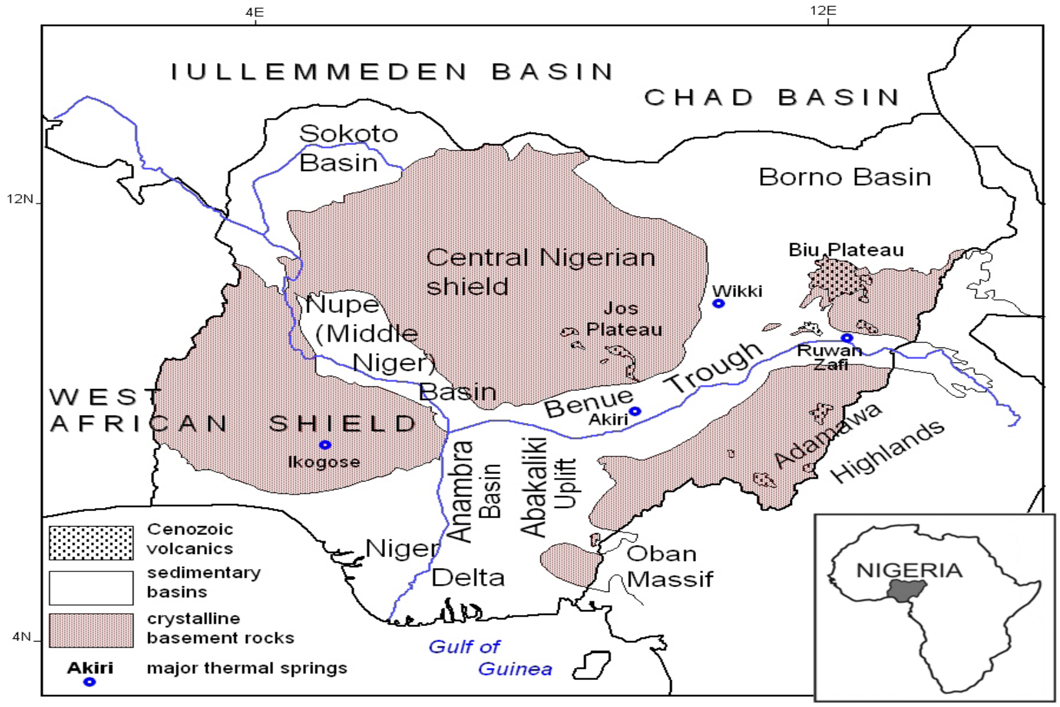


Figure 2.8: Geological setting and locations of the major structural units in Nigeria. (Alozie et al., 2011)

The basins, interpreted partially as troughs and rifts, were subjected to synsedimentary tectonic deformations during Cretaceus to Neogene times and affected by magmatic – volcanic episodes, which resulted in present structural pattern. The Niger Delta is the deepest part of that major Nigerian sedimentary belt and the maximal thickness of sediments exceeds 9 km there (Kurowska and Schoeneich, 2010). Benue Trough is subdivided into Lower Benue Trough comprising Anambra Basin and Abakaliki Anticlinorium (Uplift), Middle and Upper Benue Trough (together with Yola Arm, Gongola and Kerri Kerri basins) and the maximal thickness of sediments reaches even 6 km in some parts of the trough (Kurowska and Schoeneich, 2010). In the north–east the Benue Trough is overlaid by sediments of Nigerian part of Chad Basin called Borno Basin, where the deepest part consists of 4 km thick Cretaceous to Quaternary sediments and according to the other authors it may be much deeper about 7 km deep cc. The Middle Niger Basin (Nupe or Bida Basin), which is only about 0.5 - 1 km deep in most of the area and does not exceed 2 km in the deepest parts is a large western branch of Benue Trough (Kurowska and Schoeneich, 2010). The Sokoto Basin on the north-western outskirts of Nigeria is a part of large Iullemmeden Basin that extends far to the north. The Sokoto Basin maximal depth is about 1 km on the north-western margin of the country (Kurowska and Schoeneich, 2010) but in the Niger and Mali territory it exceeds 2 km. Apart from the two major Nigerian provinces: Precambrian crystalline and Cretaceous to Quaternary sedimentary, the third type of rocks present: Cainozoic volcanics, mainly in the eastern part of the country (Kurowska and Schoeneich, 2010). The products of Cenozoic magmatic and volcanic activity are numerous trachyte-phonolitic and basaltic plugs within Benue Trough and basaltic lava plateaus from among which the most prominent are: Biu Plateau with its over 80 volcanoes and extensive basaltic lava flows of Jos Plateau (Kurowska and Schoeneich, 2010). The geological structure of the area influences general distribution of geothermal heat in the upper earth crust and additionally, specifically for Nigeria, influences geothermal exploration extent within each geological province in the country. The other source of geothermal information is a surface manifestation of geothermal activity. There are several warm and hot springs and seepages marking the areas of potential geothermal anomalies in Nigeria, most of them located within sedimentary basin of Benue Trough (Kurowska and Schoeneich, 2010).

2.11.1 Geothermal Investigation of Nigerian Crystalline Province

The world average heat flow in continental Precambrian shields is about 41± 10 mW/m^2 and such value is expected for Nigerian Precambrian basement complex (Kurowska and Schoeneich, 2010). However, not much has been investigated in that matter in Nigeria. The only widely known heat flow estimation by Verheijen and Ajakaiye (1979) was carried out in the centre of Ririwai ring complex being one of the granitic ring structures of Younger Granites Province of Northern Nigeria, located within Precambrian shield. In the result of research the average heat flow of 0.92 ± 0.04 HFU (38.5 ± 1.7 mW/m^2) was obtained which is almost equal to the world average (Kurowska and Schoeneich, 2010). In the south-western part of Nigeria a thermal spring called Ikogosi is located within quartzite-schist formation of Nigerian basement complex. The spring water temperature is 37°C. It is used for swimming pool being a significant local tourist attraction and one of the places of geothermal (direct) use in Nigeria (Kurowska and Schoeneich, 2010). Akiri is another thermal spring and seepage, which occur mainly within sediments of the Middle and Upper Benue Trough. The water of the warmest springs in that area has the temperature of about 54°C and it suggests the occurrence of some geothermal anomalies (Alozie et al., 2011). There is another warm spring just discovered in Rafin Reewa, near Lere, to the north-west of Jos Plateau (central shield). The temperature of spring water is 42°C and it flows from migmatic and gneissic rock formation (Garba et al., 2011). Several springs have been presently known in Jos Plateau and all of them provide cold, fresh water, commonly used by local community. The existence of Ikogosi warm spring and that recent discovery suggest that distribution of geothermal heat within Precambrian basement formations in Nigeria can be diversified due to local anomalies.

2.11.2 Geothermal Investigation of Sedimentary Provinces

2.11.2.1 Southern sedimentary province

Subsurface temperature distribution in the southern part of sedimentary province in Nigeria was studied by Nwachukwu (1975, 1976), Avbovbo (1978) and Onuoha and Ekine (1999). They used corrected bottom hole temperature (BHT) data measured in oil exploration wells drilled in Niger Delta and Anambra basins. According to those earlier studies by the first two authors, the lowest values of geothermal gradient were found in the centre of Niger Delta within the thick tertiary sediments: 1,3 –1.8°C/100m or 2.2 – 2.6°C/100m in Warri-Port Harcourt area (Avbovbo). The northward trend of gradient increase was found resulting in maximum value of 5.5°C/100m in the area of Agwu-Enugu-Nsuka towns, within Cretaceous rocks containing coal beds in Anambra Basin. The medium values of geothermal gradient (2.9 – 4.7°C/100m) were found along the coastal line in the South. The geothermal gradients in off-shore parts of Niger Delta calculated by Avbovbo were 3.3 – 4.7 °C/100m. The latter research conducted shows diversity in geothermal gradient within Anambra Basin. The values calculated in 17 points (wells) range from 2.5 to 4.9°C/100m and the heat flow estimated on the basis of these gradients was 48-76 mW/m^2. In that research, the high temperature zone within Agwu-Enugu-Nsuka and constant trend of subsurface temperature increase from south towards the north was not confirmed (Kurowska and Schoeneich, 2010).

2.11.2.2 Central and northern sedimentary province

Geothermal characteristics of the Bida (Nupe, Middle Niger) Basin as well as Borno and Sokoto basins was studied on the basis of thermal data collected during pumping tests in water wells. The data base shows that temperature gradient in Borno Basin ranges from 1.1 to 5.9°C/100m, in Sokoto Basin: 0.9 to 7.6 °C/100m (Kurowska and Schoeneich, 2010). The zone of highest gradients in Sokoto basin is elongated in SW-NE direction, parallel to general strike of major sedimentary formations which are very thin in that area (about 200 m). This suggests that a significant source of geothermal heat is located below sedimentary complex, in Precambrian basement and perhaps is related to some deep tectonic active structure (Kurowska and Schoeneich, 2010). The values of geothermal gradients found to the north of Nigeria, within the other part of Iullemmeden Basin in Niger, are even higher than in Sokoto Basin.

There are very few temperature data from Bida Basin and many of the existing ones were taken in very shallow water wells, however the most reliable measurements taken in more than 100m deep water wells show that in SE part of the basin the geothermal gradient is about 2-2.5 °C/100m (Kurowska and Schoeneich, 2010).

The springs in Middle Benue Trough flow from the Cretaceous, porous sandstones, some of them are located within areas famous from barite mining and traditional salt production based on salty sediments. In such area one of the hottest springs (53.5°C) is located near Akiri, however the most famous Nigerian warm spring is Wikki (32°C) flowing from Gombe Sandstone in Yankari Game Reserve (Kurowska and Schoeneich, 2010). Another hot one (54°C) is located in the North of Benue Trough, within a huge tectonic structure -Lamurde anticline, nearby Numan and is called Ruwan Zafi. The water of the springs is heated by geothermal gradient on its way from unknown depths, in unconfined sandstone aquifer. Within the Middle Benue Trough several minor thermal seepages were found nearby Awe where the temperature of the water ranges from 34 to 38.5°C. Warm water is provided to the surface also by two artesian wells found in that area. Temperatures of the water flowing from those wells are 43.5°C and 34°C. They were drilled in the end of 1970s or beginning of 1980s and left for the local community as a source of domestic water (Kurowska and Schoeneich, 2010).

The geothermal analysis based on geothermal gradients indicated areas of higher than average gradient values and geothermal anomalies within sedimentary basins. The areas of geothermal anomalies with gradients above 5°C/100m found in the present study might be prospective for geothermal energy utilization.

2.12 GEOLOGICAL SETTING OF THE STUDY AREA.

The area is located at the fringes of the Jos Plateau, to the SW (Figure 2.7), the centre of the Nigerian an Orogenic Younger Granite province of Jurassic age, and directly east of the nearby Rishiwa ring complex. The area is well drained by a good network of rivers most of which take their source from the nearby ring complexes of the Jos Plateau (Figure 2.9). The Geology it is composed of migmatite gneiss as the oldest rocks, Pan African granites and bauchites. The bauchite is an unusual rock of acid to intermediate composition, containing, in addition to fayalite, extremely iron rich pyroxenes (ferrohedenbergite and orthoferrosilite), (Garba et al., 2012). The topography of the area is more or less flat laying with the migmatites occurring as low lying exposures, while the granitic rocks stands out conspicuously thereby dotting the landscape.

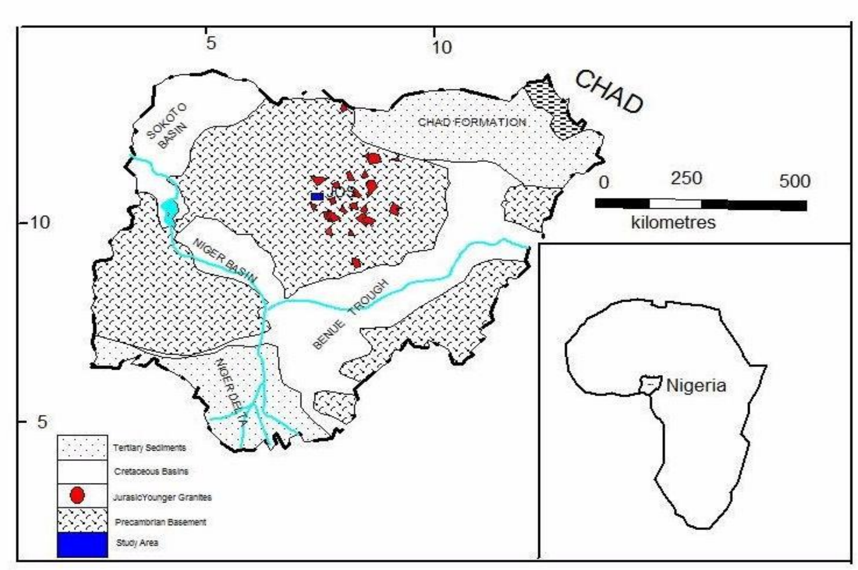


Figure 2.9: Sketched Geological Map of Nigeria Showing the Study Area (Garba et al 2012).

2.13 GEOCHEMICAL ANALYSIS OF THE WATER IN RAFIN REEWA HOT SPRING

Two chemical parameters observed to be in excessively high concentrations, makes the water from Rafin Reewa hot spring unique among the known springs occurring in the Crystalline Hydrogeological Province of Nigeria (Garba et al., 2012): These are sodium and bicarbonate. Sodium, according to (Garba et al., 2012), is released by weathering of plagioclase from the host rocks, since it do not exist in the atmosphere except as particulate matter. Thus, with the only source of sodium being the products of weathering of the crystalline rocks, sodium is the second cation after calcium in meteoric water of the Crystalline Hydrogeological Province, within the range of concentrations of 0.8 to 20.0 mg/l and 5.0 mg/l as an average concentration (Garba et al., 2012). However, water from the Rafin Reewa hot spring has 88.51 mg/l of sodium (see Table 2.5.), 17 times higher than the average concentrations in meteoric water. This sodium could not have been leached from the thin (maximum 30 metres) weathered mantle on the site of the spring. This then suggest that it can only come from the earth interior through fractures in the fresh crystalline rocks (Garba et al., 2012

The second parameter making Rafin Reewa water so different is its high content of bicarbonates, 207 mg/l (see Table 2.5); six times higher than the average concentration in meteoric water. Bicarbonate in meteoric water has two sources: one is atmospheric carbon dioxide dissolved by rain water, and the second is carbon dioxide present in the humus soil, which is absorbed by water during infiltration (Garba et al., 2012). Both sources provide on average 35 mg/l, maximum 100 mg/l. This is not enough to justify the high content of bicarbonates in Rafin Rewa hot spring. It then means that the bubbling warm water from the spring is not only meteoric water, it must have another origin, most likely the volcanoes that are located within the Younger granite province. With the average geothermal gradient in Crystalline Hydrogeological Province of Nigeria at only 1.8 ^{O}C/100m (Garba et al., 2012), and with allowance for cooling on its passage upwards, the depth from which the water is coming from must be more than 1 kilometre, since the temperature of water, 42.5 ^{O}C, suggests that the water comes from a great depth. Also, a gas with the smell of hydrogen sulphide bubbles and emanates from the spring as its water ascends to the surface. The water and gas are of endogenic origin, flowing from depth not less than 700 metres below ground level, thus making the spring the only known occurrence of juvenile water in Nigeria (Garba et al., 2012).

Rafin Reewa hot spring originated from the Quaternary to Recent magmatic activity that affected the Jos Plateau area of Nigeria, and which possibly after mixing with meteoric water flows out as an ascending spring through regional lineaments that transcends the area (Garba et al., 2012). Table 2.7 below shows the laboratory analysis of Rafin Reewa warm spring.

Table 2.7: Cation analysis of Rafin Reewa hot spring. (Source: Schoeneich 2001).

PH	8.10
	Concentration
Total Dissolved solids	214 mg/l
Calcium	1.50mg/l
Magnesium	0.06 mg/l
Sodium	88.51 mg/l
Potassium	1.64 mg/l

2.14 LEVELIZED COST OF GEOTHERMAL ELECTRICITY

The purpose in economic evaluation is to check the profitability of the project without considering where resources come from and they go; and respectively accept or refuse the project looking at how profitable it is. Economic evaluation consists of commercial or social profitability analyses depending on the purpose of the entrepreneur (Kula and Erkan, 2004)

The economic incentive to develop geothermal power, of course, must be the profit potential of the investment. Developing a new geothermal resource is a long and expensive process. Initial development steps are risky and upfront capital costs are important. Consequently, a major part of the cost of power is related to the reimbursement of capital invested and associated returns. According to Hance (2005), it is estimated that capital reimbursement and associated interest account for 65% of total cost of geothermal power.

One complication is a larger uncertainty in project development, due to the risk of poorly performing production wells. Similarly, over the life of a project, reservoir degradation can play an important role in costs (since additional production wells will be required) and in performance (lower output while remedial measures are taken) (IRENA, 2013). These factors tend to introduce greater uncertainty into the development of geothermal projects and may increase financing costs, compared to technologies such as wind. However, this uncertainty factor is typically manageable in mature geothermal markets where financing institutions have previous experience with the industry (IRENA, 2013).

The LCOE of renewable energy technologies varies by technology, country and project, based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology (IRENA, 2013).

Given the capital-intensive nature of most renewable power generation technologies and the fact that fuel costs are low, or often zero, the weighted average cost of capital (WACC), often also referred to as the discount rate, used to evaluate the project has a critical impact on the LCOE (IRENA, 2013).

The LCOE of a geothermal plant is determined by the usual factors, such as installed costs, O&M costs, economic lifetime and the weighted average cost of capital. However, the analysis for geothermal is a more dynamic question than for some other renewables. The cost of generating geothermal electricity is normally expressed on a kWh basis otherwise referred to as the levelized unit cost of electricity. Levelized Cost of Energy (LCOE) is the constant unit cost (per kWh or MWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its life time (Ngugi, 2012). Knight (2009) has defined the levelized as the times series of the capital and operating expenditure divided by the net power supplied, discounted to their present values. While Knight only considers capital and operational cost in his computation, other variants exist that include tax and depreciation (Ngugi, 2012). It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital. It is a very useful industrial tool for comparing technologies with different operating characteristics. It is on this cost basis that the geothermal projects are evaluated for investment, approval and financing by prospective investors, governments, consumers or regulators and bankers or credit providers (Ngugi, 2012).

In addition to the levelized cost, geothermal cost is oftentimes expressed as an investment or installation cost per unit of plant capacity i.e. per MWe. This cost includes all capital expenditure necessary to construct a plant in addition to interest (cost of debt) during construction (Ngugi, 2012). It must be understood that the investment cost is a measure of financial requirement. Low or high investment cost may not necessary indicate lower or higher levelized cost of electricity. This is because the operation and maintenance cost might outweigh the capital investment for lower investment cost resulting to high levelized cost and vice versa (Ngugi, 2012).

2.14.1 Levelized Cost Factors

Installation costs are all initial costs excluding transmission and distribution that are incurred in the construction and commissioning of a power plant. The costs can be categorized into resource exploration, appraisal, production, drilling and plant construction costs.

1. Exploration costs

Exploration is the first step. This stage begins with various kinds of prospecting and field analysis and ends with the drilling of the first commercial geothermal well (Konyali, 2010). At this stage the existence and properties of geothermal reservoir is searched. The costs under this category include the cost of desk top data review, detailed surface study, infrastructure development and drilling of exploration wells.

2. Confirmation

The confirmation phase allows for drilling of full size production wells at multiple locations; those costs occurring at the 'unsuccessful' sites are included in the total confirmation costs. Those 'successful' wells drilled at the final location are assumed to supply geothermal fluid to the power plant (US DOE, 2006).

This stage ends with the confirmation of the 25% of the capacity of the project.

The confirmation phase allows for drilling of full size production wells at multiple locations; those costs occurring at the 'unsuccessful' sites are included in the total confirmation costs. Those 'successful' wells drilled at the final location are assumed to supply geothermal fluid to the power plant (US DOE, 2006).

3. Production drilling costs

Production drilling entails drilling to provide adequate geofluid to operate a specific size of plant at full capacity and reinjection wells.

4. **Site Development**

The site development phase includes all the remaining activities. This involves power plant design and associated technological choices, drilling and well testing.

5. **Power plant construction**

There are many factors that influence the cost of geothermal power plant. In general, they are affected by the cost of steel, other metals and labor, which are universal to power industry (Konyali, 2010).

Geothermal power plant costs depend on such factors;

i. Resource type (steam or hot water),
ii. Resource temperature,
iii. Reservoir productivity,
iv. Power plant size,
v. Power plant type
vi. Cost of capital,
vii. Environmental regulations
viii. Operation and maintenance

The first three factors influence the number of wells which are concern with plant capacity. The next three items determine the capital cost, and the last two affect the cost of running the plant (Konyali, 2010)

2.15 Economies of Scale

Economies of scale might significantly decrease the specific cost of some components. Sanyal (2004) estimates that capital costs of geothermal projects with capacity ranges of

5 to 150 MW decline exponentially with their capacity according to the following relationship:

$$CC=2500e-^{0.0025(P-5)} \qquad 2.12$$

Where, CC represents capital costs and P the project's power capacity.

Most of these economies of scale are related to activities (costs) that have to be borne independently of the project's capacity (e.g. excavation, road building, electric, phone and other connections, etc.).

2.16 FINANCING MECHANISMS AND MACRO-ECONOMIC ENVIRONMENT

The prime objective of every project is to be profitable. For a geothermal project, profits are related to the difference between the price obtained for power and the cost of producing it. The financial structure, conditions and related costs are an important factor influencing the levelized cost of energy and profitability of the project.

Besides the amount of the initial capital investment, the origin of the money invested and the way it is secured will influence the resulting cost of power. The cost of borrowing money is directly related to the interest rate and the length of the debt period. Both these parameters (i.e. interest rate & debt length) may vary widely according to conditions and circumstances.

1. Interest Rate.

Capital owners expect return for the money they lend or invest. Theoretically, financial markets are like all other markets: interest rates are determined by the amount of capital supply (investors - money lenders) and the amount of capital demand (entrepreneurs -

money borrowers). High demand for capital will raise its price (i.e. interest rate), while low demand will decrease its price. Inversely, large capital supply will decrease its relative value and thus interest rate, while low supply will raise it. Entrepreneurs compete with each other to obtain capital at the lowest price to realize their project while investors compete with each other to invest their money in the most lucrative business (Hance, 2005).

2. Debt Length.

In order to secure the revenue flow of the project, commercial banks will also require the developer to have a power purchase agreement (PPA) that covers at least the length of the debt period. This power purchase agreement is negotiated with local power authorities and guarantees that the power plant will be able to deliver its power to the grid at a fixed price for a certain period of time. The length of the debt is usually tied to the length of the power purchase agreement, although the PPA is usually slightly longer (Hance, 2005).

Geothermal power plants usually have a planned lifetime of 30 years. However, power purchase agreements typically last 10 to 20 years. This means that the debt payback period of the project has to fit into the power purchase agreement period. The power purchase agreement period is thus an important factor that determines the minimum price of electricity that makes the project viable.

2.17 OPERATION AND MAINTENANCE COSTS

Operation and Maintenance (O&M) costs consist of all costs incurred during the operational phase of the power plant. Economic analysis usually distinguishes fixed and variable O&M costs, but in the case of geothermal power production, variable costs are relatively low and the marginal cost of power production increase is thus considered to be minimal. Consequently, geothermal power plant operators will keep capacity as high as possible in order to minimize the cost of each kWh produced (Hance, 2005).

1 Operation costs

Operation costs include all expenses related to the operation of the power plant. An important part of these costs is labor. Other cost components include spending for consumable goods (e.g. lubricants, chemicals for H_2S abatement, scaling and corrosion control, vehicle fuel, spare parts, etc.), taxes and royalties, and other miscellaneous charges (e.g. waste disposal, parasitic load for various kind of pumps (e.g. cooling system, lighting and other internal electricity uses.) (Hance, 2005).

The size of the power plant is another important parameter that affects labor costs. The number of operators needed to run a geothermal plant is relatively independent of its size. Therefore, most existing power plants ranging from 15 to 100 MW require similar crews of 5 to 7 employees (working on 24-hour/7-day shifts). Significant economies of scale thus apply and small plants have substantially higher labor costs than large plants. For some tasks, human workforce is progressively replaced by remote control technologies (Hance, 2005).

Besides labor costs, expenses related to chemical and other consumables goods may also be important and vary widely according to the geochemistry of the brine. Other miscellaneous expenses may apply according to the resource characteristics (e.g. downhole pumps electric load), geographical location and weather conditions (snow removal and fire prevention), etc. Insurance costs are another component of operating costs which have been dramatically increasing in recent years (Hance, 2005).

2. Maintenance costs

Maintenance costs encompass all expenses related to the maintenance of the equipment (field pipes, turbine, generator, vehicles, buildings, etc.) in good working status. This includes a large variety of tasks (e.g. machinery overhaul, painting, road repair, etc.) and some activities may be subcontracted to specialized companies..

Hance (2005) estimated the annual cost of power plant maintenance as 5% of the initial capital costs. He considered an initial investment of $1400/kW and estimated that maintenance costs average $9/MWh.

Besides maintaining the production and injection wells, pipelines, roads, etc., expenses related to steam field maintenance mainly involve make-up drilling activities. Make-up drilling aims to compensate for the natural productivity decline of the project startup wells by drilling additional production wells. The well productivity decline is a complex phenomenon mainly explained by the pressure and/or temperature drop of the reservoir. Siting injection wells is therefore often a tradeoff between maintaining the resource pressure around production wells and cooling the surrounding resource area with injection fluids (Hance 2005).

More generally, the resource productivity decline rate is directly related to its capacity to supply energy to the power plant. Resource and power plant capacity have to be balanced to ensure sustainable power production throughout the lifetime of the power plant. The size (capacity) of the power plant is thus a major factor affecting resource productivity decline. Well productivity decline rates may vary widely according to the geothermal resource. The power system technology is also expected to influence the productivity decline rate. While air-cooled binary power plants inject 100% of the brine used by the power system back into the reservoir, water-cooled flash plants lose 75 to 80% of the steam through evaporation in cooling towers (Hance, 2005). The quantity of steam obtained from the brine is highly variable and depends on the energy and chemical characteristics of the resource. If natural recharge of the resource does not compensate this loss, well productivity will decrease along with the pressure of the reservoir. Additional sources of water may be needed for vapor dominated systems to mine the heat from the reservoir and maintain generation. Appropriate reservoir assessment and management is essential to maintain production capacity. Other resource characteristics (e.g. resource permeability, brine enthalpy and scaling potential.) may also affect individual well production declines. Since the size of the power plant is an important parameter affecting O&M costs, Sanyal (2004) estimated and modeled this effect for power plants capacities ranging from 5 to 150 MW. The relationship obtained is exponential:

$$\text{O\&M costs} = 2e^{-0.0025(P-5)} \qquad 2.13$$

P = the power production capacity of the power plant.

3 Royalties and Taxes

Royalties correspond to payments the power producers are required to make to the owners of the geothermal resource. Exact royalty values are difficult to provide since terms and conditions of geothermal leases vary, notably according to the resource owner (private vs. government). When power plants and steam fields were managed by distinct companies, the value of royalties was calculated as a percentage of the value of resource used to produce power.

2.18 Calculation of Levelized Cost of Electricity (LCOE)

The purpose of calculating the levelized cost of electricity (LCOE) of geothermal power is to compare it other renewable energy resources. As earlier stated, LCOE is the price at which electricity from a geothermal resource need to be produced in order for the power station to break even over the lifetime of the project. This calculation involved a wide range of costs parameters for the power plant and discounts these costs over the lifetime of the project. The sum is then divided by the discounted electricity generated from the plant. This is the standard method of estimating cost of energy, and the results for the LCOE can be compared to estimations from other energy resources (Broliden & Hellstadius, 2013). The formula for calculating the LCOE is presented in equation 2.13 (IRENA, 2013).

$$LCOE = \frac{\sum_t^n \frac{\mathrm{It+Mt+Ft}}{(1+r)^t}}{\sum_t^n \frac{E_t}{(1+r)^t}} \qquad 2.13$$

Where,

LCOE = Levelized cost of electricity

n = Lifetime (years)

r = Discount rate (%)

I_t = Investment expenditures in year t

M_t = O&M expenditures in year t

F_t = Fuel expenditures in year t

E_t = Electricity generation in year t

2.18.1 Net Present Value

NPV is defined as the sum of the total discounted cash flows over the lifetime of a project (Broliden & Hellstadius, 2013). Consequently this method is comparing the present value of future cash flows with the cash flows of today. The NPV-method is considered the standard method for assessing the profitability of long-term projects. A NPV that is above the zero line means that the investment will add value to the firm, therefore investors seek to undertake projects with as high NPV as possible (Broliden & Hellstadius, 2013). For an investor deciding on a project, the magnitude of the present value of course also influence the decision-making. If the project is very capital intensive and high risks are involved, the investor will require a higher return of the project and thus a higher NPV. The formula for calculating NPV for projects is presented in Eq. 2.14 (Broliden & Hellstadius, 2013).

$$NPV = \sum_{t}^{n} \frac{C_t}{(1+r)^t} \qquad 2.14$$

Where,

NPV= Net present value

Ct = Cash flow in year t

r = Discount rate (%)

2.18.2 Generated Electricity

The amount of electricity produced determines how much electricity that can be sold and thus the revenues of the power plant. Since the production of electricity is dependent on the plant technology the process of calculating the generated electricity is different for different types of power plants (Broliden & Hellstadius, 2013). The process of calculating the generated electricity for geothermal binary plants can be divided in to three steps, which are presented below (Broliden & Hellstadius, 2013):

(1) Calculating the available thermal power (ATP)

(2) Calculating the net generated electric power (NEP)

(3) Calculating the produced electricity

(1) The available thermal power (ATP) is the amount of heat that can be extracted from the geothermal fluid to the secondary fluid in the binary power plant. During the heat exchange in the power plant, the working fluid is heated by the geothermal fluid, which in turn is cooled and pumped back into the ground. The formula for calculating the ATP is presented in euation 2.15 (Broliden & Hellstadius, 2013).

$$ATP = m \dot{\times} C_p \times (T_{in} - T_{out}) \qquad 2.15$$

Where,

ATP = Available thermal power (kW)

T_{in} = Temperature of incoming geothermal fluid (K)

T_{out} = Temperature of outlet geothermal fluid (K)

C_p = Specific heat capacity of water (kJ/K*kg)

m = mass flow rate (kg/s)

ATP is used for the calculation of the net generated electric power (NEP) and is usually calculated for a geothermal outlet temperature of 50°C when making feasibility studies. (Broliden & Hellstadius, 2013). Equation 2.15 assumes that all energy recovered from the geothermal fluid is transferred to the working fluid and that no heat losses are present in the heat exchanger. However, the overall heat losses from the binary plant will be accounted for when calculating the net generated electricity in the next step of the calculation (Broliden & Hellstadius, 2013).

(2) The net generated electric power (NEP), also referred to as installed capacity or installed power, is the electricity that the power plant would produce assuming it would run with full capacity for 24 hours every day. NEP does however account for heat losses from the binary power plant (Broliden & Hellstadius, 2013). In the calculation of the NEP the cost for power plant construction, as the size of the power plant is depending on how much electricity that is intended to be produced (Broliden & Hellstadius, 2013).

There are several ways to calculate the NEP for a binary power plant. According to Broliden & Hellstadius (2013). Equation 2.16 is appropriate for feasibility study purposes, when adequate accuracy is required (Broliden & Hellstadius, 2013):

$$NEP = \frac{(0.18\times T_{in} - 10)\times ATP}{278} \tag*{2.16}$$

Where,

NEP = Net generated electric power (kW)

Tgeo, in = Temperature of incoming geothermal fluid (K)

ATP = Available thermal power (kW)

The other way to calculate the NEP is by using the thermal efficiency of the binary power plant. Thermal efficiency is defined as the NEP divided by the ATP (Broliden & Hellstadius, 2013). Equation 2.17 demonstrates the formula for calculating the NEP from the ATP and thermal efficiency (Broliden & Hellstadius, 2013)

$$NEP = {}_{th} \times ATP\ . \tag*{2.17}$$

Where, ${}_{th}$= thermal efficiency (%)

(3) Geothermal power plants have a very high capacity factor compared to other renewable energy resources, but the plant still has to be shut down for maintenance at times. This needs to be taken into consideration when calculating the plant revenues (Broliden & Hellstadius, 2013). Therefore the NEP is multiplied with the capacity factor to obtain the actual generated electric power, see equation. 2.18 (Broliden & Hellstadius, 2013).

$$Produced\ electricity = \alpha \times NEP \qquad 2.18$$

Where, α= Capacity factor (%)

These calculations are simplifications of a very complicated power production process, and therefore are not suitable for detailed and specific power plant calculations (Broliden & Hellstadius, 2013).

2.19 GETEM Software Description

The Geothermal Electric Technology Evaluation Model (GETEM) is a macro-model that estimates levelized cost of geothermal electric power in a commercial context. GETEM is coded in an Excel spreadsheet and simulates the economics of major components of geothermal systems and commercial-development projects. The model uses a matrix of about 80 user-defined input variables to assign values to technical and economic parameters of a geothermal power project. In general categories, the variables account for geothermal resource characteristics, drilling and well-field construction, power plant technologies, and development of geothermal power projects (US DOE, 2006).

A key feature of the model is that GETEM uses a subset of the input matrix to apply change factors to model components. These factors are targeted to enable a user to investigate the impacts of diverse combinations of changes.

The impacts are quantified as net levelized energy costs. GETEM accounts for the gamut of factors that comprise electric power costs but not prices. GETEM applies documented and expert-interpreted conditions such as reservoir performance, drilling and construction costs, energy conversion factors, and competitive financial frameworks. It uses empirical, industry-based reference data. It is a good tool for evaluating case-specific costs, technology trends, cost sensitivities, and probabilistic values of technology goals (US DOE, 2006).

The software utilizes a methodology for calculating the LCOE that replicates a discounted cash flow sheet. These calculations are on sheets that begin with EERE COE. This approach allows the User to vary discount rates and time duration of each phase of the project, and includes depreciation and taxes. The model also has discounted cash flow sheets (sheets that begin with Revised COE - DCF) that are used primarily to check calculations made with the preferred DOE EERE methodology. Prior versions of the GETEM model used a fixed charge rate (FCR) when determining the LCOE. (The FCR is the fraction of the total capital cost that must be recovered annually for costs associated with capital - return on equity, interest on debt, and certain taxes and insurance.) The FCR method did not allow for varying discount rates or time duration for the project phases, and was based on a fixed project life of 30 years.

GETEM's calculations are based on the assumption that the fluid in the reservoir is a liquid at a temperature which the User defines. All calculations of plant performance and cost are based on this temperature, less a calculated temperature loss in the production well bore (US DOE, 2006).

Though power sales is specified rather than plant size, GETEM's calculations of power plant cost and performance are based on the net plant output, which is the generator output less fan power and the pumping power for the working fluid, cooling water, non condensable gases (ncg) removal, condensate, etc. The model calculates the LCOE for two conversion systems: air-cooled binary and flash-steam.

The model recognizes the relationship between a binary power plant's performance and their costs, i.e., more efficient plants have higher capital costs. When the costs to develop a geothermal resource are significant, a more efficient plant will lower the LCOE even though the plant itself has a higher capital cost. The more efficient plant either provides more power sales for a given well field development, or requires fewer wells to produce the same level of sales. GETEM allows this trade-off to be performed in a macro that the user can use when providing input for the power plant. This macro varies plant performance (and cost) until the LCOE is minimized. Note this macro should be used after all other input is provided. If subsequent changes are made to the input for any of the other project areas, the macro should be re-run.

The model's summary worksheet has a summary of the calculated cost (and where relevant performance) associated with each phase of the project development - Exploration, Confirmation, Well field Development, Reservoir Definition, Geothermal Pumping, Operation and Maintenance, and Power Plant (Reservoir Definition includes results/input for flow rate, reservoir stimulation, hydraulic drawdown, thermal drawdown, and water loss.) The input worksheet is similarly laid out. The result/input for each phase are 'grouped' to facilitate both the input of data and the review of the results. Thus, GETEM enables researchers to quantify the effectiveness of research program elements, using measures that reflect power industry practices. The detail of GETEM worksheets for both input and output for binary power plant is given in appendixes A and B.

CHAPTER THREE

MATERIAL AND METHOD

3.0 INTRODUCTION

This section described the methodology adopted for the research work. The chapter will also explained how the various geothermometry equations established in the literature review are used in the calculation of the temperature of the geofluid of the Rafin Reewa hot spring (the study area). The LCOE will be evaluated using GETEM software and thereafter the result obtained will be presented in tabular form.

3.1 METHODOLOGY

The aim of this project is to arrive at the levelised cost of producing geothermal power using Rafin Reewa hot spring. To accomplish the specific objectives of the work:

i. The resource temperature at the study area is determined using the empirically and thermodynamically derived cations geothermometers by applying the geochemical analysis of Rafin Reewa hot spring waters that was established by Schoeneich in table 2.5.

ii. Parameters and variables

Since there is no extensive geothermal energy research and development at the study area, the values of parameters and variables are based primary on values established in the literature of the study area and the world in general.

a. Mass Flow Rate

The geothermal mass flow is required to calculate the available thermal power of the plant. The literature review of this study has shown that the flow of the geothermal fluid from hot springs range from 0.56 to 500 kg/s (see table 2.6). It is therefore of great interest to investigate the LCOE for a hot spring binary power plant for different geothermal mass flows. Couples with this, for geothermal power project to be economically optimized, high mass flow rates of hot water are needed. Low flow rates result in heat loss to a shallow, cooler subsurface region. Consequently, the flow rates of 100kg/s, 200kg/s, 300kg/s and 400kg/s were selected for analysis.

b. Resource Depth

The depth of the geothermal reservoir affects the cost of drilling the wells and will therefore affect the overall profitability of the geothermal power plant. The main reason for deep drilling is to achieve as high temperatures as possible. For a producing geothermal well to be sufficient in energy content, the well depth needs to be reasonable deep. As established in the literature review (see section 2.13) the depth from which the water is coming from is more than 1000m, hence in line with the prevailing drilling technology, the resource depth of 1000m, 2000m, and 3000m were chosen for analysis.

iii. The Levelized-Cost-of-Electricity (LCOE) is evaluated after taking into account the cost of plant's developmental phases, i.e. the cost of exploration, confirmation, well field development, production pumping and injection pumping. At the resource temperature of the study area and at a selected flow rates, the levelised cost of electricity is evaluated for each of the resource depth selected for analysis (i.e 1000m, 2000m, and 3000m). Likewise, the LCOE is evaluated for each of the production flow rate selected for analysis (i.e 100kg/s, 200kg/s, 300kg/s and 400kg/s).

The impacts of production flow rate and resource depth on LCOE are evaluated and compared to ascertain the predominant factor that determines feasible cost of electricity for a power generated using Rafin Reewa geofluid. The impact of the variables (production flow rate and resource depth) is evaluated using Geothermal Electricity Technology Evaluation Model (GETEM) software.

3.2 EVALUATION OF RESOURCE TEMPERATURE

The resource temperature is evaluated using the chemical analysis of the Rafin Reewa spring water provided in Table 2.5. The chemical analysis of the water shows only the various concentrations of the cations therein the water. Consequently, in evaluating the temperature of the water, only Na-K and Na-K-Ca geothermometers were applied.

From Table 2.5:

Sodium (Na) Concentration = 88.51mg/l

Potassium (K) Concentration = 1.64mg/l

Calcium (Ca) Concentration = 1.5mg/l

From equation (2.7)

$$T^{o}C = \frac{1217}{1.438 + \log\,(\frac{Na}{K})} - 273.15$$

$$T = 111.00^{\mathrm{O}}\mathrm{C}$$

From equation (2.8):

$$T^{o}C = \frac{1319}{1.470 + \log\left(\frac{Na}{K}\right)} - 273.15$$

$$T = 111.00^{\mathrm{O}}\mathrm{C}$$

From equation (2.9):

$$T^{o}C = \frac{1390}{1.750 + \log\left(\frac{Na}{K}\right)} - 273.15$$

$$T = 126.28^{O}C$$

From equation (2.10):

$$T^{O}C = 733.6 - 770.55Y + 387.189Y^{2} - 95.753Y^{3} + 9.544Y^{4}$$

$$T = 122.14^{o}C$$

From equation (2.11): Since log ($Ca^{1/2}$/Na) + 2.06 = 0.2; which is positive, then $\beta = 4/3$

$$T^{O}C = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta\log\left(\frac{Ca^{0.5}}{Na}\right) + 2.24} - 273.15$$

$$T = 832.2^{o}C$$

3.3 EVALUATION OF LEVELIZED COST OF ELECTRICITY OF THE STUDY AREA

3.3.1 General Assumption

In the evaluation of the total investment costs of the geothermal power plants at the study site, it will be assumed that the construction is greenfield. Greenfield means that no power plant has been previously present at the site, and the project is not an expansion of an already existing power plant. The study area is located at a rural area with a lot of socio-economic developmental activities taking place. Consequently, demand in electricity in the area is expected to increase drastically in the near future. Hence, in the evaluation and analysis of all data, the power plant capacity is assumed to be 50MW.

For the resource temperature, the value obtained by equation (10); Arnorsson and Stefansson (1998), is considered to be more reliable than other values, hence it is therefore preferred (see 2.9.1.2 for reason). Consequently, in the evaluation of the LCOE the temperature of the study area is taken to be $122.14^{O}C$.

3.3.2 Evaluation of LCOE with Flow Rate as the Variable

Table 3.1 to 3.4 show the result obtained from GETEM with flow rate as the variable parameter while maintaining the resource depth at 1000m, 2000, and 3000m.

Table 3.1: Levelised Cost of Electricity (Production Flow Rate = 100kg/s)

Depth (meters)	LCOE (cent/kWh)
1000	43.010
2000	48.223
3000	59.046

Table 3.2: Levelised Cost of Electricity (Production Flow Rate = 200kg/s)

Depth (meters)	LCOE (cent/kWh)
1000	49.916
2000	53.629
3000	64.937

Table 3.3: Levelised Cost of Electricity (Production Flow Rate = 300kg/s)

Depth (meters)	LCOE (cent/kWh)
1000	64.556
2000	69.163
3000	91.739

Table 3.4: Levelised Cost of Electricity (Production Flow Rate = 400kg/s)

Depth (meters)	LCOE (cent/kWh)
1000	111.050
2000	126.012
3000	-

3.3.2 Evaluation of LCOE with Resource Depth as the Variable

Table 3.5 to 3.7 show the result obtained from GETEM with resource depth as the variable parameter while maintaining the flow rates at 100kg/s, 200kg/s, 300kg/s and 300kg/s.

Table 3.5: Levelised Cost of Electricity (Resource Depth = 1000m)

Well flow rate (kg/s)	LCOE (cent/kWh)
100	43.010
200	49.916
300	64.556
400	111.050

Table 3.6: Levelised Cost of Electricity (Resource Depth = 2000m)

Well Flow rate (kg/s)	LCOE (cent/kWh)
100	48.223
200	53.629
300	69.163
400	126.012

Table 3.7: Levelised Cost of Electricity (Resource Depth =3000m)

Well Flow rate (kg/s)	LCOE (cent/kWh)
100	59.046
200	64.937
300	91.739
400	-

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 INTRODUCTION

This section will discuss the various results obtained in the course of evaluating the levelised cost of electricity.

4.1 RESULTS AND DISCUSSION

Using the geochemical analysis of the water at Rafin Reewa warm spring, the temperature of the study area is evaluated using the various cations geothermometers. With exception of the value obtained from Na-Ca-K geothermometer, the values obtained show some level of consistency. The value obtained by equation (10); Arnorsson and Stefansson (1998), is considered to be more reliable than other values, hence it is therefore preferred (see 2.9.1.2 for reason). Consequently, the temperature of the study area is evaluated to be 122.14^{O}C using geothermometer established by Arnorsson and Stefansson (1998). Also, the various temperatures obtained from the Na-K geothermometers indicate that the temperature of the geofluid in the study area is within the range of 111.00^{O}C - 126.28^{O}C. Hence, the resource can be categorized as hydrothermal geothermal resource. On the basis of the established temperature of the study area, binary power plant that operates using geofluid of temperature range of 100^{O}C – 180^{O}C is found to be the appropriate energy conversion system that can utilize resource at Rafin Reewa.

Using GETEM with well flow rate as the variable, the cost for the various developmental phases were evaluated. Table 4.1 shows the variation of the cost of geothermal power plant developmental phase as applied to Rafin Reewa hot spring.

Table 4.1: Cost of Developmental Phases (Resource Depth = 1000m)

Well flow rate (kg/s)	Project Phases cost (USD)				
	Exploration	Confirmation	Well field development	Production Pumping	Injection pumping
100	15,063,515	32,557,613	39,738,519	2,393,906	1,263,830
200	15,030,377	32,557,613	21,377,457	2,921,065	2,023,276
300	15,023,957	32,557,613	19,577,143	3,189,691	2,877,691
400	15,031,715	32,557,613	28,352,488	6,623,546	4,225,546

The result shows that, at the flow rate of 100kg/s and resource depth of 1000m, the cost of well field development is $39,738,519 (N7, 947,703,800) which is appreciably higher than the cost of developing a well field at the same depth but with a production flow rate of 300kg/s $19,577,457 (N3,915,491,400). This indicates that, the well productivity is a factor that influences the cost of well field development of a geothermal power plant. A comparison of the various costs involved in the developmental phases of geothermal power plant as shown in table 4.1 suggested that, the cost is highest during the well field development followed by confirmation. The result in table 4.1 above also shows that irrespective of the production flow rate, the costs of exploration and confirmation remain relatively unchanged but with slight differences.

The result in table 4.2 indicates that, the depth has an increasingly significant impact on almost the geothermal plant developmental cost. The result suggested that the cost as expected is high at the drilling depth of 3000m for all the projects. This is linked to additional cost incurred as a result of application of modern drilling technologies which is more expensive. The costs of production and injection pumping as shown by the result slightly changed; this is because the flow rate which these parameters depend on also remains unchanged. Figure 4.1 shows the percentage of distribution of the developmental phases towards the total developmental cost.

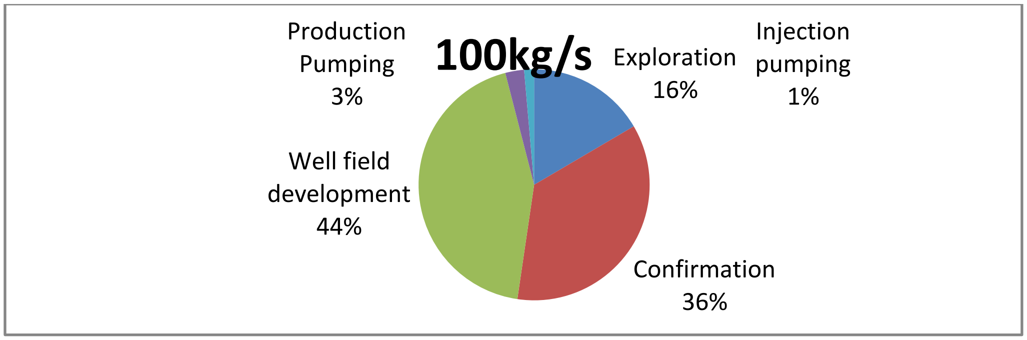


Figure 4.1: Distribution of developmental cost (Production Flow Rate =100kg/s)

Table 4.2: Cost of Developmental Phases (Production Flow Rate = 100kg/s)

Resource Depth (meters)	Project Phases cost (USD)				
	Exploration	Confirmation	Well field development	Production Pumping	Injection pumping
1000	15,063,515	32,557,613	39,738,519	2,393,906	1,263,830
2000	24,508,472	60,328,246	67,647,426	2,188,662	1,257,402
3000	42,086,146	112,006,660	120,791,814	2,040,420	1,215,130

Table 4.3 shows the variation of present value of power produced with the production flow rate. The result indicates that the lowest present value of electricity produced occurred at the resource flow rate of 400 kg/s which is 73,165kWh/kW. The low present value of electricity at this flow rate (400kg/s) shows the potential to have reasonable short installation payback period. Consequently, this illustrates that the flow rate is a significant factor in the payback period of a geothermal plant.

Table 4.3: Present Value of Power Produced (Resource Depth = 1000m)

Production Flow rate (kg/s)	Present Value of Power Produced (kW-h/kW)
100	93,048
200	90,716
300	86,227
400	73,165

The present value of power produced is also found to be influence by the resource depth as shown by Table 4.4. Comparing the two results from the table 4.3 and table 4.4, present value of power produced is lower with respect to resource depth than with production flow rate.

Table 4.4: Present Value of Power Produced (Production Flow Rate = 100kg/s)

Resource depth (meters)	Present Value of Power Produced (kW-h/kW)
1000	73,165
2000	70,627
3000	-

From the result in table 4.4, it is evident that the present value of power is minimum at the resource depth of 2000m for a given production flow rate of 100kg/s. Hence, this indicates that resource depth is more significant than production flow rate in the payback period of geothermal plant. From table 4.4, it is evident that the present value of electricity cannot be evaluated at a resource depth of 3000m. This is because the pump depth has exceeded the specific limit of 2100m at this resource depth; consequently the geothermal pumping power exceeds the plant output. Figure 4.2 shows the effect of resource depth on present value of power produced.

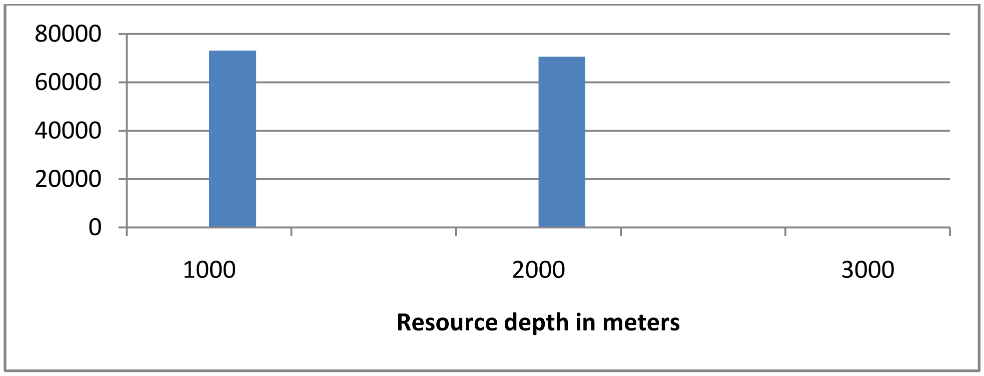


Figure 4.2: Effect of resource depth on present value of electricity produced

Table 4.5: Cost of Power Plant (Resource Depth = 1000m)

Well Flow rate (kg/s)	Cost of Power (USD)
100	663,609,961
200	787,025,857
300	1,019,614,568
400	1,580,095,757

Table 4.6: Cost of Power Plant (Production Flow Rate = 100kg/s)

Resource Depth (meters)	Cost of Power (USD)
1000m	663,609,961
2000m	673,560,745
3000m	694,939,597

Table 4.5 and table 4.6 above shows that the expected cost of installing a power plant at study area increases with production flow rate and resource depth. Comparing the results in the two tables, the increase in cost of installing a power plant at the study area is more significant with the production flow rate.

The cost of O&M of a power plant is influence by the resource depth of the geofluid as well as the production well flow rate as indicated in table 4.7. The flow rate affects the cost of O&M appreciably than the resource depth more particularly at high flow rate. Consequently, when the two factors are compared, the flow rate is the determining factor in evaluating the cost of O&M. One important note is that, the cost of O&M will rise appreciably as the components of the power plant aged.

Table 4.7: Cost of O&M

Resource depth (metre)	Cost of O&M (cent/kWh)			
	100 kg/s	200 kg/s	300 kg/s	400 kg/s
1000	1.05	1.20	1.54	2.56
2000	1.17	1.29	1.65	2.89
3000	1.43	1.56	2.17	-

The variations of the LCOE with respect to the production flow rates and resource depths are presented in table 4.8. From the results of the LCOE in table 4.8, analysis has shown that, the LCOE at a given flow rate increases as the depth of the resource increases but not remarkably high. For at a flow rate of 100kg/s, LCOE is evaluated to be 43.010 cent/kWh (N86.02 /kWh) at depth of 1000m, while LCOE is 48.223 cent/kWh (N96.45/kWh) at depth of 2000m. Furthermore, LCOE at depth of 3000m is 59.046 cent/kWh (N118. 09/kWh).

Table 4.8: Variation of LCOE with Resource Depth and Production Flow Rate

Resource depth (metre)	Levelised Cost of Electricity (cent/kWh)			
	100 kg/s	200 kg/s	300 kg/s	400 kg/s
1000	43.010	49.916	64.556	111.040
2000	48.223	53.629	69.163	127.189
3000	59.046	64.937	91.739	-

As seen on the figure 4.3, the LCOE at a certain resource depth rises significantly with the well production flow rate. At a depth of 1000m, the LCOE is 43.010 cent/kWh (N86.02 /kWh) at a flow rate of 100kg/s and increase appreciably to approximately 111.040 cent/kWh (N222.08 /kWh) when the flow rate increases to 400kg/s. Consequently, a notable increase in LCOE is observed within the two variables but more pronounceable with the flow rates. Figure 4.3 to 4.6 shows how these variables affect the LCOE graphically.

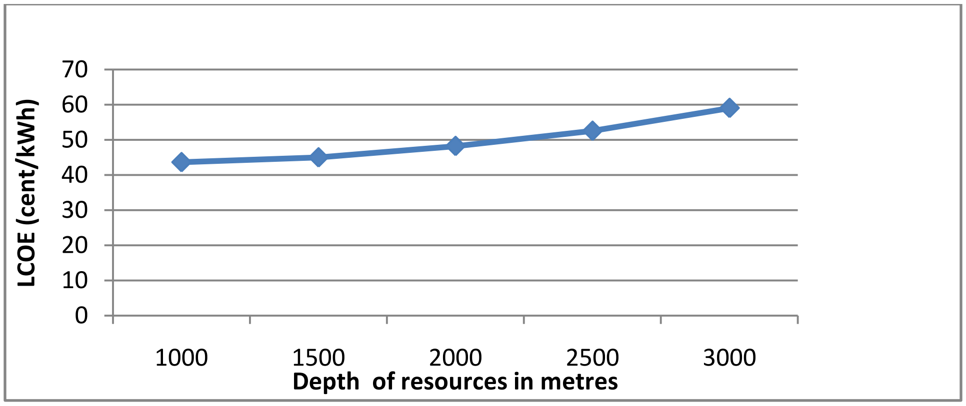


Figure 4.3: Levelised Cost of Electricity (Production Flow Rate = 100kg/s)

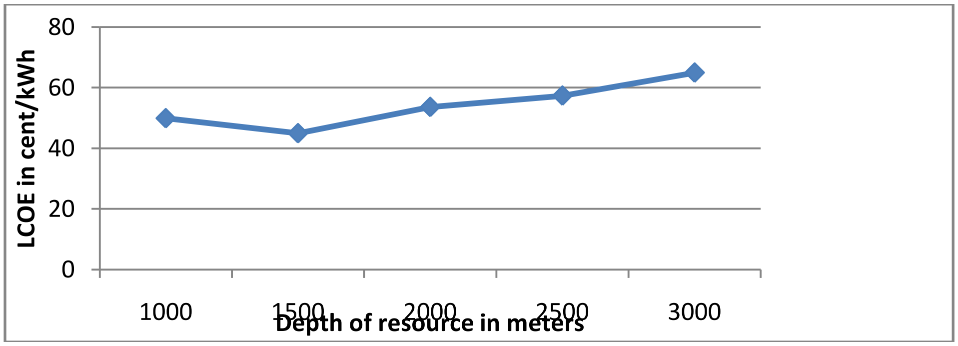


Figure 4.4: Variation of LCOE with Resource Depth (Production Flow Rate = 200kg/s)

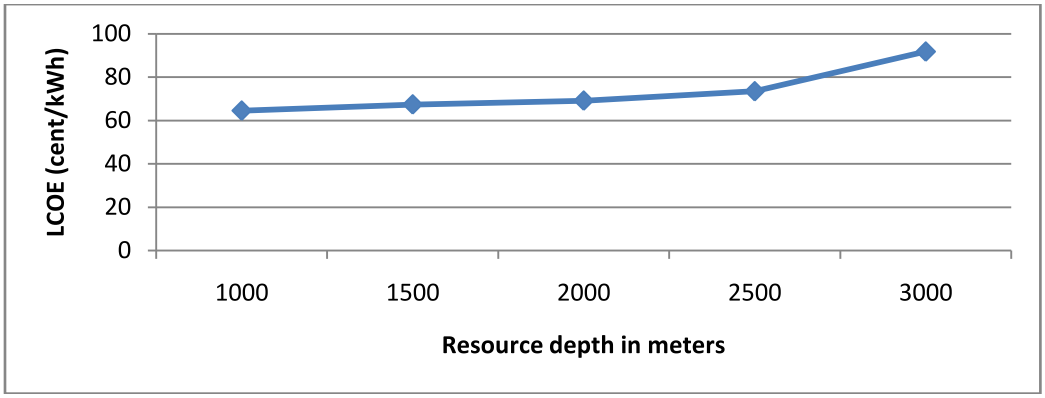


Figure 4.5: Variation of LCOE with Resource Depth (Production Flow Rate = 300kg/s)

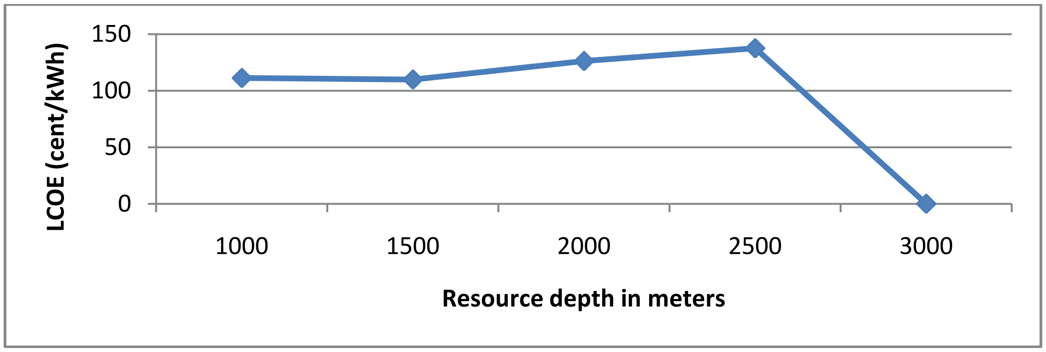


Figure 4.6: Variation of LCOE with Resource Depth (Production Flow Rate = 400kg/**s)**

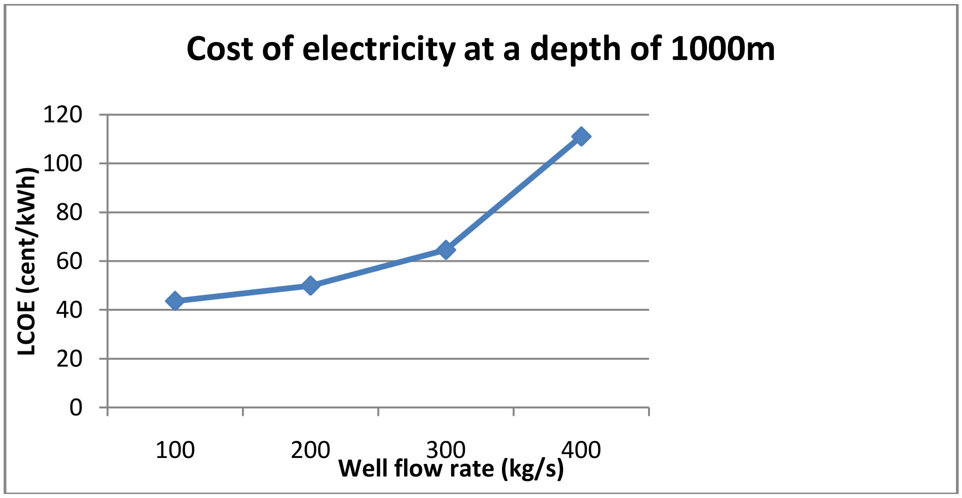


Figure 4.7: Variation of LCOE with production flow rate.

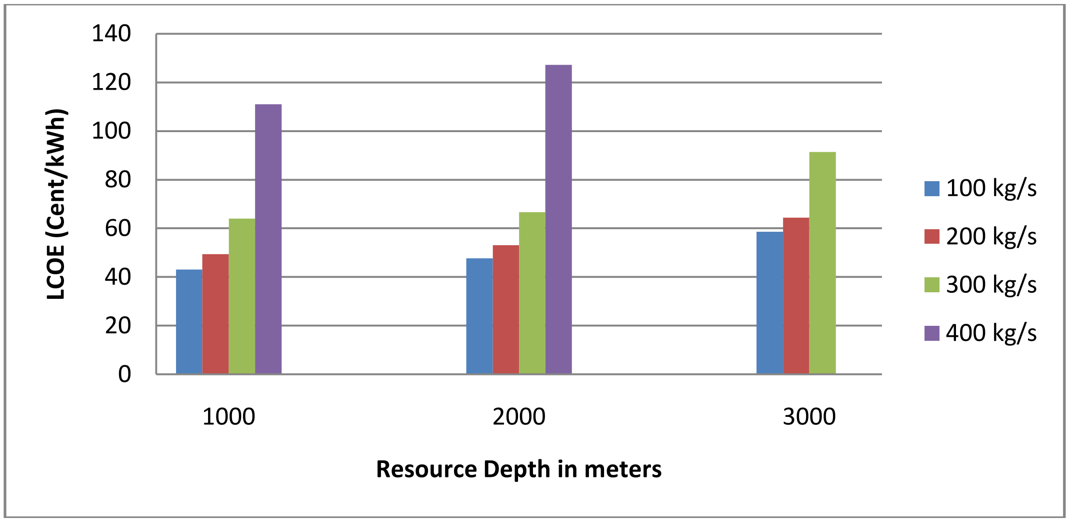


Figure 4.8: Impact of resource depth on LCOE

A different view of the result is to identify LCOE based on flow rates for comparison as shown in figure 4.8. This view shows more clearly that the lower flow rate of 100kg/s is desirable under almost any resource depth. In fact, the 400kg/s flow rate appears to be impractical at a depth of 3000m as indicated by the missing column of 400kg/s at 3000m in figure 4.8. The influences of the three (3) different geothermal gradients do not appear to be very significant at these flow rates as illustrated by the close proximity of the columns. It appears that the flow rate is the most influential variable over resource depth. This suggests that an average flow rate with a modest resource depth; such as production flow rate of 100kg/s and resource depth of 1000m, may likely outperform a high flow rate at a lower resource depth.

The net brine effectiveness, .or, the net electrical energy produced by the plant per unit mass of geofluid, has been identified as the primary indicator of the improvements in the cycle performance.

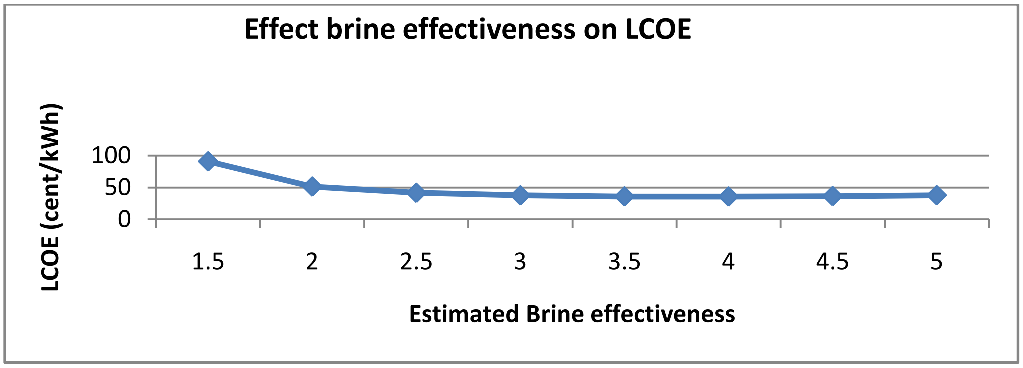


Figure 4.9: Effect of net brine effectiveness on the LCOE

The levelised cost of electricity is a direct function of the Plant performance (net brine effectiveness) as indicated by figure 4.9 (Note that a value >1 indicates an increase in performance, i.e., brine effectiveness.). At the net brine effectiveness of 1.5, the cost of electricity 90.988 cent/kWh (N181. 98/kWh), while at brine effectiveness of 4.0, the LCOE is 35.963 cent/kWh (N71. 92/kWh). This indicates that the higher the net brine effectiveness, the lower the LCOE.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 SUMMARY

1. The study established that the temperature of the geofluid at the study area is 122.14°C
2. It is possible to generate electricity from the geofluids at Rafin Reewa hot spring by using standard air-cooled binary-cycle technology.
3. Levelised cost of electricity (LCOE) analysis carried out using a Geothermal Electricity Technology Model (GETEM) indicates that well output (production flow rate), resource temperature and resource depth have a direct relationship with the levelized costs of electricity.
4. Analysis shows that both the flow rate and resource depth affect the LCOE with flow rate having the most significant effect.
5. The analysis of this study indicates that there is a direct relationship between the various cost factors and levelised cost. This direct relationship of the various factors to the levelized cost means that the levelized cost can be optimized by undertaking cost factor selection so as to obtain the least cost factor combination.
6. If the reservoir were able to supply only 100 kg/s at depth, the plant cost would vary from $663,609,961 to $694,939,597 (N132, 721,992,200 – N138, 987,919,400) for 50MW plant capacity depending on depth.
7. Brine effectiveness (plant performance) influenced the levelised cost of electricity significantly.

8. If a mass flow rate of 100 kg/s can be sustained from the 120°C reservoir, the cost of power plant will be less but with high present value of power produced.
9. Lowest cost of electricity of 43.010cent/kWh (N86.02/kWh) could be achieved with a flow rate of 100 kg/s and depth of 1000m from a 122.14°C Rafin Reewa hot spring reservoir using an air-cooled binary system.

i. Comparing the lowest LCOE obtained by this research study with other competitive power technologies available in Nigeria, the LCOE of 43.010cent/kWh (N86.02/kWh) is high but low when compare with the LCOE of solar CSP and PV technologies. Under these circumstances, it appears that low grade geothermal energy could be a practical source of power. While it is expected that a geothermal power project in Nigeria would use a binary cycle plant and thus would not emit any steam.

5.2 CONCLUSION

A study has been carried out at Rafin Reewa hot spring with the aim of evaluating the levelised cost of electricity generated from the resource located at the study area.

Using cations geothermometers, the study shows that the temperature of the geofluid at the study area is 122.14^{o}C. Hence, this indicates that electricity can be to generate from the geofluids at Rafin Reewa hot spring by using standard air-cooled binary-cycle technology.

Through the use of Geothermal Electricity Technology Model (GETEM), the study established that both the mass flow rate and the resource depth have significant effect on Levelised cost of electricity (LCOE). But mass flow rate has more impact on the LCOE than the resource depth. In conclusion, the study shows that the levelised cost of electricity (LCOE) using the resources at the study area is 43.010cent/kWh (N86.02/kWh) at a flow rate of 100 kg/s and depth of 1000m from a 122.14°C Rafin Reewa hot spring reservoir using an air-cooled binary system.

Although levelised cost of energy as indicated by this study is currently high and the prevalence of installed and operating geothermal power plants is still somewhat limited, great potential for advancement of geothermal systems still exists.

While research on the geothermal potential in Rafin Reewa is still in the infant stage, several factors analyzed in this report appear very promising for the future. With an appropriate amount of funding, more conclusive evidence of this potential can be unearthed through research and eventual development. After all, the ability of a geothermal facility to provide consistent, base-load power cannot be ignored.

5.3 RECOMMENDATIONS

1. In arriving at the results of this study, no consideration was given to the optimum water withdrawal rates in relation to the size of the reservoir, the amount of heat flow in the reservoir or the possibility of soil subsidence in the study area. The study of this aspect may be significant value prior to the actual exploitation. Hence, it is recommended that these parameters should served as research area for further study.
2. It is obvious that the cost data used in this study is time dependent. As the prices of various items in the exploitation, confirmation, well field development and other aspect change, the cost of power will be affected, in some cases quite considerably. Hence, it is recommended that this study be periodically updated.

3. The potential of geothermal energy in evolving Nigerian energy markets is large and warrants a comprehensive research and demonstration effort to move this technology to commercial viability, especially as the country approaches a period when gap between demand for and generation of electricity is coming wider by day.
4. The analysis shows that the development of new geothermal energy resources will not be limited by the size and location of the resource in Nigeria, and it will occur at a critical time when grid stabilization with both replacement and new base-load power will be needed. Adding the geothermal energy option to the Nigeria energy portfolio will reduce growth in natural gas consumption and slow the need for adding/maintaining the fossil fuel facilities to handle Nigerian cripple power sector.
5. As we expect that the cost of power potential demonstrated in this study warrants a comprehensive research and demonstration effort to begin moving toward the period when replacement of retiring fossil and new capacity growth will most affect the Nigerian electrical supply.
6. While the results presented in this study are applicable to the study site conditions selected for analysis and the selected variables, the result can be easily adapted to incorporate the conditions at any similar location. The specific site conditions can be updated to reflect the specific conditions, and the levelised cost of electricity can be evaluated to reflect the conditions at that location.
7. Recognizing that current flow on renewable energy technologies is inadequate, it is recommended that demonstration projects on various renewable energy forms

be widely established especially geothermal energy; so that the performance and efficiency with which services are delivered can be calculated and sensitized.

5.4 CONTRIBUTION TO KNOWLEDGE

The study established that:

1. The geofluid temperature and LCOE of 43.010 cent/kWh (N86.02/kWh) are suitable for an air-cooled binary geothermal power plant at Rafin Reewa hot spring at a flow rate of 100kg/s and a resource depth of 1000m.
2. The total plant cost, exclusive of exploration wells, for an air-cooled binary power plant of 50MW for Rafin Reewa hot spring is $663,609,961 (N13, 272,198,200) at a flow rate of 100kg/s and a depth of 1000m.
3. The study informs the ongoing debate of how to provide a more sustainable and secure energy supply for Nigeria for the long term, without compromising our economic capacity and political and social stability, and while minimizing environmental impacts.

5.5 LIMITATIONS

1. The study didn’t establish the amount of geofluid reserve of the Rafin Reewa hot spring.
2. Insufficient literatures on geothermal energy technologies of hot springs in Nigeria.

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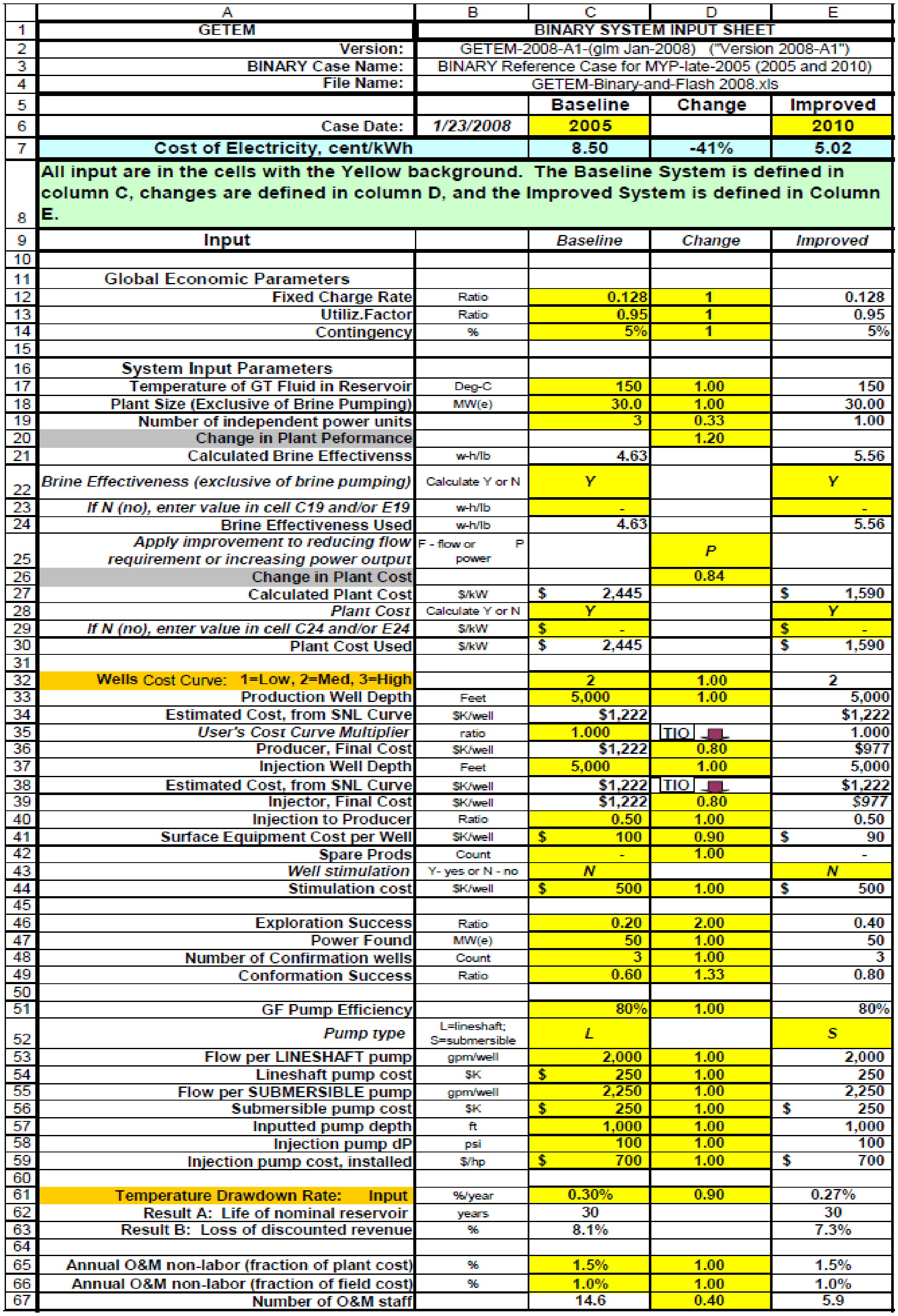
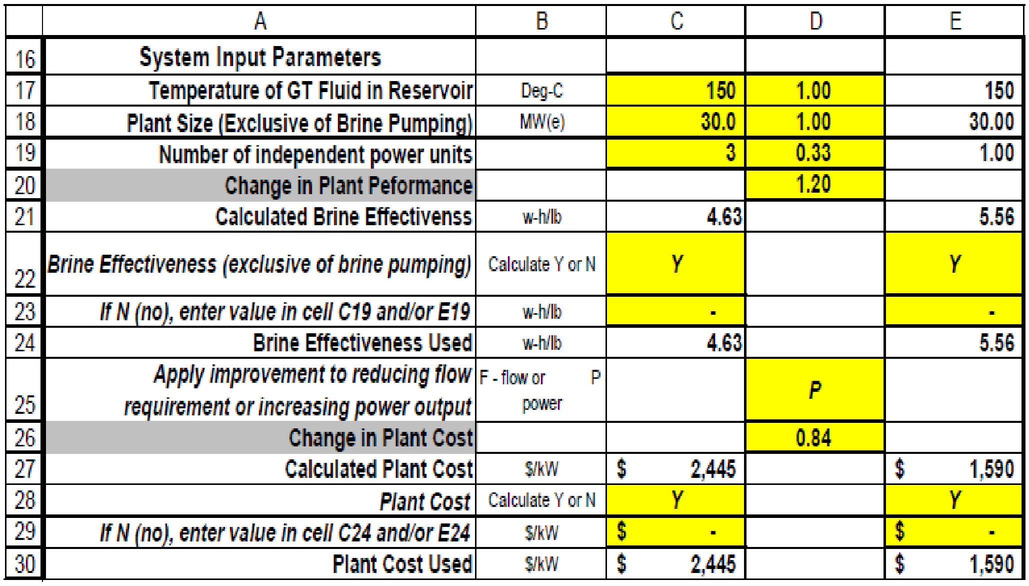
APPENDIX A1**: GETEM Input for Binary Worksheets**



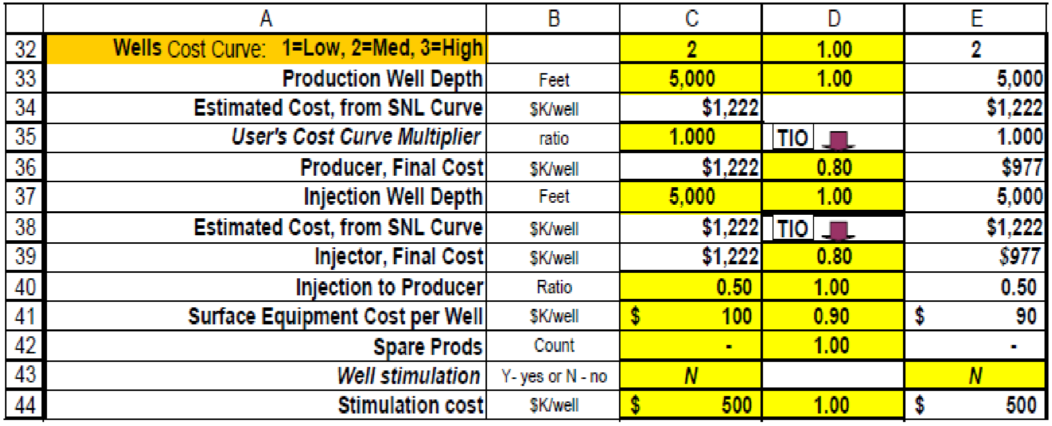
	A	B	C	D	E
1	GETEM	BINARY SYSTEM INPUT SHEET			
2	Version:	GETEM-2008-A1-(glm Jan-2008) ("Version 2008-A1")			
3	BINARY Case Name:	BINARY Reference Case for MYP-late-2005 (2005 and 2010)			
4	File Name:	GETEM-Binary-and-Flash 2008.xls			
5			Baseline	Change	Improved
6	Case Date:	1/23/2008	2005		2010
7	Cost of Electricity, cent/kWh		8.50	-41%	5.02
8	All input are in the cells with the Yellow background. The Baseline System is defined in column C, changes are defined in column D, and the Improved System is defined in Column E.				
9	Input		*Baseline*	*Change*	*Improved*
10					
11	Global Economic Parameters				
12	Fixed Charge Rate	Ratio	0.128	1	0.128
13	Utiliz.Factor	Ratio	0.95	1	0.95
14	Contingency	%	5%	1	5%
15					
16	System Input Parameters				
17	Temperature of GT Fluid in Reservoir	Deg-C	150	1.00	150
18	Plant Size (Exclusive of Brine Pumping)	MW(e)	30.0	1.00	30.00
19	Number of independent power units		3	0.33	1.00
20	Change in Plant Peformance			1.20	
21	Calculated Brine Effectivenss	w-h/lb	4.63		5.56
22	*Brine Effectiveness (exclusive of brine pumping)*	Calculate Y or N	*Y*		*Y*
23	*If N (no), enter value in cell C19 and/or E19*	w-h/lb	-		-
24	Brine Effectiveness Used	w-h/lb	4.63		5.56
25	*Apply improvement to reducing flow requirement or increasing power output*	F - flow or P power		*P*	
26	Change in Plant Cost			0.84	
27	Calculated Plant Cost	$/kW	$ 2,445		$ 1,590
28	*Plant Cost*	Calculate Y or N	*Y*		*Y*
29	*If N (no), enter value in cell C24 and/or E24*	$/kW	$ -		$ -
30	Plant Cost Used	$/kW	$ 2,445		$ 1,590
31					
32	Wells Cost Curve: 1=Low, 2=Med, 3=High		2	1.00	2
33	Production Well Depth	Feet	5,000	1.00	5,000
34	Estimated Cost, from SNL Curve	$K/well	$1,222		$1,222
35	*User's Cost Curve Multiplier*	ratio	1.000	TIO	1.000
36	Producer, Final Cost	$K/well	$1,222	0.80	$977
37	Injection Well Depth	Feet	5,000	1.00	5,000
38	Estimated Cost, from SNL Curve	$K/well	$1,222	TIO	$1,222
39	Injector, Final Cost	$K/well	$1,222	0.80	$977
40	Injection to Producer	Ratio	0.50	1.00	0.50
41	Surface Equipment Cost per Well	$K/well	$ 100	0.90	$ 90
42	Spare Prods	Count	-	1.00	-
43	*Well stimulation*	Y- yes or N - no	*N*		*N*
44	Stimulation cost	$K/well	$ 500	1.00	$ 500
45					
46	Exploration Success	Ratio	0.20	2.00	0.40
47	Power Found	MW(e)	50	1.00	50
48	Number of Confirmation wells	Count	3	1.00	3
49	Conformation Success	Ratio	0.60	1.33	0.80
50					
51	GF Pump Efficiency		80%	1.00	80%
52	*Pump type*	L=lineshaft; S=submersible	*L*		*S*
53	Flow per LINESHAFT pump	gpm/well	2,000	1.00	2,000
54	Lineshaft pump cost	$K	$ 250	1.00	250
55	Flow per SUBMERSIBLE pump	gpm/well	2,250	1.00	2,250
56	Submersible pump cost	$K	$ 250	1.00	$ 250
57	Inputted pump depth	ft	1,000	1.00	1,000
58	Injection pump dP	psi	100	1.00	100
59	Injection pump cost, installed	$/hp	$ 700	1.00	$ 700
60					
61	Temperature Drawdown Rate: Input	%/year	0.30%	0.90	0.27%
62	Result A: Life of nominal reservoir	years	30		30
63	Result B: Loss of discounted revenue	%	8.1%		7.3%
64					
65	Annual O&M non-labor (fraction of plant cost)	%	1.5%	1.00	1.5%
66	Annual O&M non-labor (fraction of field cost)	%	1.0%	1.00	1.0%
67	Number of O&M staff		14.6	0.40	5.9

Appendix A2: GETEM Input for Resource Temperature and Power factor



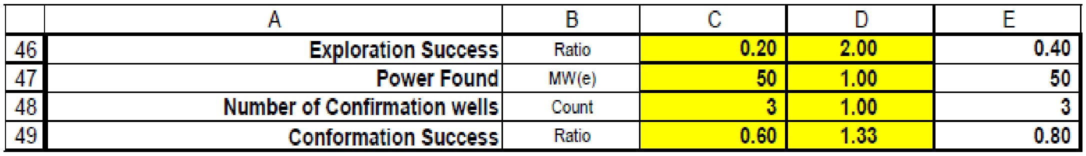
	A	B	C	D	E
16	System Input Parameters				
17	Temperature of GT Fluid in Reservoir	Deg-C	150	1.00	150
18	Plant Size (Exclusive of Brine Pumping)	MW(e)	30.0	1.00	30.00
19	Number of independent power units		3	0.33	1.00
20	Change in Plant Peformance			1.20	
21	Calculated Brine Effectivenss	w-h/lb	4.63		5.56
22	*Brine Effectiveness (exclusive of brine pumping)*	Calculate Y or N	*Y*		*Y*
23	*If N (no), enter value in cell C19 and/or E19*	w-h/lb	-		-
24	Brine Effectiveness Used	w-h/lb	4.63		5.56
25	*Apply improvement to reducing flow requirement or increasing power output*	F - flow or P power		*P*	
26	Change in Plant Cost			0.84	
27	Calculated Plant Cost	$/kW	$ 2,445		$ 1,590
28	*Plant Cost*	Calculate Y or N	*Y*		*Y*
29	*If N (no), enter value in cell C24 and/or E24*	$/kW	$ -		$ -
30	Plant Cost Used	$/kW	$ 2,445		$ 1,590

Appendix A3: GETEM Input for Cost of Production and Injection Wells



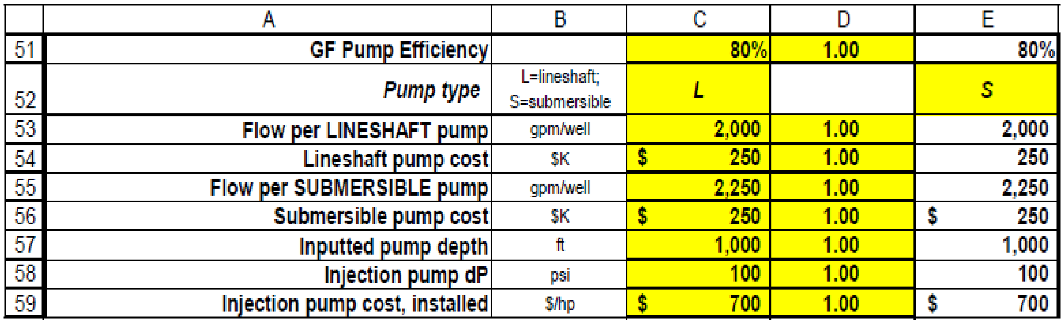
	A	B	C	D	E
32	Wells Cost Curve: 1=Low, 2=Med, 3=High		2	1.00	2
33	Production Well Depth	Feet	5,000	1.00	5,000
34	Estimated Cost, from SNL Curve	$K/well	$1,222		$1,222
35	*User's Cost Curve Multiplier*	ratio	1.000	TIO	1.000
36	Producer, Final Cost	$K/well	$1,222	0.80	$977
37	Injection Well Depth	Feet	5,000	1.00	5,000
38	Estimated Cost, from SNL Curve	$K/well	$1,222	TIO	$1,222
39	Injector, Final Cost	$K/well	$1,222	0.80	$977
40	Injection to Producer	Ratio	0.50	1.00	0.50
41	Surface Equipment Cost per Well	$K/well	$ 100	0.90	$ 90
42	Spare Prods	Count	-	1.00	-
43	*Well stimulation*	Y- yes or N - no	*N*		*N*
44	Stimulation cost	$K/well	$ 500	1.00	$ 500

Appendix A4: GETEM Input for Exploration and Confirmation



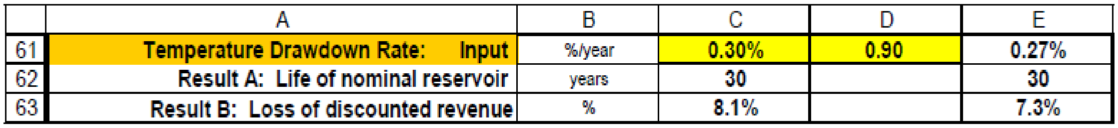
	A	B	C	D	E
46	Exploration Success	Ratio	0.20	2.00	0.40
47	Power Found	MW(e)	50	1.00	50
48	Number of Confirmation wells	Count	3	1.00	3
49	Conformation Success	Ratio	0.60	1.33	0.80

Appendix A5: GETEM Input for Production and Injection Pump



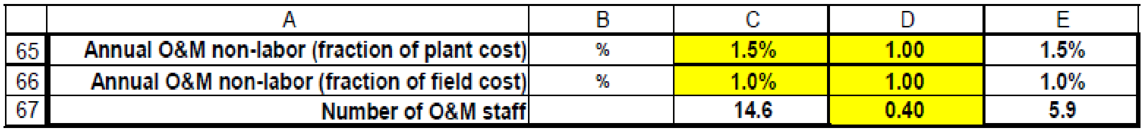
	A	B	C	D	E
51	GF Pump Efficiency		80%	1.00	80%
52	*Pump type*	L=lineshaft; S=submersible	*L*		*S*
53	Flow per LINESHAFT pump	gpm/well	2,000	1.00	2,000
54	Lineshaft pump cost	$K	$ 250	1.00	250
55	Flow per SUBMERSIBLE pump	gpm/well	2,250	1.00	2,250
56	Submersible pump cost	$K	$ 250	1.00	$ 250
57	Inputted pump depth	ft	1,000	1.00	1,000
58	Injection pump dP	psi	100	1.00	100
59	Injection pump cost, installed	$/hp	$ 700	1.00	$ 700

Appendix A6: GETEM Input for Reservoir Drawdown and Makeup



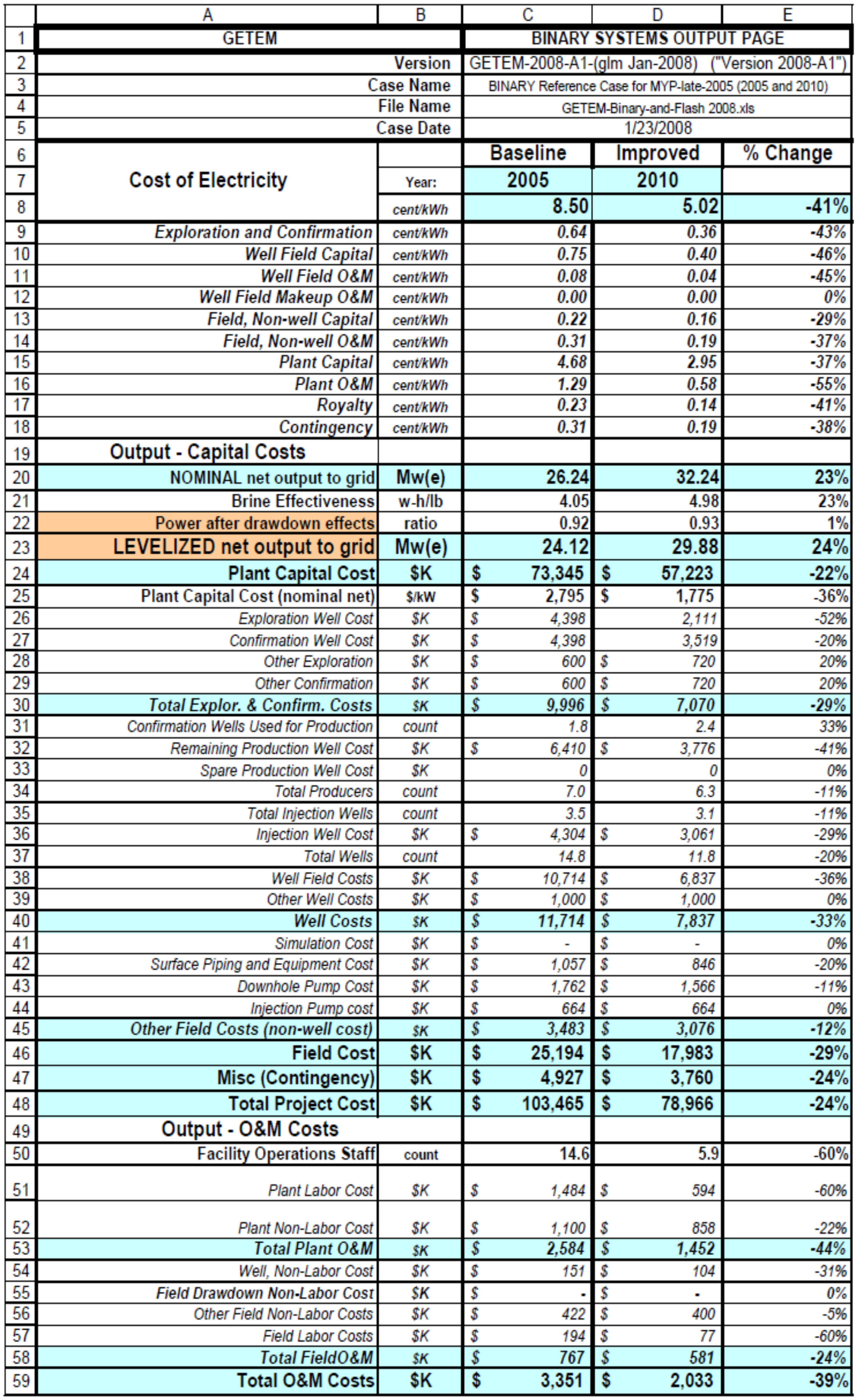
	A	B	C	D	E
61	Temperature Drawdown Rate: Input	%/year	0.30%	0.90	0.27%
62	Result A: Life of nominal reservoir	years	30		30
63	Result B: Loss of discounted revenue	%	8.1%		7.3%

Appendix A7: GETEM Input for Operation and Maintenance



	A	B	C	D	E
65	Annual O&M non-labor (fraction of plant cost)	%	1.5%	1.00	1.5%
66	Annual O&M non-labor (fraction of field cost)	%	1.0%	1.00	1.0%
67	Number of O&M staff		14.6	0.40	5.9

Appendix B: Output Sheet for Binary Power Plant Technology



	A	B	C	D	E
1	GETEM		BINARY SYSTEMS OUTPUT PAGE		
2		Version	GETEM-2008-A1-(glm Jan-2008) ("Version 2008-A1")		
3		Case Name	BINARY Reference Case for MYP-late-2005 (2005 and 2010)		
4		File Name	GETEM-Binary-and-Flash 2008.xls		
5		Case Date	1/23/2008		
6	Cost of Electricity		Baseline	Improved	% Change
7		Year:	2005	2010	
8		cent/kWh	8.50	5.02	-41%
9	*Exploration and Confirmation*	cent/kWh	*0.64*	*0.36*	-43%
10	*Well Field Capital*	cent/kWh	*0.75*	*0.40*	-46%
11	*Well Field O&M*	cent/kWh	*0.08*	*0.04*	-45%
12	*Well Field Makeup O&M*	cent/kWh	*0.00*	*0.00*	0%
13	*Field, Non-well Capital*	cent/kWh	*0.22*	*0.16*	-29%
14	*Field, Non-well O&M*	cent/kWh	*0.31*	*0.19*	-37%
15	*Plant Capital*	cent/kWh	*4.68*	*2.95*	-37%
16	*Plant O&M*	cent/kWh	*1.29*	*0.58*	-55%
17	*Royalty*	cent/kWh	*0.23*	*0.14*	-41%
18	*Contingency*	cent/kWh	*0.31*	*0.19*	-38%
19	Output - Capital Costs				
20	NOMINAL net output to grid	Mw(e)	26.24	32.24	23%
21	Brine Effectiveness	w-h/lb	4.05	4.98	23%
22	Power after drawdown effects	ratio	0.92	0.93	1%
23	LEVELIZED net output to grid	Mw(e)	24.12	29.88	24%
24	Plant Capital Cost	$K	$ 73,345	$ 57,223	-22%
25	Plant Capital Cost (nominal net)	$/kW	$ 2,795	$ 1,775	-36%
26	*Exploration Well Cost*	$K	$ 4,398	2,111	-52%
27	*Confirmation Well Cost*	$K	$ 4,398	3,519	-20%
28	*Other Exploration*	$K	$ 600	$ 720	20%
29	*Other Confirmation*	$K	$ 600	$ 720	20%
30	*Total Explor. & Confirm. Costs*	$K	$ 9,996	$ 7,070	-29%
31	*Confirmation Wells Used for Production*	count	1.8	2.4	33%
32	*Remaining Production Well Cost*	$K	$ 6,410	$ 3,776	-41%
33	*Spare Production Well Cost*	$K	0	0	0%
34	*Total Producers*	count	7.0	6.3	-11%
35	*Total Injection Wells*	count	3.5	3.1	-11%
36	*Injection Well Cost*	$K	$ 4,304	$ 3,061	-29%
37	*Total Wells*	count	14.8	11.8	-20%
38	*Well Field Costs*	$K	$ 10,714	$ 6,837	-36%
39	*Other Well Costs*	$K	$ 1,000	$ 1,000	0%
40	*Well Costs*	$K	$ 11,714	$ 7,837	-33%
41	*Simulation Cost*	$K	$ -	$ -	0%
42	*Surface Piping and Equipment Cost*	$K	$ 1,057	$ 846	-20%
43	*Downhole Pump Cost*	$K	$ 1,762	$ 1,566	-11%
44	*Injection Pump cost*	$K	$ 664	$ 664	0%
45	*Other Field Costs (non-well cost)*	$K	$ 3,483	$ 3,076	-12%
46	Field Cost	$K	$ 25,194	$ 17,983	-29%
47	Misc (Contingency)	$K	$ 4,927	$ 3,760	-24%
48	Total Project Cost	$K	$ 103,465	$ 78,966	-24%
49	Output - O&M Costs				
50	Facility Operations Staff	count	14.6	5.9	-60%
51	*Plant Labor Cost*	$K	$ 1,484	$ 594	-60%
52	*Plant Non-Labor Cost*	$K	$ 1,100	$ 858	-22%
53	*Total Plant O&M*	$K	$ 2,584	$ 1,452	-44%
54	*Well, Non-Labor Cost*	$K	$ 151	$ 104	-31%
55	*Field Drawdown Non-Labor Cost*	$K	$ -	$ -	0%
56	*Other Field Non-Labor Costs*	$K	$ 422	$ 400	-5%
57	*Field Labor Costs*	$K	$ 194	$ 77	-60%
58	*Total FieldO&M*	$K	$ 767	$ 581	-24%
59	Total O&M Costs	$K	$ 3,351	$ 2,033	-39%