# THE FUTURE OF GEOTHERMAL ENERGY IN WEST AFRICA

## Enhanced Geothermal Systems Solutions

Victor Ibe

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TAMPEREEN AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

**PREFACE**

In September 2010, we made a school trip from Tampere University of Applied Sciences Finland, where I have been studying Environmental Engineering for the past 3.5years, to Iceland shortly after the Eyjafjallajökull eruptions. We visited the monumental geothermal plants and witnessed first-hand other direct applications of this enormous heat emanating from below the Earth. The country at the time had a population of a little over 300,000 inhabitants but yet had made much effort towards establishing a sustainable living environment. These efforts have led to numerous environmental awards from different international bodies and also placed Iceland on a mentor platform for many other nations.

I have ever since seen the bright side of a geothermal-powered West Africa, even though most of the light in this respect is cast on the so-called “geothermal hotspots” due to the special potential of those regions. Born and brought up in Lagos, Nigeria, I have paid close attention to the energy situation in the West African region and always hoped that one day there would be possibilities for greener decentralized options. I confidently predict? a future not too far ahead when geothermal energy will produce sufficient power to drive the future West African economies. Innovations in research and development thus give hope through Enhanced Geothermal Systems, as will be discussed in further detail.

Western Africa is undoubtedly endowed with abundant mineral resources and energy potentials, which, unfortunately, can be defined at present as ‘under-utilized’. However, it is absolutely unsustainable to live passively amidst such potential agents of change as the resources under our feet, when we have all it takes to activate the green energy future. Today there are quite a number of topics which come to mind when the issue of renewable energy is raised. However, I have a special interest and confidence in what is obtainable from the evergreen geothermal reserves of the Earth. The future is possible.

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Degree Programme in Environmental Engineering

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**ABSTRACT**

In the last two decades, the energy situation in West Africa has received rather negative remarks in terms of output quality and environmental friendliness. The problems of intermittent power supply and unavailability, especially in the rural areas, are on the rise as population increases and service quality drops.

This study analyses geothermal energy for the sake of basic understanding in order to shed more light on Enhanced Geothermal Systems as a preferred option, reviewing the possible challenges and viability of a project of this nature in the region. The present energy status is considered in more detail, together with reasons underlying it. More so, it reflects on the past, present and future trends to give an idea of what the actual future would look like depending on the choices we make today.

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Key words: enhanced geothermal energy, hydrothermal, hydrofracture, hotspots.

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# 1 INTRODUCTION

The present energy situation in Western Africa reflects commendable efforts which have brought us to a pivot that should mark the start of a progressive energy revolution in the direction of renewable, and readily available, sustainable energy options. In spite of West Africa’s previous energy achievements, there is room to build a future of uninterrupted power supply by creating reliable backups or even upgrading existing systems to more reliable ones. Unfortunately, only 1 out of 3 people in west Africa enjoy access to electricity and sadly, the situation is expected to worsen by 5% yearly for the next 20years (Doblas, M., et al 2002).

However, this study communicates the possibilities, challenges and feasibility of installing geothermal systems as reliable options for the West African green energy future. Geothermal energy is one on the least considered power alternatives due to regional geological conditions, but with technological research and development in Environmental Engineering, the future is possible. I see Enhanced Geothermal Systems (EGS) as a viable option which would stand, irrespective of these limiting location setbacks, and have therefore analysed the limiting factors which have plagued the past, present and future of this energy resource in West Africa.

The aim of this study is to identify the reasons for the present energy situation in West Africa and suggest an alternative back up energy supply which seemingly can be presented as the best renewable energy option for the region. There are actually more renewable energy options which can be considered as also viable with the potentials endowed on the region but we fix our focus on just one, which is the EGS.

It is quite difficult to implement a study of this nature without reviewing literature from others who have made similar related researches in this light. This document was facilitated and made possible by comparing data obtained from TAMK library, TAMK library e-resources, various journals, articles and web sources. Much knowledge was also obtained from our visits to the Icelandic geothermal stations.

# 2 GEOLOGY OF WEST AFRICA

## 2.1 History

The region consists of 15 countries which together form the Economic Community of West African States (ECOWAS) territory and occupies an area of about five million square meters (UNOWA, 2012). Detailed geological information of West Africa is quite difficult to obtain due to issues of access and availability. Only until recent times have more age long analysis been researched (Wright, J., et al 1985).

Dating back to the periods of geological time, the Achaean through the Proterozoic times specifically, the West African region gained its present topographical formations from the magmatic metamorphosis which transpired. During this period, due to underly- ing tectonic activities, orogeny belts developed within the West African craton (Liberty, 2008).

## 2.2 Geological materials

The West African craton represents one of the five African cratons which have existed since the Precambrian times and have been stable for over two billion years. It is composed of stable crystalline basement rock materials which form part of the African plate (Doblas, M., et al, 2002). The entire continent developed a structure made up of mostly metamorphic and granite rocks as is evident today as a result of the prehistoric geothermal activities (Wright, J., et al 1985). Moreover, the West African craton also accommodates volcanic sedimentary rocks and irons as well as minerals and well priced metals (or gems) in its eastern and central regions (Liberty, 2012).

## 2.3 Geological Development

Between the end of the Precambrian times and the beginning of the Cambrian era, there were a lot of magmatic activities within the West African craton. The movement of magma through the mantle and the metamorphoses which followed were triggered by the built up pressure in the earth's insulation and this processes have defined the present strata and rock nature obtainable in West Africa today. (Doblas, M., 2002)

Unfortunately, in the interest of conventional geothermal energy production in West Africa, there are not many evidences of volcanic activities which would suggest the logical viability of entire region to be powered by geothermal energy. From Olduvai Formation 3, 2003 however, it is emphasized that one glaring geothermal hotspot location in the region is the Cameroon rift which is expected to have existed since the Cainozoic era and stretches across a lengthy magnitude. The appearance of this rift was caused by early significant volcanic occurrences in the region, tending towards separating western Africa from central Africa. (Olduvai Formation 3, 2003)

# 3 GEOTHERMAL ENERGY

## 3.1 Basic facts

Information available about geothermal energy before the 1970's is not to be relied on as much as those from recent times. Lately, there are more tangible updates due to varying research and development in the field area. Even though this concept has been around for a while, newer discoveries and technological advancement make every step clearer as we go on. (DiPippo, 2008)

Geothermal Energy however is clean energy readily available in form of heat at the core of the earth and can be converted to meet our energy consumption needs today. Deep down the center of the earth has been known to be tremendously hot at its core through geological time, primarily due to the radioactive decay of elements which produce heat (Wright, J., et al 1985). The temperature at of the earth tends to increase with depth. A number of scientists have tried to dig deep into the earth in search of how hot the core could be in the actual sense. It was estimated that at a depth of 5100km from the surface, the heat ranges from about 4300$^{o}$C to 6000$^{o}$C at the molten iron liquid outer area of the core. Further probing to a distance of 6350km showed that the temperature varies from 4500$^{o}$C to 6600$^{o}$C at the inner solid part which represents the center of the core. (DiPippo, 2008)

This universally assessable heat energy has been, continuously converted to electricity and used in other direct application systems like warming swimming pools, and space heating in colder countries over the years. The heat available for use which emanates from the core is estimated to be able to sustain about 42 million MW of power. (Kage, A., Bales, D., Gawell, K. 2007)

The working operations of a geothermal system unit can be classified into surface and subsurface processes. This enables a two-way clear distinction of the entire ground work activities from the operations carried out above the ground. It simply distinguishes the source where the geothermal fuel starts from the other stage where electricity production or direct application is processed.

## 3.2 Basic operation of geothermal systems

To verify the tangibility of electricity generation through geothermal systems, there should be guaranteed availability of heated fluid which preferably should be naturally occurring at around temperatures of more or less than 175$^{o}$C. For energy to be generated, this fluid needs to be either readily available on site in naturally occurring favorable conditions called geothermal reservoirs or then it needs to recharged artificially as in Enhanced Geothermal Systems (EGS). This is obtainable from the subsurface and determines the choice surface systems, i.e. the plant and turbine type required at that station. (Kutscher, C. 2000)

The heat in the Earth’s core needs to be transferred to the surface by fluid circulation of some hydrothermal medium, magma networks, or even hot springs in order for steam to be derived and sent to the turbines for electricity production or other direct applications. Water with gaseous impurities heated by subsurface rocks is the typical nature of geothermal fluids (Povarov, K. 2005).

### 3.2.1 Surface processes

The entire processes from fluid source point, to the energy production phase, operating above the ground are defined as the surface processes. This describes the facilities, technologies and activities carried out on ground level where extracted heat resource is collected, processed and transmitted for energy conversion. On this platform, hot fluid is recovered and processed and the recovered steam is directed to spin the turbine blades through special equipment. The electricity produced is then sent to the grid and further to the consumers all on the surface. (Taylor, M., 2007)

### 3.2.2 Subsurface processes

This encompasses the operations and activities below the earth at a geothermal resource site. It describes the nature of the geothermal reservoirs and the conditions responsible for their nature as related to their extraction processes. The developments within this stage involve exploration, drilling and maintenance of the recovered resource. It requires careful high technological applications and could be expensive. (Taylor, M., 2007)

### 3.2.3 Production of Electricity

In order to produce electricity from a geothermal resource, there needs to be synergic interaction between station's plant equipment systems and natural geothermal conditions. This interaction is activated by extracting hot fluid from an identified geothermal reservoir for example, through established technically secure installations from the ground, and channeling derived steam to the surface station where it drives a turbine and produces electricity. (DiPippo, 2008)

## 3.3 Drilling

Drilling operations on a geothermal production site are usually preceded by some site preparation in order to ease the process and reduce the possibilities of avoidable distractions once the project activities commence. DiPippo (2008) mentioned the importance of being able to access the site by road before and during the site development phase as this can be quite difficult in volcanic regions having unsteady topography for example.

Drilling is done using similar equipment as in oil exploration and since this technology has been around for a while, it makes it a bit easier to obtain drilling equipment. Usually, three test holes are drilled during the initial stage. Samples from these drills are studied and documented as they give a clearer understanding of the profile and rock structure of the selected site. The samples have to be carefully checked and analyzed over and over before the site can be recommended for geothermal energy production. (Edwards L.M., 1982)

Some accidents are possible during the construction stage and could include the occurrence of a blowout or leakage of $H_2S$, $CO_2$ and other dangerous gases. Blowouts are being checked nowadays by legal demands on installing special equipment which can sense sudden pressure impulses and control the situation. Typically this special control equipment release the valves in order to lock the flow of the high pressured fluid until the process is calmed with cold water for example. Gas meters are not expensive and should be installed randomly and strategically on site to raise alarms in case of leakage which could be fatal. (DiPippo, 2008)

### 3.4 Plant Type

Turbines are basically selected depending on the fluid type available on site. This could either yield dry steam or a mixture of steam and water at source point, depending on the subsurface conditions. The two basic fluid types are either liquid dominated, which contain thermally stable water and vapour coexisting together, or vapour dominated, which are predominantly concentrated with steam. (Grant, M., and Bikley, P. 2011) The three plant types listed and explained subsequently have been designed to work specifically with each of the variable geothermal fuel types possibly obtainable on site.

#### 3.4.1 Flash steam plant

This plant distinctively separates high energy steam from its coexisting mixture of hot water without much pressure loss for usage advantages. This separation is made possible because of the difference in their physical properties and the process is known as flashing as the name implies. In 2007, flash steam plants already accounted for 56% of the total installed geothermal plants. (DiPippo, 2008)

Flash steam plants have been further developed to more specific types namely the single-flash power plants and double-flash power plants, with both functioning distinctively with respect to fluid pressure difference. The former is only able to function with high pressure superheated steam resource while the latter requires both high and low pressure vapour. (DiPippo, R., 1999)

Geothermal fluid usually comes above the earth, to the surface as a mixture of superheated water and vapour. The vapour which is used to drive turbines is either flashed from this mixture or used directly from high concentration naturally occurring vapour supplies. The latter is almost ready to be sent to the turbines and therefore avoids the flashing stage. However, it is rare but relatively more economical. (Letcher, T. 2008)

### 3.4.2 Dry steam power plant

This is used in vapour dominated sources where very hot dry steam is obtained naturally and channelled through special heat tolerant tubes directly to the turbine blades. These systems are usually designed with special attention paid to removal of possibly condensed water traces and other impurities coming from the source before it gets to the blades in order to improve the efficiency of the system. The natural dry steam resource for powering this system is not very common and thus, there were only two of these plants in operation as of 1999. (DiPippo, R., 1999)

## 3.5 Binary cycle power plants.

In the binary system, the geothermal fluid travels within a closed loop from the source point as hot fluid through the surface and back as cold fluid after its enthalpy has been altered due to energy intake by the system. It works as a system of two entirely different fluids with significantly different boiling points, but having simply heat exchange relationships and no real contacts. The first fluid is the geothermal fluid itself coming from the subsurface at a higher temperature while the secondary fluid is the heat acceptor, which has a lower boiling point. (DiPippo, R., 1999)

The heat acceptor, iso-pentane ($C_5H_{12}$) for example, evaporates fast at room temperature to drive the turbine blades and is condensed again, collected and returned to continue the cycle (DiPippo, R., 2008). The process shown in figure 1, (Geothermal Technologies Program. 2011, modified) shows the relationship between both fluids in normal working conditions.

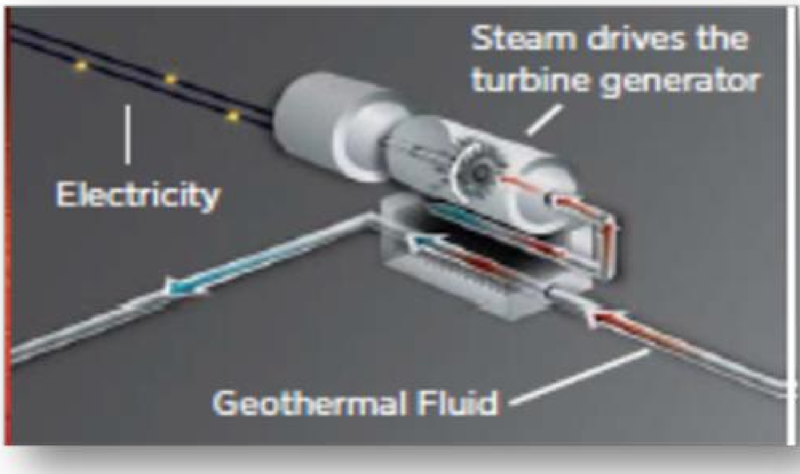


FIGURE 1. Energy production utilizing binary cycle (Geothermal Technologies Program. 2011 modified).

### 3.6 Global Geothermal Energy Production

Around the world, in 24 countries, the benefits of geothermal energy are currently being utilized. Due to the variable hydrothermal conditions, which are better at some locations and not favorable for energy production at others, only several countries have been harnessing this resource and the trend shows that since 1950, global production has risen from 200MW to 10,715 MW as of May 2010. The United states has maintained the largest production of electricity from geothermal resources while the situation has attenuated in Argentina. Iceland, considering its population has made reasonable efforts so far. (Lester, B. 2010) The table 1 below shows the progressive pattern of energy production from geothermal systems in the past 20 years. The results have been presentenced in 5 year intervals starting from 1990 records till 2010.

TABLE 1. International installed geothermal capacity between 1990 and 2010 (Lester, B. 2010).

| Country | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|
| | | | Megawatts | | |
| Argentina | 0.7 | 0.7 | 0.0 | 0.0 | 0.0 |
| Australia | 0.0 | 0.2 | 0.2 | 0.2 | 1.1 |
| Austria | 0.0 | 0.0 | 0.0 | 1.0 | 1.4 |
| China | 19.2 | 28.8 | 29.2 | 28.0 | 24.0 |
| Costa Rica | 0.0 | 55.0 | 142.5 | 163.0 | 166.0 |
| El Salvador | 95.0 | 105.0 | 161.0 | 151.0 | 204.0 |
| Ethiopia | 0.0 | 0.0 | 8.5 | 7.0 | 7.3 |
| France | 4.2 | 4.2 | 4.2 | 15.0 | 16.5 |
| Germany | 0.0 | 0.0 | 0.0 | 0.2 | 6.6 |
| Guatemala | 0.0 | 33.4 | 33.4 | 33.0 | 52.0 |
| Iceland | 44.6 | 50.0 | 170.0 | 322.0 | 575.0 |
| Indonesia | 144.8 | 309.8 | 589.5 | 797.0 | 1,179.0 |
| Italy | 545.0 | 631.7 | 785.0 | 790.0 | 843.0 |
| Japan | 214.6 | 413.7 | 546.9 | 535.0 | 535.2 |
| Kenya | 45.0 | 45.0 | 45.0 | 127.0 | 167.0 |
| Mexico | 700.0 | 753.0 | 755.0 | 953.0 | 958.0 |
| New Zealand | 283.2 | 286.0 | 437.0 | 435.0 | 628.0 |
| Nicaragua | 35.0 | 70.0 | 70.0 | 77.0 | 88.0 |
| Papua New Guinea | 0.0 | 0.0 | 0.0 | 39.0 | 56.0 |
| Philippines | 891.0 | 1,227.0 | 1,909.0 | 1,931.0 | 1,904.0 |
| Portugal | 3.0 | 5.0 | 16.0 | 16.0 | 29.0 |
| Russia | 11.0 | 11.0 | 23.0 | 79.0 | 82.0 |
| Taiwan | n.a. | n.a. | n.a. | n.a. | 3.3 |
| Thailand | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Turkey | 20.6 | 20.4 | 20.4 | 20.4 | 82.0 |
| United States | 2,774.6 | 2,816.7 | 2,228.0 | 2,544.0 | 3,086.0 |
| World Total | 5,831.7 | 6,866.8 | 7,974.1 | 9,064.1 | 10,715 |

# 4 ENERGY SITUATION IN WEST AFRICA

## 4.1 Energy demand

The energy situation in West Africa, considering its effect on local economies and the safety of our planet demands special attention in order for improvements to be made. Adenikinju A. 2008, cited that electricity supply from present sources in West Africa however, is not steady and due to the demand heights, people seek other alternatives not seeming to mind so much about the cost or what is at stake. Ghana for example is able to provide electricity to less than 60% of her national population, while Cote d'ivoire, Benin and Senegal supply less than 40%. Generally, rural areas suffer more shortage than urban ones. Kappiah, M., (2010) also mentioned that in West Africa today, only about 40% of people are able to get electricity to their homes in the cities, while in the villages, less than 8% get electricity.

There is an obvious margin between the forces of demand and supply of electricity around the West African region. The total power supply is not enough to satisfy the demands of the growing civil society due to lack of vibrant investment in the sector (Kappiah, M., 2010). Population, industrialization and the factors which drive development are naturally energy hungry; therefore it is impossible to sustain these economies without adequate supply, considering the trend. Obvious stress marks are visible on the regional economics which will either get better or worse depending on choices made today and in the near future.

In 2006 for example, there were cases where local businesses owned by private individuals have been closed down due to power shortages. Two specific examples were cited by Adenikinju A. 2008 from Nigeria and Ghana. The mains supplies as viewed from various angles of the economy are not capable of sustaining the demands of the growing population. The growing demand shows that the present electricity carriage capacity in West Africa has been exceeded and if not properly controlled, could lead to an energy crisis (Adenikinju A. 2008).

People generally look for easier alternative means to an end especially when a particular problematic issue is being prolonged. Sometimes the biggest concerns is the 'now factor' and the future would have to take care of itself. The tendency is seemingly not sustainable and we should already start thinking in the direction of global energy improvement or apparently no improvement at all. It wouldn't be fair if one region of the world goes green and the others continue with unsustainable practices. At the end of the day the climate still suffers. Satisfying the problem of power demand should be done sustainably to the absolute.

Over a study period of 17 years, a close observation of the West African energy demand trend as seen from the graph above has not really shown signs of improvement. It also shows that with the present centralized energy supply situation, energy catastrophes might not be totally avoided in the future due to an already exceeded carriage capacity. The total mains supply in 2005 was about 42 000GWh, triggering the demand to a peak value of 6,830MW. With the current energy demand growth rate at 7% yearly, in the next 8 years, the demand is expected to reach peak value of 22,000MW. (Kappiah, M.)

The figure 2 below, (Kappiah, M., modified) shows the growing rate of electricity demand in West Africa over a 17 year study period. The results have been presented in at least four year intervals starting from 2003 to 2020 as can be seen from the chart. It represents historical reports and a calculated future prediction, following the trend in its progressive pattern.

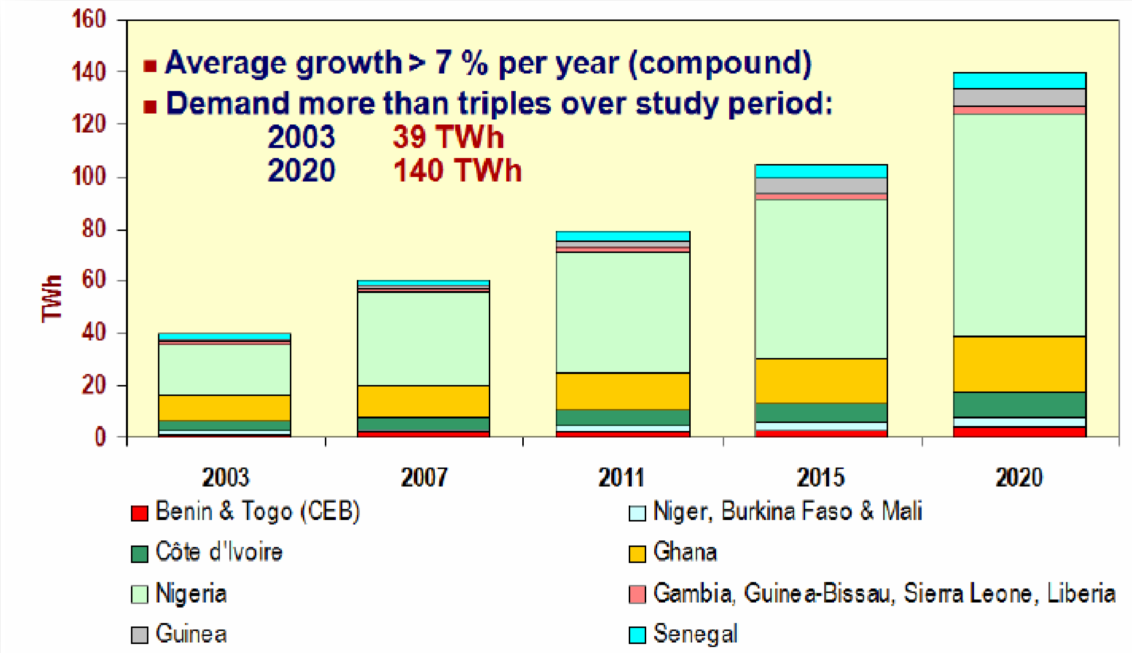


FIGURE 2. Electricity demand trend in West Africa (Kappiah, M., modified).

Additionally, the alternative used to compliment for power failures in the region is majorly fossil fuel power generators. Individuals, industries and businesses often have back up power generators which are powered by diesel or petroleum, generating an estimate capacity of 1000MW of electricity. These are steady sources of green house gas (GHG) emissions to the environment and are used almost on a daily basis. (The Infrastructure Consortium for Africa, 2007)

### 4.2 Regional energy development programs

Within the Economic Community of West African States (ECOWAS) nations, there are a number of co operational programs which have been created for the sole purpose of regional energy development in the past couple of years. They include; The Regional Solar Program (RSP), The Regional Biomass Program (RBEP), The Multifunctional Platform Project (MFP), to mention a few. Some programs have been initiated by ECOWAS while others are as a result of external cooperation with support from at least the EU and Germany. These programs are diversified, touching the different West African energy endowments like solar, biomass, thermal, and hydroelectricity. Major concerns due to the situation in the region have been concentrated on balancing the electricity available to the rural and urban areas, extending grid connections, improvement and proper maintenance of facilities and infrastructure, and creating energy diversity. (Adenikinju A. 2008)

In 1999, the West African Power Pool (WAPP) was adopted and established by ECOWAS. This energy program would pioneer electrical grid connection through 8 countries in the region in a bid to collectively deal with the problems associated with energy stability, affordability and sustainability. It was estimated that between the past 9years and the next 8years, her investments towards achieving set goals in the region would amount to 18 billion US dollars. (Adenikinju A. 2008)

The West African Gas Pipeline (WAGP) is another regional developmental project created by ECOWAS to research and develop the accessibility of people to basic energy needs around the West African region. In 2007, it was already estimated to supply thermal stations in Benin, Ghana and Togo. (The Infrastructure Consortium for Africa, 2007)

## 4.3 Installed energy capacity in West Africa

The major energy source in the region constitutes thermal and hydroelectricity. Thermal energy in the region is basically dependent on coal as the resources required for central distribution of natural gas from Nigeria for example, are not yet fully functional. Out of the 15 countries within the ECOWAS nations three major key players were Ivory Coast, Nigeria, and Ghana who contributed together 87% of the energy and consumed 83% in the region. Most others do not possess the necessary resources to produce their own energy so they rather depend on neighboring successes (Gnansounou, E. 2008).

Excluding individual back up energy options, about 10.2 GW standard capacity of energy was produced in West Africa as of 2005. The total installed hydroelectricity capacity in the region amounts to 40.5% while the total thermal energy capacity has a value of 59.5% (Gnansounou, E. 2008). From the chart shown in figure 3 (EIA, 2007, modified) these values have been rounded up and so they give an estimate of the detailed situation. The pie chart in figure 3 shows energy distribution between the key energy sources in West Africa as of 2005.

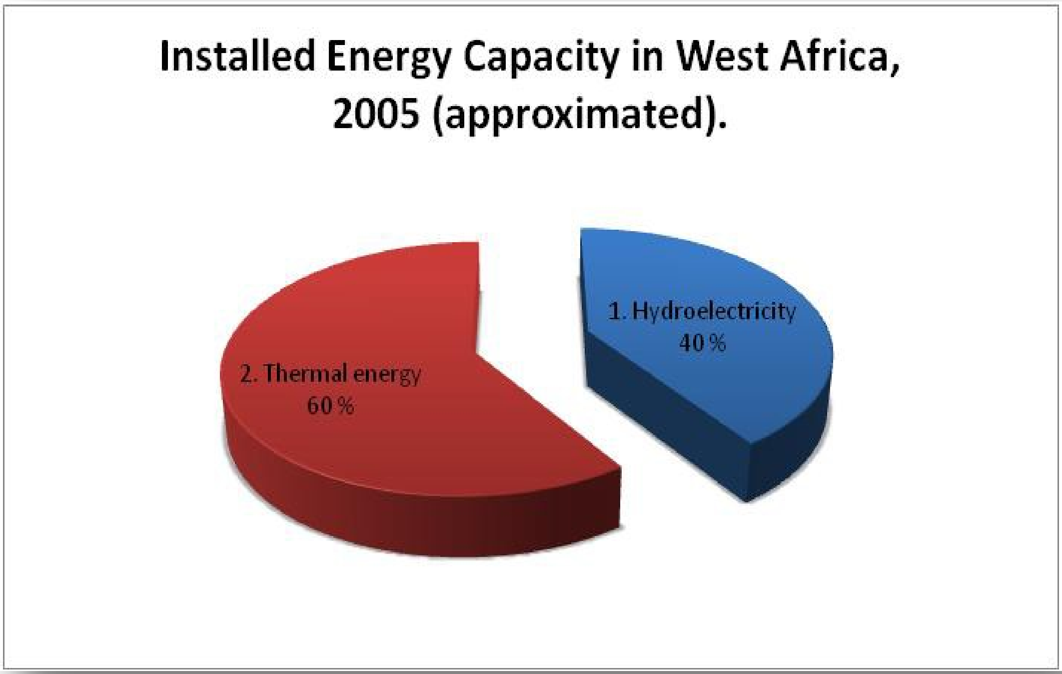


FIGURE 3. Distribution of installed energy capacity in West Africa 2005 (EIA, 2007 modified).

Hydroelectricity and thermal electricity have huge environmental impacts. Especially thermal energy use is associated with deforestation, air pollution, acid rain, ozone depletion, radioactive emissions and global warming in general. Pollutants like $CO_2$, $SO_2$, $NO_x$, and CFCs are constantly released through thermal energy production. (Dincer, I., and Rosen, M. 2011)

# 5 ENHANCED GEOTHERMAL ENERGY

## 5.1 Brief Introduction

As interesting and reliable as conventional geothermal energy seems, it has its own short comings just like every other energy sources. Apparently, it however seems that optimizing its process techniques could lead to better energy future and engineers are optimistic about it. Recent researches are rather focusing more on enhancing these Geothermal Systems as an alternative for the future.

Enhanced Geothermal Systems (EGS) are very similar to the traditional geothermal energy systems but have a few but very important differences which have attracted a lot of interests on the former over the years. Geothermal energy is absolutely reliant on naturally occurring favorable hydrothermal conditions, while EGS is typically associated with artificial stimulation of subsurface unfavorable geothermal conditions to make them possible for energy production. (Climate Techbook, 2009)

The idea behind EGS is to utilize present engineering technologies in developing techniques for accessing geothermal energy irrespective of location or geological constrains. This development is expected to create a breakthrough in the energy market by supplying clean electricity commercially at an economically suitable price around the world. (Tester, J. et al, 2006).

This promising technology however gives hope of reliable renewable energy for regions around the continents which have had the least considerations for geothermal energy production due to location. West Africa which happens to be our focal point in this study stands the chance of being powered efficiently with geothermal energy, following the research and development trends, and working along with them.

## 5.2 EGS Process and Model

The early EGS precondition was identified as hot dry rock (HDR) obtainable from certain depths below the ground. As the name implies, the EGS process starts with finding

heated rocks always available at some depth below the surface of the Earth. Varying geological conditions mean that the depths where this heat could be located differ with location. Nowadays, this condition is really not referred to as hot dry rock, but Enhanced Geothermal System conditions. (DiPippo, 2008)
After the necessary preliminary normality procedures of identifying, sampling and analysis of experimental drills the actual EGS harnessing process commences after approval, with the proper safety measures observed. The steps have been summarized subsequently.

### 5.2.1 Site preparation

In spite of the irrelevance of special geothermal conditions when considering EGS technologies, it is however wise to take into consideration certain factors which would help to reach the desired heat region with less depth and less efforts for economic reasons.

- Heat flow
- Geology
- Distance from supply units
- Land access
- geochemistry

A good understanding and determination of the above listed factors give more confidence before the project starts and this way extra costs can be averted. Unfortunately, there are yet no remote sensing technologies that give easy accurate and perfect leading information of subsurface conditions for EGS development. Suitability determination has to be carried out carefully with series of tests and calculations which could be difficult. (US Department of Energy, 2008)

### 5.2.2 Injection wells

After the process has been planned, the injection wells can be drilled using same technology and equipment applicable to oil and gas exploration. Supporting casings and tubing which structure the drills and create suitable channels are available and in use.

Injection wells basically create the path way which introduces the geothermal fluid (cold water) which is not naturally present to the heated rocks. This fluid is delivered at high pressure enough to fracture the hot rocks and help the water travel through. This process is known as hydrofracturing. This hot water is the main geothermal fuel needed and is collected by the production wells. (US Department of Energy, 2008)

### 5.2.3 Production wells

The production wells are drilled in order to establish contact with the artificial reservoir which has been created. These wells create the final cycle path in the subsurface region. The hot water is successfully collected from this source and ready to be utilized as geothermal fuel. Production wells may be drilled at several spots in order to recover enough geothermal fluid to meet energy demands. (US Department of Energy, 2008)

Importantly, after the drilling, stimulation and fluid recovery process have been verified, engineers must determine the shape and capacity of the reservoir to make it possible to strategically install newer wells. This can be determined by the use of calculation models, remote seismic imaging, radioactive tracing techniques, and a host of other technological methods in use today.

The figure 4 below (Geothermal Technologies Program. 2011, modified) shows a simplified working process of an EGS as explained in the subsections above, taking into consideration basic major highlights. It also gives an idea of how conventional geothermal systems work except for the artificial stimulation. In practicality the system can be more complex depending on design.

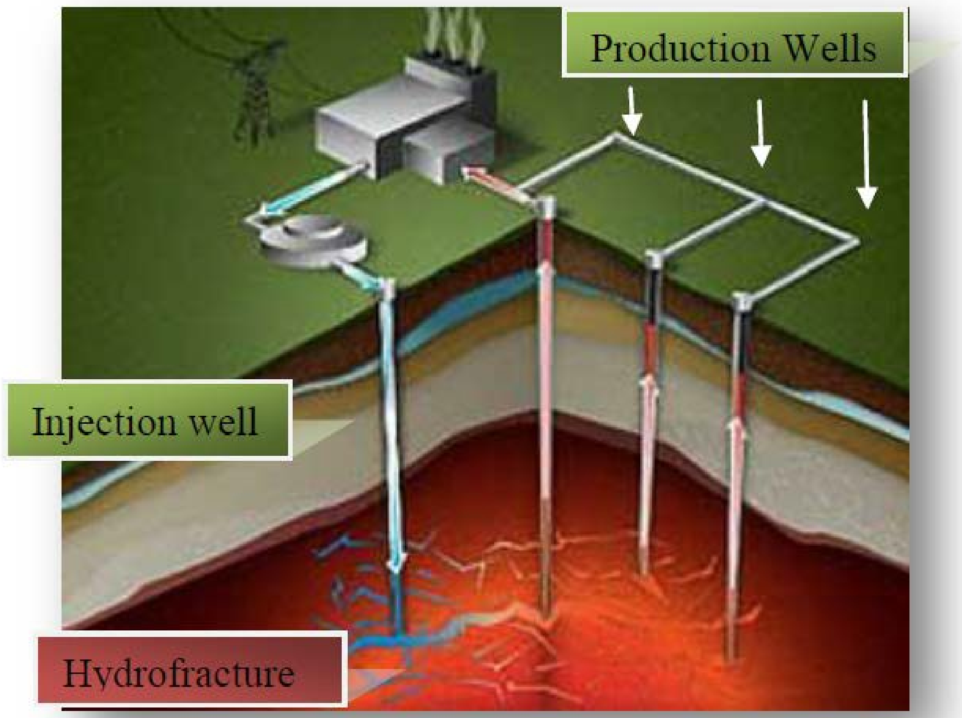


FIGURE 4. Working model of an EGS (Geothermal Technologies Program. 2011, modified).

### 5.2.4 Production of Electricity

Similar to geothermal power plants, electricity production in EGS systems is conventionally done by flashing steam from the hot fluid and channeling it to the turbines in order to produce electricity. However the method with which this is done, to a large extent contributes to the overall efficiency of the system. Planning and installing a binary plant as the surface generator would generally help to improve efficiency, reduce cost and conserve water resources and the environment (DiPippo, 2008).

## 5.3 Some advantages of EGS

### 5.3.1 Doubled geothermal productivity

Enhanced geothermal systems take advantage of the production limitation encountered by traditional geothermal systems and can increase their capacity potentials. With EGS technologies the output capacity of geothermal systems can be maximized by taking full advantage of hotspots. However, it is possible and realistic to connect the wells at the sub surface levels by driving pressurized fluid through the well fractures. With increased pressure, more fractures are made and well connections can thus be achieved. Statistically, it is expected to more than double the total capacity of energy being produced in the US. The US presently holds the largest geothermal energy production in the world today. (Garman, D., 2004)

### 5.3.2 Longer life time of geothermal wells

Geothermal systems have been in operation since before the 70s' (DiPippo, 2008). Due to certain reasons, the fracture networks within the hot rock structure may become clogged and less productive. With fluid injection technique which is a component of the EGS, these fractures can be reopened there by increasing the possibility of these wells to survive for very many more years. (Garman, D., 2004)

### 5.3.3 Location

Location variability is one very important advantage of the EGS. It is possible to commence geothermal energy production almost anywhere with proper application of its knowledge. The earth's core universally connects all the continents and based on this fact, it is possible produce energy once the right preliminary research essentials have been carried out. The only differences could be economical, considering the depths needed to be covered before reaching the desired heat resource. However, compensational installation of a binary plant greatly reduces this distance due to lower temperature requirements. (Climate Techbook, 2009, Tester, J. et al, 2006)

### 5.3.4 Environmental friendliness

EGS is a modern source of energy which produces almost zero emission of green house gases (GHG) especially when combined with a binary plant. However, little traces of these gases can be released during the drilling and construction stages of the project if not carefully considered. After this stage, the system runs almost independently as a clean, green energy source. (Climate Techbook, 2009, DiPippo, R., 2008)

Moreover, one very important fact about the EGS is its ability to support continuous steady supply of electricity as a good replacement for other less efficient systems in use today which still have noticeable footprints. For example, coal fired plants and fossil fuel power plants still significantly contribute to a huge percentage of GHG emissions today.

## 5.4 Major setbacks confronting EGS as a viable alternative

Enhanced geothermal systems are still in their developmental stages and not yet being commercialized. The prospects with EGS are very positive and promising but they are not tangible at the moment. This however means that the future of these systems is rested and dependent on research, development, and the required financial support for facilitation. According to Tester, J. et al, 2006, it will take another 12years of consistency and research form now before we can actually commercialize EGS.

This new energy resource is not totally understood yet but still in the process and sometimes it might present some surprises due to high temperatures recoverable from the subsurface. The chances of a failed drill are as high as 75% presently and comparing this with the costs involved might discourage funding and investors in this area. (Climate Techbook, 2009)

## 5.5 Cost

Looking from the perspectives that binary cycle plants could work at lower temperatures, thereby averting the need for drilling long distances, and also the possibilities related to harnessing geothermal energy from abandoned oil wells and weak producing geothermal wells, we can assume in this study that EGS costs almost equal normal geothermal drilling costs.

Development costs of geothermal energy are often difficult to predict due to the uncertainty related to geothermal drilling. More so, a common misconception is that cost related to geothermal drilling is a major factor limiting geothermal development. The investment cost of geothermal power plant is divided into cost of surface equipment and activities and the cost of subsurface investments. The surface cost includes cost of surface exploration, and the plant and steam-gathering system, while the cost of subsurface investment is that of drilling. The cost from surface equipments is comparable to other construction works and can be estimated with same accuracy. (Valgardur S., 2002) However, higher uncertainty associated with the cost of drilling comes number of wells required for the plant. Figure 3 (Valgardur S., 2002) below reveals how the total investment cost of a 20 MW plant in Namafjall, Iceland, depends on the number of steam wells required for this plant.

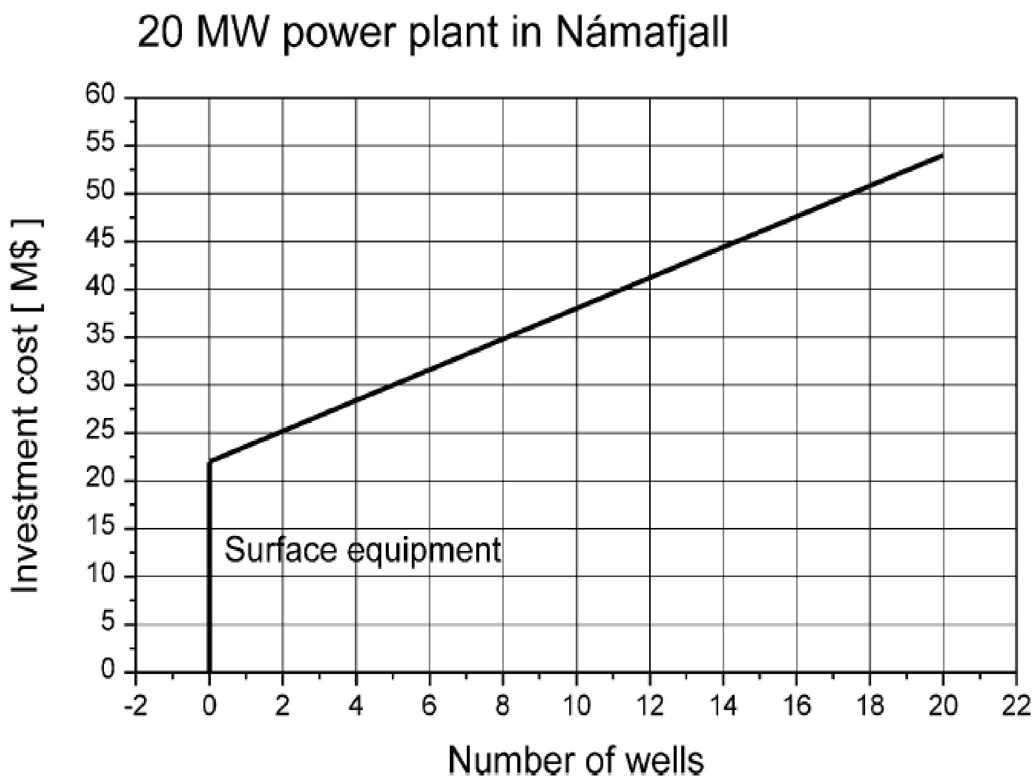


FIGURE 5. Cost of investment for a 20 MW power plant in Namafjall
(Valgardur S., 2002)

Recent advances in drilling and exploitation technologies such as EGS have increased efficiencies resulting in lower overall cost as seen in Table 1 (K. Bloomfield., P. Laney., 2005).

TABLE 2. Geothermal drilling cost from 1970's through mid 1990's (K. Bloomfield., P. Laney., 2005).

Geothermal drilling costs from the 1970s.(in year 2000 dollars)

| Depth Interval (ft) | Number of Wells | Total Footage | Total Cost ($K) | Average Depth (ft) | Average Cost/Well ($K) | Median Cost/Well ($K) |
|---|---|---|---|---|---|---|
| 0–1,249 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1,250–2,499 | 4 | 7,460 | 1,908 | 1,865 | 477 | 369 |
| 2,500–3,749 | 6 | 18,086 | 7,615 | 3,014 | 1,269 | 1,254 |
| 3,750–4,999 | 9 | 42,732 | 10,677 | 4,748 | 1,186 | 792 |
| 5,000–7,499 | 25 | 151,033 | 48,985 | 6,041 | 1,959 | 1,800 |
| 7,500–9,999 | 11 | 94,996 | 27,385 | 8,636 | 2,490 | 2,415 |
| 10,000–12,499 | 4 | 40,994 | 15,676 | 10,249 | 3,669 | 3,538 |
| 12,500–14,999 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15,000–17,499 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17,500–19,999 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20,000+ | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 59 | 355,301 | 111,246 | 6,022 | 1,886 | 1,792 |

Geothermal drilling costs from the mid 1980s through mid 1990. (in year 2000 dollars)

| Depth Interval (ft) | Number of Wells | Total Footage | Total Cost ($K) | Average Depth (ft) | Average Cost/Well ($K) | Median Cost/Well ($K) |
|---|---|---|---|---|---|---|
| 0–1,249 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1,250–2,499 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2,500–3,749 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3,750–4,999 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5,000–7,499 | 3 | 19,863 | 4,014 | 6,621 | 1,338 | 1,472 |
| 7,500–9,999 | 17 | 150,297 | 33,684 | 8,841 | 1,981 | 1,892 |
| 10,000–12,499 | 5 | 52,174 | 8,828 | 10,435 | 1,766 | 1,875 |
| 12,500–14,999 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15,000–17,499 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17,500–19,999 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20,000+ | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 25 | 222,334 | 46,526 | 8,893 | 1,861 | 1,792 |

The cost associated with generating power from geothermal resources has decreased by 25% over the last decades (Wiser, R., et al, 2003). However, exploration and drilling remain expensive in the general sense. The cost of drilling alone could account for as much as one - third to one – half of the total cost of geothermal project (K. Bloomfield., P. Laney., 2005). Locating the best resources is often difficult hence; developers usually drill a number of dry wells before a viable resource is discovered. A viable geothermal well generally generates between 2MW and 5MW of electricity and each may cost from $1 million to $ 5 million to drill. (National Geothermal Collaborative, 2012)

As compared to traditional power plants, geothermal power plants employ the use of renewable energy source which is not susceptible to price fluctuations (National Geothermal Collaborative, 2012). Modern geothermal plants generate electricity from per kilowatt-hour (kWh). This is comparable to other electricity choices today upon considering the cost over the lifetime of a plant as shown in Table (K. Bloomfield., P. Laney., 2005).

TABLE 3. Comparison of cost of energy from a geothermal energy source to traditional energy sources (National Geothermal Collaborative, 2012).

Table 1. **Cost of New Electricity Production** (cents/kilowatt hour)

| Technology | Geothermal Flash | Geothermal Binary | Wind | Hydropower | Natural Gas | Turbine |
|---|---|---|---|---|---|---|
| | | | | | *Combined Cycle (Baseload)* | *Simple Cycle (Peaking)* |
| Capital & Financing Cost | 3.50 | 5.14 | 3.49 | 4.62 | 0.93 | 6.93 |
| Fixed Operating Costs | 1.43 | 3.08 | 1.79 | 1.12 | 0.19 | 2.43 |
| Taxes *(credit)* | *-0.54* | *-0.91* | *-0.34* | *0.29* | *0.01* | *0.12* |
| **Total Fixed Costs** | **4.39** | **7.28** | **4.93** | **6.03** | **1.12** | **9.49** |
| Fuel Cost | 0.12 | 0.08 | 0.00 | 0.00 | 3.83 | 5.11 |
| Variable O&M Costs | 0.01 | 0.00 | 0.00 | 0.00 | 0.24 | 1.09 |
| **Total Variable Costs** | **0.13** | **0.08** | **0.00** | **0.00** | **4.06** | **6.20** |
| ***Total Levelized Costs*** | ***4.52*** | ***7.37*** | ***4.93*** | ***6.03*** | ***5.18*** | ***15.69*** |

Usually, the cost associated with geothermal plants is a function of the resources exploration and plant construction. In comparison to oil and gas exploration, owing to the cost of exploitation, geothermal developers must be sure they have reliable and realistic resources prior to disbursing million of dollars needed to develop geothermal resources (National Geothermal Collaborative, 2012).

### 5.6 Cost summary

EGS reservoirs and energy production till date are pilot projects and as such are still within the experimental capsule to be made a viable source of commercial energy. It is however estimated that with steady progress in research and development, EGS would be commercially available in the next 12 years (Climate Techbook, 2009, An Evaluation of Enhanced Geothermal Systems Technology, 2008). EGS is currently at its development stages and currently relies on promising advancement in technology, energy incentives, and consistence (Climate Techbook, 2009).

# 6 ENVIRONMENTAL CONCERNS WITH EGS

## 6.1 Air and water pollution

Drilling, hydrofracturing, pipe installations and other subsurface activities associated with erecting a geothermal facility, could stimulate the release of potentially harmful gases from below the earth surface. These activities could also cause dissolved minerals to come in contact with the water table. Harmful gases like $CO_2$ and $H2_S$ usually occur in larger concentrations than other GHGs from those depths. There is however a few well known methods applied in order to capture and avoid the problematic emission of these gases to the atmosphere. Elements like boron could also be poisonous to vegetations and animal life when it interferes with ground water.

Using the binary cycle plant completely avoids and release of these gases by absolutely limiting their contact with the outside since the entire operation is done in a closed loop. This simply means that this plant type guarantees zero emission in operation. More so, proper geochemical studies on the site and taking into consideration the right precaution measures, helps to avoid catastrophes. (Tester, J. et al, 2006, Kage, A. et al, 2007)

## 6.2 Anthropogenic disturbance of hydrothermal features

In countries like Iceland for example, geysers, hot springs and mud pools are exceptionally beautiful and create worldwide renowned tourist attractions. Keam, F., et al (2005) cited that quite a number of scenarios can be identified where these few beautiful natural manifestations have been negatively affected somehow or totally destroyed due to installation of geothermal energy facilities. However, the beauty of EGS is rather focused on creating new geothermal conditions in sites which do not have any hydrothermal networks and as such not considered productive (Tester, J. et al, 2006).

### 6.3 Water Usage

In West Africa, Changes in climatic conditions, increased surface heat, and a host of Anthropogenic factors already affect the availability of water from time to time (United Nations Economic and Social Council, 2007). This means that any water intensive projects in these regions would be a huge problem, as this will likely combat with the available water resource for resident biodiversity use. However in sites where EGS are being developed, water demand cannot really be compromised. According to Tester, J. et al, 2006, the largest demand for water with EGS goes to the drilling processes, fluid stimulation of hot rocks, and use as the general propagation medium. The rest of the fluid is stored for top up in case of shortage.

Depending on the size of the project, the volume of water required for these purposes vary and may create a very sensitive reason for environmental concern. The positive side to this is that for example, during the drilling phase, the drilling fluid, which is often water, can be treated and reused, reducing the demand for more water. Moreover, in binary cycle plants, the water is circulated within a loop and the only extra water needed might be little quantities for top up.

### 6.4 Occupational risks

It is difficult to absolutely guarantee an accident free work place almost anywhere in the world. However, the likelihood of disastrous occurrences can be greatly controlled by implementation of suitable risk management programs. Accidents can occur through unprecedented blowouts, broken pipes, etc, which are not new to drilling sites. The control is better nowadays due to closer attention to regulations, and careful geology studies of the proposed site. (DiPippo, 2008)

# 7 DISCUSSION AND CONCLUSION

Critically, let us initially look briefly at some of the negative impacts of existing energy production sources in West Africa today. Afterwards we can weigh our options and try to balance from our previous EGS knowledge.

Briefly mentioned earlier in chapter 4, was the issue of power interruptions, folding up a lot of businesses owned by the local people. For many of these people, petty businesses which depend to a large extent on the availability of electricity, is the only means from which they sustain their livelihood and families in West Africa. In 1998, 2006 and 2007, a drought in Ghana affected water availability at the Akossombo dam and caused series of black outs, not just to the nation alone but also to other dependent nations like Togo and Benin which at the time ended them up in a recession. In 2001, huge nations like Nigeria, suffered remarkable power shortage due to the draining at the kanji dam, the largest dam in the country and drought. Guinea, Senegal and Mali have had technical problems leading to power intermittency also (Gnansounou, E. 2008, Adenikinju A. 2008). If basic primary energy demands are not met, it is difficult to talk about development and saving the planet.

Poor access to electricity therefore has left obvious wounds on the face of the economy, impeding the overall development of the region. It is however a common fact that faulty management cultures, corruption, and unsustainable decisions like seen in other developing economies around the world, lead to the poor energy standards of most countries in West Africa.

In spite of the availability problems associated with the present electricity supplies through hydroelectricity, there are also a number of environmental concerns which need proper attention especially because of the nature and cultures in West Africa. According to Gevorkian, P. 2010, creation of dams alters natural water courses and destroys natural aquatic and terrestrial factors. Hydropower has some effects on the environment which need to be considered carefully in relationship with the following list;

- West Africa is home to a huge amount of biodiversity, some of which are already endangered.
- Water quality alteration and downstream aquatic life reproduction
- Water nutrient quality
- Increased water related diseases
- Also people lose their homes and cultural geographical origins.

On the other hand, it has become a very important factor nowadays that our choices of power generation should be free from harmful green house gases and harmful emissions to the environment. Thermal energy which is not in the category provides a greater percentage of energy to the region, but burns on coal and is therefore not an environmentally friendly option considering the harmful gas emissions involved. A huge percentage of the West African demography depends on hydro electricity and thermal energy and this simply means a continuous trend in economic and environmental destruction if corrections are not introduced (Gnansounou, E. 2008). In most countries there are strict environmental laws which are adhered to carefully and because of this there is greater trust attached to newer renewable energy systems.

Generally there is need for more a sustainable energy option which counters the major disadvantages presented by the present West African energy infrastructure. One which is reliable, sustainable and can be easily adapted as either a central or decentralized option, also considering management. Enhanced Geothermal Systems, when developed for commercial utilization, obviously could perfectly back up for power intermittency, unreliability, and unavailability in the region. Amongst other possible renewable energy sources like solar wind and biogas, Enhanced Geothermal Systems, if adapted, still represents the most trusted option which can supply enough steady electricity for large communities. (DiPippo, 2008)

However, a major skepticism debated in EGS issues is the drilling depth required but however, equipping the system with a binary plant deals with this problem substantially. Due to the low boiling point of the secondary liquid, it works efficiently in geothermal energy sites where only little heat source has been recovered at shallow depths. In other words, with this plant type we really do not need to drill to the core to find heat. There is zero emission with binary cycle plants because of the closed loops, meaning that this plant type is green and clean.

Although the costs of installing Enhanced Geothermal plants in specific regions in West Africa might presently seem unrealistic, this simply depicts an initial problem associated with almost every new developmental project and the trends have shown its improvement ever since. Abandoned oil wells can also be rekindled by diverting their initial purpose towards enhanced geothermal energy production as this reduces the depth to be drilled (Climate Techbook, 2009).

Conclusively, although West Africa might be experiencing difficult times with her present energy situation, there is more than enough resources and potentials in the ECOWAS region guaranteeing a bright future. If more attention is paid on enforcing environmental laws in a bid to curb corruption in the energy sectors considering for example, all aspects of the WAPP projects, there should be progressive results. Assuming the best EGS systems are installed for the benefit of the region, and the wrong people have to control it, the reinforcement might just turn out not to make much difference.

More so, proper planning should be made before any new financial projects are executed in the region because a with a careful look at things the whole world is working towards cutting down emissions and a right investment in the wrong direction might mean revisiting this same issue again in the nearest future. So far, there have not been obvious considerations of EGS in West Africa; probably due to the basic ideology that there are other options to consider but it is high time we started considering this possibility for a green future.

However, if we think of the disadvantages of other systems compared to that of EGS in West Africa, we will have good reason to rethink the options which we consider and the choices we make. For example, there is a lot of solar potentials in West Africa but then climatic variations suggest need for batteries in order to store the energy generated. With batteries come the concerns of purchase, availability, storage, accidents, and disposal. The thought of this alone on a large scale should make us think of a second option, wind.

Wind energy also is affected by variation, availability and might also take up a lot of arable land space, create sight and noise concerns, and so on. In a region like West Africa where crop cultivation is the source of survival for many especially in the rural areas, this option might spark up controversies, even though it solves the original problem of energy production when possible.

Realistically, considering the present economic situation of West Africa, and the fact that there is still manageable source of energy, it might not be easy to make very huge quick changes to the entire energy system. However, it is reasonable to have a plan for installing decentralized enhanced geothermal systems at strategic locations where they can power large communities or simply back up for failures. A centralized vision might be to gradually replace first thermal energy with a larger scale EGS project. Let’s embrace the future with hope, research, and work, and our economies would live to show for it. Let us embrace sustainability.

# 8 REFERENCES

Adenikinju A. West Africa Energy Security Report. Fall 2008. Read 07.06.2012. http://www.beg.utexas.edu/energyecon/IDA/Smart_Development/WAESR_Fall_08.pdf

An Evaluation of Enhanced Geothermal Systems Technology. Geothermal Technologies Program. 2008. Read 7.6.2012. http://www1.eere.energy.gov/geothermal/.../evaluation_egs_tech_2008.pdf

Climate Techbook. October. Enhanced geothermal systems. PEW Centre on global climate change 2009. Read 7.6.2012. www.pewclimate.org/docUploads/EGeotherm%2010%2009(2).pdf

Dincer, I., and Rosen, M. 2011. Thermal Energy Storage: Systems and Applications. 2nd Edition. United Kingdom: John Wiley & Sons Ltd.

DiPippo, R. 1999. Small Geothermal Power Plants: Design, Performance and Economics, GHC Bulletin.

Doblas, M., Lopez-Ruiz, J., Cebria, J., Youbi, N., Degroote, E. 2002. Mantle insulation beneath the West African craton during the Precambrian-Cambrian transition. GeoScience World 30 (9), 839-842.

Edwards L.M., G.V. Chilingar, H.H. Rieke III and W.H. Fertl. Eds. 1982. Handbook of Geothermal Energy, Gulf Publishing Company, Houston, TX.

EIA, 2007. [Online]. International Energy Data and Analysis, Energy Information Administration. Read 22.5.2012. http://www.eia.doe.gov/emeu/international/contents.html

Foster, V., & Briceno-Garmendia, C. 2010. Africa's Infrastructure: A Time for transformation. Washington: World Bank.

Garman, D. Geothermal Technologies Program. Enhanced Geothermal Systems. 2004. Read 22.05.2012. www.nrel.gov/docs/fy04osti/36317.pdf

Geothermal Technologies Program. 2011. [Online]. Enhanced Geothermal Systems basics. Updated 02.16.2011.Read 22.05.2012. http://www1.eere.energy.gov/geothermal/

Gevorkian, P. 2010. Alternative Energy Systems in Building Design. USA: The McGraw-Hill Companies.

Gnansounou, E. 2008. Boosting the Electricity Sector in West Africa: An Integrative Vision. IAEE Energy Forum 17 (3), 23-29

Grant, M., and Bikley, P. 2011. Geothermal reservoir engineering. 2nd Edition. Academy Press.

K. Bloomfield., P.T. Laney. 2005. Estimating well cost for Enhanced Geothermal System Applications. U.S. Department of Energy National Laboratory.

Kage, A., Bales, D., Gawell, K. [Online]. A Guide to Geothermal Energy and Environment. 2007. Read 7.6.2012. http://geo-energy.org/reports/environmental guide.pdf

Kappiah, M. Power Kick for Africa. Renewable Energy Policies for Sustainable African Development. 21-23 June 2010. Accra.

Keam, F., Luketina, K., & Pipi, Z. 2005. “Definition and Listing of Significant Geothermal Feature Types in the Waikato Region, New Zealand”, Proc World Geothermal Congress, Antalya, Turkey, Paper 0209, 24-29

Kutscher, C. [Online]. The Status and Future of Geothermal Electric Power. 2000. Read 7.6.2012. http://www.nrel.gov/docs/fy00osti/28204.pdf

Lester, B. 2010. World on the Edge: How to Prevent Environmental and Economic Collapse. New York: W.W. Norton & Company.

Letcher, T. 2008. Future Energy: Improved sustainable and clean options for our planet. 1st Edition. China: Elsevier.

Liberty International Mineral Corporation. [Online]. Read 18.05. 2012. http://www.libmin.com/

National Geothermal Collaborative. [Online]. Geothermal Energy: Technologies andCosts.Read2.6.2012.http://www.geocollaborative.org/publications/Geothermal_Energy_Technologies_and_Costs.pdf

Olduvai Formation3. 2003. [Online]. The Tectonic History of Africa. Updated 12.23.2003.Read22.05.2011.http://archserve.id.ucsb.edu/courses/anth/fagan/anth3/Courseware/OlduvaiForm/3_Tectonic_History_Africa.html

Povarov, K. Distribution of Impurities and Gases between Steam and Water Phases of the Geothermal Fluid in the Low Pressure Zone, April 2005. Read 2.6.2012. pangea.stanford.edu/ERE/pdf/IGAstandard/Russia/.../W00046.PDF

Taylor, M. November 2007. The state of geothermal energy, Read 2.6.2012. http://www.geo-energy.org/reports/Geothermal%20Technology%20Part%20I%20-%20Subsurface%20Technology%20(Nov%202007).pdf

Tester, J. et al, 2006. The Future of Geothermal Energy: Impact of Enhanced Geothermal systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology.

The Infrastructure Consortium for Africa. 2007. Power Supply Situation in Africa. Read2.6.2012.http://www.icafrica.org/fileadmin/documents/ICA_Annual_Report_2007_-_FOR_WEB.pdf

United Nations Economic and Social Council. Economic Commission for Africa: African Review Report on Drought and Desertification. 5th Meeting of the African Committee on Sustainable Development (ACSD-5). 22-25 October 2007. Addis Ababa.

UNOWA: United Nations for West Africa. 2012. [Online]. Updated 31.05.2012. http://unowa.unmissions.org/

US Department of Energy. 2008. [Online]. An Evaluation of Enhanced Geothermal systems Technology. Read 2.6.2012.
http://www1.eere.energy.gov/geothermal/pdfs/tech_eval_draft.pdf

Valgardur S., Investment cost for Geothermal Power Plants. Geothermic 31 (2002) 263 – 272.

Wiser, R., Porter, K., Robert, G., Kappel, C. National Geothermal Collaborative. Evaluating State Renewables Portfolio Standards. September 3, 2003.

Wright, J., Hastings, D., Jones, W., Williams, H. 1985. Geology and Mineral Resources of West Africa. London: George Allen & Unwin.