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Application of Geophysical Methods on Geothermal Resource Exploration: A Case of Shores of Lake Malawi

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Abstract **-** East African Rift System (EARS) is one of the major tectonic structures of the earth where thermal energy of the interior of the earth escapes to the near surface. Estimated Geothermal energy resource potential in the EARS is more than 14,500 MW. Currently, other countries such as Malawi, Zambia, and Mozambique have not gone beyond the systematic inventory work of the resource potential exploration. There is a possibility of geophysical, geo-chemical and geological surveying methods to be used for geothermal energy investigations in Malawi. For each of these methodologies, there is a typical physical/chemical property to which the technique is sensitive to. The concept of the paper is to detail the applications of geophysics in the location of geothermal reservoir rocks with precise depth by use of seismic velocity through its electrical conductivity, magnetic or/and gravitative methods along the shores of Lake Malawi. The integration modern geophysics (Seismology) methods and its data is key in order to obtain a better understanding of the thermal rock as a whole, which is the ultimate goal of exploration in the paper. In absence of detailed drilling in Malawi, this methodology provides a perfectly general and internally consistent approach to estimating at least the upper limit of thermal rocks in terms of temperature and exact depth.

Index Term**--** **Geothermal, Thermal rock, Renewable energy, Climate change, Seismology, Malawi.**

1. INTRODUCTION

Geothermal energy is a natural heat from the earth's interior stored in rocks and water within the earth's crust [1]. This heat creates the thermal rock, molten rock, or magma beneath the surface crust [2]. The main source of this energy is the constant flow of heat from the earth's interior to the surface [3]. Volcanoes, geysers, heat radiation and fumaroles are the visible evidences of the great reservoir of heat, which lies within and beneath the earth's crust [4]. According to Chideh (2006), geothermal resources can take a range of forms; (1) Hydrothermal systems which comprise of (a) Wet steam {hot water} systems, which is due to high pressure underneath earth's crust. (b) Dry steam system, which occurs at lower pressure under the crust of the earth. (2) Geopressurised reservoirs from the brine solution which acquires much energy from high pressure at the depth of 3000m [5]. This can give (a) thermal energy from high temperature, (b) chemical energy from dissolved CH_4 gas and (c) mechanical energy from pressurised brine solution. (3) Hot dry rock reservoir, at a depth of 3000m which are very hot and can heat water when pumped in through drilling [6].

Malawi lies at the southern end of the EARS within latitudes 9˚S and 18˚S and longitudes 32°E and 36°E. The country is defined by 94,000Km² land area (80%) and 24,000Km² water surface in which Lake Malawi (about 586 km long and 16 - 80 km wide) dominates as shown in Figure 1 and 2. This position provides convective and conductive systems of high heat fluxes from the crustal rocks which are favourable conditions for a geothermal resource reservoir as manifested in the earth's interior heat escaping to the surface [7].

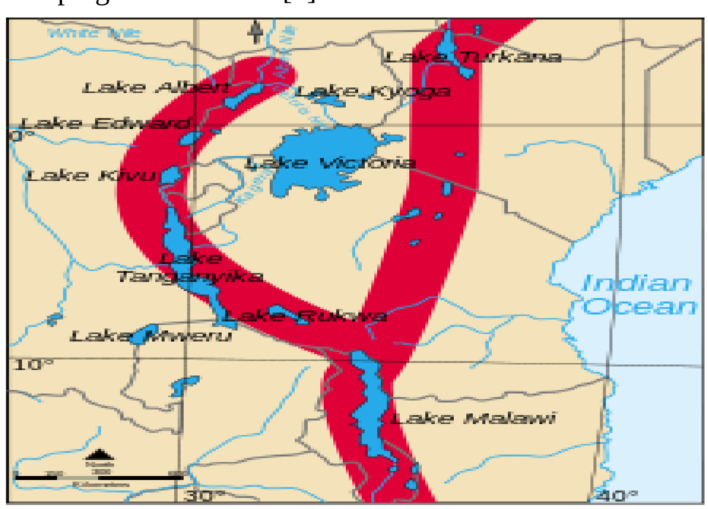


Fig. 1. East African Rift System (source; EARS gallery)

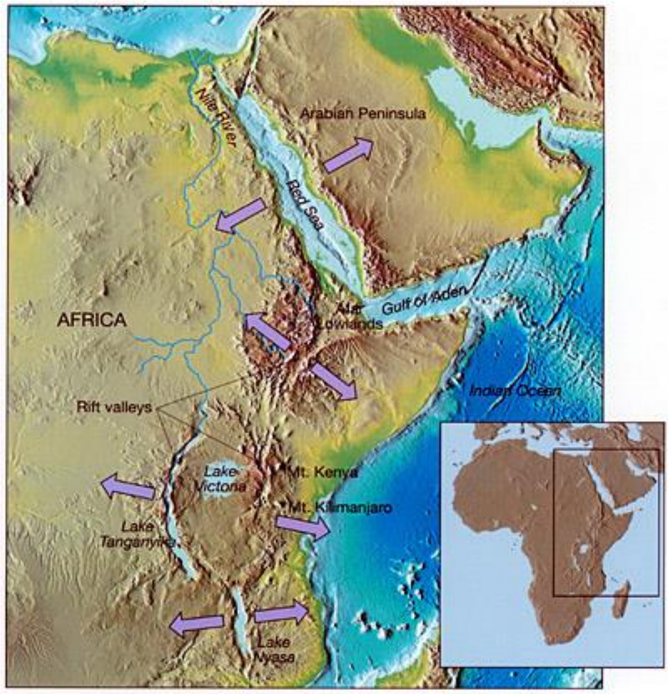


Fig. 2. East African Rift System (source; UNU-GTP)

Among the alternative sources of energy in Malawi, it can be opined that geothermal energy might potentially lead. This is due to the current attention it is getting in the region (EARS) as well as other factors such as being green, renewable and sustainable [8]. However, Malawi Government seems not to have done much in exploiting geothermal energy supply due to reasons such as insufficient studies, technical capacity and funds – rendering a potentially great energy source untapped [9]. This is also recognized in the National Energy Policy which projects up the contribution of these renewable energy sources to 5% and 20% by the years 2020 and 2050 respectively [10]. As discussed by Gondwe et al [11], in the current Model for Energy Supply System Alternatives and their General Environmental Impacts (MESSAGE) study for the analysis of different supply options, geothermal energy is expected to begin contributing to Malawi's energy mix before the year 2021. In the MESSAGE the geothermal potential of Malawi is estimated at 200MW. In his presentation at the 2003 meeting in Kenya, Kalindekafe [12] stressed "in the name of environmental fortification and social economic enhancement of Malawi, efforts should instantly be made to start the process of geothermal resource exploitation in Malawi".

Kaonga et al, [13], recommended further investigations of all thermal springs through geophysical surveys to delineate the precise orientations of the fault conduits and thermal rocks bringing the hot waters to the surface. There should be continuous monitoring of rock temperature, discharge and various hydrochemical parameters over a period of a year to determine the seasonal fluctuation of these parameters in order to estimate the degree of intermixing of the underground thermal rocks with surface waters[14]. Although Dulanya [15] undertook such an exercise on some of the Malawi springs, his calculations were only based on the chemical data reported in the Malawi Geological Survey Department (MGSD) bulletins published 50 years ago. In 2003, the MGSD reviewed hot spring resources for suitability for geothermal power. During this assignment all known hot springs were recorded with a GPS and plotted on a map [16]. Furthermore, in 2007 Zuze et al, [17] did a study on silica and cation geothermometers to determine the subsurface temperatures of thermal springs. The results predicted a highest subsurface temperature of 240°C, therefor an attempt to estimate the depth reservoirs needs to be conducted in such areas too [18].

This research concept attempts to describe how to partly address the great and increasing needs of Malawi for energy access through renewable, low emissions energy – with a focus on geothermal energy in Malawi. The geothermal potential in Malawi is very promising because in some parts of the country, it is already known and utilized in small scale [19]. A number of hot-springs resources exist in the Malawi from north to south which are currently utilised for domestic purposes and tourism only as shown in Figure 2. If properly explored, these could become important for the country's development for power generation. The Eh/pH diagram of some of Malawi's hot-springs indicates that the chemical composition of most hot-springs are partly influenced by surface conditions [20]. These results therefore, imply that the chemical conditions of these springs might be very different at greater depth and this should be the subject for further research. Temperatures for these springs range from mild to boiling, neutral to basic and most of the water is soft [15].

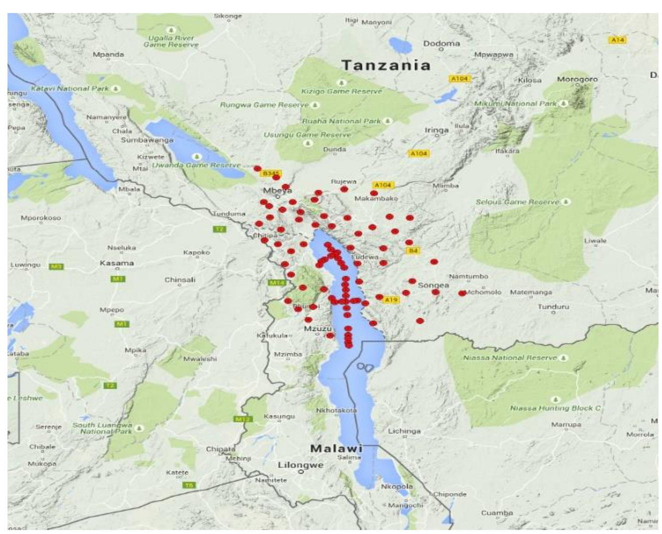


Fig. 3. Map showing Major hot springs in Malawi Map

The aim of this research proposition is to put forward a detailed means, step by step, on how the assessment of the underneath geothermal rock along the shores of Lake Malawi will be carried out. This will help to determine the feasibility of the enhanced geothermal energy exploration in Malawi. Three main questions will be dealt in this research concept: 1) Do hot dry rocks exist along the Malawi lake? 2) Are these available thermal rocks located at good depth for Enhanced Geothermal Systems (EGS) in Malawi? 3) Is the temperature of these underneath rock adequate for EGS? This will assist renewable energy sector in Malawi to advance the exploration of geothermal development and build capacity plus expertise in the field of geothermal utilization and related policy based on credible underneath thermal data. Thus the research will contribute to the overall objective of the Geothermal Compact in Malawi.

2. SPECIFIC OBJECTIVES

The current work sought to

I. Map up the surface geographical position and the exact depth of underground hot dry rock reservoirs along the shores of Lake Malawi.
II. Determine the exact temperature ranges of the underneath thermal dry rocks.
III. Identify the underground hot dry rock reservoirs which are more close to the water resource (Lake Malawi)

3. RATIONALE

Like other countries in the great lift valley, Malawi is subjected to high population at a growth rate of 2% per annum [21]. On the contrary, the production of electricity is static and far from addressing the needs of its population. This is putting a lot of pressure on already few natural resources, which is followed by catastrophic environmental impacts. However, Malawi lies in the great lift valley and there are already signs of the presence of geothermal energy reservoir underneath mostly in off shore areas of Lake Malawi. Furthermore, the presence of the lake as a resource means, that if we can find hot dry rock, then drill up to there and then the water near-by can be injected in, in-order to extract heat from the rocks, and thereafter, the water can be pumped to turn the turbines to produce electricity as shown in Figure 4. The electricity produced for the geothermal reservoir might not the only benefit the country, but also there will be conservation of biomass at national level [22].

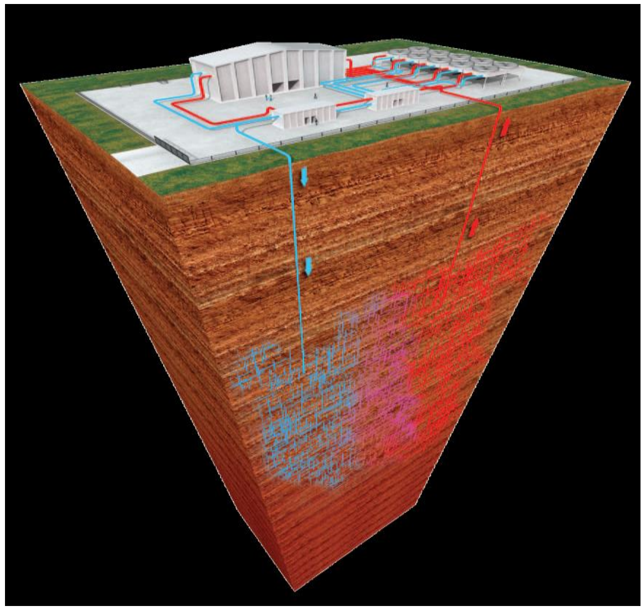


Fig. 4. fluid is injected into a well, circulated through the hot rock in the subsurface, and then pumped to the surface, where the fluids or steam runs turbines to produce electricity.

4. RESEARCH METHODOLOGY

4.1. GEOTHERMAL ROCKS EXPLORATION METHODOLOGY

Geophysics is the study of the earth by the quantitative observation of its physical properties and its surroundings by methods such as seismic, electrical and electromagnetic, magnetic and radioactivity methods. In geothermal geophysics, we measure the various parameters connected to geological structure and properties of geothermal systems. In lay man's language, geophysics is all about x-raying the earth and involves sending signals into the earth and monitoring the outcome [34].

Geothermal rocks exploration aims at identifying the hot hard rock resource, in terms of surface and depth extent, volume fluid properties, and collecting all necessary information for taking decisions on investing towards a geothermal power plant [23]. Geothermal exploration might include the following surveys; (1) Geological survey, (2) Mapping thermal manifestations, (3) Geochemical survey, (4) Thermal gradient measurements, (5) Gravity survey, (6) Monitoring micro seismic activity, (7) Reflection seismic and (8) Deep exploration drilling and testing [24]. This research concept shall be based on the use of Reflection seismic method. Seismic method is a used for studying seismic energy propagation through the earth. This method which is used to study seismic velocities of rock units in the subsurface with an aim of sub-surface strength, horizontal and vertical discontinuity of the geothermal rocks will be exploited in this research [25].

4.2.THE APROACH STRATEGY

Firstly, underground thermal radiant images will the retrieved from geological satellite (Land Sat 5) which will be over layered with past thermal images obtained from the MGSD. These images will show structural layers of different underground strata in the specified locations over a period of time. The underground imagery maps will be that of a range of 0 to 1km (towards land) form the lake margin thought-out the range of Lake Malawi. Thus a narrowed down study area and specifically it is in the heart region of the Africa Great lift vary and also in close proximity to the lake where water for enhance geothermal can be easily sourced. Only the areas which show to have stratus of thermal rocks underneath will be investigated further.

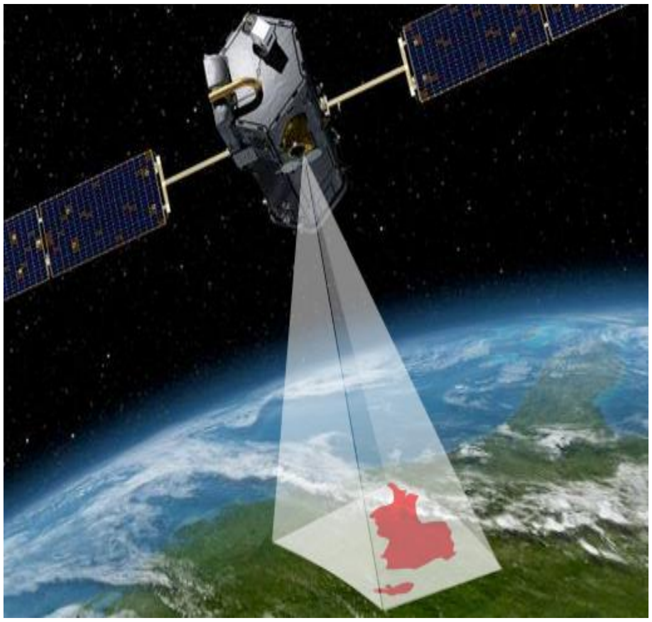


Fig. 5. Land Sat 5 (source; NASA gallery 2006)

Secondly, the exact coordinates of the areas of viable heat radiation with the strata of the rocks underneath, will be digitalised with the use of a GPS satellite finder and then plot these possible sites on a map. Recording will help to ensure that all possible sites are easily accessed throughout the research cycles. Areas with the underground thermal rocks being closer the lake will be investigated first.

Then at the region of interest (where the satellite images show higher thermal energy transit) the area will divided into a collection of cells of approximate twenty cell. Each cell will be of 3m by 3m (as specified by the seismometer) and at a distance of 10m between cells so as to avoid interference of seismic waves from each seismometer. In each cell will be placed a seismometer and the readings will be collected on a daily basis for two months so as to give enough data for analysis which should give credible results.

4.3.INSTRUMENTATION

A surface network of seismometers will be used at each identified site. The seismometer device will send the electric signals down earth and records and interprets the incoming signal (feed-back) from down the earth. For instance, to measure the distance at which the rock is located from the ground [26]. This will be achieved by measuring the travel time for a signal from a seismometer (as a sender) to the ground, the back to the seismometer again (as a + receiver). Since signals travel at the speed of light ($3 \times 10^8 ms^{-1}$), the distance between the seismometer (ground level) and the reflecting rock will be calculated using the formula:

$$d = c.\Delta t$$

Where $\boldsymbol{d}$ = Range (distance between seismometer and underground rock)

$\boldsymbol{c}$ = Propagation velocity ($3 \times 10^8 ms^{-1}$)

$\boldsymbol{\Delta t}$ = Signal travel time

Since the position of each seismometer is known with great accuracy, the position of underground rock can be deduced once the distance between the seismometer and underneath rock is known.

Seismomic method will use two transmitter electrodes (A and B) that will be stack into the ground up to 2-4m and then two receiver electrodes (M and N), and connected between them will be an electric transmitter. They will all be set up in a direct line and in the middle there shall be an electric or a voltage meter that will receives the data that bounces back after a shot of electricity is sent into the ground and thereby mapping the ground rocks beneath [27].

To determine the temperature, MTT-measurement (Magnet-Thermal-Totellurics) technique will be used, which is based on the interaction of thermal sensors in the seismometer and the underground rock's magnetic heat field. By measuring this magnetic heat (energy in-transit) pretty thorough readings of the layout of the underground rocks will be made, up to even 30km down, depending on the depth of the target thermal rock. The MTT is also a component subsidiary removable component of the seismometer device

[28]. Each seismometer in each cell will directly be recording the approximate temperature of the underground thermal rock.

The simplified geothermal relationship for thermal conduction is (conductive heat transfer only):

$$Q_{cond-z} = -K\frac{\Delta T}{\Delta Z} \ldots\ldots\ldots\ldots\ldots\ldots. Equation\ 1$$

The parameter **k**, the thermal conductivity (W/m°C), is a material constant, which ranges between 1 and 5 W/m°C, with the low values usually associated with sedimentary formations and the higher for crystalline rocks. The thermal gradient, $\Delta T/\Delta z$, gives information on the increase of temperature with depth, and its distribution can be important information for understanding and delineation of the geothermal resource, both on a regional scale and local scale as show in Table 1. If the conductive hear transfer, Q, is 80-100 mW/m^2 or higher, it will indicate geothermal conditions in the subsurface is practical [29].

4.4. ROCK HEAT TRANSFER CALCULATION

For this study we will use the solution for a thermal rock as described below. If a parallelepiped ground surface of square horizontal cross-section of width $\boldsymbol{4d^2}$ and height $\boldsymbol{h}$, at an initial temperature $\boldsymbol{T_0}$ has its top at a depth $\boldsymbol{l}$ below the ground surface (maintained at zero temperature for $\boldsymbol{t} \geq \boldsymbol{0}$), and if the subsurface had an initial temperature of zero everywhere, then the temperature $\boldsymbol{T}$ at time $\boldsymbol{t}$ at any point a horizontal distance $\boldsymbol{x}$ away from the center of the body and at a depth $\boldsymbol{z}$ will be given by:

$$T(x,z,t) = \frac{T_0}{4} erf\left(\frac{d}{2\sqrt{\propto t}}\right)\left\{er\,f\left(\frac{x+d}{2\sqrt{\propto t}}\right) - erf\right\}\left\{er\,f\left(\frac{h+l-z}{2\sqrt{\propto t}}\right) - er\,f\left(\frac{h+l+z}{2\sqrt{\propto t}}\right) - er\,f\left(\frac{l-z}{2\sqrt{\propto t}}\right) + er\,f\left(\frac{l+x}{2\sqrt{\propto t}}\right)\right\} \ldots\ldots. Equation\ 2$$

Source; Geothermal Resources Council Transactions, 2012

α = Thermal diffusivity $=K/pc$,

K = Thermal conductivity of surrounding rock,

c = Specific heat of surrounding rock,

p = Density of surrounding rock, and

$erf(x)$ =Error Function $= \frac{2}{\sqrt{\pi}}\int_0^x e^{-u^2}du \ldots\ldots\ldots\ldots Equation\ 3$

4.5.THERMAL ENERGY RESERVE ESTIMATION

Energy reserves underneath at any given prospect within a given depth range will be estimated from the calculated temperature radiant distribution around a rock body [30]. For the purposes of the energy reserves estimations herein we assume a depth limit of 4 km. The approach to calculate the geothermal reserves per unit area (of the ground surface of the prospect) associated with a heat body from the calculated temperature distribution will be;

$$E = dc_v(T - T_0) - R/F/L\ldots\ldots. Equation\ 4$$

E = MW reserves per km^2 at a distance x from the center of the caldera,

d = The depth down to which the energy reserves rocks are to be estimated,

c_v = Volumetric specific heat of the reservoir rock.

T = Calculated average temperature (in absolute unit) between the ground surface and depth d at a distance x from the center of the caldera,

T_0 = Rejection temperature in absolute unit (equivalent to the average annual ambient temperature),

F = Power plant capacity factor (the fraction of time the plant produces power on an annual basis),

R = Overall recovery thermal efficiency (the fraction of thermal energy in- place in the reservoir that is converted to electrical energy at the plant), and

L = Power plant life.

These assumptions are conservative and will be relaxed where warranted

The parameter $c_v in\ (4)\ is\ given\ by$:

$$C_v = \rho_r C_r (1 - \emptyset) + \rho_f C_f \emptyset \ldots\ldots\ldots\ldots\ldots\ldots Equation\ 5$$

ρ_r = Density of rock matrix,

c_r = Specific heat of rock matrix,

ρ_f = Density of reservoir fluid at temperature T,

c_f = Specific heat of reservoir fluid at temperature T, and

$\emptyset$ = Reservoir porosity.

The parameter R in (4) is a representation of:

$$R \frac{W.r.e}{\overline{cf}\ (T - T_0)} \dots\dots\dots Eqaution\ 6$$

Where

$r =$ Recovery factor (the fraction of thermal energy-in-place that is recoverable at the surface as thermal energy),

$\overline{cf} =$ Average specific heat of reservoir fluid within the temperature range of T_0 to T,

$W =$ Maximum thermodynamically available work from the produced fluid, and

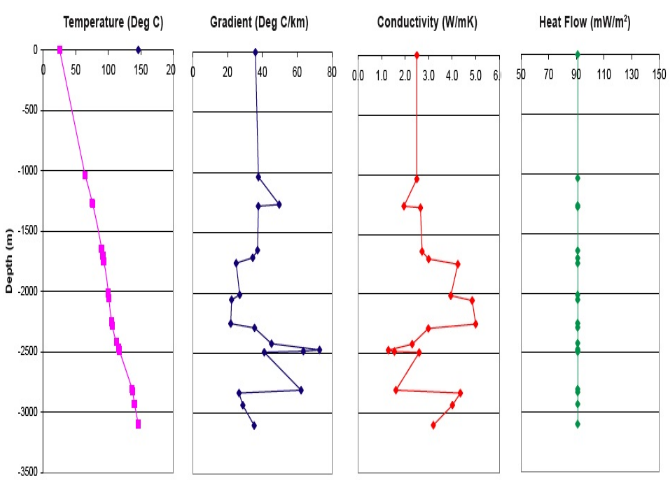
$e =$ Utilization factor, which accounts for mechanical and other energy losses that occur in a real power cycle.

The parameter W in (6) is derived from the First and Second Laws of Thermodynamics:

$$dq = c_f T, and$$

$$dW = dq(1 - T_0 / T) \ \dots\dots..Equation\ 7$$

Table 1: Depth against temp, gradient, conductivity and heat flow



The relationship between temperature, geothermal gradient, rock thermal conductivity and heat flow is that geothermal gradient varies inversely as thermal conductivity.

4.6.DATA ACQUISITION

Data will be obtained from each seismometer in each cell and thereafter, compared to the observed data against the waveform pattern for each cell. The advantage is that data will already be in digital format, hence easy to process. The readings of temperature and the depth will be collected at noon every day because there are more wave interactions due to maximum surface temperature. This will be done for 3 month so that enough data should be collected for analysis at each specific area of study.

4.7.DATA PROCESSING

To come up with accurate underground anomaly maps showing the depth with temperature of the rocks at that depth with good scale of proper coordinates with the ground reference, the acquired data comparison from all cells will enable to build a seismicity map of the underground rock with its temperature using the 3D Arc map software application version 10.6. The map will show the vertical distance (depth) of the thermal rocks into a scale. Then the maps will be geo-referenced to enhance visibility and interpretations for the Government and potential investors in Malawi.

4.8.DATA INTERPRETATION

From the maps made for each specific thermal potential area of enhanced geothermal investigation, the areas which are close the lake with the underground thermal rocks being closer to the ground, with the temperature greater than 100^0C (temperature at which water can be turned to steam) and with thermal conductivity transfer of above 80-100 mW/m^2, will be regarded as qualified areas for enhanced geothermal drilling in Malawi.

4.9.METHOD JUSTIFICATION

This research will be subjected to Reflection Seismic Geothermal Exploration Methodology. Although a seismic method is of high cost, but with credible penetration to depth down to 30 km, depending on instrumentation used and scope of the study. This method will provide excellent imaging of subsurface structures and fault zones and targets of geothermal production wells in Malawi [31]. Seismology is very sensitive for outer interruption like electromagnetic waves when it interferes into its sensors. This will we be taken into account. Processed seismic data will give information about subsurface geology, including rock types with its exact temperature [32]. It can also be correlated with gravity surveys to define more accurate velocity models which provide more accurate depth estimates hence can assist in locating drilling locations and during exploitation of a geothermal field. Since Seismic Reflection use high resolution and precision seismic reflection images, thus, ensuring time and cost efficient development and sustainability of the geothermal field [33].

5. KEY MILESTONES AND DELIVERABLES FOR THE RESEARCH PROJECT

The underground thermal recordings will assist the Malawi government to increase its renewable energy access through low emissions geothermal energy development. This will help to reduce the reliance on biomass energy and mitigate some related environment impacts which Malawi as a country is facing and at the same time reduce the inadequate electric production on EGECO. The proposed research might extend up to (and possibly through) the stages of exploratory drilling, after which major infrastructure, financing agents or commercial developers would step in to work with government of Malawi an exploration of enhancement of geothermal. It will also expand knowledge and capacity that enables further actions on utilization of the geothermal in Malawi as a country. An important aspect of the outcome to the proposed research might support to the respective government to move forward from positive exploration results and submit potential geothermal projects into funding pipelines for exploration drilling in Malawi.

As a country we shall also attract private sectors and even international companies to invest in geothermal energy exploration based on pre-found knowledge of these geo-reserves, which on other hand will bring more green pastures to Malawians. The electricity which may be produced form these geo-resources might be used on rural electrification, local industries and even added to the national grid depending on the scale of the reservoirs to be exploited after the research.

6. CONCLUSION

In Malawi, luck of early stage exploration underneath temperature is a barrier preventing geothermal energy from making a bigger contribution to meeting energy demand at present. As such, the rationale for the Project is highly justifiable. The project will boost up the highly competitive need of electricity in terms of cost per MW. Geothermal energy holds significant promise for the development of low-carbon energy systems in Malawi. This will be one of the lowest cost source of renewable electricity, and it will also have the ability to meet base-load power demand and backstop fluctuating supply from other renewable sources in Malawi. In this proposed study of the Geothermal Resource Exploration concept, it will be possible to consider all the ramifications or nuances of using a Geophysical Methods in an engineered heat-mining concept. As stated in the *Introduction* to this paper, only a geophysics application systems will be considered. Geothermal could be a vital component of low carbon electricity systems – where resources allow in Malawi.

7. ACKNOWLEDGMENT

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8. CONFLICT OF INTERESTS

The authors have not declared any conflict of interests

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