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ASSESSING GENERATING CAPACITY OF RWANDA GEOTHERMAL FIELDS FROM GREEN FIELD DATA ONLY

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ABSTRACT

"Geothermal resource assessment for green fields" is the evaluation of the expected potential of supplied geothermal electricity that might become available for exploitation of a given reservoir. Different methods of assessment, such as counting volcanoes, surface thermal flux, surface CO_2 flux and the stored heat method known as the Monte Carlo method are applied in the present report using the available data for Rwanda. This approach could be considered as level 0 to obtain a first course estimate of Rwanda's generating capacity. The assessment is presented for two cases, the overall country and the promising Karisimbi volcano geothermal field. The results range from 26 to 345 MWe. In the case of the evaluation of the potential as a whole, very different results are found, from approximately 100 MWe (by counting the volcanoes) to 26 MWe (by considering that the heat is transferred by conduction only); a recovery factor of 1% is applied for the electricity conversion capacity. In the case of the Karisimbi volcanic field, results differ from 17 MWe for the surface CO_2 flux to 80±40 MWe for the surface thermal flux and finally 345 MWe for the Monte Carlo volumetric method. Those results represent the best guess of accessible energy and what can be turned into electricity at the present stage of geothermal development in Rwanda. An average generating capacity from the four methods studied is approximately 120 MWe, of which 50 MWe can be considered as a reasonable initial target for geothermal generation in Rwanda in say the next 5-6 years. However, this estimation should not be regarded as proven until drilling and additional surveys can confirm the accessibility of the resource and the reservoir properties are determined. Furthermore, the protection of the whole National Volcanoes Park must be considered prior to any development of the Karisimbi field.

1. INTRODUCTION

Rwanda is currently confronted by an energy supply problem. Biomass dominates as the principal source of primary energy for 90% of the population, while imported petroleum fuels on the other hand dominate the local industrial energy supply. Electricity is used by only 6% of the population. Production of electricity in Rwanda is mainly from hydro resources but, since 2004, the capacity of hydroelectric power plant has lowered significantly as a consequence of low reservoir levels. Therefore, part of the hydro capacity was replaced by thermal power to ensure a stable power supply; today, it represents half of the electricity production in the country. The high prices of oil are putting a strain on the national budget and presently constitute a serious hurdle to the economic growth for a landlocked developing country such as Rwanda. The current available electricity capacity in the country is 54.6 MW and the average cost of electricity is about 0.22 USD/kWh. Therefore, to minimize dependency on energy imports, save foreign currency and create conditions for the provision of a safe, reliable, efficient, cost-effective and environmentally appropriate source of energy, geothermal development seems to be the long term solution that could end the current energy crisis.

The development of geothermal energy resources in Rwanda is in early stages compared to other East African countries. Geothermal exploration really started in 2006 with a view of diversifying energy sources in the generation of electricity and meeting the electricity demand in the country. The volcanoes, the geological context and the hydrothermal manifestations of Rwanda are an indication of the existence of potential geothermal systems. The potential is located within the western branch of the East African rift, which extends along the western borders of Tanzania, Burundi, Rwanda and Uganda; this branch is less developed and less active seismically and volcanically compared to the eastern branch. Rwanda hosts two prospective areas for geothermal potential: (1) the northwest part of the country comprising the Volcanoes National Park which is part of the Virunga chain and the hot springs of Gisenyi; and (2) the southwest part of the country with the Bugarama field located at the faults associated with the western branch of the East African Rift near Lake Kivu. Geothermal investigations indicated the Karisimbi volcano area as a potential for large, high-temperature geothermal systems, while the rift in the southwest part of the country along Lake Kivu is believed to present an environment for low- to moderate-temperature resources (Demange et al., 1983 and Newell et al., 2006).

In this context, it is, therefore, important to know how much geothermal potential is actually available for Rwanda to meet its energy demand despite the lack of knowledge about the resource itself. The purpose of the current work is to answer this question. The report gives an estimate of the energy capacity of Rwanda geothermal resources by using green field data through different methodologies. Four schemes of geothermal resource assessment are applied in this report: the Monte Carlo volumetric simulation technique, surface CO_2 flux, surface heat flux, and counting volcanoes. The resource assessment is carried out in two scales, a country scale and a field scale. The report is structured as follows: Section 2 provides an overview of the geothermal resources, the definition, the classification and utilisations. Section 3 presents the Rwanda fields with an emphasis on the Karisimbi volcano field with the available data and information. Section 4 details the methodology used for the assessment of the resource. Sections 5 and 6 give the results of the assessment and are presented respectively for the country scale and field scale. Finally, the results are discussed in Section 7.

2. GEOTHERMAL RESOURCES

2.1 Generalities

Geothermal energy is the natural heat contained within the Earth that can, or could, be recovered and exploited by man. Heat flows from the interior of the earth to the surface by conduction, or convection by hot water mass transfer. The most obvious manifestations of the earth's thermal energy are in areas of recent volcanism and tectonic activity. Therefore, temperature increase with depth, volcanoes, geysers, hot springs, etc. are, in a sense, the visible or tangible expressions of the heat in the interior of the Earth, but this heat also engenders other phenomena that are less discernible by man. Geothermal resources are distributed throughout the world; the greatest concentration of geothermal energy is in volcanic regions but may also be found as warm groundwater in sedimentary rocks.

According to Muffler and Cataldi (1978), a geothermal resource is what should more precisely be called an accessible resource base, that is, all of the thermal energy stored between the Earth's surface

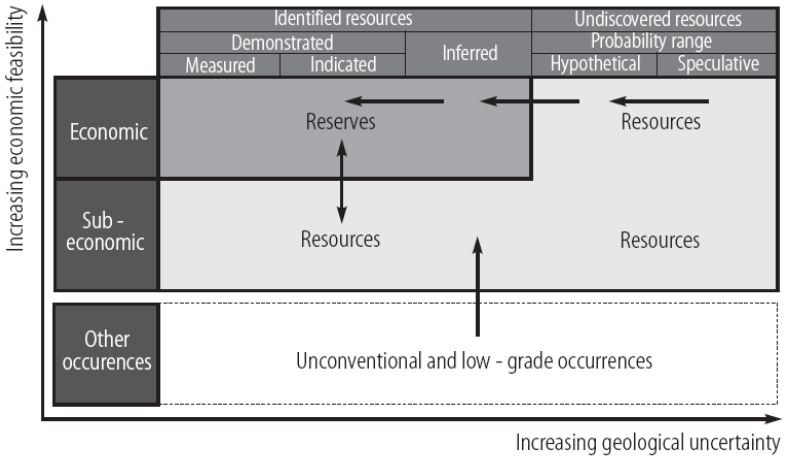

FIGURE 1: McKelvey diagram (modified from Goldemberg et al., 2000)

and a specified depth in the crust, beneath a specified area and measured from local mean annual temperature. The accessible resource base includes the useful accessible resource base (resources) which could be produced at a price which will become competitive with other types of energy within a reasonable period of time. This category includes the identified economic resource (reserve), part of the resources of a given area that can be extracted legally at a cost competitive with other commercial energy sources and which is known and characterised by drilling or by geochemical, geophysical and geological evidence. Those terminologies are easily illustrated through a modified McKelvey diagram (Figure 1) in which the degree of geological assurance regarding resources is set along the horizontal axis and the economic feasibility (effectively equivalent to depth) is set along the vertical axis (Muffler and Cataldi, 1978).

2.2 Classification of geothermal resources

Geothermal resources have been classified as low-, medium- and high-enthalpy resources*,* according to their reservoir fluid temperatures. The temperature is used as a classification parameter because it is the easiest to measure and understand and it also quantifies the energy content of the fluid to be drawn from the subsurface. Table 1 reports the classification proposed by a number of authors. To avoid confusion and ambiguity, the temperature values or ranges involved are determined in a case by case manner since terms such as low, intermediate and high are meaningless, at best, and frequently misleading.

TABLE 1: Classification of geothermal resources by temperature

Type	(a)	(b)	(c)	(d)	(e)
Low-enthalpy resources	< 90°C	< 125°C	< 100°C	≤ 150°C	≤ 190°C
Intermediate-enthalpy resources	90-150°C	125-225°C	100-200°C		
High-enthalpy resources	> 150°C	> 225°C	> 200°C	> 150°C	> 190°C

Source: (a) Muffler and Cataldi (1978); (b) Hochstein (1990); (c) Benderitter and Cormy (1990); (d) Nicholson (1993); (e) Axelsson and Gunnlaugsson (2000).

2.3 Utilisations

Utilisation of a geothermal resource involves the extraction of mass and heat from a geothermal reservoir. Geothermal water has been used for centuries for bathing, cooking and heating. Today, geothermal resources can be used at a various range of temperature as illustrated in the Lindal diagram (Figure 2). Geothermal utilisation is commonly divided into two categories, direct and indirect. For direct heat use, space heating, bathing, agricultural, aquaculture and industrial uses are the best known forms of utilisation. In 2004, the worldwide use of geothermal energy was 76 TWh/yr for direct use with an installed capacity for direct applications of 28,268 MWth (Lund et al., 2005). The production of electricity is by far the most important indirect utilization of geothermal energy. Direct electricity

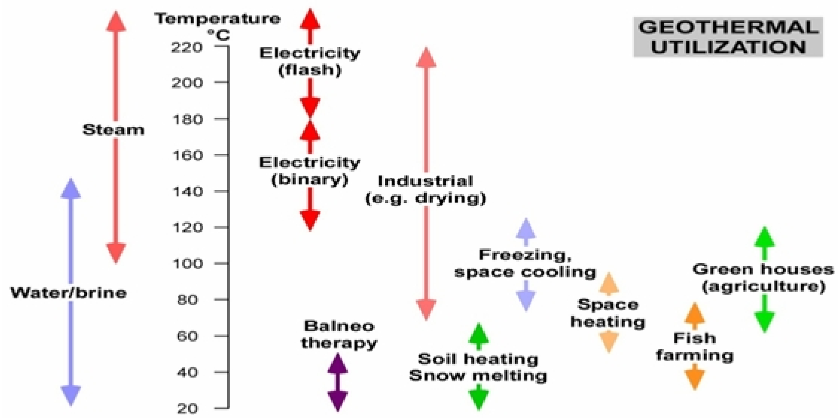

FIGURE 2: Geothermal utilisation at different temperatures (modified from Lindal, 1973)

generation is commonly limited to fluid temperatures above 180°C, but considerably lower temperatures can be used with the application of binary fluids. The worldwide use of geothermal energy in 2004 was about 57 TWh/yr of electricity with an installed electric capacity of 8,933 MWe (Bertani, 2005).

3. DATA SOURCES

3.1 Geological information

The East African rift system (EARS) is a continental rift zone that appears to be a developing divergent tectonic plate boundary. The East African rift (Figure 3) is of Cenozoic age (McConnell, 1972) and remains active as numerous active volcanoes and seismic activity show. The EARS consists of two main branches called the Eastern Rift Valley and the Western Rift Valley. Rwanda is part of the western arm of the East African rift system, the Western rift, also called the "Lake Albert rift" or "Albertine rift". The Western rift is bordered by some of the highest mountains in Africa, including the Virunga Mountains, Mitumba Mountains, and Ruwenzori range and contains the Rift Valley lakes, which include some of the deepest lakes in the world (up to 1,470 m deep at Lake Tanganyika). All of the African great lakes were formed as a result of the rifting, and most lie within its rift valley.

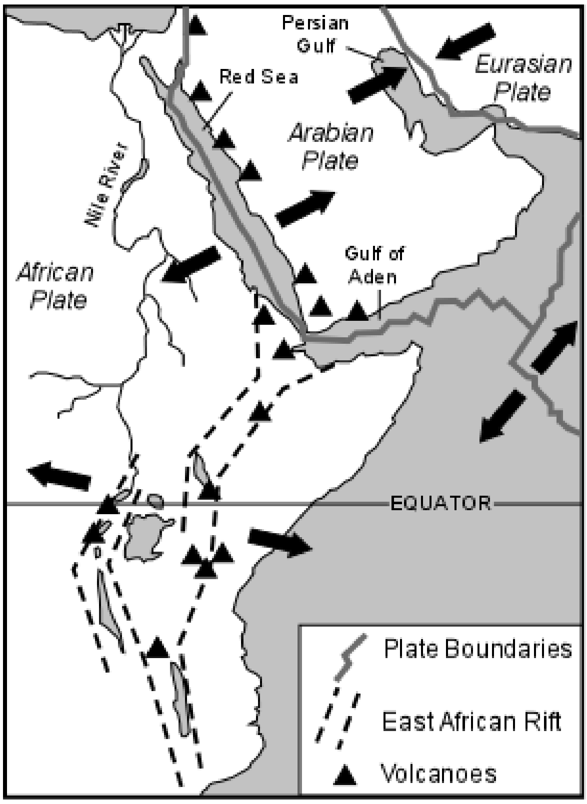

FIGURE 3: The East African rift (Tulane University, 2009)

The geology of Rwanda is similar to the geology of neighbouring Burundi and southern Uganda. It consists of granite, migmatites, gneisses and micaschists of the Paleoproterozoic Ruzizian basement overlain by the Mesoproterozoic Kibaran belt. The Kibaran, composed of folded and metamorphosed sediments, mainly schist and quartzite intruded by granite, covers most of Rwanda (BRGM, 1987). Cenozoic to recent volcanic rocks occur in the northwest and southwest parts of the country. Some of these volcanoes are highly alkaline and are extensions from the Virunga volcanic area of southwest Uganda and eastern Democratic Republic of Congo (Schlüter, 2006). The alkali composition of the rocks indicates a great depth of magma generation below both rifts.

Rwanda hosts two prospective areas for geothermal potential: the Volcanoes National Park and the faults associated with the Western Branch of the East African Rift near Lake Kivu. Following preliminary reconnaissance studies (Demange et al., 1982), three important zones presenting a geothermal potential interest for electricity production were selected: 1) The northwest zone which comprises the Virunga volcanic complex; 2) The hot springs of Gisenyi which are located in the northern part of Lake Kivu; and 3) The southwest zone which comprises the Bugarama field in the southern part of Lake Kivu area (Figure 4). The Virunga volcanic complex is made up of eight stratovolcanoes, five of which (Muhabura-Gahinga-Sabyinyo-Bisoke-Karisimbi) are on the Rwanda side while two actives ones, Nyiragongo and Nyamulagira, are in Congo (Figure 5). These five are commonly defined as the National Volcanoes Field. In this report a special emphasis is put on the southern flanks of the Karisimbi volcano.

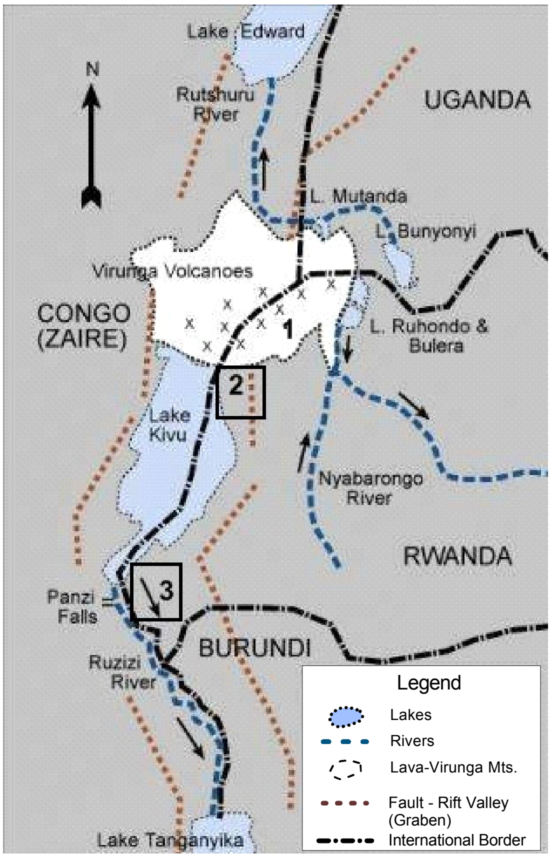

FIGURE 4: Potential geothermal zones in Rwanda (Ford, 1997)

3.2 The Karisimbi field

The Karisimbi field comprises the National Volcanoes Park prospect and the Gisenyi prospect. This field was subjected to detailed surface exploration in 2006 by the Chevron Company, Ltd. (Newell et al., 2006) and in 2008 by the BGR - Federal Institute of Geosciences and Natural Resources (BGR, 2009). In this section the field is described and the important investigations are depicted.

3.2.1 Description of the field

As stated previously, the Karisimbi field is part of the National Volcanoes Park. No geothermal manifestations such as fumaroles or alteration have been reported in the Rwandan part of this area. However, a couple of hot springs is located south and out of the volcanic field with the highest temperature of 64°C at Karago. Figure 6 shows the study area.

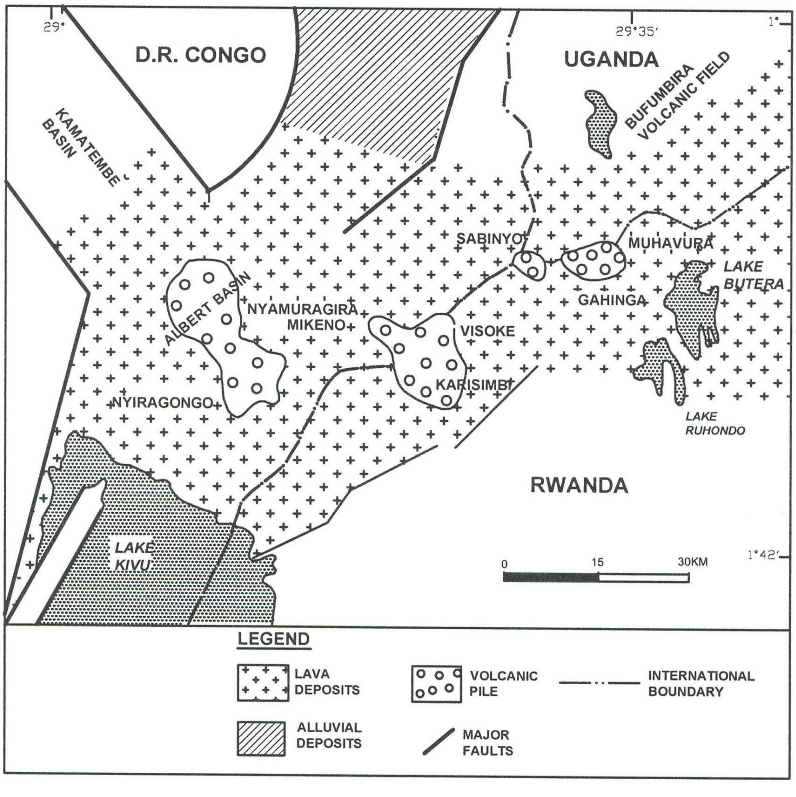

FIGURE 5: Volcanoes in the Virunga volcanic complex (De Mulder, 1986)

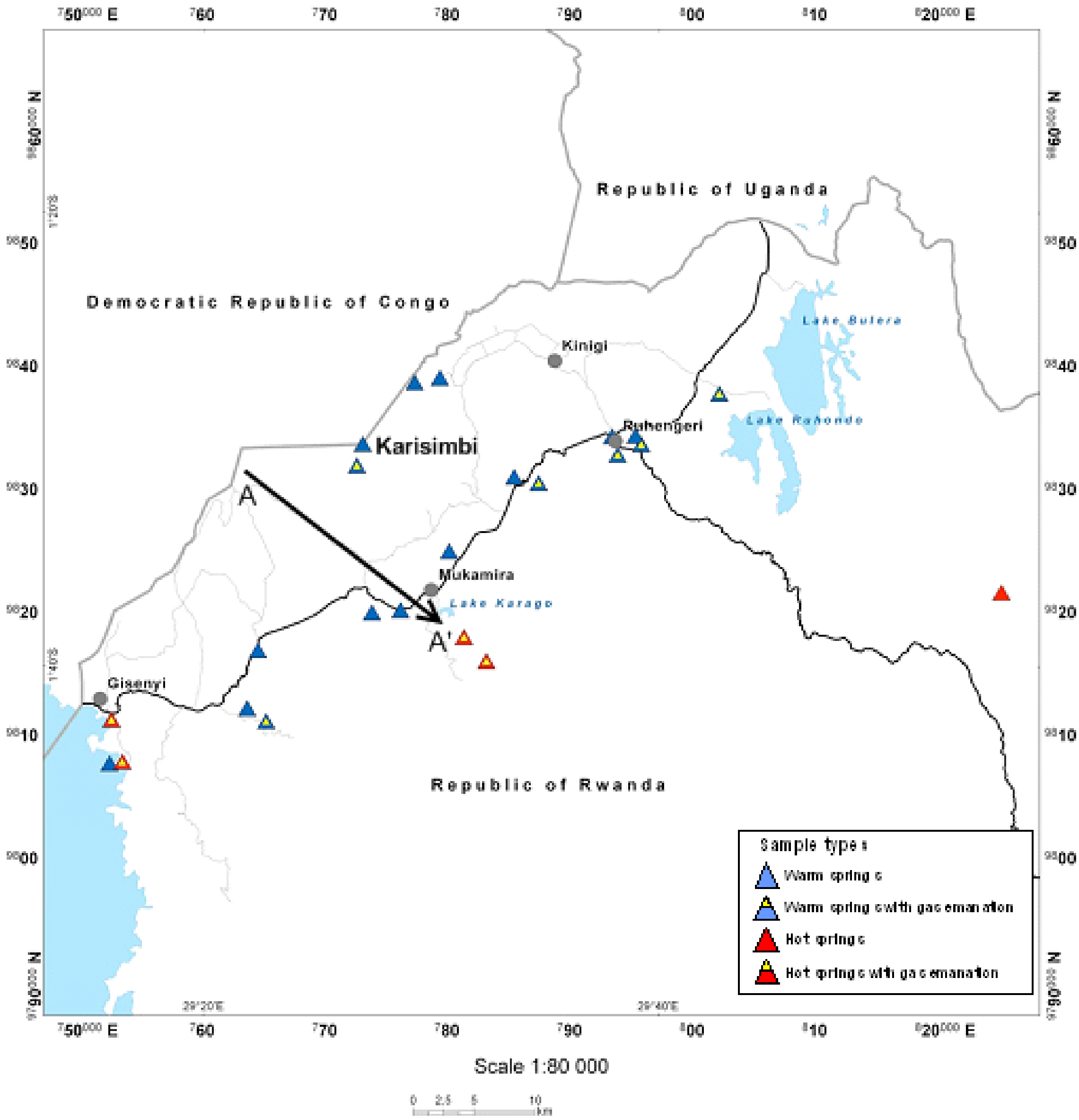

FIGURE 6: The study area in the Karisimbi volcano area, Rwanda; triangles show location of springs sampled for geochemistry analysis and the black line the location of resistivity cross-section A-A' (modified from BGR, 2009 and Ármannsson and Eyjólfsdóttir, 2009)

The Gisenyi prospect consists of a hot spring with several small vents located along the eastern shore of Lake Kivu several kilometres south of the town of Gisenyi and near the local brewery. The hot springs, which issue from a brecciated and silicified quartzite, produce Na-HCO_3 waters with temperatures between 70 and 75°C. The geochemistry of the waters in Gisenyi suggests the existence of a geothermal system of moderate reservoir temperature ranging from 150 to 210°C, calculated from chemical geothermometers (Newell et al., 2006; BGR, 2009).

The Karisimbi field was selected and investigated by the Federal Institute for Geosciences and Natural Resources from Germany (BGR) through the Geotherm programme from November 2007 to June 2009 for detailed assessment. The study area was about 600 km^2 and ranges from Lake Kivu in the west to Lake Ruhondo in the East, including a little part of the Volcanoes National Park (Figure 6). The methods used for the assessment included remote sensing, geochemical sampling of surface manifestations, a geochemical survey of soil gasses and soil temperature and, finally, geophysical surveys. The following sections present the findings of the assessment. More surveys to define the location for exploratory wells are expected in the beginning of 2010.

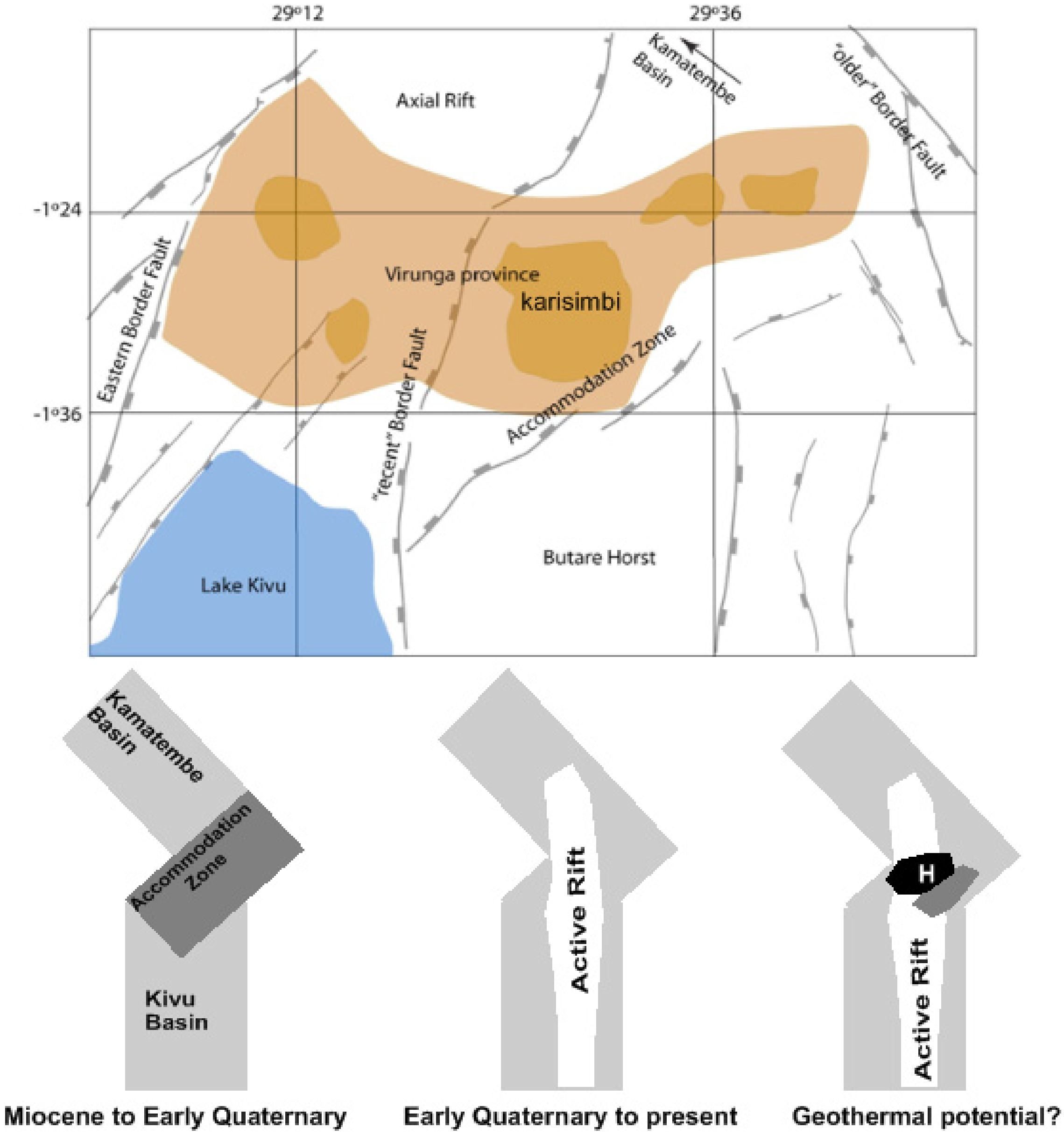

FIGURE 7: The Virunga range; Top: Structural sketch map; Bottom: Evolution of the rift system and its geothermal potential with H showing the main heat source (Gloaguen et al., 2008)

3.2.2 Remote sensing

Considering the inaccessibility of some areas within the National Volcanoes Park, remote sensing was carried out in the Karisimbi field. Aerial photographs of the Karisimbi volcano prospect were reviewed and a structural analysis was performed, based on processed data from high-resolution stereogrammetric DEMs of approximately 4.500 km^2 of this volcanic region. The work suggests that the study area could host a medium- to high-enthalpy reservoir due to the combined presence of abundant water, strong faulting and a fissuring combination of basement inheritance and Quaternary faulting and the presence of subsurface heat (Gloaguen et al., 2008). It is suggested that present day tectonics are localized in the axial north-south basins. Therefore, the geothermal potential is expected to be maximal on the Eastern part of the accommodation zone bounding the Butare block, roughly southeast of the Karisimbi volcano. There, surface and underground waters are expected to flow in abundance, faulting is high and heat sources are proximite (Figure 7).

3.2.3 Water geochemistry

Water samples were collected from various sources in the field: rainwater, snow, rivers, lakes, cold springs, mineralised springs and hot springs (Figure 6). Twenty four water samples for cations, anions, stable isotopes, strontium and tritium as well as gas samples were taken and analysed by ÍSOR – Iceland Geosurvey. Temperature at the sampling sites ranges from 2.6°C (at a volcano's summit) up to 73.1°C. The most prominent spring with the highest temperature in the study area is at Gisenyi (73.1°C) and the second highest temperature was measured at Lake Karago (64.1°C). Outflow rates of the sampled springs are rather small, in the range of up to 4 l/s. Some springs do show relatively weak gas emanations (BGR, 2009). It is also assumed that further hot springs are located in Lake Kivu. The geothermometry suggests geothermal systems in which the temperature is probably in excess of 150°C (Ármannsson and Eyjólfsdóttir, 2009). As stated above, all the hot and warm springs are found outside the proposed high-temperature field. The geothermometers are, therefore, more likely to be showing expected sub-surface temperature of the faulted area of the escarpment to the south of the volcanic range.

3.2.4 Soil gas geochemistry

Soil gases have been used as an exploration tool for geothermal energy through the detection of anomalous gas levels to identify areas with higher vertical permeability and a better connection to the volcanic-hydrothermal system at depth. This methodology is based on the fact that gases deriving from a geothermal reservoir reach the surface more easily than the steam that can condense at the surface where the groundwater flow can transport the resulting energy out of the system (Fridriksson et al., 2006). To do so, a soil gas survey in an area of approximately 467 km^2 in the Karisimbi field (Figure 6) was performed by the Institute of Technology and Renewable Energies from Spain (BGR, 2009). The average distance between each sampling site was 200 m and the aim was to detect soil gas anomalies on a relatively small scale. Measurements of *in situ* CO_2 and H_2S fluxes, ^{222}Rn and $^{222}Rn/^{220}Rn$ ratio and soil temperature (40 and 15 cm depth) were carried out for the southern flanks of the Karisimbi summit. The gas geochemistry results indicate relatively high concentrations of CO_2, ^{222}Rn, H_2 and CH_4 together with relatively high $He/^{40}Ar$, CO_2/O_2 and $^{40}Ar/^{36}Ar$ ratios and suggest the existence of a volcanic-hydrothermal system and permeable vertical structures in the area (BGR, 2009). The potential existence of an underlying volcanic-hydrothermal system and vertical permeable structures could be the cause of these observed surface anomalies.

3.2.5 Geophysical surveys

A magnetotelluric (MT) and transient electromagnetic (TEM) resistivity survey was carried out in the Karisimbi field by the Kenya electricity company (KenGen) to see if a resistivity anomaly would be associated with the volcanic activity (KenGen, 2009). Figure 8 shows a resistivity cross-section of the southern slopes of Karisimbi volcano. The results indicate a low-resistivity anomaly, covering an area of about 50 km^2, south of Karisimbi volcano. The most prominent anomalies are those found along a northeast trending accommodation fault zone at the northern boundary between the Butare horst structure and Kivu basin and on the southern slopes of Karisimbi (Figure 7). The anomaly on the southern slopes of Karisimbi volcano was interpreted to reflect the occurrence of a high temperature geothermal system (BGR, 2009). The reservoir temperature is believed to be more than 210°C as discussed by Newell et al. (2006).

3.2.6 Conceptual reservoir model

The first conceptual model of the Karisimbi field (Figure 9) was proposed by Gíslason (2009). The model is based on geophysical data as well as geological and geochemistry information from BGR (2009). A heat source is visualised as an intrusion of magma body into the granitic basement rock under the Karisimbi volcano at a depth of about 5-6 km depth (red area, Figure 8). An uprising boiling zone is assumed to be capped by a cap rock or deposits of secondary minerals closing off the

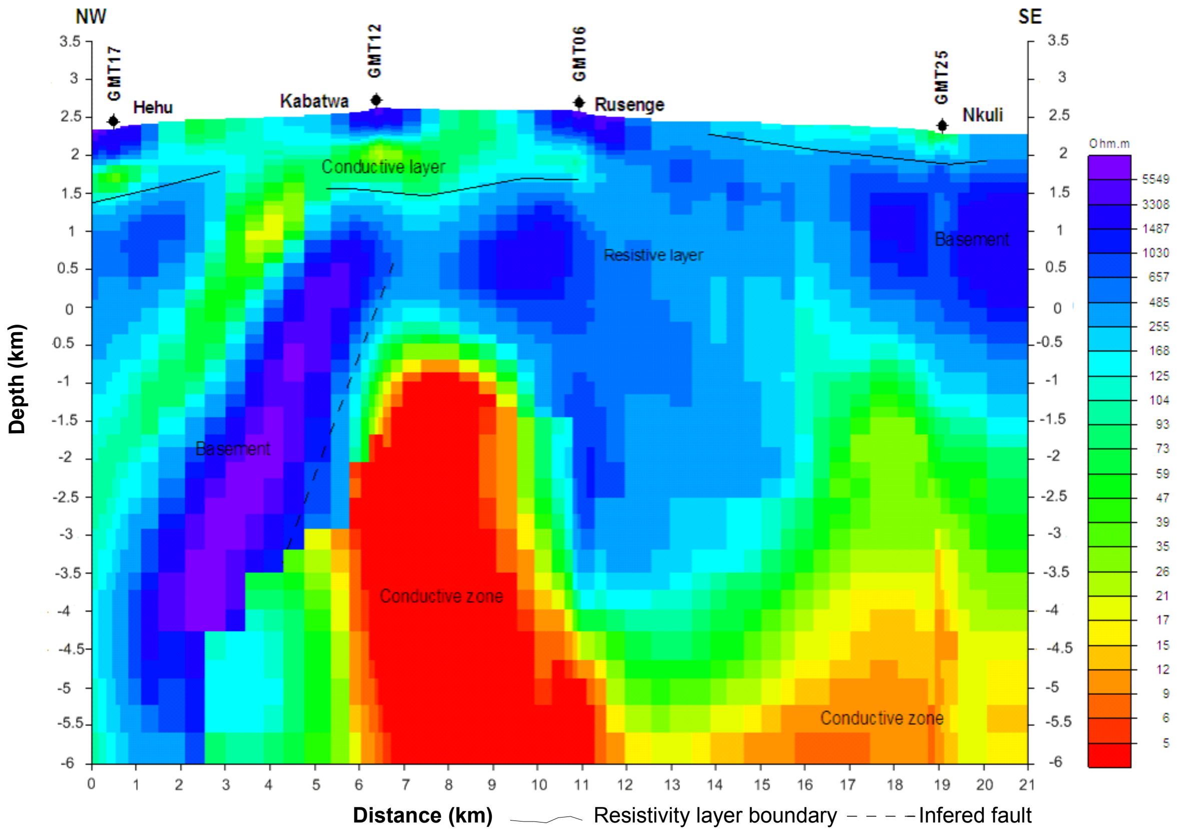

FIGURE 8: Resistivity cross-section A-A' passing along the southern slopes of Karisimbi volcano; for location see Figure 6 (BGR, 2009)

high-enthalpy reservoir. Water from the surface penetrates down to the reservoir where it is heated and rises up to appear in the hot spring at Karago and a few warm springs in the surroundings (Figure 9). The steam from the reservoir is believed to condense below the cap rock while non-condensable gases including CO_2 escape at the surface, creating high gases flux.

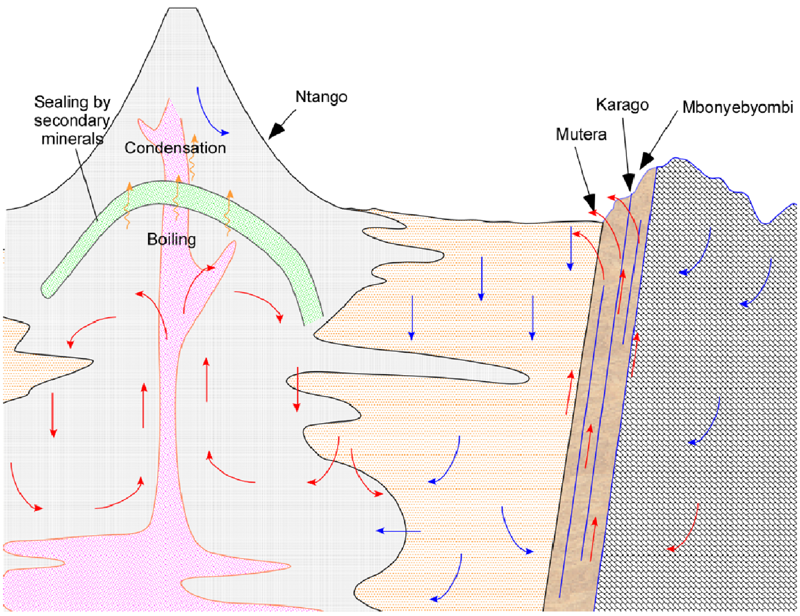

FIGURE 9: A conceptual reservoir model (Gíslason, 2009); for location see profile A-A' in Figure 6

3.3 The south-west prospect

The geothermal prospect in the southwest field is controlled by the faulting of the western branch of the East Africa rift system. The Bugarama prospect (Figure 10) is located in the Rubyiro River valley, approximately 13 km southeast of the town of Cyangugu. This valley appears to be a graben, which is a block of down-dropped rocks bounded by normal faults. The manifestations are hot and warm springs and travertine deposits, currently being mined as feedstock for a nearby cement factory. The hot springs are issuing along the

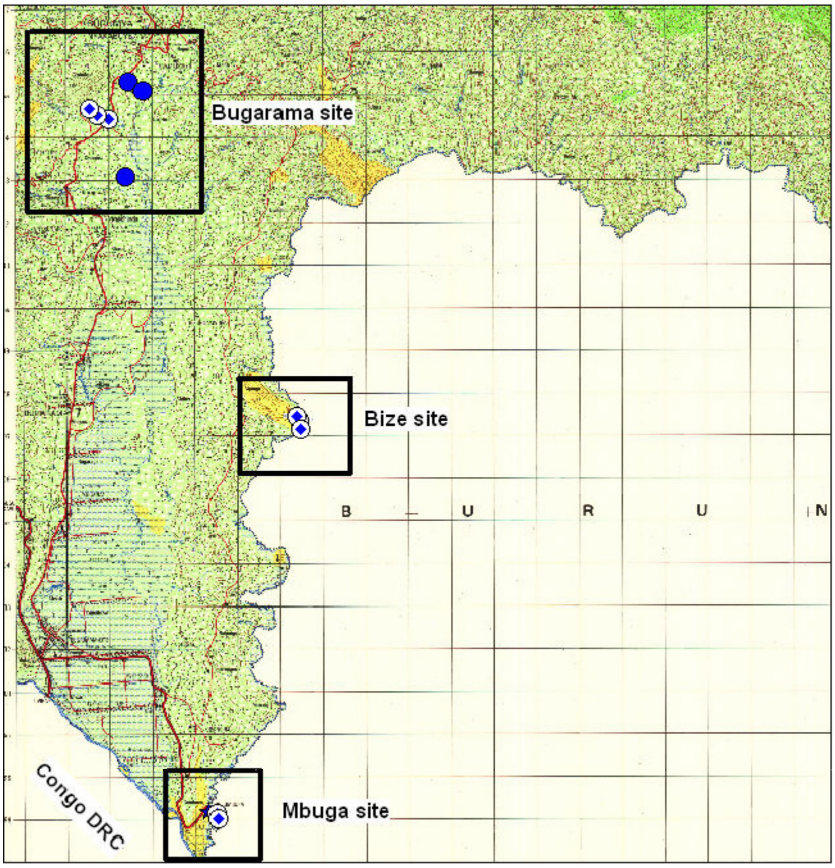

FIGURE 10: Geothermal prospects in the southwest area of Rwanda

western edge of the graben as dilute Na-HCO_3 water with temperatures up to 50°C. The hot springs form a large pool on top of the travertine deposit. Flow rates are estimated to be greater than 50 l/s, and influx is accompanied by a large quantity of gas. The higher temperature vents along the shores of the pool are depositing reddish brown iron oxide. The geochemistry of the waters in Bugarama suggests the existence of a low-temperature geothermal system with a resource temperature between 100 and 130°C (Newell et al., 2006).

4. ASSESSMENT METHODOLOGY

4.1 Criteria of methodology used

"*Resource assessment is a statement made at a given time using a given data set and a given set of assumptions concerning economics, technology, etc. Both data and the assumptions can change rapidly: the former primarily in response to exploration activities, the latter in response to technology development, economics, environmental constraints, social policy, ... Consequently a resource assessment is of only transitory value and must be updated periodically" (Muffler, 1981).*

Through the history of geothermal exploration and development, several techniques have been applied to assess geothermal resources all over the world ranging from simple correlations to detailed modelling. The approach in this report was to select methods that are suitable for Rwanda based on the available data presented in Section 3. Four methods were, therefore, selected: Counting volcanoes, surface thermal flux, the carbon dioxide diffuse method (surface CO_2 flux) and the Monte Carlo generating capacity simulation.

4.2 Counting volcanoes

The "counting volcanoes" method is based on Stefansson's assessment (1998). The association between geothermal resources and volcanic activity has been recognised for centuries and this has been interpreted in geological terms that high temperature geothermal resources are found in volcanic areas of the world (Muffler, 1976). Bodvarsson (1982) estimated the terrestrial energy current through the crust of Iceland (Figure 11). His model shows clearly the direct association of the energy realised through volcanic eruptions and the energy current observed at the surface as geothermal manifestations and indicated that the distribution of volcanoes might be applied to estimate the geothermal potential of a given area.

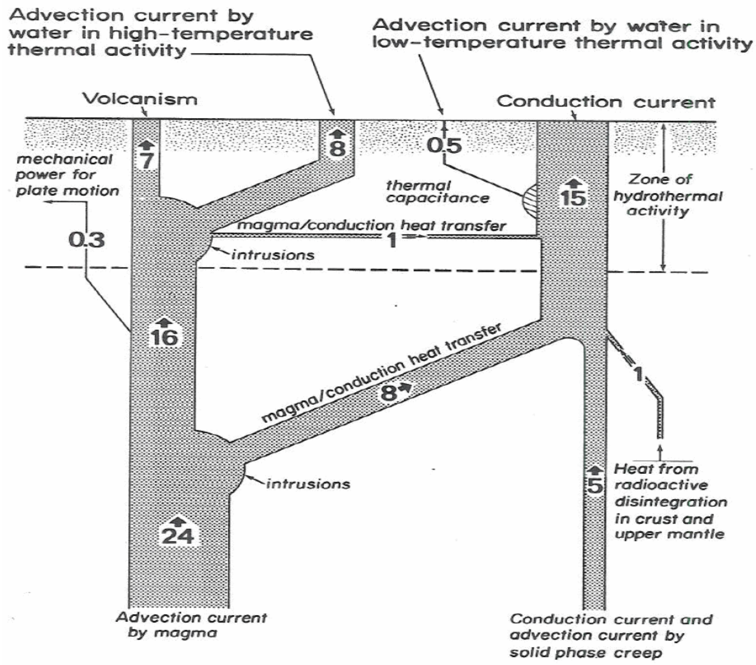

FIGURE 11: Terrestrial energy currents (GW) in Iceland (Bodvarsson, 1982)

Based on those indications, Stefánsson (2005) established an empirical relationship between a countrywide geothermal potential and the number of volcanoes in the same region to estimate the geothermal potential of regions where the knowledge on geothermal resources is limited. A linear relationship is observed between the number of volcanoes and the country scale generating capacity. The slope of this line gives a world average generating capacity for a single active volcano, here approximately 160 MW (Figure 12). This correlation was applied for Rwanda considering the volcanism in the region to estimate the geothermal potential of the country (see Section 5).

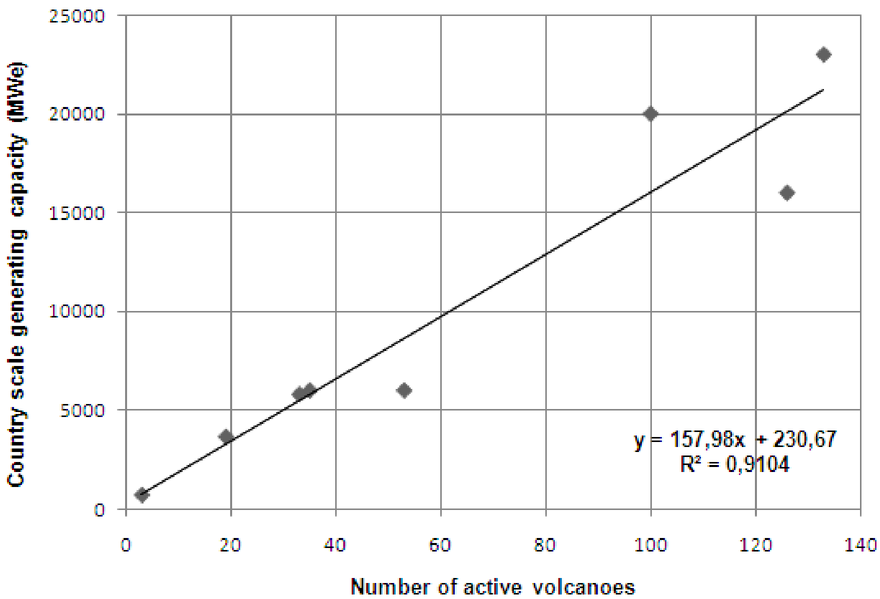

FIGURE 12: Correlation between the number of active volcanoes and estimated geothermal potential (Stefánsson, 2005)

4.3 Surface thermal flux

This method is based on the calculation of the heat flux that is transferred through the soil. Benseman (1959a) was the first to introduce a plot of heat flux data versus ground temperatures at 0.35m depth to predict steaming ground losses (Benseman, 1959b). Thompson et al. (1964) used the same approach but for ground temperatures at 0.15m depth. The method commonly used is based on the correlation between the soil temperature at 15 cm and the measured surface heat flux (Dawson, 1964).

Assuming that conduction is the main mode of heat transfer in the uppermost portion of a soil, the formula for heat flow is given by:

$$Q = kA\, dT/dz \tag{1}$$

Where Q = Heat flow based on soil temperature (W);
k = Thermal conductivity of the soil (W/°C m);
A = Surface area (m^2);
dT/dz = Thermal gradient (°C/m).

For Rwanda, the soil temperatures were measured in an area of approximately 470 km^2 in the Karisimbi volcano field at two different soil depths, 15 cm (T_{15}) and 40 cm (T_{40}) to estimate the average soil temperature gradient in the study area (Figure 6). Air temperature (T_{air}) was also measured at each sampling site. Equation 1 was applied for the calculation of the heat flow for three cases T_{15}-T_{air}; T_{40}-T_{air}; T_{40}-T_{15} (see Section 6).

4.4 Soil CO_2 flux

The measurement of the soil CO_2 flux is receiving more attention for both geothermal prospection and volcanic surveillance. The CO_2 flux has been used to estimate the heat release by diffuse degassing structures (Brombach et al., 2001; Chiodini et al., 2001, 2004; Frondini et al., 2004). These studies calculated the total amount of steam released at depth based on the assumption that the fluids which supply the diffuse degassing process have, at depth, the same composition as those emitted by the fumarole vents of highest temperature and flow rate. The thermal energy was then computed by multiplying the steam flux by the enthalpy of the steam minus the enthalpy of the liquid at ambient temperature. A similar study from Fridriksson et al. (2006) carried out in the Reykjanes geothermal area SW-Iceland described the estimation of the heat flow released by diffuse degassing processes in the area by considering the carbon dioxide (CO_2) discharge from steam vents and steam emanating fractures. The different steps for this calculation were as follows:

1. Measurements of the total CO_2 output which gives the total CO_2 flux through the soil, F_{CO2} in tons/day;
2. Analysing the chemical composition of fumaroles of the area that can be considered representative of the composition of the fluids before steam condensation and defining the CO_2 concentration in the steam, C_{CO2} in g/kg steam; and
3. Computing the total steam output and the heat released during the condensation process and cooling of the condensates to the ambient temperature.

These calculations can be illustrated as follows:

$$F_{H2O} = F_{CO2}/C_{\ CO2} \tag{2}$$

$$Q = F_{H2O} x\ h_s \tag{3}$$

where F_{CO2} = Measured CO_2 flux in the area (tons/day);
C_{CO2} = Concentration of the CO_2 in the steam (g/kg);
F_{H2O} = Steam flux (kg/s);
h = Enthalpy of the steam (kJ/kg); and
Q = Heat flow (MW).

In Rwanda, no fumaroles have been reported yet and for this reason, in order to calculate the heat flow in the Karisimbi volcano field by using the surface CO_2 flux method, Equations 4 and 5 from Arnórsson and Gunnlaugsson (1985) will be used to estimate the CO_2 concentration at different temperatures (detailed in Section 6).

a. The geothermometer equation from Arnórsson and Gunnlaugsson (1985) gives the concentration of CO_2 in mmole/kg of steam in fumaroles:

$$T = -44.1 + 269.25Q - 76.88Q^2 + 9.52Q^3 \tag{4}$$

where Q = Concentration of CO_2 in log [CO_2] (mmole/kg); and
T = Temperature (°C).

b. The temperature equation for the aqueous concentration of CO_2 in geothermal fluid according to Arnórsson and Gunnlaugsson (1985) is:

$$CO_2 = -1.09 - 3894.55/T + 2.386 \, logT \tag{5}$$

where T = Temperature (K);
CO_2 = Concentration of CO_2 (mole/kg).

4.5 Monte Carlo assessment

The Monte Carlo simulation or stored heat method is a volumetric method. It is usually used to estimate stored heat and recoverable power reserves in the early life of geothermal reservoirs and can be considered a first modelling method since it neglects the response of the reservoir. This method involves estimating the energy production potential of a geothermal system, based on available data and the present technology.

The Monte Carlo calculation is based on the generation of multiple trials to determine the expected value of a random variable. This method relies on a specified probability distribution of each of the input variables and generates an estimate of the overall uncertainty in the prediction due to all the uncertainties in the variables (Kalos and Whitlock, 2008). The common distribution types of poorly known parameters are the rectangular distribution, the triangular distribution, the uniform distribution and the normal distribution. Normal and triangular distributions are suitable when actual data are limited but it is known that the values in question fall near the centre of the limits. In the absence of any other information, rectangular distribution is a reasonable default model. By choosing one random value for each variable out of their probability distributions, one possible outcome of the volumetric method can be calculated. If this process is then repeated several times, a discreet probability distribution for the outcome begins to form. After a successful simulation, the output gives the probability of exceeding a certain level of power potential. For this work, we assume a geothermal reservoir containing hot rock and a single phase liquid water. The most likely, minimum and maximum values for the parameters will be determined for each case. In this work, the Monte Carlo simulation was run for two cases, the country scale and the Karisimbi volcano field scale by using @RISK spreadsheet-based software (Palisade Corp., 2004).

5. ASSESSMENT OF THE COUNTRY SCALE GEOTHERMAL POTENTIAL

5.1 Counting volcanoes

It is known that recent volcanic activity occurring in the Virunga volcanic field has extended into Rwanda (Figure 5). The approach used for this method is, therefore, to apply the empirical relation (12) and thereby estimate the geothermal potential of Rwanda by considering the National Volcanoes Park field. The correlation between the number of active volcanoes and the estimated geothermal potential is expressed by Equation 6:

$$y = 157.98x + 230.67 \tag{6}$$

Based on Equation 6, the geothermal potential for electricity capacity is approximately 160 MWe per active volcano. Knowing that in the Virunga mountain chain 2 volcanoes out of 8 are active and by applying correlation 6, the estimated potential for the Virunga chain is 320 MWe. Since the Virunga chain is divided between three countries, Rwanda, DRC and Uganda, the capacity for Rwanda can be estimated as a third of the Virunga potential. Based on this very simple approach, the geothermal potential for electricity capacity in Rwanda is approximately 100 MWe.

5.2 Monte Carlo assessment of the natural heat flux

For the country scale, Equation 1 was considered to calculate the heat flow. Furthermore, by assuming that 10% of this heat energy, Q, can be recovered and that only 10% of that recovered energy can produce electricity, the electricity capacity E (MWe) can be expressed as follows:

$$E = 0.01Q \tag{7}$$

Due to lack of reasonably deep wells in Rwanda, it was not possible to locate regional thermal gradient data for the country. It was, therefore, decided to perform a Monte Carlo assessment of the country's total heat flow. The parameters used for the simulation and the probability distributions applied are summarized in Table 2. The most likely, minimum and maximum estimates are given as well as probability distributions for the different input parameters.

TABLE 2: Input data for Rwanda Monte Carlo countrywide heat flow

Parameters	Units	Most likely	Probability distribution		
			Type of distribution	Minimum value	Maximum value
Area	km^2	26,338	Constant	-	-
Thermal conductivity	W/m°C	2.5	Triangular	2	3
Thermal gradient	°C/km	40	Rectangular	20	60

The simulation runs totalled 10,000. The electricity capacity of the country was calculated from Equations 1 and 7 by using the random parameters in Table 2. The results are presented using relative frequency histogram (Figure 13) and the cumulative frequency distribution (Figure 14). Figure 13 illustrates that the most likely capacity of the country is 26 MWe. The results show a distribution probability of 90% for a range of 14-39 MWe with a minimum capacity of 12 MWe (5% probability) and a probability of 10% to have a maximum capacity of 45 MWe. Figure 14 shows that there is 50% chance of producing 26 MW.

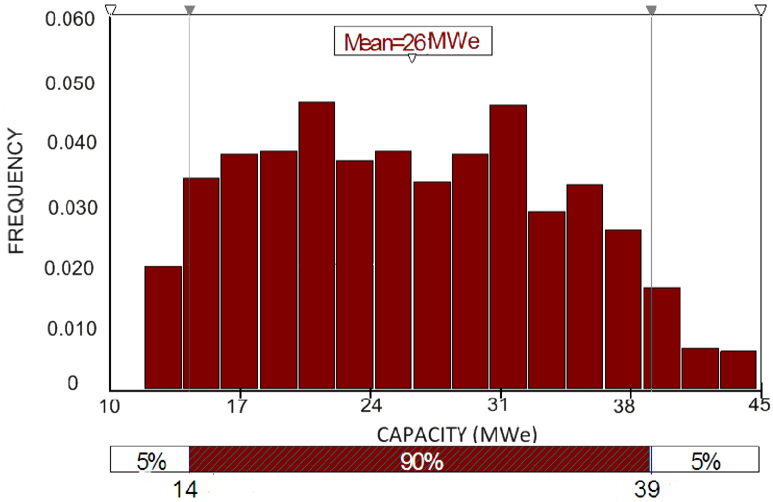

FIGURE 13: Frequency distribution for Rwanda electricity capacity based on natural heat flux assessment

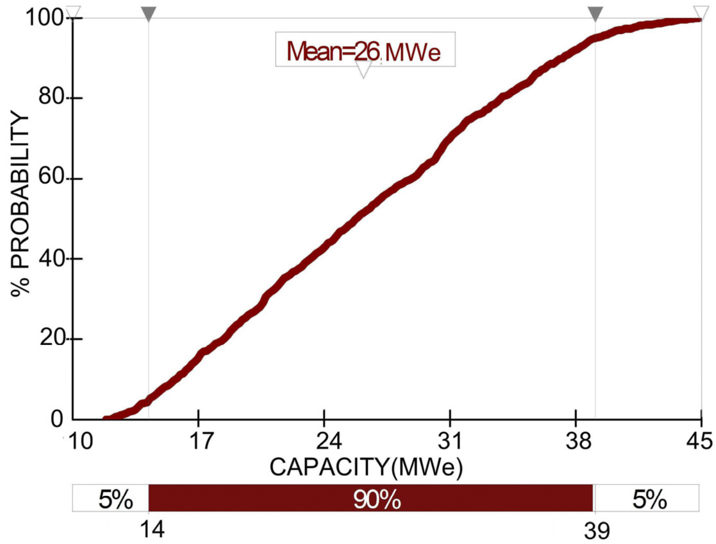

FIGURE 14: Cumulative frequency distribution for Rwanda based on natural heat flux assessment

6. DETAILED ASSESSMENT OF THE KARISIMBI VOLCANO FIELD

6.1 Surface thermal flux

In this section, from the available data on the soil temperature survey, three thermal gradients T_{15}-T_{air}; T_{40}-T_{air}; T_{40}-T_{15} were plotted. Figures 15, 16 and 17 illustrate the temperature gradient in the area varying from 0 to 10°C/m. By using Equation 1 (Section 4.3), the heat flow was calculated for the thermal gradient range. The thermal conductivity, *k* in Figures 15, 16 and 17 was considered 2.5 W/m°C. The heat fluxes calculated were averaged for all the data points and calculated, respectively, as approximately 24, 10 and 16 W/m^2. These can be expressed as approximately 16±8 W/m^2. In order to crudely relate the averaged heat in the survey area to the heat flow of whole volcano, the following is assumed: Firstly that the average heat flux of 16±8 W/m^2 is valid throughout the volcano; and secondly that the characteristic surface area of elevated heat flow is the same as the resistivity anomaly deduced by the resistivity survey (Figure 8). The heat flow Q for the low-resistivity area covering 50 km[2] is, therefore, 800±400 MWth. Finally, assuming that 10% of the total heat flow can be recovered for the electricity generation, the electricity capacity is 80±40 MWe.

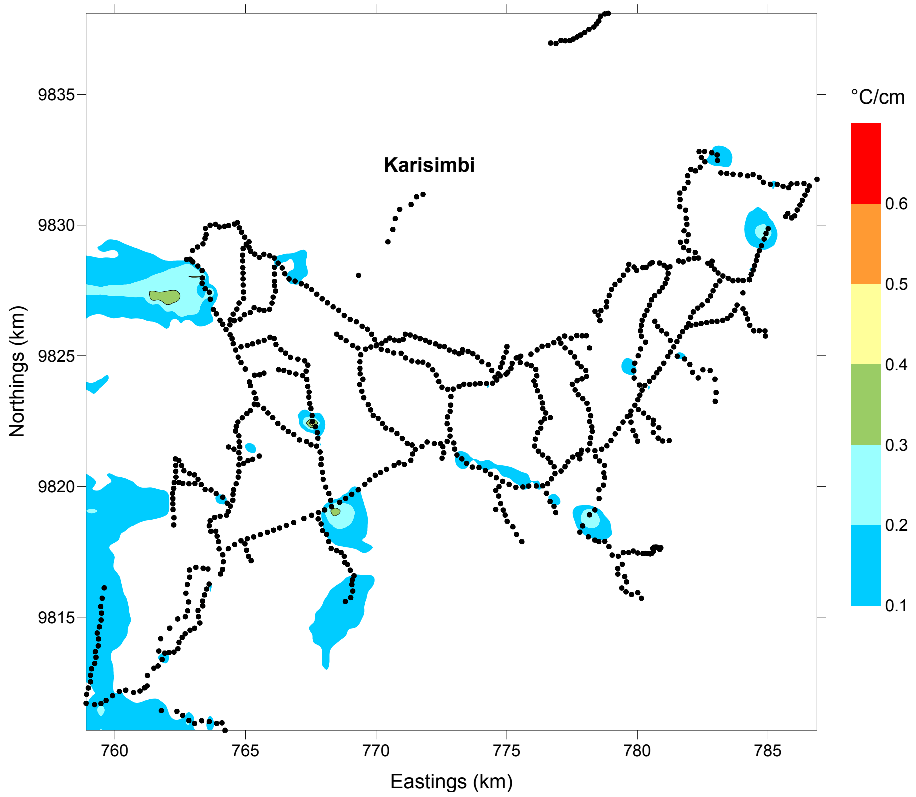

FIGURE 15: Thermal gradient T_{15}-T_{air} for the Karisimbi field; the average gradient is 10°C/m

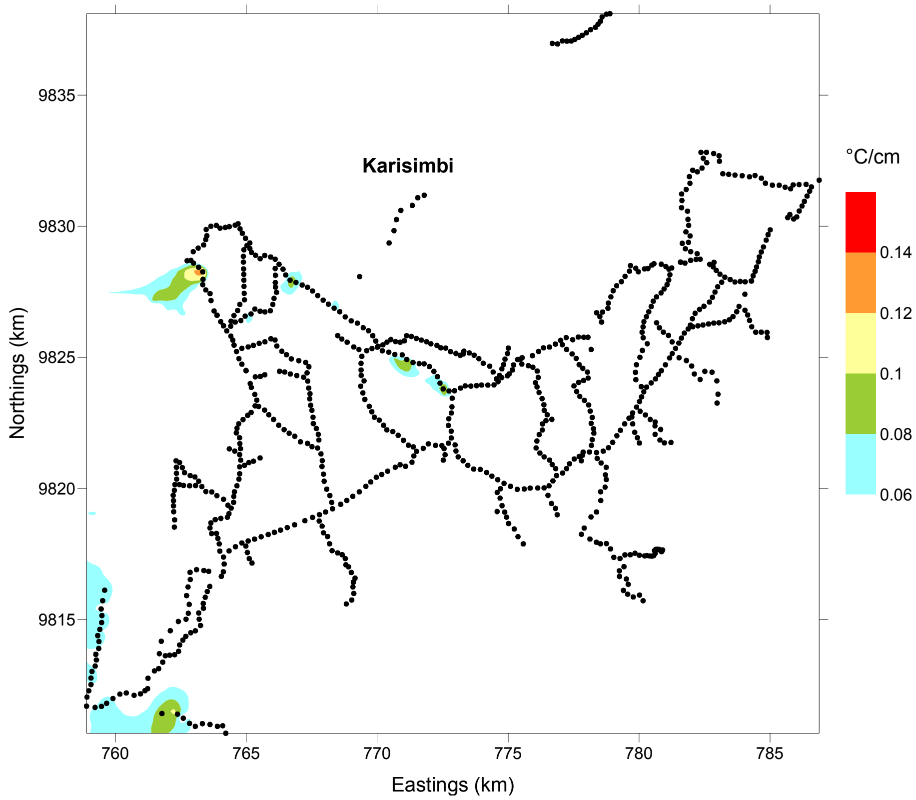

FIGURE 16: Thermal gradient T_{40}-T_{air} for the Karisimbi field; the average gradient is 4°C/m

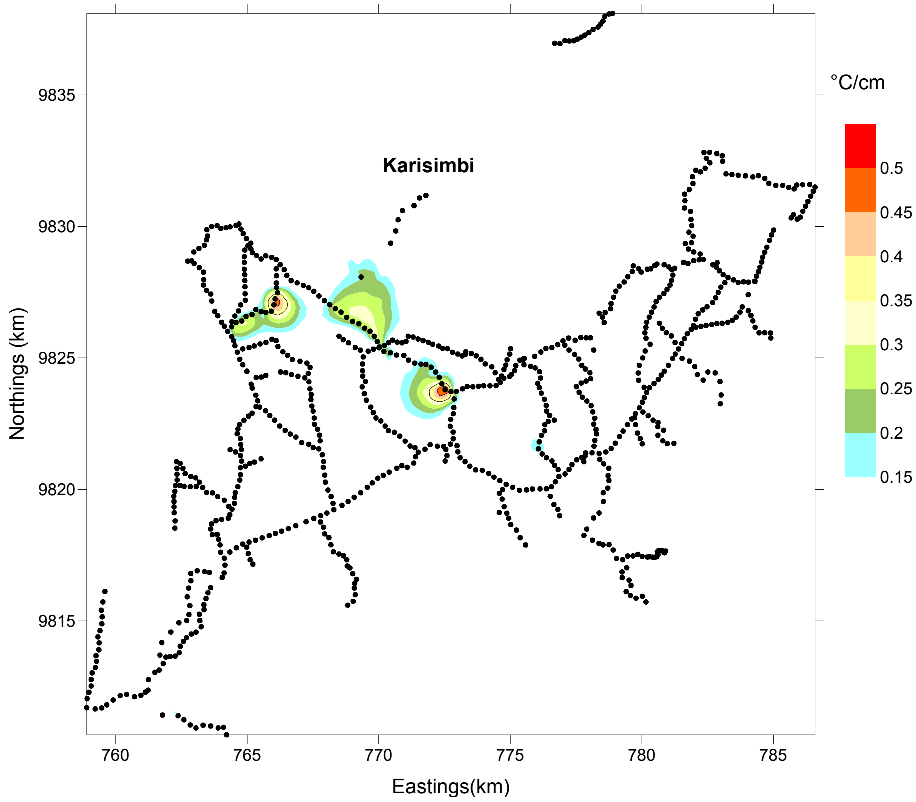

FIGURE 17: Thermal gradient T_{40}-T_{15} for the Karisimbi field; the average gradient is 6°C/m

6.2 Soil CO_2 flux

In the Karisimbi volcano field, 845 measurements of soil flux were performed in a study area of approximately 470 km^2. The average distance between each sampling site was 200 m with the aim of detecting soil gas anomalies on a relatively small scale. The distribution of CO_2 flux is presented in Figure 18 showing some areas with relatively higher values. The range of CO_2 flux measured was

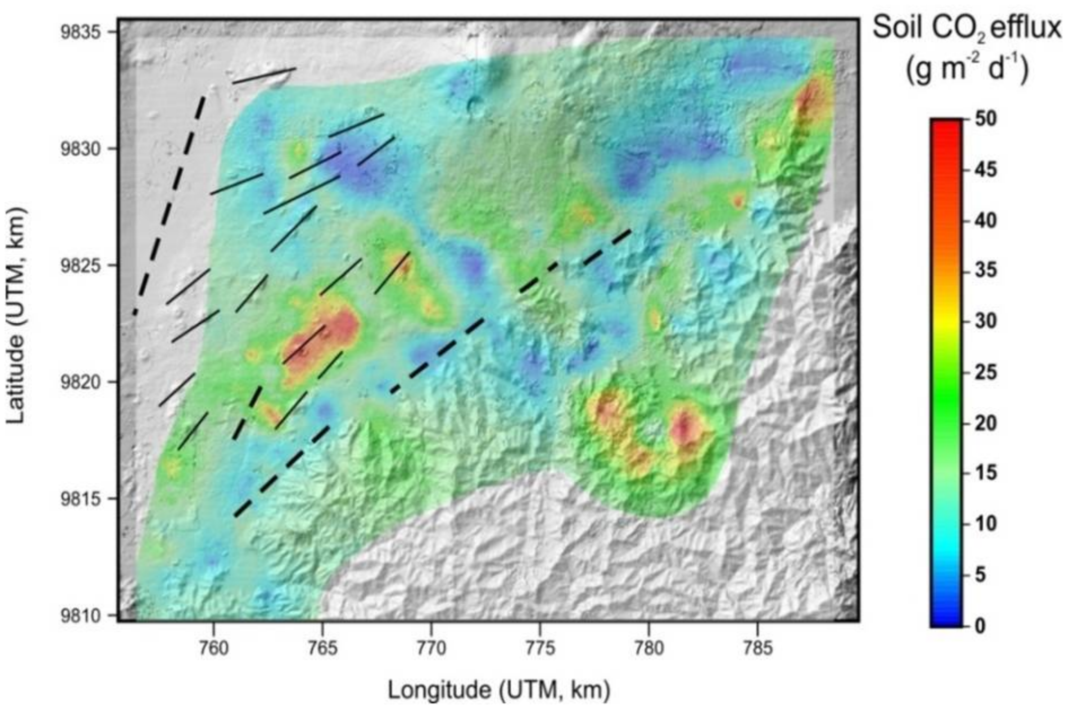

FIGURE 18: Measured diffuse soil CO_2 emission in the Karisimbi volcanic field (BGR, 2009)

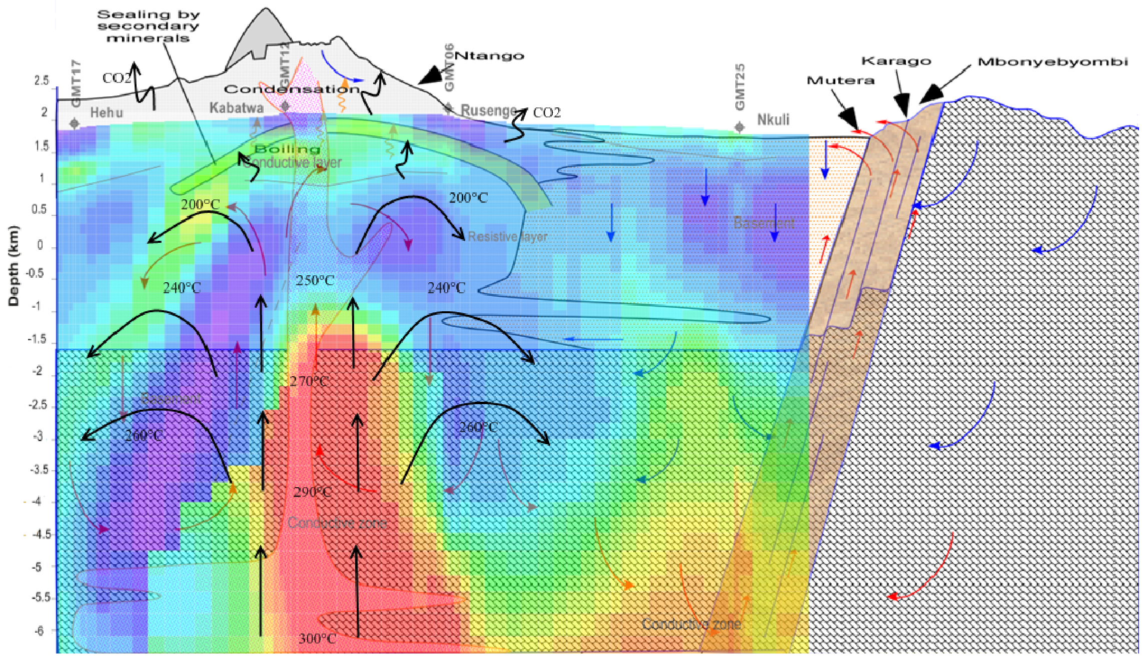

FIGURE 19: Estimated temperature distribution for the Karisimbi volcano field (based on the CO_2 soil flux, the conceptual reservoir model and the resistivity cross-section)

from 0 to 236.7 g/m^{2}day and the total estimated CO_2 emission F_{CO2} from the study area was 6.8 tons/day (BGR, 2009).

In this section, the quantity of heat that can be produced from the reservoir is estimated based on measurements of the CO_2 flux. As said before, in Rwanda there is neither steam seen on surface nor wells that allow for calculating the concentration of CO_2 in the steam. Secondly, the temperature of the reservoir is still unidentified. To estimate these two unknown parameters, a generalized model was established based on a typical high-temperature reservoir that is liquid dominated and follows the boiling point with depth temperature and pressure distribution (Figure 19). The maximum reservoir temperature is assumed to be 300°C. As the boiling water rises, the temperature decreases gradually to 200°C below the cap rock where condensation of steam occurs while the CO_2 gas of volcanic origin continues its ascent to the surface where it generates the CO_2 soil flux. The average temperature of the reservoir is assumed to be 240°C.

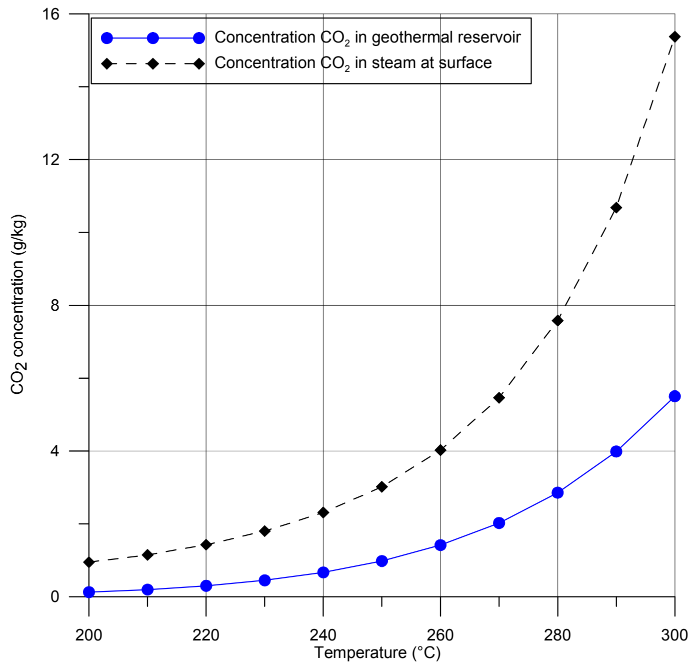

FIGURE 20: Calculated CO_2 concentration in steam and reservoir for the Karisimbi volcano field

By considering a temperature distribution range from 200 to 300°C, the CO_2 concentration in the steam is calculated using Equations 4 and 5 (Section 4.4). The results are illustrated in Figure 20; it can be observed that the concentration of CO_2 at a given temperature is always lower in the reservoir than at the surface.

The measured range of the concentration of CO_2 flux in the Karisimbi volcano field is from 0 to 236.7 g/m^2/day (BGR, 2009). Figure 21 shows the calculated heat flux (kW/m²) with varying concentrations of CO_2 as a function of reservoir temperatures. It can be observed that the heat flux increases with an increasing CO_2 flux for a given temperature.

Finally, to determine the heat flow in the study area (Figure 18), Equations 2 and 3 (Section 4.4) were applied by assuming the total CO_2 flux, F_{CO2} in the study area to be 6.8 tons/day and a reservoir temperature of 240°C. These conditions correspond to 2.3 g/kg C_{CO2} concentration in the steam (Figure 21). By applying these parameters, the calculated heat flow Q is 95 MW with a steam flow F_{H2O} of 34 kg/s. Finally, by assuming that a steam flow of 2 kg/s can produce 1 MWe, the electricity capacity can be estimated as approximately 17 MWe.

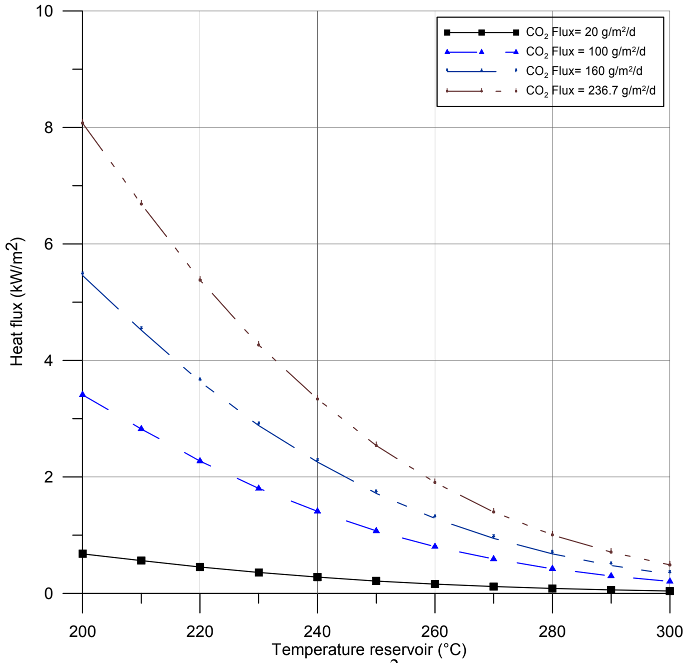

FIGURE 21: Heat flux (kW/m²) at different reservoir temperatures for the Karisimbi volcano field

6.3 Monte Carlo generating capacity assessment

Based on the volumetric method from Muffler and Cataldi (1978), the total stored heat in the reservoir is assumed to be equal to the sum of the stored heat in the rock and water:

$$H_t = H_r + H_w = (1-\emptyset)\rho_r c_r V(T_i - T_f) + \emptyset\rho_w c_w V(T_i - T_f) \quad (8)$$

where H = Heat energy (kJ);
$\emptyset$ = Porosity of the rock (%);
c = Specific heat (kJ/°C kg);
ρ = Density (kg/m³);
V = Hot rock volume (m³), with $V=Ah$;
A = Surface area of the reservoir (m²);
h = Thickness of the reservoir (m);
T_i = Average reservoir temperature (°C);
T_f = Base temperature (°C);
Subscripts *r, w* and *t* refer to rock, water and temperature, respectively.

H_t defined by Equation 8, is usually referred to as the accessible resource base and can be converted to recoverable power in MW by the following equation:

$$E = (H_t R_f \eta)/FL \quad (9)$$

where E = Power plant capacity (MWe);
R_f = Recovery factor (%);
η = Conversion efficiency (%);
F = Plant capacity factor (%); and
L = Plant life (years).

Here L, the plant life, represents the fraction of the total time in which the power generation is in operation and is used to give an average output in MWe; η represents the conversion efficiency to convert the recovered heat to electricity, R_f is the recovery factor to determine the amount of heat that can be extracted and F is the plant capacity factor that combines the plant availability and the capacity.

Most of the variable parameters used to calculate the power potential are not known with certainty and were quantified as separate probability distributions. The most likely area and thickness of the reservoir were estimated from the resistivity cross-section in Figure 8. The most likely reservoir fluid temperature was taken as 240°C but can vary from 200 to 300°C. A base temperature of 155°C was used, corresponding to 6 bars inlet for a condensing turbine. A conversion efficiency of 13% from raw heat to electricity was assumed and a plant life of 30 years. Various input parameters to this analysis are summarized in Table 3. The most likely estimates are given as well as estimated probability distributions and minimum and maximum values for the different input parameters.

An estimate for the electric power which could be produced from the Karisimbi volcano field with a reservoir temperature of 240°C was calculated according to Equations 8 and 9 by using the parameters in Table 3. The simulation runs numbered 10,000. The results show a distribution probability of 90% for a range of 190-540 MWe with a most likely capacity of the Karisimbi volcano field for 30 years of plant life equivalent to 345 MWe (Figure 22). From Figure 23, the probability for output greater or equal to 335 MWe is 50 percent.

TABLE 3: Monte Carlo geothermal input data for Karisimbi volcano field in Rwanda

Parameters	Units	Most likely	Probability distribution		
			Type of distribution	Minimum	Maximum
Area	km^2	40	Triangular	30	50
Thickness	m	1250	Triangular	1000	1500
Rock density	kg/m^3	2750	Triangular	2500	3000
Rock specific heat	kJ/kg°C	0.84	Triangular	0.79	0.9
porosity	%	0.1	Triangular	0.05	0.15
temperature	°C	240	Triangular	200	300
Base temperature	°C	155	Constant		
Fluid density	kg/m^3	814	Constant		
Fluid specific heat	kJ/kg°C	4.78	Constant		
Recovery factor	%	0.2	Triangular	0.15	0.25
Conversion efficiency	%	0.13	Triangular	0.1	0.15
Plant life	years	30	Constant		
Load factor	%	0.95	Constant		

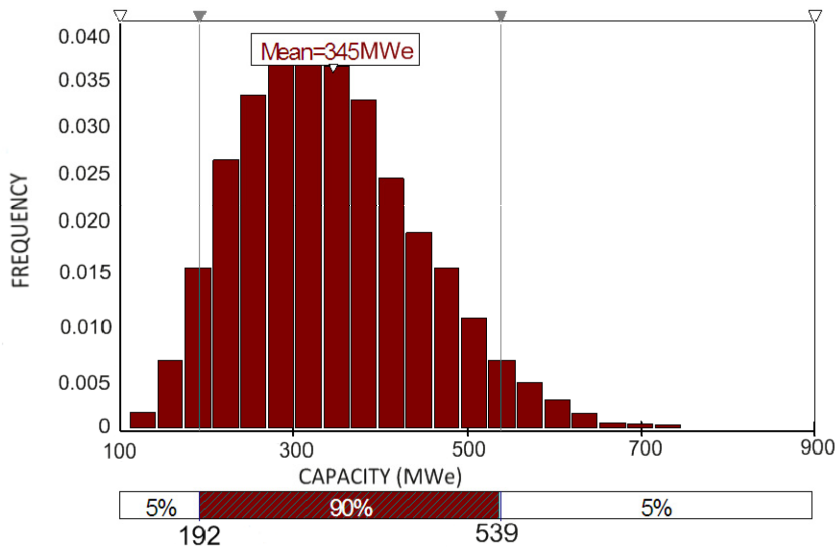

FIGURE 22: Frequency distribution of electricity capacity for the Karisimbi volcano field

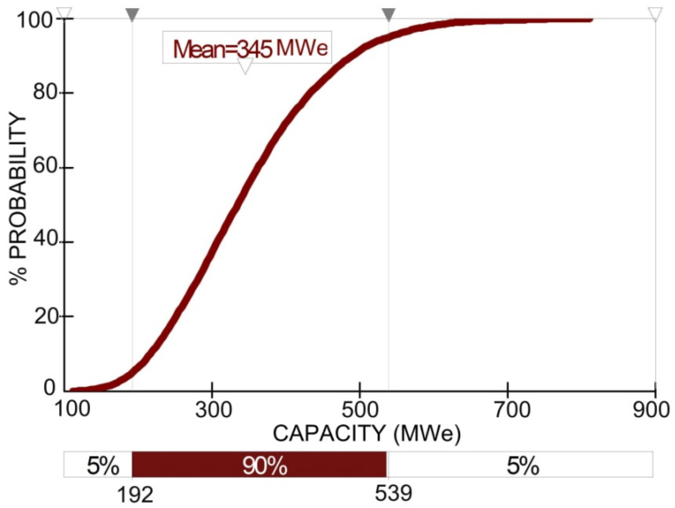

FIGURE 23: Cumulative frequency distribution for the Karisimbi volcano field

7. DISCUSSION AND CONCLUSIONS

The estimation of the power potential in Rwanda produced different but realistic results when compared to the estimation that was previously done for the country (McNitt, 1983 and Gawell et al., 1999). The generating capacity of Rwanda geothermal potential has been estimated ranging from 17 to 345 MWe, depending on the methods used (Table 4). In the case of the potential as a whole, results ranged from 100 MWe in the counting volcanoes method to 26 MWe for the Monte Carlo method, by considering that the mineable heat is transferred by steady heat conduction only. In the case of the Karisimbi volcano field, results differed from 17 MWe for the surface CO_2 flux to 80±40 MWe for the surface thermal flux and finally 345 MWe for the Monte Carlo simulation, in which heat and mass reserves are aggressively mined for the benefit of the Rwanda people. Those results represent the best guess of the amount of accessible energy and what can be turned into electricity. The average generating capacity from the methods is approximately 120 MWe of which 50 MWe can be considered as a reasonable initial target for geothermal generation in Rwanda, in say the next 5-6 years. It is important to appreciate what this resource assessment is and what it is not. It is the best guess of Rwanda's capacity considering the available data but does not take into consideration problems that could down-rate the potential or the economics of getting the stored heat and mass to the surface.

TABLE 4: A summary of generating capacity estimates for Rwanda

Method	Most likely (MWe)	Error (MWe)
Counting of volcanoes	100	
Surface heat flux	80	±40
Surface gas flux	17	±1
Monte Carlo assessment (Country scale)	26	±12
Monte Carlo: Karisimbi	345	±150
Average	**120**	**±50**

Rwanda needs a safe and clean source of energy for its people. At present, the government of Rwanda is deciding the future strategy for solving the country's need for electricity. When looking at available options, the concept of geothermal power appears one of the best options, given that the resource is there and the development cost is acceptable. This study gives just an idea of the geothermal potential; however, this approach should show that investment in drilling exploration wells to confirm the reservoir conditions and well productivity is reasonable. Another important point is that the development of this resource should be economically and environmentally feasible for the Rwandan population. The limitations of the development of the resource, apart from the technical factors, relate to the accessibility of the resource (how deep do we need to drill?), the market (price of the electricity or heat?) and the environment. Before investing in the development of the geothermal resource, those parameters must be considered. In an environmental point of view, the protection of the national park in the Karisimbi volcano region of Rwanda that houses families of gorillas must be a priority before carrying out a project in the Karisimbi volcano field. Also, land in Rwanda is very scarce so the management of the land must be taken into account. On the other hand, the government of Rwanda is fighting to provide electricity at affordable prices to the population and to reduce deforestation and the use of costly fuel oil; therefore, geothermal utilisation could be the solution. All those aspects must be considered and mitigations proposed for the development of the resource. A periodical update of this assessment is recommended as new data becomes available; as it develops, all related aspects must be considered.

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