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Evaluation of Geothermal Potential in Eastern Africa: Insights from Multicriteria Analysis and Geospatial Techniques

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ABSTRACT

Eastern Africa faces a significant energy deficit, with demand driven by transportation, domestic, and industrial needs. Despite the availability of substantial geothermal resources, their exploitation remains limited due to a lack of adequate information and technical capacity across many African countries. Geothermal energy, being a clean, reliable, and sustainable source, offers a promising alternative to conventional energy sources such as fossil fuels and hydropower, which often have high prices (oil and gas) and are environmentally unsustainable or seasonally constrained. This study addresses the knowledge and technological gaps by identifying and mapping geothermal potential zones across Eastern Africa using a Multi-Criteria Decision Analysis (MCDA) framework integrated with the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and ArcGIS. Five primary geothermal indicators were evaluated: proximity to hot springs and geysers, presence of active and young volcanic rocks, occurrence of major faults, regional heat flow, and land surface temperature. Each criterion was weighted using Fuzzy AHP, with hot springs and major faults receiving the highest significance in identifying geothermal prospects. The analysis revealed thirteen zones with extremely high geothermal potential: six in Ethiopia, two in Kenya, two in northern Tanzania, two in Uganda, and one between Rwanda and Burundi. Additional zones in northern Malawi, other regions of Kenya, Rwanda, and parts of Tanzania also demonstrated very high potential. The results were validated using known geothermal wells, confirming the effectiveness of the model. This research not only enhances the understanding of geothermal potential in the region but also provides a strategic tool for guiding future exploration and investment decisions.

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1.0 Introduction

Fossil fuels and biomass, accounting for 70–90% of total energy use, are the primary energy sources in Africa. This dependency has led to deforestation, environmental degradation, and high import costs for oil and gas. Most countries rely on costly diesel-based thermal generation, except Eritrea and Djibouti (Awaleh, M. O. et al., 2015; Lowenstern, J. B. et al., 1999). To reduce import burdens, environmental impact, and foreign currency expenditure, many African nations are increasingly turning to domestic renewable energy sources to meet growing energy demands (Omenda, P. & Teklemariam, M., 2010).

The main sources of renewable energy are solar, wind, hydro, tidal, biomass, and geothermal. According to recent data from the United Nations Sustainable Development Group, about 55% of the energy used in African countries comes from renewable sources, and by 2023, renewables accounted for around 3% of Africa's total electricity generation (futures.issafrica, 2025; unsdg.un, 2025). However, while renewable sources such as solar, wind, and hydro are clean, safe, and offer low operational costs after initial investment, their reliability remains a challenge. This highlights the urgent need to assess the renewable energy potential in Eastern Africa to address the region's growing energy demands sustainably. Among the available options, hydropower currently dominates electricity generation in many African countries. Yet, its heavy dependence on rainfall makes it increasingly vulnerable to climate variability, as demonstrated by recent droughts and irregular rainfall patterns (Merem, E. et al., 2019). Given these limitations, attention is turning toward more stable alternatives, particularly geothermal energy. Unlike solar and wind, geothermal power is not affected by weather fluctuations, eliminating concerns over intermittency and energy storage. Notably, geothermal facilities boast some of the highest capacity factors, reaching up to 95%, making them exceptionally reliable and efficient (Bloomfield, K. et al., 2003). Therefore, geothermal energy emerges as a highly promising and underutilised solution for addressing Africa's persistent energy challenges.

Beyond electricity generation, geothermal energy serves a wide range of direct-use applications, making it a highly versatile energy source. In Kenya, for instance, geothermal energy is used not only for power production but also for heating swimming pools at the Borogia Hotel and warming over 50 hectares of greenhouse farms as early as 2003 (Mburu, M., 2009). Internationally, Iceland is a leading example of district heating powered almost entirely by geothermal energy, providing heat to homes, schools, and public buildings. Similarly, China and the United States have developed extensive geothermal heating systems for residential and industrial purposes. In colder climates, geothermal heat pumps are also widely used to efficiently heat and cool buildings by leveraging subsurface temperature stability (Mburu, M., 2008). These diverse applications underscore the renewable, natural, and environmentally friendly nature of geothermal energy, as highlighted by Barbier, E. (2002); Cambazoğlu, S. et al. (2019). By offering both power generation and direct-use options, geothermal energy contributes significantly to sustainable development and energy diversification.

The occurrence of geothermal resources has been primarily linked to subsurface heat sources such as heat from the Earth's mantle and the radioactive decay of minerals within the crust. These processes generate the thermal energy that heats underground water, ultimately forming geothermal systems (Fisher, R. S., 1998; Hoke, L. et al., 2000). Areas with elevated geothermal gradients typically coincide with zones of high heat flow driven by these deep-seated mechanisms.

In addition to heat sources, geothermal activity is strongly influenced by surface and structural features. Key indicators include hot springs, geysers, fault systems, heat flow variations, and the presence of igneous or volcanic rocks. Studies by McGuire, J. J. et al. (2015) and Zhang, Y. et al. (2020) have shown that geothermal resources often occur in proximity to these features, particularly along fault zones and near-surface manifestations. Moreover, regions with geothermal activity are frequently characterised by higher-than-average heat flows and temperatures (Ejiga, E. G. et al., 2022). As a result, many researchers have investigated the spatial distribution and characteristics of these indicators to better quantify geothermal potential (Mangi, M., 2017; Nyblade, A. A. et al., 1990; Omenda, P. & Simiyu, S., 2015; Saibi, H., 2009; Tshibalo, A. et al., 2015; Zemedkun, M. T., 2012).

While studies in other parts of Africa have identified geothermal indicators, their development remains limited. For instance, Tshibalo, A. et al. (2015) highlighted the presence of geothermal features in South Africa, primarily linked to radioactive decay and deep fault systems, yet the study lacked detailed exploration methods or follow-up development strategies. Similarly, in North Africa, Saibi, H. (2009) reported geothermal indicators in Algeria, including hot springs with temperatures reaching up to 98°C. However, these resources remain untapped for domestic or industrial applications, largely due to the absence of systematic exploration and utilisation efforts.

In contrast, Eastern Africa, particularly within the East African Rift System (EARS), shows considerable geothermal potential. Research by Mangi, M. (2017); Nyblade, A. A. et al. (1990); Omenda, P. and Simiyu, S. (2015); and Zemedkun, M. T. (2012) has demonstrated the region's favourable geothermal characteristics, including high heat flow, active faulting, volcanic activity, and surface manifestations such as hot springs and geysers. Despite this promise, only a limited number of geothermal fields, mainly in Kenya and Ethiopia, have been developed into productive energy sites. This underutilisation underscores the need for more targeted research and investment in Eastern Africa to identify and develop additional geothermal resources. Although the energy demand in the region is growing rapidly, much of its geothermal potential remains unmapped and unexploited, due in part to limited technical expertise, exploration infrastructure, and financial capacity. Advancing geothermal development in Eastern Africa will require not only identifying potential sites but also building the institutional and technological frameworks necessary for their sustainable exploitation.

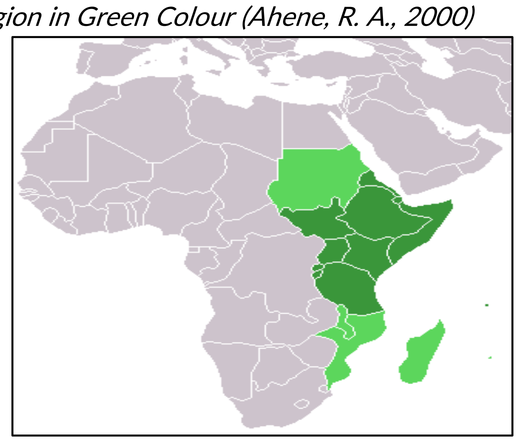
Thus, this work bridges the mentioned gap by studying indicators of geothermal resources and combining them to identify the potential area for geothermal resources using the multicriteria decision-making analysis (MCDA) approach. This approach has been used by numerous scholars, including Tüfekçi, N. et al. (2010), who did an investigation in Western Anatolia, Turkey. They evaluated the weight and index overlay and determined the potential areas for geothermal resources, where they succeeded in developing the map of potential areas in Western Anatolia. Also, Yalcin, M. and Kilic Gul, F. (2017) did the same analysis in the Akarçay Basin, Turkey, using the MCDA approach to obtain the areas with geothermal resources. Furthermore, Elbarbary, S., et al. (2022) did a detailed investigation of recognising high-potential areas for geothermal resources in Africa. That work was done using Geographic Information System (GIS) to combine geological, geothermal, structural, and heat flow data in identifying the geothermal resources. In that work, Elbarbary, S., et al. (2022) evaluated the weighted overlay of each property by using the analytic hierarchy process (AHP) technique. That study successfully identified 14 potential areas for geothermal resources. Based on Esen, H. (2023), AHP methods provide many advantages, including simplifying the problem, assembling multicriteria difficulties in hierarchic order, mixing quantitative and qualitative factors in the analysis, being used in large and complex problems, and being applied in any field. Despite these advantages, the AHP techniques encounter some challenges, including that their results and decisions do not reflect the human way of thinking. Therefore, fuzzy AHP was developed by Saaty, T. L. (1984) to counteract that challenge.

Therefore, this study builds on previous efforts by employing the fuzzy AHP technique to address the limitations of standard AHP in capturing human judgement under uncertainty. The fuzzy AHP method allows for more nuanced weighting of geothermal indicators. Combined with spatial analysis in ArcGIS, this approach enables the identification of potential geothermal zones in Eastern Africa.

1.1 The Location and Geological Features of the Study Area

The study area is found in the East of Africa, a region that comprises several countries such as Ethiopia, Tanzania, Kenya, Rwanda, Zimbabwe, Mozambique, Madagascar, and others, as depicted in Fig. 1. By 2019, the East Africa region was estimated to have a population of approximately 437 million people (Irena, 2019), whereas in 2024, it is estimated to be 500.7 million people (PopulationPyramid.net, 2024; Worldometer, 2025). All these people are heavily relying on energy for various purposes like industrial production, home use, transportation, and aquaculture. Despite having a significant geothermal potential, which is approximated to be 18,000 MW (Fridleifsson, I. & Ómarsdóttir, M., 2013; Kombe, E. Y. & Muguthu, J., 2019; Merem, E. et al., 2019; Omenda, P. & Teklemariam, M., 2010). The region only generated 900 MW of electricity from geothermal energy in Kenya and Ethiopia in 2019, contributing to only 4.2% of the total electricity generated (Irena, 2019). East Africa has been attracting many geothermal researchers due to the availability of the EARS. The system contains geothermal conditions and geological factors that are significant in the development of geothermal resources; these factors make it an ideal location for our case study.

Figure 1
The Map of Africa Showing the Eastern Africa Region in Green Colour (Ahene, R. A., 2000)



The EARS is one of the most significant geothermal systems in the world, where heat from the Earth's interior migrates to the surface through volcanic eruptions, earthquakes, and hot springs (Omenda, P. & Simiyu, S., 2015). The elevated heat in the EARS is attributed to mantle heat flow, thin-skinned thrust, heat transfer from below the rift margins, and crustal heat production (Nyblade, A. A. et al., 1990). This region is home to several hot springs that are good indicators of geothermal flow systems related to geological structures such as faults and fractures. For example, over 200 geysers and hot springs are associated with volcanic activities in Kenya, and more than 50 hot springs are in Tanzania's Northern and Southern regions.

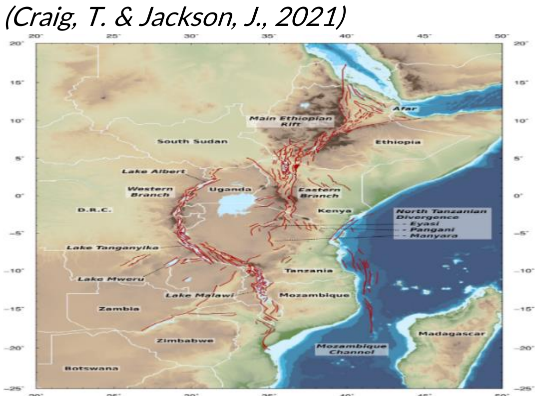
Other countries in the region, such as Ethiopia, Uganda, Djibouti, and Rwanda, also show indicators of geothermal resources within the EARS (Kebede, S., 2012). The region is tectonically active, with active volcanoes and magmatic rock, leading to seismic events and earthquakes occurring from Ethiopia to Mozambique (Kebede, F. & Kulhánek, O., 1991).

Also, the EARS is divided into segments, which can be further divided into different units. There are five primary fault orientations that characterise specific rifts. These orientations often correspond to the directions of Precambrian shear zones or rifts in the Permo-Triassic Karoo Supergroup. The Karoo originated in a vast basin in the southern region of Africa, but remnants of it can be found as far north as Kenya. This suggests that the Karoo sedimentary rift basin once extended along the East African rift, but significant changes occurred in its northern portion (Davison, I., 2021).

1.2 Branches of the East African Rift System (EARS)

The eastern and western branches make up the two divisions of the EARS (Fig. 2). The Western branch of the rift extends from Lake Albert in Uganda to Southern Malawi and encompasses the African Great Lakes (Lake Nyasa and Tanganyika). Meanwhile, the Eastern branch runs from northern Tanzania through Kenya to Eritrea and Djibouti. Lake Victoria separates the western and eastern branches of the rift. The Eastern branch began 15 million years ago, while the Western branch started 10 million years ago (Davison, I., 2021; Hochstein, M. P., 2005). While both branches are crucial structures of rifts, they are also quite distinct. Volcanic activities are more active in the eastern branch since this region has a thinner lithosphere and there is a presence of active mantle plumes, while the western branch rifts are less tectonically active and filled with massive sediment and water. The Western branch is also associated with hydrocarbon deposits. Meanwhile, the Eastern branch of the EARS is home to a high-potential geothermal resource base in Africa, which creates the Ethiopian and Kenyan rifts. Southeast African countries, including Djibouti, Uganda, Eritrea, and others, have smaller but significant resource bases (Kombe, E. Y. & Muguthu, J., 2019; Omenda, P. & Teklemariam, M., 2010).

Figure 2
The Eastern and Western Branches of the EARS (Craig, T. & Jackson, J., 2021)



1.3 The Morphology of the EARS

The Afar (Ethiopian) and East African (Kenya) domes are two massive lithospheric domes that shape the morphology of the EARS on a large scale (Fig. 3). The Turkana depression (average height of 600 meters) in northern Kenya separates them. On average, the East African Dome is 1200 meters higher than the Afar Dome. Outside these areas, the topography ranges from 300 to 900 meters (Ebinger, C. J., 1989). Both domes are associated with significant negative gravity anomalies and have diameters of around 1000 km (Fig. 3). Within the East African Dome, smaller domes, such as the Kivu and Kenya domes, can be found with radii of 100–200 km. The primary rift basins of the Western branch are mostly underwater, making outcrop research limited to the borders of the rift. However, the lakes provide two advantages for research: it is easier to collect seismic reflection data over water than over land, and the large lacustrine systems allow for the study of contemporary sedimentary processes. Many recent geothermal studies of the Western branch have taken advantage of these benefits.

The Eastern branch is dotted with small lakes but also has many outcrops. The exposed areas mostly comprise pyroclastic deposits, igneous intrusions, or volcanic flows. Understanding the stratigraphical and geochemical relationships between the volcanic sequences has been a key focus of outcrop research. However, the wide areas involved have made it challenging to develop a regional understanding of the extent and history of the igneous rocks (MacDonald, G. D. & Arnold, L. C., 1994). Comprehensive geochemical analyses of the igneous suites are limited. In some areas, there are large-scale deposits of recent (Plio-Pleistocene) fluvial-lacustrine sediments, while others are well-known locations for research into human ancestors and contain impressive fossil collections, including vertebrate bones. However, earlier sedimentary sequence exposures are relatively rare. The volcanic rocks that cover much of the rift conceal indications of its previous history, but there are a few locations within the rift where erosion through high basement blocks offers a glimpse at the deeper rift section, which contains arkosic sandstones (Renaut, R. W. et al., 1999).

Figure 3
The Morphology of the EARS Showing the Afar (Ethiopian) and East African (Kenya) Domes (Furman, T. et al., 2016)

1.4 Exploration of Geothermal Fields in East Africa

The methods for exploring geothermal resources in Eastern African countries vary based on the tectonic setting and nature of their development. The geothermal indicators in East African countries are located in the eastern and western branches of EARS. Volcanic activities dominate the eastern branch of EARS and boast geothermal resources with high temperatures and two-phase systems. The thin crust in the Eastern branch results in higher heat flows. In contrast, the Western branch is dominated by fractures and magma, with the majority of resources found in aquatic bodies and having low to moderate temperatures. These differences in characteristics guide the exploration methods for finding geothermal resources, as shown in Table 1 (Irena, 2019).

In the Eastern branch, the geothermal resources are expected to be at shallow depths; thus, geophysical, seismic, and resistivity (MT and TEM) methods are utilised to provide a picture of the reservoir structures. A clear understanding of the reservoir structure helps in selecting the best location for drilling a well. The gravity method is used to identify regions with active magma, which provides high heat flow in the geothermal system. Passive seismic is used to detect the presence of geothermal fluid by registering the fluid flow along fractures. Lastly, the geochemistry methods measure the radon and carbon dioxide gas in springs and fumaroles. The presence of these gases indicates the leakage region and the presence of a degassing magma chamber. The same methods are used for exploring geothermal resources in the Western branch, where fractures and faults dominate. However, the use of M.T. is not necessary in this branch. Passive seismic and gravity methods detect faults and other fracture zones that host geothermal reservoirs. The thermal method determines heat flow in both the eastern and western branches. In the thermal method, a 100-400 m well is drilled to measure the geothermal gradient and temperature in the geothermal reservoir (Irena, 2019; Omenda, P. et al., 2016).

Table 1
Methods Employed in Exploring Geothermal Resources in East Africa (Omenda, P. et al., 2016)

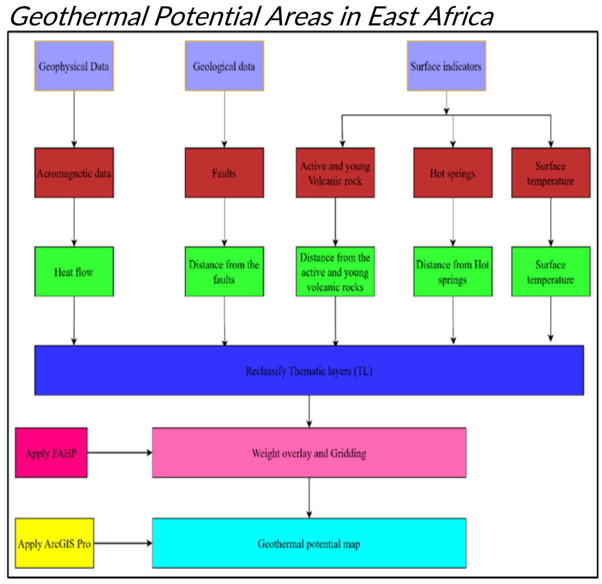
Method	Eastern Branch	Western Branch
Characteristics	Deep anomalies, magma heat sources, dispersed heat and hosted by volcanoes	Deep circulation, localised abnormalities, and fracture/fault control
Geological mapping	Fault kinematics, lithologic and structural mapping	Mapping with litho stratigraphy and structural detail
Geophysics	Gravity, seismic, M.T, TEM, thermal method, sporadic TGH	Gravity, seismic, TEM (elective M.T), thermal method, TGH
Geochemistry	Hot spring fluid, fumarole gas, and soil gas (radon and CO_2)	Hot spring fluid, fumarole gas, and soil gas (radon and CO_2)

2.0 Methodology

Based on the literature, the main indicators of geothermal resources are the presence of hot springs, geysers, active and young volcanic rocks, faults, high heat flows, and high temperatures (Davison, I., 2021; Hochstein, M. P., 2005; Kebede, F. & Kulhánek, O., 1991; Kebede, S., 2012; Meghraoui, M. & Group, I.-W., 2016; Thiéblemont, D. et al., 2016). Therefore, these indicators were evaluated and joined to evaluate the potential geothermal areas. The techniques for evaluating potential areas for geothermal resources in East Africa were conducted by following several procedures. The procedures involve:

i. Gathering the data
ii. Evaluating the weight of each input data (criteria) by using the fuzzy analytic hierarchy process (FAHP)
iii. To identify the potential areas by combining the input data and their evaluated weights using the ArcGIS software.
iv. The map algebra in the ArcGIS software was developed, and the results were displayed as low potential, medium potential, high potential, very high potential, and extremely high potential.
v. Finally, the results are validated with the aid of currently developed geothermal areas, which are found in East Africa. Fig. 4 illustrates the procedures adopted in this study.

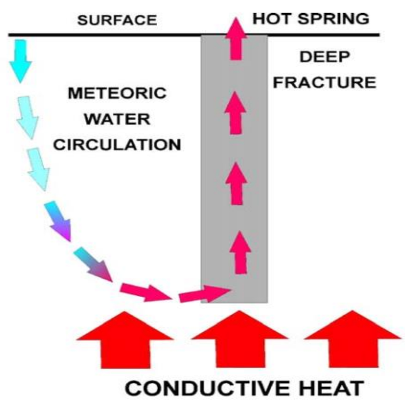
Figure 4
The Procedures Followed in Evaluating the Geothermal Potential Areas in East Africa



2.1 Data Collection

Various geophysical and surface indicators and geological properties are used to indicate the presence of geothermal energy in an area. Some of them are geological structures, rock types, heat flow, hydrothermal alteration, land surface temperatures, hot springs, and geysers, as elaborated by Şener, E. and Şener, Ş. (2021). The volcanic type of rock, especially active volcanic rock, is one of the indicators of the area that can produce geothermal energy. These rocks act as the source of heat for the groundwater, which later develops geothermal energy (Dhansay, T. et al., 2014). Geological structures such as rock fractures and faults play a role in the formation of geothermal resources (Hanano, M., 2000). These structures facilitate the circulation of fluids from the surface or aquifer to the Earth's interior, where high-temperature sources exist, as depicted in Fig. 5 (Meghraoui, M. & Group, I.-W., 2016; Thiéblemont, D. et al., 2016).

Figure 5
The Idealised Circulation of Water through the Fracture to the Heat Source (Saibi, H., 2009)



Also, the higher heat flow is regarded as another factor that indicates the presence of geothermal energy. Higher heat flow has been observed in the regions with thin Earth crust, hence having a higher ability to conduct heat from the core (or mantle) to the groundwater and then to develop geothermal energy (Njinju, E. A. et al., 2019). Based on Jones, M. (1992); Saemundsson, K. (2008). Regions with heat flow higher than 70 mW/m² have the potential for geothermal energy. Furthermore, the surface manifestation, including hot springs and geysers, is another indicator of potential geothermal areas. The hot springs and geysers indicate the presence of heat sources and the presence of a conduit, which carries the heat from the sources to the surface water (Dhansay, T. et al., 2014). Lastly, other parameters like land surface temperatures and hydrothermal alteration indicate the presence of geothermal resources, as suggested by Şener and Şener (2021).
The data used were EARS major faults, surface geology (volcanic rocks), data for hot springs and geysers, heat flow, and land surface temperatures, as these factors have a high influence on the indication of geothermal energy when compared to the rest (Dhansay, T. et al., 2014; Njinju, E. A. et al., 2019). These data were gathered from various web sites, including the International Seismological Cent re (ICS), Egyptian National Seismic Network (ENSN), and United States Geological Survey (USGS).

2.2 Pre-Processing of the Data
After collecting the data, data preprocessing was a critical step to ensure the accuracy and compatibility of input datasets before analysis. Multiple geospatial and non-spatial datasets were collected from three different websites. These datasets were first harmonised in terms of spatial resolution and coordinate reference systems to ensure spatial alignment. Noise reduction and outlier detection techniques were applied to eliminate inconsistencies, particularly in temperature datasets. Raster layers were resampled to a common resolution suitable for overlay analysis, and vector data such as faults and hot spring locations were converted into raster format using appropriate buffer zones to quantify their influence. Missing or incomplete data were addressed and removed because there were many data for the study. This preprocessing ensured that the data used in the model was clean, consistent, and analytically robust, enabling the production of reliable geothermal potential maps.

2.3 Evaluation of the Contribution of Each Criterion on the Selection of Potential Geothermal Areas Using the Fuzzy Analytical Hierarchy Process (FAHP)
The fuzzy analytic hierarchy process (FAHP) was adopted to evaluate the weight of each criterion used in evaluating the potential geothermal areas in East Africa. Several scholars have developed models for FAHP in MCDA; some of them are Buckley, J. J. (1985); Chang, D.-Y. (1996); and van Laarhoven, P. J. M. and Pedrycz, W. (1983). But in this work, we utilised the model introduced by Chang, D.-Y. (1996), a model that solves the criteria weights by introducing the triangular fuzzy numbers (TFNs). Therefore, the five criteria, including the EARS major faults, active and young volcanic rocks, hot springs and geysers, heat flow, and land surface temperatures, as depicted in Fig. 4, were evaluated by FAHP to recognise the potential geothermal areas. Table 2 depicts the scale for the FAHP technique applied in this work, as suggested by Şener and Şener (2021).

Table 2
The Comparison Scale of the FAHP Used in this Work (Adopted from Şener and Şener (2021))

Linguistic variables	TFNs	Reciprocal TFNs
Equally potential	(1,1,1)	(1,1,1)
Intermediate	(1,2,4)	(1,1/2,1/4)
Moderately high potential	(1,3,5)	(1,1/3,1/5)
Intermediate	(4,6,8)	(1/4,1/6,1/8)
High potential	(3,5,7)	(1/3,1/5,1/7)
Intermediate	(2,4,6)	(1/2,1/4,1/6)
Very high potential	(5,7,9)	(1/5,1/7,1/9)
Intermediate	(6,8,9)	(1/6,1/8,1/9)
Extreme high potential	(7,9,9)	(1/7,1/9,1/9)

2.3.1 Analysing the Criteria
Also, the higher heat flow is regarded as another factor that indicates the presence of geothermal energy. Higher heat flow has been observed in the regions with thin Earth crust, hence having a higher ability to conduct heat from the core (or mantle) to the groundwater and then to develop geothermal energy (Njinju, E. A. et al., 2019). Based on Jones, M. (1992); Saemundsson, K. (2008). Regions with heat flow higher than 70 mW/m² have the potential for geothermal energy. Furthermore, the

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Table 3

The Criteria and Their Sub-Classifications Used In Evaluating the Potential Geothermal Areas

Criteria	Sub-classification	Classification
Hot Springs	0 to 2 km	1
	2 to 4 km	2
	4 to 6 km	3
	6 to 8 km	4
	8 to 10 km	5
Major EARS faults	0 to 2 km	1
	2 to 4 km	2
	4 to 6 km	3
	6 to 8 km	4
	8 to 10 km	5
Younger igneou s and active volcanic rocks	<6 km	1
	6 to 12 km	2
	12 to 18 km	3
	18 to 24 km	4
	24 to 30 km	5
Heat flow	19-44	1
	44-60	2
	60-96	3
	96-160	4
	160-245	5
Land surface temperature	<23 ^{0}C	1
	23-26 ^{0}C	2
	26-29 ^{0}C	3
	29-32 ^{0}C	4
	32-35 ^{0}C	5

2.3.2 Mathematical Procedure to Evaluate the Criteria Weights

The weight of each criterion on evaluating the potential area for geothermal resources was evaluated by using the triangular FAHP, which is done by following the procedures below, as presented by Kahraman, C. et al. (2004):

The first procedure involved assigning the FTNs for all relations in the comparison matrix, as illustrated in Table 4. The values were assigned based on the analysis of criteria; whereas the distance from the hot springs had extremely high potential influence on recognising potential geothermal areas, distance from faults had very high potential influence, distance from the younger and active volcanic rocks had high potential influence, heat flow had moderate potential influence, and surface temperature had low potential influence.

Table 4

Comparison Matrix for All Criteria Evaluated in this Work

	Distance to hot springs			Distance to faults			Types of rock			Heat flow			Surface temperature		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
Distance to hot springs	1	1	1	1	3	5	2	4	6	5	7	9	7	9	9
Distance to faults	1/5	1/3	1	1	1	1	1	3	5	3	5	7	5	7	9
Type of rock	1/6	1/4	1/2	1/5	1/3	1	1	1	1	1	3	5	3	5	7
Heat flow	1/9	1/7	1/5	1/7	1/5	1/3	1/5	1/3	1	1	1	1	1	3	5
Surface temperature	1/9	1/9	1/7	1/9	1/7	1/5	1/7	1/5	1/3	1/5	1/3	1	1	1	1

The second step involves the determination of the values of fuzzy synthetic extent. These values were determined by using Equation (1)

$$S_{ex} = \sum_{i=1}^{m} M_{pj}^{i} \left[\sum_{j=1}^{n} \sum_{i=1}^{m} {M_{pj}}^{i} \right]^{-1} \quad (1)$$

Whereas n and m are the number of criteria and the value of M_{pj}^{i} is evaluated using Equation (2) and $\sum_{j=1}^{n}\sum_{i=1}^{m} {M_{pj}}^{i}$ is evaluated by using Equation (3).

$$\sum_{i=1}^{m} M_{pj}^{i} = (\sum_{i=1}^{m} l_i, \sum_{i=1}^{m} m_i, \sum_{i=1}^{m} u_i) \quad (2)$$

The l, m and u stand for the lower, middle and upper values for each criterion.

$$\sum_{j=1}^{n}\sum_{i=1}^{m} M_{pj}^{i} = (\sum_{j=1}^{n} l_j, \sum_{j=1}^{n} m_j, \sum_{j=1}^{n} u_j) \quad (3)$$

Then, the reverse form is evaluated by using Equation (4).

$$\left[\sum_{j=1}^{n}\sum_{i=1}^{m} M_{pj}^{i} \right]^{-1} = (\frac{1}{\sum_{j=1}^{n} u_j}, \frac{1}{\sum_{j=1}^{n} m_j}, \frac{1}{\sum_{j=1}^{n} l_j}) \quad (4)$$

The third step involved the determination of the degree of possibility, which was done by comparing each variable in relation to others, one by one. The degree of possibility is defined that:
if $M_{n+1}(l_{n+1}, m_{n+1}, u_{n+1}) \geq M_n(l_n, m_n, u_n)$ then $V(M_{n+1} \geq M_n) = sup_{y \geq x}[min(\mu_{M1}(x), \mu_{M2}(y))]$

This scenario can be evaluated by using Equation (5).

$$V(M_{n+1} \geq M_n) = hgt(M_{n+1} \cap M_n)] = \mu_{Mn+1}(d) = \begin{cases} 1, & if \ m_{n+1} \geq m_n \\ 0, & l_n \geq u_{n+1} \\ \frac{l_n - u_{n+1}}{(m_{n+1} - u_{n+1}) - (m_n - l_n)}, & otherwise \end{cases} \quad (5)$$

The fourth step involved the selection of the degree of possibility from the evaluated values. The minimum value is selected from the set of all evaluated values in each criterion, as depicted in Equation (6).

$$V(M \geq M_1, M_2, \ldots M_k) = V[(M \geq M_1) \ and \ (M \geq M_2) \ and \ldots (M \geq M_k) = min \ V((M \geq M_i), \quad i = 1, 2, 3, \ldots, k \quad (6)$$

Then, the evaluated minimum value in each criterion is assumed to be the weight vector, as expressed in Equation ((7).

$$W(i)' = min \ V((M \geq M_k), k = 1,2, \ldots n \quad (7)$$

The weight can be illustrated as shown in Equation (8) in the form of a vector.

$$W' = (W(A_1)', W(A_2)', \ldots W(A_n)') \quad (8)$$

Whereas $A_{1,2,\ldots n}$ stand for the number of criteria.

In the last step, the weights were normalised, and then the normalised weights were used to quantify each criterion in evaluating the potential geothermal areas in the ArcGIS software.

3.4 Evaluation of Potential Geothermal Areas by Applying Weights Evaluated in the ArcGIS Software

After obtaining the weight of each criterion, weights for all criteria were combined using the ArcGIS software to evaluate the potential of the areas; the final result is known as the geothermal potential index. The geothermal potential index (GPI) is a quantification index technique applied to numerically express the geothermal resource potential in the study area by combining thematic layers of the five criteria (Şener, E. & Şener, Ş., 2021). Therefore, the GPI was evaluated in the ArcGIS software using Equation (1).

$$GPI = W_1C_1 + W_2C_2 + W_3C_3 + W_4C_4 + W_5C_3 \quad (1)$$

Whereas W_1: weight of the distance from the hot springs, W_2: weight of the distance from the faults, W_3: weight of the distance from the volcanic rock, W_4: weight of the heat flow, W_5: weight of the land surface temperature, C_1: distance to hot spring criterion, C_2: distance to EARS faults criterion, C_3: distance to volcanic rock criterion, C_4: heat flow criterion and C_5: land surface temperature criterion.

3.5 Validation of the Results

The results obtained will be validated through the use of known geothermal wells which are found in the study area. Most of the geothermal wells in this study are found in Olkaria, Eburru, Menengai and Akiira in Kenya and Aluto-Langano, and Tendaho-Dubti in Ethiopia. Thus, these areas were compared with the results obtained in this work.

4.0 Results and Discussion

4.1 Results

4.1.1 Weight Evaluated for Each Criterion

After applying the fuzzy AHP for evaluating the weight for each criterion, it was found that distance from the hot springs has the highest contribution in recognising the potential geothermal area. The distance from the hot springs was weighted at 49%. The second criterion, with a high weight, was the distance from the EARS major faults; this criterion occupied a weight of 30%. The third one was the distance from the active and young volcanic rock, with a weight of 11%. The two remaining criteria, heat flow and surface temperature, occupied small weights of 7 and 3%, respectively, as illustrated in Table 5.

Table 5
The Weight Evaluated for All Criteria

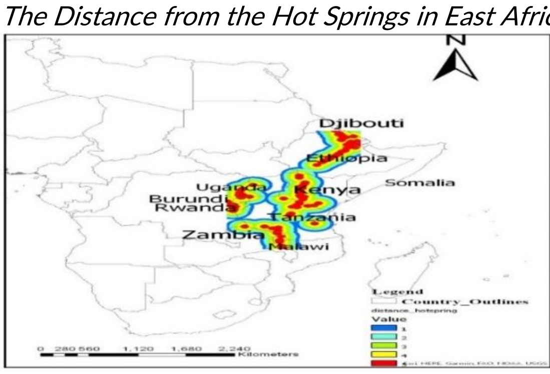
Criteria	Evaluated weight [%]
Distance to hot springs	49
Distance to faults	30
Distance to igneous rock	11
Heat flow	7
Surface temperature	3
Total weight	**100**

4.1.2 The Distance from the Hot Springs

Hot springs are the main factor which indicates the presence of geothermal energy in an area. Based on the results of fuzzy AHP, this factor contributes to the identification of geothermal potential areas by 49%, which is the highest when compared to other criteria. As shown in .

Figure 6, in East Africa, there are many hot springs, starting from Djibouti to Malawi. Many East African countries, including Djibouti, Ethiopia, Kenya, Uganda, Rwanda, Burundi, Tanzania, Zambia, and Malawi, show the presence of hot springs. The areas closest to the hot springs (indicated by the red colour or number 5) were termed as potential areas for geothermal resources, and those which are far from the hot springs (indicated by the blue colour or number 1) were defined as less geothermal potential areas, as illustrated in Figure 6.

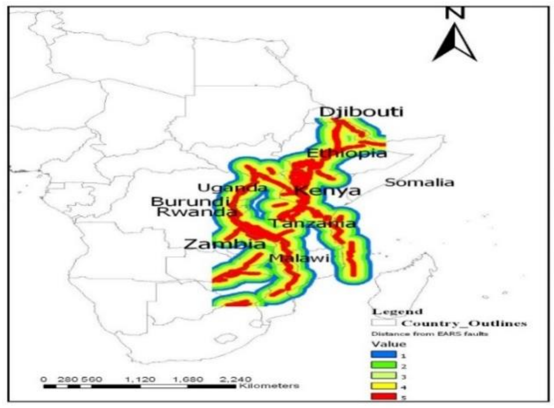
Figure 6
The Distance from the Hot Springs in East Africa



4.1.3 The Distance from the EARS Major Faults

East Africa has been passed by the large structure known as EARS; this system contains the faults, which are treated as the conduit for transferring heat from the bottom part of the Earth's crust to the underground water. Also, other indicators of geothermal energy, like active volcanic rocks, hot springs, and earthquakes, are found in this EARS. The fault system in East Africa passes through different countries, as shown in Fig. 8. Those countries include Djibouti, Ethiopia, Kenya, Uganda, Rwanda, Burundi, Tanzania, Malawi, Zambia, and Mozambique. This criterion was assessed by the fuzzy AHP as the second most significant criterion among all, as shown in Fig. 7. The areas close to the faults (number 5) system were classified as potential areas for geothermal resources, whereas those far areas were classified as less potential (number 1).

Figure 7
The Distance from the EARS Major Faults

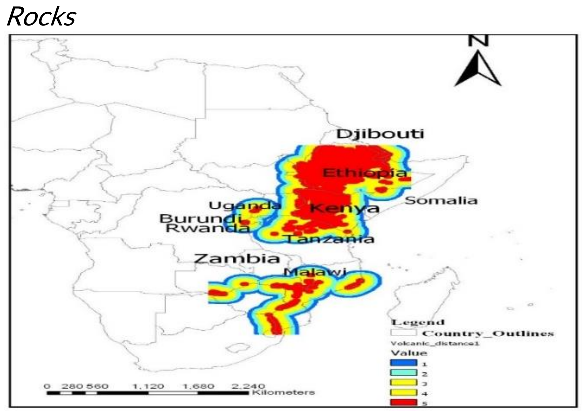


The red colour indicates the areas that are closest to the fault systems, whereas the blue colour indicates the far areas.

4.1.4 The Distance from the Active and Younger Volcanic Rocks

Volcanic rocks act as the source of heat for underground water for the development of geothermal energy. Thus, the area with younger and more active volcanic rocks is a good candidate for geothermal wells. The results from the Fuzzy AHP classified the distance from active and younger volcanic rock in the third position as the indicator of geothermal energy, with 11%. Most areas of Ethiopia, Kenya, and Djibouti show the presence of volcanic rocks. But other areas of Malawi, Zambia, and southern Tanzania show some active volcanic rock. Thus, this criterion is combined with criteria for the identification of potential geothermal areas. Fig. 8 shows the classification of the areas based on the active and young volcanic rocks; the area close to these rocks was assigned number 5, followed by numbers 4, 3, and 2, and the far one is number 1.

Figure 8
Areas Close to the Active and Young Volcanic Rocks



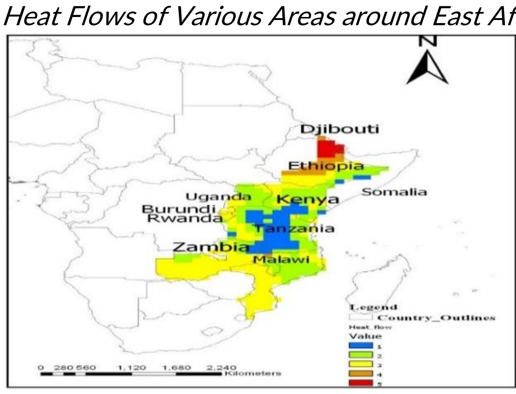
The red colour shows the closest areas, whereas the blue colour indicates areas which are far.

4.1.5 The Heat Flow in Various Areas around East Africa

The heat flow varies from area to area in East Africa, and these variations are shown in Fig. 9. The higher heat flow indicates the possibility of having high geothermal energy; hence, the classification of heat flow shows that in the north of Ethiopia and south of Djibouti, the heat flows were the highest, ranging from 160 to 245 mW/m² (number 1). At the same time, other areas of Ethiopia show higher heat flow, which ranges from 90 to 160 mW/m² (number 2). Other areas like Zambia, Malawi, and Kenya show the average heat flow, whereas central Tanzania displays low heat flow. Thus, the central part of Tanzania is not a potential area for geothermal energy due to its lower heat flow. In contrast, other parts seem to be good candidates for geothermal resources due to their higher heat flow.

Figure 9

Heat Flows of Various Areas around East Africa

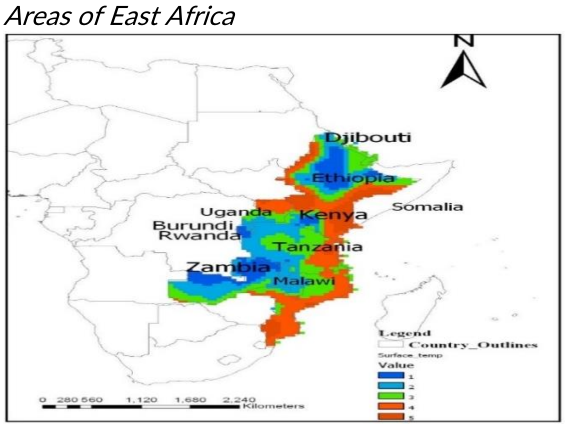


4.1.6 The Surface Temperatures in Various Areas around East Africa

The surface temperature criterion has been found to have the least impact on the identification of potential geothermal areas. Based on the fuzzy AHP results, the contribution of surface temperature to the identification of potential geothermal areas is just 3%. The areas around the coast of Tanzania, Malawi, coastal Kenya, north of Uganda, and west of Ethiopia have higher surface temperatures when compared to other areas. Therefore, these criteria add to the potential of these areas in the presence of geothermal energy (Fig. 10).

Figure 10

The Average Surface Temperatures in Different Areas of East Africa

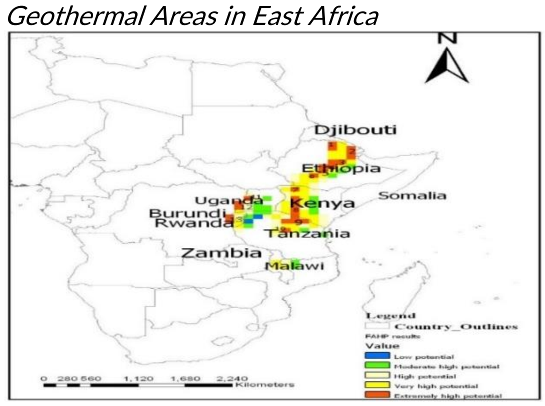


4.1.7 The Identified Potential Geothermal Areas in East Africa

After classifying all the criteria with the help of fuzzy AHP and then developing the thematic layers in ArcGIS software, the next procedure was to combine the thematic layers with the evaluated weights. The combinations of these thematic layers developed five different zones: extremely high potential, very high potential, high potential, moderate-high potential, and low potential areas, as depicted in Fig. 11. 13 areas were identified as extremely high-potential geothermal areas, 6 of them in Ethiopia, 2 in Kenya (1 in the northern part and 1 in the zone that contains many geothermal fields), 2 in northern Tanzania, 2 in Uganda, and 1 between Rwanda and Burundi. But other areas, like Lake Malawi (Nyasa), many areas in Kenya, and some parts of Tanzania, Rwanda, Uganda, and Burundi, were identified as very high-potential areas for geothermal energy.

Figure 11

The Areas which were Identified as Potential Geothermal Areas in East Africa



4.2 Discussions

This study identified 13 potential geothermal areas, many of which are found in Ethiopia and Kenya. All six areas that have been discovered in Ethiopia are located in the Aluto-Langano and Tendaho-Dubti areas, north of Ethiopia, and others in the Ethiopian Rift, including Tendaho, Alalobeda, Tendaho-Dubti, Tendaho, Ayrobera, Corbetti, Tulu Moye, Fantale, Butajira, Wondo-Genet, Boku, Daguna, Fango, Boseti, Abaya, Kone, Dofan, Hala, Abijata, Gedemsa, and Mateka. Furthermore, three major regions in Kenya have been identified as potential geothermal areas: the north, central, and south in the Kenya Rift system. These areas contain many geothermal fields like Olkaria, Eburru, Menengai, Korosi, Paka, Silali, Akiira, Lake Magadi, and the Barrier volcanic complex. Other countries that have been discovered to have potential geothermal areas are Tanzania in the north, Malawi in the north close to Tanzania, Uganda, Rwanda, and Burundi.

The results of this study were validated through ground truthing and comparison with existing literature to ensure their accuracy and reliability. Specifically, the model outputs were compared with known geothermal sites such as Olkaria and Eburru in Kenya, as well as Aluto-Langano and Tendaho-Dubti in Ethiopia. These sites, which are actively exploited or confirmed geothermal fields, are located within the zones identified by the model as having extremely high geothermal potential (areas 1, 2, and 8 on Fig. 11). This spatial correlation indicates a strong agreement between the model predictions and actual geothermal activity on the ground. Furthermore, the findings align with those of Elbarbary, S. et al. (2022), who identified 14 potential geothermal sites across Africa, many of which overlap with the high-potential areas delineated in this study. The consistency between the model results, field evidence, and established scientific literature confirms the robustness of the approach used and supports the use of these outputs as a reliable reference for guiding further detailed geothermal exploration, including drilling programs.

Also, it was found that the formation of geothermal resources in East Africa is largely influenced by the EARS's major faults since almost all identified potential geothermal areas are found in the EARS. Another factor that was highlighted as the main cause of geothermal fields is the young and active volcanic rocks, which act as the source of heat for underground water. This has been confirmed by several studies, including Dhansay, T. et al. (2014) and Omenda, P. et al. (2016), who have pointed out that the EARS contains young and active volcanic rocks with Pleistocene to recent ages. The contribution of deep faults in the western part of the EARS to the formation of geothermal resources has also been emphasised by Hanano, M. (2000); Irena (2019); Omenda, P. et al. (2016); and Omenda, P. and Simiyu, S. (2015).

This study focused on identifying areas with geothermal resources based on key surface and subsurface indicators. However, to build on these findings, it is important to expand the scope of research by assessing the potential quantity of energy that could be generated from these identified resources. Therefore, it is recommended that future studies address this gap by conducting quantitative assessments of geothermal energy production potential, including reservoir capacity estimation and energy output modelling.

5.0 Conclusions

African nations need other energy sources, and geothermal energy seems to meet the requirements. However, the prior study estimated that the geothermal potential in East Africa is approximately 18,000 MW, but only 900 MWe is produced. Country-wise, Kenya leads the way in utilising its geothermal resources, producing more than 877 MWe and having many projects in development. Ethiopia is the second country in East Africa, producing only 7.3 MWe. Other countries in East Africa are still conducting surface explorations.

In addition, this study investigated the areas that are potentially for geothermal resources in Eastern Africa. This area has been passed by an important geological system called the Eastern African Rift System (EARS), which plays a key role in generating geothermal resources. This is due to active volcanic areas in the eastern branch and active faults and fractures in the western branch, which act as heat conductors and transmit heat from the mantle to the crust to form geothermal resources. With the application of fuzzy AHP and ArcGIS, we identified 13 areas that have extremely high potential in geothermal resources. The distribution of the identified areas was as follows: 6 of them in Ethiopia, 2 in Kenya, 2 in northern Tanzania, 2 in Uganda, and 1 between Rwanda and Burundi. Furthermore, many other areas, including the north of Malawi, many areas in Kenya, and some parts of Tanzania, Rwanda, Uganda, and Burundi, were identified as very high-potential areas for geothermal energy. The identified areas are confirmed by some of the geothermal wells, which are producing.

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7.0 Competing Interest

The authors state that none of their known financial conflicts or interpersonal connections might have had an impact on the work presented in this paper.

8.0 Conflict of Interest

We declare no conflict of interest.

9.0 Ethical Statement

This material is the authors' own original work, which has not been previously published elsewhere.

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