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Review Article

Current Status, Future Prospects, and the Need for Geothermal Energy Exploration in Cameroon: Comprehensive Review

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Cameroon is a country in Central Africa that relies heavily on hydropower, fossil fuels, solar, and biomass for its energy needs. However, the unstable and intermittent nature of these energy sources makes them unreliable, and there is a pressing need for a more secure and sustainable energy supply. Geothermal energy, which is abundant in Cameroon due to its favorable geological characteristics, has not been fully explored as a potential energy source. This study is aimed at providing a comprehensive review of the current status and future prospects of geothermal energy in Cameroon, based on publications related to geothermal energy in Cameroon, geological, and geophysical studies. The objectives of this study are to analyze the existing literature on geothermal energy in Cameroon, to identify the challenges and opportunities associated with geothermal energy development, and to make recommendations for future research and policy decisions. The results indicate that geothermal energy in Cameroon is still in its infancy, with limited research and development in the field. However, the country has geothermal potential, particularly in the Adamawa and Cameroon volcanic line (CVL) areas. The review highlights the challenges and barriers to geothermal energy development in Cameroon, including limited financial resources, technical expertise, and regulatory frameworks. The findings of this study suggest that Cameroon has significant potential for geothermal energy development, and that further exploration and investment in this area could contribute significantly to a more secure and sustainable energy supply in the country.

1. Introduction

Geothermal energy has been identified as a promising renewable energy source that can contribute significantly to meeting the energy demand of countries across the globe [1]. Cameroon like many other developing countries faces energy supply challenges that hinder its vision for 2035 of becoming an emerging country and a leader in the agro-industrial market of the Economic Community of Central African States (ECCAS) and the Economic Community of West African States (ECOWAS). To address its energy demand and supply issues, Cameroon, through its National Development Strategy for 2030 (NDS30), has decided to increase its installed energy capacity from 1,650 MW to more than 5,000 MW by 2030 [2]. As can be seen in Figure 1, the future energy generating facilities in the country will heavily rely on hydroelectric power, accounting for 97.87% of the total commissioning capacity of 5,340 MW, followed by the extension of the Kribi gas power plant for the period 2026-2029 [1].

This overreliance on hydro, biomass, gas power plant, and solar, as indicated in the NDS30, will lead to significant environmental degradation and contribute to Cameroon's vulnerability to climate change and secure energy supply. This is because, firstly, hydropower depends on the availability of rain, which can be affected by droughts or other

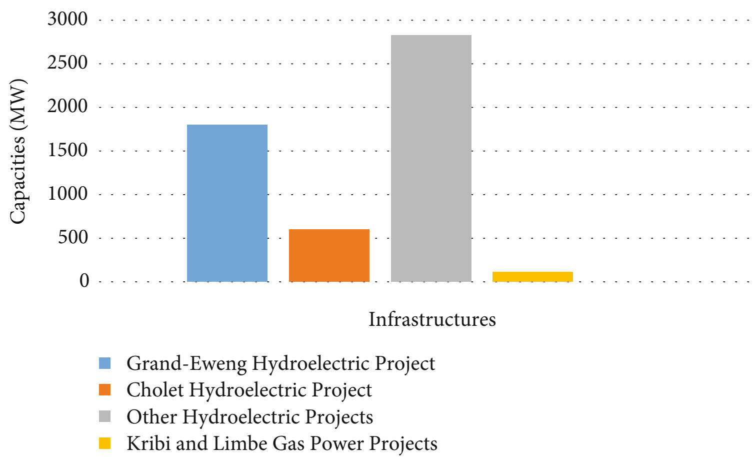

FIGURE 1: Commissioning of energy infrastructure in Cameroon for the period 2026-2029 [2].

weather-related factors [3]. During dry seasons, the water levels in rivers or dam can drop, leading to a decrease in the energy production of hydropower plants. This can result in power outages and an interruption in the energy supply. Further, hydropower plants can be affected by changes in water quality due to factors such as sedimentation, which can reduce the efficiency of power generation. Additionally, hydropower plants can be impacted by extreme weather events such as floods, which can damage infrastructure and lead to shutdown or decrease in energy production. Secondly, it is expected that biomass energy potential for both energy and nonenergy uses will be limited to 392-498 Mtoe by 2030 [4, 5]. Additionally, it has to meet strict sustainability standards before considered a viable renewable energy source [4, 6]. In Cameroon, unsustainable use of biomass resource has led to significant deforestation with an annual clearance rate to 100,000 ha/year [7]. Thus, relying on biomass as a renewable energy has limitation because the amount of biomass available is limited, and if it is not sustainable managed, it can lead to deforestation and loss of biodiversity. Thirdly, solar energy capacity worldwide has grown substantially to reach 849,473 MW in 2021 [8]. In Cameroon, its capacity was 14 MW in 2021 [8]. However, solar energy, particularly photovoltaic (PV) energy, is characterized by intermittent energy generation, which can be overcome only by energy storage [9]. Moreover, solar energy is cloudy-weather and environmental limited [9]. Finally, fossil fuel resources are finite, expensive, and depend on their availability and market price fluctuation. They contribute to greenhouse gas emissions.

In light of these challenges, it is imperative to explore clean and renewable energy sources such as geothermal energy [3, 10, 11], which can provide reliable and sustainable energy to Cameroon while reducing greenhouse gas emission. This comprehensive review is aimed at providing an overview of the current status and future prospects of geothermal energy in Cameroon.

In this study, we analyzed the existing estimates on geothermal potential of Cameroon, the current policies and regulatory frameworks in place to promote geothermal energy, and the technical and economic feasibility of geothermal energy development. We also discuss the potential benefits and challenges associated with geothermal energy in Cameroon, and the need for further exploration of geothermal resources in the country. Ultimately, this review aimed at contributing to the development of a sustainable energy mix in Cameroon that meets the country's energy need while also contributing to its economic and social development.

1.1. Literature Review. Geothermal energy is a renewable energy source that harnesses the earth's heat to generate electricity [1]. It is a reliable and consistent energy source that produces low emissions, making it an attractive option for countries seeking transition to cleaner energy. Here, we provide a review of the literature on geothermal energy, including global and regional trends in geothermal energy development, discussion of the geological features and characteristics of Cameroon that are favorable for geothermal energy development, and analysis of the existing policy and regulatory frameworks for geothermal energy in Cameroon.

1.1.1. Global and Regional Trends in Geothermal Energy Development. The use of geothermal energy for power generation has been growing steadily worldwide as can be seen in Figure 2. According to Huttrer [12], the total capacity of geothermal energy has shown an increased trend. In 2010, it was around 10 GWe, which increased to approximately 13 GWe in 2018. However, as of 2020, the total capacity had increased further to 15.95 GWe, and it is projected to reach 19.361 GWe in 2025 [13].

Recently, the number of countries reporting direct utilization of geothermal energy has increased over time, with 88 countries reporting in 2019, 82 countries in 2015, compared to 78 in 2010, 72 in 2005, 58 in 2000, and 28 in 1995 [14, 15]. Geothermal energy has been attracting a great number of countries. Between 2015 and 2020, 1,159 wells were drilled for power projects, US $10,367 millions were spent on power projects, and five new countries joined the list of geothermal energy producers as can be seen in Figure 3.

By 2050, geothermal energy alone will have the potential to generate 1400 TWh per year, which is around 3.5% of

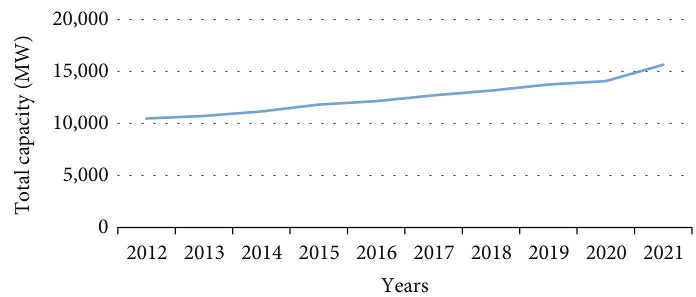

Figure 2: Total installed geothermal capacity in the world [8].

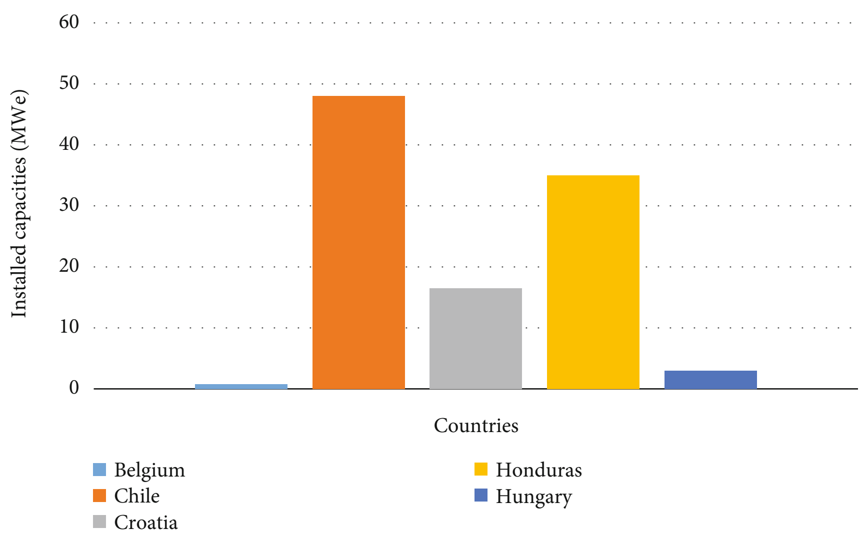

Figure 3: List of new countries joining geothermal producers in the period 2015-2020 [12].

global energy production [16]. Such a contribution would reduce CO_2 emissions by approximately 800 Mt per year [17]. Geothermal energy is therefore expected to play an increasingly important role in the sustainable and clean energy transition alongside other renewable energy sources [11], particularly in regions where tectonic and volcanic activities have brought magma closer to the earth's surface [1]. The majority of the installed capacity is in the United States, Indonesia, and the Philippines [8].

In Africa, the total capacity of geothermal energy was 870 MW in 2021 [8]. Among the countries harnessing this renewable energy source, Kenya stands out as the leader, accounting for an impressive 99.19% share of Africa's geothermal capacity. Kenya last development in this sector has been remarkable. As depicted in Figure 4, Kenya's geothermal power plants boasted a capacity of 863 MW in 2021 [8]. Over 40% of electricity production in Kenya comes from geothermal sources [18]. The country has been actively exploring ways to utilize renewable energy source to support various economic and industrial sectors. In 2022, Fortescue Future Industries collaborated with the Kenyan government to build a 300 MW, geothermal-powered ammonia and fertilizer production plant in Naivasha [18]. Ammonia production plant is an example to how Kenya is harnessing its geothermal energy resources to support economic development and promote sustainable industrialization.

As summarized in [19], geothermal energy potential also exists in several other African countries, including Ethiopia, Tanzania, Rwanda, Uganda, Djibouti, Eritrea, and Cameroon. Some of these countries have already initiated geothermal exploration and development projects. There is potential for other African countries like Cameroon to also harness this renewable energy source in the future.

1.1.2. Geothermal Energy: Overview and Potential in Cameroon. Few studies have investigated geothermal potential in Cameroon. For instance, the study carried out by Keng [20], on geology and geochemistry of the thermal springs of Cameroon, explored 40% of the country and identified more than 130 thermomineral springs in Cameroon. Among these springs, 26 have a temperature between 26°C and 74°C as can be seen in Figure 5, with the highest temperature being that of the spring located at Woulndé (74°C). The presence of these springs in Cameroon suggests that there may be potential for geothermal energy in the aforementioned areas. Since 1976, no other relevant studies on the exploration of thermal springs have been done.

Between 2012 and 2016, studies on review on renewable energy in Cameroon with a section on geothermal energy

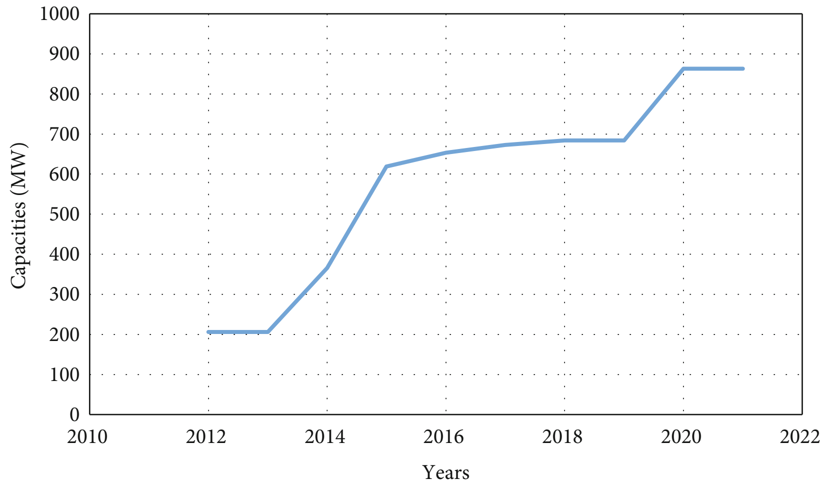

Figure 4: Total geothermal capacity in Kenya [8].

Figure 5: Temperature of different thermal springs in Cameroon [21].

were conducted by [22–25]. The authors used the existing literature to assess the potential of renewable energy in Cameroon. They acknowledged the fact that Cameroon has potential for geothermal energy development, particularly in three specific areas in Cameroon (Ngaoundere, Mounts Cameroon, and Manengouba with Lake Moundou). However, these studies agreed that there is a limited literature on the potential of geothermal energy in Cameroon, and that the existing literature was nonconclusive about the potential of geothermal energy.

Between 2017 and 2022, three recent papers were published in the open literature on the theme "geothermal energy" and "Cameroon" which are [26–28]. Only [26] was found in the Scopus databases. From the study carried out by [27] on "Appraisal of geothermal resources and use in Cameroon", the author(s) examined the resources and opportunities for the direct and indirect use of the geothermal energy in Cameroon. They also identified geothermal sites using thermal methods and evaluated the potential for using geothermal energy for various applications, including electricity production in the country. They found that the hottest spring (74°C at Woulndé) is located in the central region of Cameroon, at the intersection between the Cameroon volcanic line (CVL) and the Adamawa shear zone. Further, their findings revealed that the largest number of springs is located in the region of Adamawa, and that the mentioned hottest spring of Woulndé presents a temperature of 600°C at 1,000 m depth, estimated by geothermometer, and so it which can be used for power generation. The study concluded that a geothermal power plant of 5 MW could be constructed at Woulndé hot spring. The author(s) also discussed the various applications of geothermal energy in Cameroon, including space heating, agriculture drying, aquaculture, and direct use applications. However, despite the availability of enormous potential indirect use applications, no use has been made of low-enthalpy fluids.

1.1.3. Geothermal Energy Potential in Cameroon: Geological and Geophysical Context. Several other studies have investigated the geology and the geophysics of Cameroon with the aim to identify the geological structures and features and to delineate the subsurface, respectively.

From a geological point of view, the crust in Cameroon is characterized by two main geological structures, the Pan-African-Mobile Belt in the north and the Congo Craton in the south, with several main structural features such as the Sanaga Fault, the Cameroon volcanic line, and the Adamawa Plateau [29–38]. These features have been partially modeled using various geophysical methods such as gravity, magnetic, and seismic data [29–38]. From the review of [29–38], it comes out that the geological structures and features of Cameroon have been shaped by tectonic activity over millions of years, and that those main features are the following:

(i) Cameroon volcanic line (CVL), which is a 1,600 km-long line of volcanoes that runs through Cameroon. The CVL is associated with a seismic zone that includes the Central Africa Shear Zone (CASZ) and Mount Cameroon

(ii) Sedimentary basins located at the northern part of Cameroon

(iii) Adamawa Plateau, surrounded by the CASZ

(iv) CASZ, which is a major tectonic feature in Cameroon that surrounds the Adamawa Plateau and is associated with the CVL

(v) Congo Craton, which is a large area of stable continental crust in central and southern Africa that downthrusts the Pan-African Mobile Belt (PMB) in northern Cameroon

(vi) Sanaga Fault, which is a major fault in southern Cameroon that has been characterized as a left-lateral deformation

The modeling and knowledge of these geological structures and features can provide a better understanding of the subsurface structure. Additionally, it can aid to identify areas with high geothermal energy potential. From these geological structures and features of Cameroon as summarized by authors in [29–38], some valuable information concerning opportunities for the development of geothermal energy in the country can be drawn. Firstly, the presence of the CVL suggests that there may be areas of high heat flow in the region, as volcanic activity is often associated with geothermal systems [11]. Additionally, the sedimentary basins in the northern part of Cameroon may contain sedimentary rocks that are good hosts for geothermal reservoirs [11]. Furthermore, the presence of the CASZ and the Sanaga Fault suggest that there may be areas of high permeability where fluids could circulate and recharge geothermal reservoirs [11]. The Foumban Shear Zone (FSZ) and the northern margin of the Congo Craton are also potential areas for geothermal exploration due to their association with seismic activity and the potential for fractured and permeable rocks. These geological studies [29–38] including the work done by [21], have therefore, identified several potential geothermal areas in Cameroon, including Mount Cameroon area, Mandara Mountains, and Logone Birni Basin. These studies have proved important insights into the geology, tectonics, and structure of these regions, which are critical in identifying potential geothermal reservoirs. The information provided by the geological structures of Cameroon can be of interest to geothermal energy development as it can provide information about the subsurface structure and processes while contributing to the occurrence of geothermal resources.

Geophysical works provide valuable information on the subsurface structure and tectonic activity in a region, which can in turn be used to assess the geothermal energy potential of the area. For instance, the survey carried out by Fantha et al. [29] used the geophysical potential field data to map the major lineaments across Cameroon. Tectonic lineaments are geological features that result from the movement of tectonic plates, and they often correspond to areas of high geothermal activity due to the increased permeability of the subsurface rocks in these areas. Potential field data, such as gravity and magnetic data, can be used to map tectonic lineament by identifying areas of contrast in the subsurface that are related to changes in the physical properties of the rocks, such as density and magnetic susceptibility [29]. These contrasts can be interpreted as faults or shear zones, which can serve as pathways for fluid flow and heat transfer, making them favorable locations for geothermal energy production. Fantah et al. [29] used gravity and EMAG2 data to identify and characterize the major lineaments across the country. Their result revealed that the main lineaments across Cameroon were laterally extended with a dominant N45°E orientation, and the depth of these lineaments varies between 1 and 35 km. Additionally, they found that some of the identified faults are still active. By mapping the major lineaments across the country, the study identifies potential areas for geothermal exploration. Those lineaments could be potential targets for geothermal drilling. The study also suggests that some of the identified faults are still active, which could have implications for geothermal development, as they could provide pathways for fluid flow and enhance the permeability of the reservoir.

Ngatchou et al. [31] studied the source characterization and tectonic implications of the M4.6 Monatele (Cameroon) earthquake on19 March 2005. From their work, the knowledge of the geological and geophysical characteristics of the region can be used for geothermal exploration and development. For instance, the presence of the Sanaga Fault, a tectonic lineament in Central Africa, suggests that there may be potential for geothermal energy in the region. The geological and geophysical data can help identify suitable areas for exploration and drilling, assess the geothermal potential of the region, and estimate the costs and risk of the geothermal development.

Shandini et al. [36] carried out a study on the structural setting of the Koum sedimentary basin (North Cameroon) derived from EGM2008 gravity field interpretation. The authors used geophysical methods such as gravity data modeling and spectral analysis to image the subsurface structure of Koum basin. The 3D modeling of the Koum basin shows that it is a half graben bounded by subvertical faults. Such geological structures can provide favorable conditions for geothermal energy development, as they can create geothermal reservoirs that can be exploited for energy production. Additionally, the authors found that the thickness of the Cenozoic sediments in the Koum basin is up to 4.5 km, which indicates the potential for high geothermal gradients and high temperatures at depth, which are key factors for geothermal energy production. Finally, they identified faults that reach 6 km depth with predominant NW-SE trend, as well as E-W trending faults along the contact between the sedimentary section and the basement complex in the northern edge, which are important for geothermal exploration. Such fault zones can serve as pathways for geothermal fluids to rise to the surface and can also indicate areas of potential geothermal activity. Therefore, the information from this study can be used to guide further geothermal exploration in the Koum basin and other similar geological structures in Cameroon.

Koumetio et al. [37] in their study provided information on the presence of a dense intrusive igneous body in the upper crust of Kribi-Edea zone and contacts between rocks of different densities at different depths. This information is relevant for geothermal exploration as intrusive igneous bodies can act like a heat source for geothermal systems, and the presence of contacts between rocks of different densities can create potential sites for fluid circulation and heat transfer. Additionally, the depth intervals estimated for the contacts and igneous blocks can provide valuable information for drilling and exploration of potential geothermal reservoir.

From the work done by [38], several potential implications for geothermal energy development in the Garoua sedimentary basin in Cameroon can be drawn. Firstly, the presence of a sedimentary basin suggests the possibility of a hydrothermal system that could be exploited for geothermal energy. The accumulation of sandstone within the basin could potentially serve as a reservoir for geothermal fluids. Secondly, the identification of a thinner continental crust beneath the basin may indicate the presence of higher geothermal gradients in the area. Thinner crust is typically associated with higher heat flow and geothermal activity, which could potentially be harnessed for energy production. Finally, the uplifted Moho in the basin may suggest the presence of geothermal anomalies associated with the extensional process that formed the basin. This could potentially result in areas of increased heat flow and geothermal activity that could be explored for energy development.

Mouzong et al. [39] presented a novel approach for constructing a background density model for predicting gravity data in Northern Cameroon and its surroundings using artificial neural networks (ANN) with the Levenberg-Marquardt algorithm. The study found that this approach yielded highly accurate statistical predictions of gravity values with low error. The authors concluded that this approach provides a promising method for enhancing the analysis, interpretation, and modeling of gravity data collected on a sparse grid of recording stations in the region. The improved quality of gravity data modeling can aid in identifying potential geothermal resources in the area. Geothermal exploration often relies on identifying geological structures that indicate the presence of geothermal resources, and gravity data can be used to map out these structures. Therefore, the use of ANNs to improve gravity data modeling could potentially lead to more accurate identification of geothermal resources and aid in their development in Northern Cameroon and its surrounding.

Marcel et al. [40] provided insights into the geodynamics of the lithosphere beneath the region. The isostatic regional anomalies obtained from the study reveal two major crustal zones, with the southern part of the CVL including Mount Cameroon, coastal and oceanic zones showing the highest values, while the northern part comprising Kumbo zone, lakes Monoun, and Nyos exhibiting lower magnitudes. The study also indicates that the upper mantle with higher density than asthenosphere and crust may influence the highly positive gravity anomalies observed in the study area. The findings of the study suggest that the mountains of the study areas, including Mount Cameroon and Koumbo regions, may not be located in zones where the conditions of complete isostatic compensation are satisfied, which may be the cause of asthenospheric uplift leading to upward flow of materials from depth through volcano vents or fractures. These insights could have implications for understanding the geothermal potential of the region and associated volcanic hazards. The study could provide a basis for further exploration of geothermal potential of the region and could help in identifying areas of potential volcanic hazards.

Assembe et al. [41] provide information about the geodynamic evolution of the northern Edge. The study identified lineaments and shear zones that have affected both the North Equatorial Fold Belt (NEFB) and the Congo Craton (CC) in the area. The differentiation between the CC and NEFB made it possible to outline a subvertical boundary at N03°20′E; they also identified lineaments of WNW-ESE, W-E, NW-SE, SW-NE, and WSW-ENE directions, produced by pre-Neoproterozoic events that have experienced syn-to-late and post-Neoproterozoic reactivations. Geological information from this study highlights the multistage tectonic evolution of the area, which has been affected by alternating compressions and extensions. The presence of pre-Neoproterozoic lineaments that have been reactivated during syn-to-late and post–Neoproterozoic events suggests a complex tectonic history for the region. From geophysical perspective, the study shows the usefulness of aeromagnetic data in detecting lineaments and shear zones, which are important structures for understanding the geodynamic activity of the region. The results suggest ongoing neotectonic activity in the Congo Craton (CC)/North Equatorial Fold Belt (NEFB) transition zone, which is related to the ongoing movements that affect the African plate. The geological and geophysical characteristics of the area can be used in conjunction with other data to assess the potential for geothermal resources. The identification of shear zones and fractures affecting both the CC and NEFB suggests the presence of geothermal reservoirs that can be exploited for energy production. The sinistral NW-SE to WNW-ESE displacements and neo-tectonic activity inferred in the CC/NEFB transition zone also indicate the potential for geothermal systems associated with active faulting and fluid flow. Additionally, the presence of the mentioned pre-Neoproterozoic events suggests the possibility of multiple geothermal systems with different characteristics. Therefore, this study can be used to guide further exploration for geothermal resources in the Metet-Zoatele area and other similar regions in Cameroon.

Njeudjand et al. [42] showed that Cameroon has geothermal potential due to the presence of Precambrian basement, Proterozoic, and Archean volcanic series, which are the main heat sources of Cameroon. The study estimated the depth of underground structure using EMAG2 magnetic data and advanced processing techniques. The estimated depths range from 0.3 km to 31 km, and the comparative study 2D magnetic modeling shows that the basement is affected by faults in the main directions of N-S, NE-SW, NW-SE, and WNW-ESE. The resulting structure map simplifies the future hydrological and geothermal exploration in the area. The study provides important information for geothermal exploration and development in the Adamawa region of Cameroon.

Other studies have investigated recently the estimation of the Curie-point depth (CPD), geothermal gradient (GG), and heat flow. Njeudjang et al. [43] carried out a study on the estimation of the CPD, geothermal gradient, and heat flow in the Adamawa volcanic region of northern Cameroon. The results revealed that the CPD in the area varies between 15.97 and 41.16 km, with an average of 27.52 km, while GG varies between 14.09 and 36.31°C/km, with an average of 22.27°C/km, and heat flow varies between 35.23 and 90.78 mW/m^2, with an average of 55.68 mW/m^2. The results suggest that there are several areas in Adamawa with high heat flow values, which are indicative of potential geothermal resources. By identifying these areas with high heat flow values and geothermal potential, it may be possible to develop more efficient and cost-effective geothermal energy projects in Cameroon. The findings may be useful for guiding government and private sector exploration of geothermal resources in the region.

Another study conducted by Mono et al. [44] discussed the estimation of Curie-point depths, geothermal gradients, and near-surface heat flow from spectral analysis of aeromagnetic data in the Loum-Minta area of Cameroon. The results revealed that the Curie-point depth varies between 5.22 and 14.35 km with an average of 9.09 km, and the heat flow varies between 101.05 and 277.77 mW/m^2 with an average of 180.59 mW/m^2, which indicates the presence of high geothermal potential. Additionally, the geothermal gradient varies between 40.42 and 111.11°C/km with an average of 72.24°C/km, which further support the potential for geothermal energy development in the area. These results suggest anomalous geothermal conditions and are recommended for further geothermal exploration in the region.

Mouzong et al. [45] carried out a critical review of the previous study [44] about the estimation of Curie-point depth, geothermal gradient, and near-surface heat flow from spectral analysis of aeromagnetic data in the Loum-Minta area of Cameroon. The authors of this review argue that the previous study failed to take into account various parameters such as seismic and geological data, which would have helped to better calibrate the results. Additionally, they suggest that the window size used in the previous study was too small to accurately estimate the Curie-point depth, resulting in erroneous results. The author(s) recommend using information on regional geology and seismicity to estimate the Curie-point depth and to integrate other independent data to determine the thermal and mechanical behavior of the crust in Cameroon. They also suggest defining a sufficiently large grid to capture the response of deep magnetic structures. Despite these controversial results, the area of Loum-Minta should be further explored for geothermal potential assessment.

Based on the previous information related to the geothermal and geological characteristics and features of Cameroon, as well as on the datasets from [46, 47], a thematic map that highlights the potential sites and the potential utilization of geothermal energy was generated as can be seen in Figure 6. It can be observed from this figure that the thermal spring sites are concentrated in the Adamawa and western part of Cameroon, which correlated well with previous studies on geological and geothermal characteristics of Cameroon. Figure 6 also highlights the possible types of geothermal energy utilization, such as industrial processes and heating.

This thematic map displayed in Figure 6 can serve as a valuable tool for policymakers, energy planners, and investors to make informed decisions regarding the development and utilization of geothermal resources for sustainable energy solutions. Additionally, a superficial heat flow (SHF) map associated with the temperature of some thermal springs was generated using Oasis 8.4 software, see Figure 7.

Figure 7 presents also coordinates of some potential sites of interest, according to Le Maréchal [21], and can be considered as a preliminary geothermal resource's exploration map of Cameroon.

1.1.4. Geothermal Development in Cameroon: Current Status and Comparison with Other Renewable Energy in Cameroon. Cameroon has several sources for electricity generation, including hydroelectric, thermal, gas, and renewable. Hydropower and fossil fuels are the main technologies used to generate electricity in Cameroon. In 2020 the electric installed capacity in Cameroon was 1529 MW, composed of hydroelectric plants (61.7%), thermal (24.1%), gas (14.1%), and solar PV (0.1%) [48, 49].

The Cameroon's renewable electric capacity increased only 13% in the decade from 2012 to 2021, passing from 731 MW (with 728 MW of hydroelectric plants and 3 MW of solar) to 826 MW (with 812 MW of hydroelectric plants and 14 MW of solar), according to IRENA [8]. Up to now, only 63.5% of the population has access to electricity, while the electric demand is estimated at 1379 MW, but the offer is only 1047 MW, with a deficit of around 330 MW [48].

Geothermal energy is currently the only renewable source able to generate electric energy in a constant, steady, and predictable way and therefore can be dispatched as base-load energy. Consequently, geothermal power plants have the highest capacity factor among all the renewable power plants in operation. In addition, it has been recognized as one of the most promising renewable energy sources with the highest technical potential in Cameroon, according to the global energy assessment report [15]. Among other renewable energy sources, geothermal energy has the highest capacity factor which can reach 95% in new power plants.

Geothermal energy is therefore a reliable source of energy that can provide a consistent and stable supply of electricity, making it an attractive option for countries seeking to diversify their energy mix.

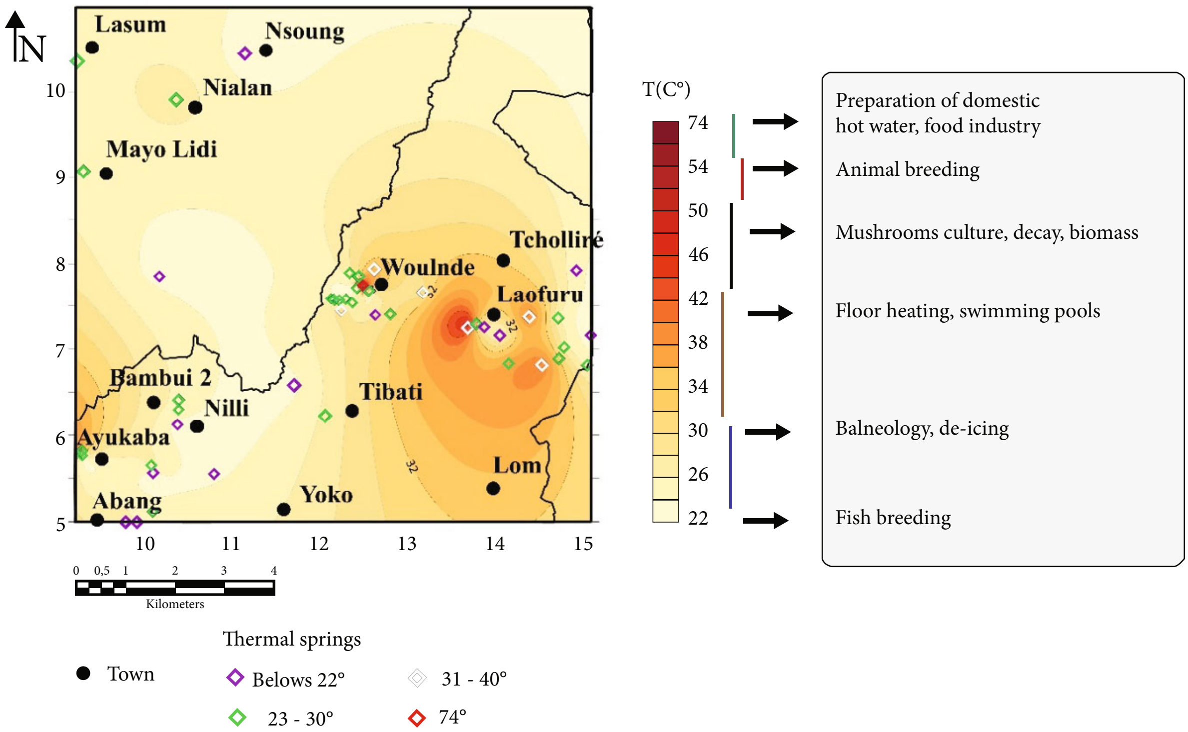

FIGURE 6: Geothermal potential and potential utilization zones in Cameroon.

As of 2023, there are no geothermal fields in operation in Cameroon. From geological and geophysical studies, it comes out that the CVL and regions around the Adamawa plateau are the main areas for geothermal exploration in Cameroon. As mentioned before, studies on Curie-point depth, geothermal gradient, and heat flow indicate the presence of low- to medium-temperature geothermal systems below the CVL volcanoes. Cameroon has significant geothermal potential that can be harnessed for electricity generation. However, there is a need for more exploration activities to better understand the geothermal resources in the country and attract more investments.

1.1.5. Challenges and Opportunities for Geothermal Energy Development in Cameroon. There are several barriers to geothermal energy development in Cameroon. Some of the main ones include the following:

(i) Limited data and knowledge of geothermal resources: Cameroon has limited data and knowledge about its geothermal resources, making it difficult to identify suitable locations for geothermal development

(ii) Lack of technical expertise: there is a shortage of skilled professionals with experience in geothermal exploration and development in Cameroon, which limits the country's ability to fully assess and develop its geothermal resources

(iii) High upfront costs: geothermal energy development requires significant upfront capital investment, which can be a challenge for Cameroon's limited financial resources

(iv) Regulatory and policy issues: the lack of clear policies and regulations to support geothermal development in Cameroon has slowed progress in the sector

(v) Competition with other energy sources: Cameroon has abundant oil and gas resources, which provide strong competition for geothermal energy development

(vi) Environmental and social impacts: even though geothermal projects have lower environmental and social impacts than other renewable projects, they must be carefully managed to avoid any negative consequence for local communities and the environment

(vii) Infrastructure challenges: the lack of adequate infrastructure, including roads, power transmission lines, and water supply, can make it difficult to develop geothermal resources in Cameroon

Despite its potential, geothermal energy development in Cameroon is still in its early stages. However, there are also several opportunities for geothermal energy development in Cameroon, such as

(i) Large untapped potential: Cameroon's geothermal potential remains largely unexplored and undeveloped, providing an opportunity for investments in exploration and development

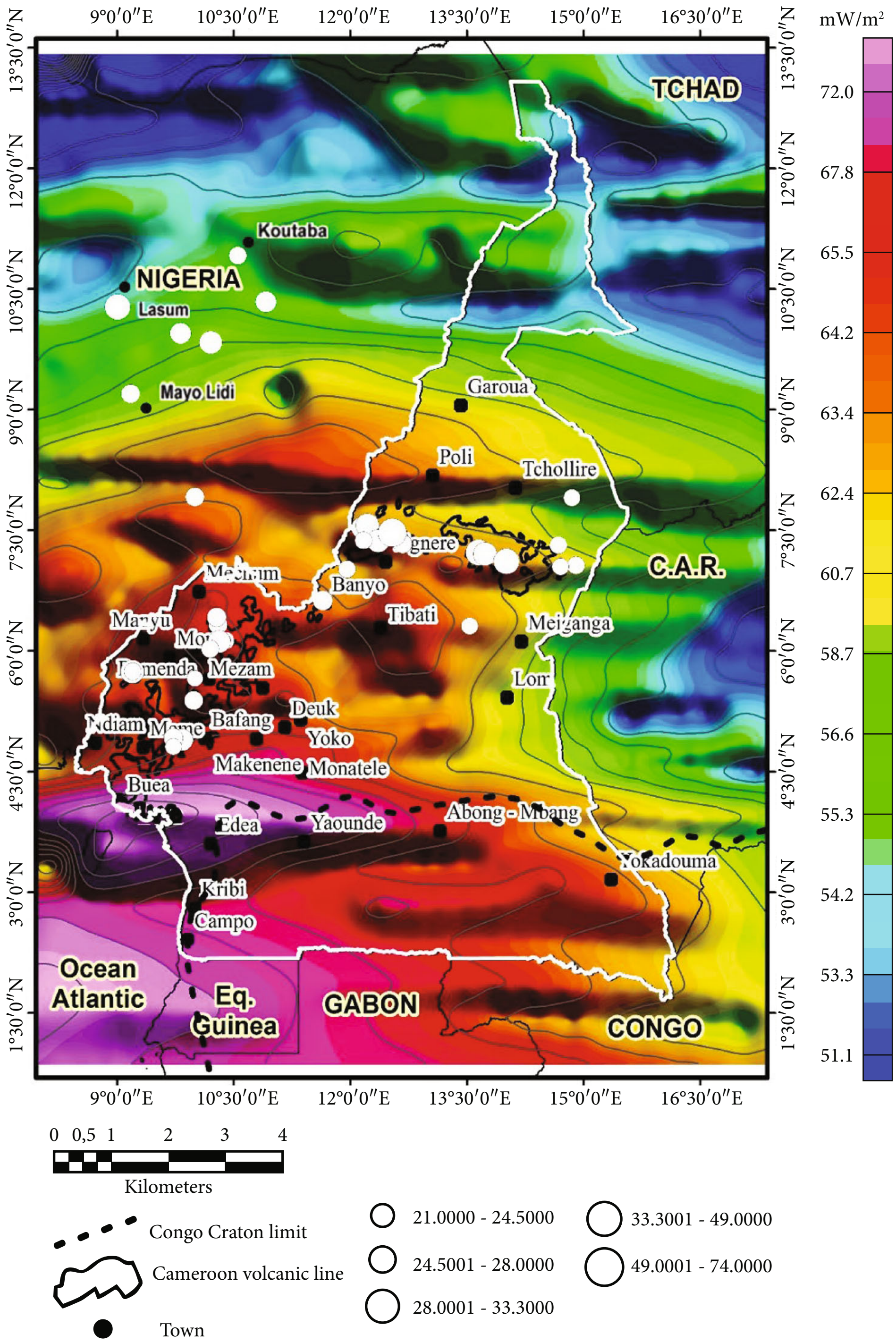

FIGURE 7: Surface heat flow map. White circles represent the temperature range of different thermal spring's sites in North and West Cameroon from [21]. Interrupted lines represent the Congo Craton limit from and black continuous line represents the contours of Cameroon volcanic line [29].

(ii) Favorable geological conditions: the CVL and the Adamawa areas of Cameroon have favorable geological conditions for geothermal energy, including volcanic formations and hots springs

(iii) High energy demand: Cameroon has a growing energy demand, and geothermal energy could help to meet this demand, particularly in rural areas where access to electricity is limited

(iv) Supportive policy environment: the Cameroonian government has shown commitment to promoting renewable energy, including geothermal energy, through policies and regulatory frameworks even if it does not focus on a particular renewable energy. The law governing the electricity sector of 2011 in Cameroon prioritizes renewable energy for rural electrification [50]. It provides an opportunity for the exploration and development of geothermal energy in Cameroon. With proper incentives, partnership, and community engagement, geothermal energy can become a significant contributor to Cameroon's energy mix, particularly in rural areas

(v) Diversification of energy mix: developing geothermal energy would help Cameroon to diversify its energy mix, reducing reliance on traditional sources such as hydroelectricity and thermal power

1.2. Geothermal Energy Utilization and Market in Cameroon. Geothermal energy has great potential as a clean and renewable source of energy in Cameroon. In this review, the various applications of geothermal energy were explored and evaluated including its market potential and economic viability, the regulatory framework, and policies related.

Agriculture in Cameroon is emerging as a promising industry, and young people are returning to the land, due to donor-funded projects, in particular the World Bank-funded Agricultural Competitiveness Project (PACA). The main cash crops cultivated include cocoa, coffee, cotton, bananas, rubber, palm oil and kernels, and peanuts. The important food crops are plantains, cassava, corn, millet, and sugarcane [51].

Agriculture is a vital sector in Cameroon providing employment to a significant proportion of the population. However, the agricultural sector in Cameroon is facing several challenges, including limited access to modern technologies, low productivity, and insufficient infrastructures.

Ammonia is a critical component of nitrogen fertilizer, which is essential for plant growth. Geothermal energy can be used to produce ammonia without relying on fossil fuel. This can help reduce the cost of fertilizer production and increase the availability of affordable fertilizers for farmers, which can improve agricultural productivity. The use of geothermal energy for ammonia production can also contribute to the country's efforts to reduce greenhouse gas emissions and promote sustainable development.

Cameroon aims to be a leader in the agro-industrial market of the Economic Community of the Central African States and the Economic Community of the West African States. This objective can be facilitated by the development and use of geothermal energy in the country.

The economic viability of geothermal energy in Cameroon is dependent on a variety of factors, including resource availability, infrastructure development costs, and regulatory frameworks.

The success of geothermal projects heavily depends on the presence of supportive policies and regulatory environments [1]. Despite some governmental policies and programs to promote renewable energy sources, including geothermal energy, there is a need for a more comprehensive and coordinated regulatory framework to support the development of geothermal energy in Cameroon. This includes policies related to geothermal exploration and development, power purchase agreements, and feed-in tariffs, among others.

Implementing a regulatory framework that supports the development of geothermal projects is crucial for Cameroon to achieve its renewable energy goals. Such a framework would provide a conductive environment for investment in geothermal projects, streamline the licensing process, and ensure that projects are developed in compliance with environmental and safety regulations. With the implantation of supportive policies and regulatory frameworks, Cameroon could harness its geothermal resources to provide affordable, reliable, and sustainable energy to its citizens.

1.3. Environmental and Social Considerations of Geothermal Energy in Cameroon. Geothermal energy exploration and production may have potential environmental impacts, like the emission of GHG to the atmosphere, mainly carbon dioxide and hydrogen sulfide. Another environmental impact could be the initial requirement of water at the start of the operation of large flash power plants, particularly in areas with water scarcity, as well as the noise pollution that could affect wildlife. [52–55]

To mitigate and minimize those potential environmental impacts of geothermal power projects, best practices have been implemented in all the world such as the use of advanced technologies to minimize air pollution, the use of closed-loop cooling system, and the use of turbine and geothermal well silencers [52–55] to reduce noise to acceptable levels to not disturb wildlife.

The development of geothermal power projects can also have social impacts on local communities, such as the use or acquisition of some lands that can disrupt their livelihoods. This can be minimized and compensated with the creation of local unskilled jobs for the communities, besides the proper payment of the partially affected lands that can be rented or bought at commercial prices.

In any case, some practices and measures adopted in the development of geothermal projects worldwide [52–55] include the following:

(i) Work with local community and authorities to ensure that land acquisition or rent is done in a transparent and participatory manner and that affected communities are properly compensated

(ii) Prioritize local hiring and procurement to ensure that the local economy benefits from geothermal energy development

(iii) Work with local communities and authorities to identify and protect cultural heritage sites and traditional practices

(iv) Implement health and safety measures to minimize risks to local communities, and provide training and education to ensure that communities are aware of potential risks and how to mitigate them

1.4. Prospects for Geothermal Energy Development in Cameroon. Geothermal energy is not currently a significant source of energy in Cameroon, as the country does not have any operating geothermal power plants. However, the high potential for geothermal energy development in Cameroon is expected to start to be significantly harnessed in the next coming years. With increasing demand for energy and heat and growing concern over the environmental impact of traditional energy sources, geothermal energy is a relevant part of the solution to the needs of Cameroon.

The NDS30 emphasizes the importance of sustainable energy development in Cameroon long-term development strategy. The geothermal energy development in Cameroon would obviously create job opportunities, reduce the country's dependence on fossil fuels, and contribute to a more sustainable energy mix.

In the short term, it would be very important to complete the process of data collection and exploration to better understand the geothermal potential in Cameroon. This will require significant investments in geothermal exploration, including drilling and geophysical surveys. By identifying suitable locations for geothermal power plants, Cameroon can create a foundation for the development of geothermal projects in the medium and long-term perspectives. Short-term perspectives may also include opportunities to develop small-scale geothermal projects that can provide power to remote communities and help reduce dependence on fossil fuels. These projects can be implemented through partnerships with local communities and the support of international organizations.

In the medium term, it would be important to establish a favorable policy and regulatory framework environments for geothermal energy development in Cameroon. It may also include the development of larger-scale geothermal power projects to supply electricity to the national grid, to strengthening of institutions and capacities. This would requires significant development of appropriate infrastructure, such as transmission lines and power plants. This will also involve partnerships with the private sector, local communities, and international organizations to support the development of sustainable geothermal energy systems in Cameroon.

In the long term, the project can focus on the expansion and scaling up of geothermal energy development, which will require continued investment in research and development, infrastructure, and capacity building. Cameroon could also consider partnering with other countries like Kenya or international organizations to access technical and financial support for geothermal development over several decades. Geothermal energy could significant reduce the costs of producing ammonia. This could help to increase export to neighboring countries in the ECOAS and ECCAS. The utilization of ammonia could support the ambition of the country of being a leading country in the ECOWAS and ECCAS market by increasing its competitiveness, energy security, environmental sustainability, and economic diversification.

2. Conclusion and Recommendations

This review has provided an overview of the geothermal energy resources, exploration, and development activities in Cameroon, as well as the potential environmental and social impacts of geothermal energy projects. The key findings and insights from this review indicate that while geothermal energy in Cameroon is still in its early stages of exploration and development, the country has significant potential for geothermal energy utilization, both for electricity generation and direct use. However, there are several challenges that need more comprehensive exploration and more supportive regulatory framework that will encourage private investments in the sector.

To promote the development of geothermal energy in Cameroon, it is recommended that policy makers and investors take steps to do the following:

(i) Conduct thorough geological surveys and exploration in order to identify potential geothermal resources

(ii) Develop policies and regulatory frameworks to support geothermal energy development, including incentives for investment and streamlined permitting processes

(iii) Build local capacity and expertise in geothermal energy, including training programs for workers and support for research and development

(iv) Establish partnerships between government, private sector, and local communities to ensure sustainable and inclusive development of geothermal energy

(v) Implement effective risk mitigation strategies, including technical, financial, and environmental measures

(vi) Prioritize direct-use applications of geothermal energy, such as district heating and cooling, to maximize its economic and social benefits

(vii) Encourage international cooperation and knowledge sharing to leverage best practices and technologies for geothermal energy development

These recommendations can serve as a starting point for the development of geothermal energy in Cameroon and other countries.

Data Availability

The data supporting the conclusions of this article were derived from published literature.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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