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Long-term deep geothermal energy reservoir beneath East Africa: Insights from seismic tomography

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HIGHLIGHTS

- A seismic tomography model is used to identify a sustainable source of geothermal energy beneath East Africa.
- The identified lithospheric heat reservoir extends 4000 km across the East African Rift System.
- For exploration purposes, the geolocations of areas with the highest temperature potential are provided.
- The economic and financial implications for the development of geothermal energy in East Africa are discussed.

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ABSTRACT

We identify a long-term geothermal energy source in East Africa that is derived from a seismic tomography model that was built using a combination of a new dataset from a seismic network installed in the Indian Ocean and data from the International Federation of Digital Seismograph Networks. A heat reservoir extending laterally for about 4000 km within the lithosphere beneath East Africa is identified as a long-lived geothermal energy source that can last for millions of years. The temperature assessment reveals that the reservoir has excess temperatures ranging from ~100 °C–146 °C relative to the surrounding ambient mantle at a depth of 50 km. The heat flow at the base of the Earth's crust is an indicator of heat transfer to the Earth's surface. For exploration purposes, the geolocation of target points with the highest subsurface temperature potential is provided. The economic and financial implications of the identified large heat reservoir for the development of geothermal energy in East Africa are discussed.

1. Introduction

Renewable energy sources are crucial for mitigating climate change by replacing fossil fuels, reducing greenhouse gas emissions, and promoting a sustainable energy future. Geothermal energy is expected to become a significant part of total renewable energy production in the coming years. A recent International Energy Agency (IEA) report estimates that geothermal energy could meet up to 15 % of global electricity demand growth by 2050, given current technology breakthroughs and associated cost reductions [1]. Because geothermal energy is derived from the Earth's interior, where heat is released through continuous and renewable processes, geothermal power plants can operate at maximum capacity throughout the day and year. They provide sustainable, clean, and safe electricity generation, heat/cooling production and storage. For example, Geothermal energy derived from volcanic hotspots has been well developed in Iceland [2] and represents 29 % of the total electricity generated in the country. In contrast, geothermal development in East Africa has remained limited despite its apparent potential. The International Geothermal Association (IGA) has estimated that its geothermal energy potential is ~20,000 megawatts (MWe) [3]. Currently, there are few geothermal plants in the region, mainly in Kenya and Ethiopia, where the combined geothermal energy capacity is only ~137 MWe. Rapid population growth and urbanization in East Africa are significantly increasing the energy demand, both for direct consumption (households, transport) and for agricultural and industrial use, putting pressure on energy production and resources. Geothermal energy could meet all of East Africa's growing electricity and heat needs by 2050, according to policy scenarios discussed in [1]. Therefore, there

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is a need for robust methods to identify economically viable geothermal prospects in the region. Understanding the structure of the Earth beneath East Africa is crucial for this purpose.

The dynamics of the Earth's interior are driven by mantle convection, which involves the downwelling of cold material, such as slabs, and the upwelling of hot material, such as plumes [4–6]. This process ultimately releases heat from the Earth's system. Moreover, the heat produced by radioactive elements in igneous rocks, as well as stratigraphic thermal conductivity [7], or by magma in areas with active volcanoes, plays an essential role in generating geothermal resources. The steady geothermal field occurs mainly in the lithosphere, where seismic tomography imaging has revealed low-velocity anomalies [5,6,8]. Several of these anomalies are associated with mantle upwelling, known as mantle plumes, which have a lifespan of several million years [9]. The identified geothermal sites in East Africa are located within high-temperature (>100 °C) hydrothermal systems associated with rift-related volcanic and magmatic activity. In this context, the values of the geothermal gradient in East Africa vary from <20 °C/km to >200 °C/km. The highest values range from 103 °C to 298 °C/km, and coincide with young Quaternary volcanics associated with the active stage of East African rifting [3]. This elevated geothermal gradient at the Earth's surface may arise from radioactive decay within rocks, mantle convection, mantle upwelling (plumes), and magma supplied by volcanic systems—all continuous heat sources from the Earth's interior. However, thermal anomalies are unevenly distributed within the Earth's interior. Hotspots, plate tectonic boundaries (such as mid-ocean ridges and subduction zones), and continental rifts serve as the primary pathways for Earth's heat release.

Moreover, seismic tomography has revealed two extensive Large Low-Shear-Velocity Provinces (LLSVPs) in the Earth's mantle beneath South Africa and the Central Pacific [5,6]. These provinces are anchored at the core–mantle boundary, where temperatures reach approximately 3000 K. Hot material from these LLSVPs travels through the mantle, undergoing partial melting at the base of the lithosphere to create magma that fuels surface volcanoes. This geothermal heat presents an opportunity for electricity generation and direct use. Given the significance of geothermal energy, a growing body of literature focuses on identifying geothermal energy prospects in Africa using diverse methodologies, including geophysical, geochemical, and geological approaches. For instance, geochemical methods analyze the chemical composition of thermal fluids (e.g., hot springs) to determine the temperature and characteristics of the geothermal reservoir. Geological methods investigate lithology, volcanic history, structural controls, and hydrologic regimes of potential geothermal fields. Both of these methods were employed by [10] to estimate geothermal resources in three East African Rift System (EARS) countries: Ethiopia, Kenya, and Tanzania. Nevertheless, both geochemical and geological methods of geothermal exploration have limitations that prevent the proper location of geothermal sources [10]. These limitations include reliance on surface and subsurface sampling that may not be representative, potential for sample contamination, difficulty of interpreting complex fluid mixtures, and limited depth penetration. In the literature relying on geophysical methods, one strand uses Geographic Information Systems (GIS) to integrate geological thematic layers (rock units and faults), geophysical layers (heat flow derived from aeromagnetic data and seismicity), and geothermal layers (hot springs and volcanoes) over the African continent and use them to identify zones of high geothermal potential (see [11] and references therein). The other strand uses magnetic (defractal, spectral) methods and magnetic data to estimate surface heat production and thermal conductivity of the African bulk crust (see [12] and references therein). These geophysical methods have notable limitations, including depth resolution and subsurface variability. However, an alternative geophysical approach to geothermal exploration is travel time tomography [13], which is also limited in depth resolution.

To address the gap in depth resolution of geothermal reservoirs revealed by different methods used so far in the literature, this study aims to use a high-resolution seismic tomography model based on full-waveform inversion to locate deep potential reservoirs extending from the base of the Earth's crust down to the core–mantle boundary. Detailed images of thermal reservoirs are essential to assess long-term geothermal projects and could reduce the risk of investing in small-scale reservoirs associated with expensive drilling programs [14]. To our knowledge, this study is the first to use the full-waveform inversion model to highlight large-scale hot material extending from the core–mantle boundary to the base of the Earth's crust and to assess large-scale geothermal reservoirs (≥4000 km) subjacent to the crust in the East African region. This approach has several advantages over those currently used in the literature [10,12,13]. First, by geolocating potentially larger heat reservoirs within the lithosphere beneath East Africa, we provide crucial information for the subsurface exploration phase. This allows for the optimal location of geothermal plants and maximizes the likelihood of developing sustainable geothermal reservoirs. Second, identifying heat reservoirs connected to the core–mantle boundary guarantees a long-term reservoir that can be supplied for millions of years. This opens the door to the development of enhanced geothermal systems (EGS) in East Africa, especially in areas where the rock is hot but has no natural permeability or fluids. The rest of the paper is organized as follows. Section 2 describes the relationship between seismic wave velocity and temperature, as well as the methodology for converting shear wave velocity into temperature. Section 3 discusses the results. Section 4 analyzes the economic implications for geothermal development in East Africa, while Section 5 concludes with institutional and financial recommendations.

2. Methods

Temperature plays an important role in the dynamics of the lithosphere and mantle. However, it is difficult to measure at lithospheric and mantle depths. Although geothermobarometry can be used to construct the geothermal profile for the lithosphere and shallow mantle, it is effective only in regions where sufficient data are available for well-constrained temperature and pressure estimates [15–18]. Seismic waves are sensitive to various parameters, such as anelasticity, partial melt, pressure, and temperature [19]. For a given pressure level P, the seismic velocity V_d is defined as:

$$V_d(P,T,\omega) = V_d(P,T,\infty) \times \left[1 - \frac{Q_d^{-1}(P,T,\omega)}{2\tan(\pi\lambda/2)}\right], \tag{1}$$

with $d \in \{\alpha, \beta\}$. α and β represent the P-wave and S-wave velocity, respectively. T is the temperature, ω the frequency, and $V_d(P,T,\infty)$ is the high-frequency velocity of the seismic wave that can be assessed using the compositions of xenoliths and the single crystal elastic parameters from ultrasonic measurements. $Q_d(P,T,\omega)$ is the attenuation as defined in [18]. λ is a dimensionless parameter that is assumed to be small for seismic waves ($0 < \lambda < 1$). For a given temperature gradient, we can evaluate the heat flux, which is defined by [20]:

$$Q = k\frac{\partial T}{\partial z}. \tag{2}$$

Where k is the thermal conductivity and z is the direction in which the temperature varies. Heat is brought into the lithosphere by a plume that rises from the asthenosphere or deep mantle at the speed of ~10 cm/yr [21]. The seismic resolution of mantle plumes has improved significantly in recent decades due to an increase in seismological data from both continental and oceanic regions, which has enabled the development of higher resolution tomographic models. The RHUM-RUM experiment, which deployed Ocean Bottom Seismometers in the Indian Ocean in 2012, has been instrumental in improving the resolution of seismic shear wave structures from East Africa to the western part of the ocean in recent regional tomographic models [8,22–24].

We infer the temperature of the lithosphere and asthenosphere beneath East Africa, around the hotspot and surrounding areas (Fig. 1),

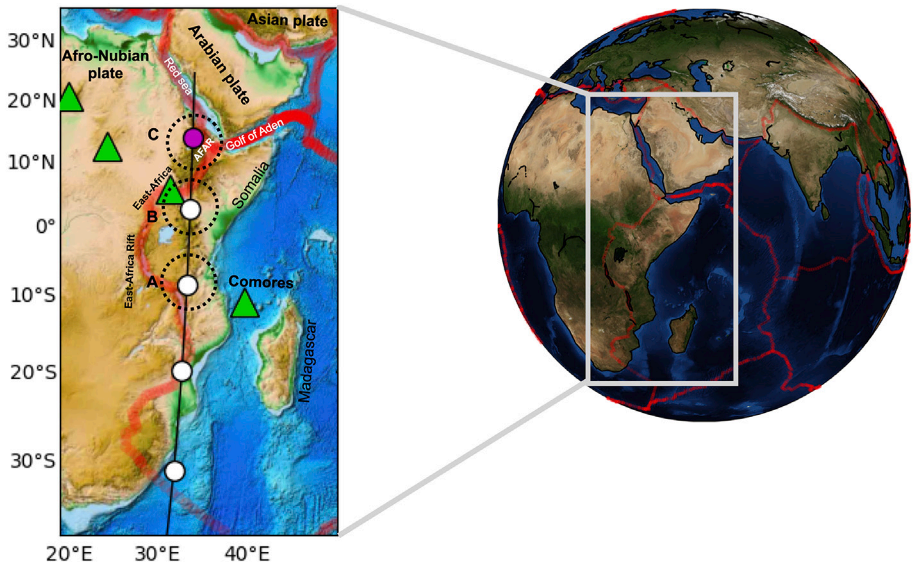

Fig. 1. Geological map of East-Africa around the Afar. The global map shows the position of the target region on the globe. The target region is shown on the left, the triangle shows the Afar Lake in Eastern Africa.

by converting seismic shear velocity perturbations, $\delta \ln V_s$, into temperature, from a recent regional tomographic model, SEMINDO-WM3 [8]. This model was constructed using a well-constrained upper mantle model [24]. We define a scaling factor f that allows us to correct the velocity perturbation in the seismic tomographic model:

$$f = \delta \ln V_{Sinput} / \delta \ln V_{Soutput}. \tag{3}$$

f is set to approximately one from the resolution test (Fig. 7) performed in SEMINDO-WM3 [8]. The low shear velocity anomaly (i.e., $\delta \ln V_s < 0$) is associated with hot upwelling material. In contrast, the high-velocity anomaly (i.e., $\delta \ln V_s > 0$) corresponds to downwelling cold material. From the 2D cross-section along the East Africa hotspot, we set the positive shear velocity perturbation (i.e., $\delta \ln V_s > 0$) to zero to represent only the low-velocity anomaly and assess the temperature of the hot field. This approach allows optimal evaluation of the Earth's temperature derived from seismic shear wave velocity anomalies.

3. Results

The analysis of recent seismic data has identified heterogeneities in the Earth's structure in the Indian Ocean, around La Réunion, Madagascar, and East Africa. Although most attention has been focused on the La Réunion hotspot, we have investigated the tomographic model along the East Africa Rift, revealing a continuous seismic low-velocity anomaly originating at the core–mantle boundary (CMB, at 2800 km depth) and driven by thermal instabilities in the region (Fig. 2). The width of the anomaly is ∼1000 km, it is broad in the lower mantle since it originates from the South Africa Large Low-shear-Velocity Province (LLSVP). Temperature, pressure, and seismic velocity increase with depth. Low-velocity zones (e.g., mantle plumes) are interpreted as hot material in which seismic waves travel slower than average, while fast-velocity zones (e.g., cratons, subducted slabs) are interpreted as cold material in which seismic waves travel faster than average. We identify low-velocity zones as a sustainable geothermal source beneath East Africa. This makes the region one of the largest geothermal potentials in

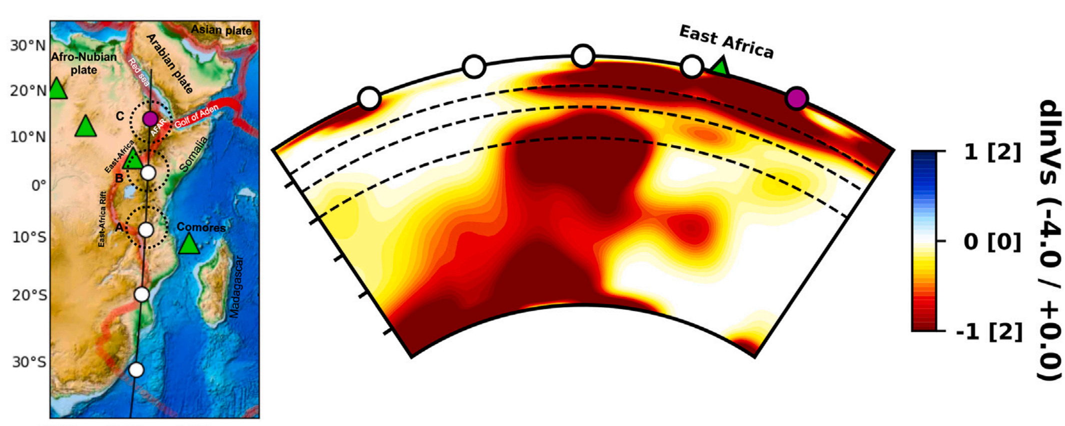

Fig. 2. A broad mantle plume rising from the core–mantle boundary toward the upper-mantle beneath East Africa, the position shear velocity anomalies (i.e., $d\ln V_S > 0$) were set to zero for this cross-section. The black dashed lines represent the 410 km, 610 km discontinuities, and 1000 km depth. The ±1 % and ±2 % shown on the color bar indicate that the perturbation in the lower mantle is ±1 %, while it is ±2 % in the upper mantle. The insert map on the left shows the region where the cross-section was performed. Points A, B, and C surrounded by dotted circles on the insert map, indicate a stronger underlying low-velocity anomaly.

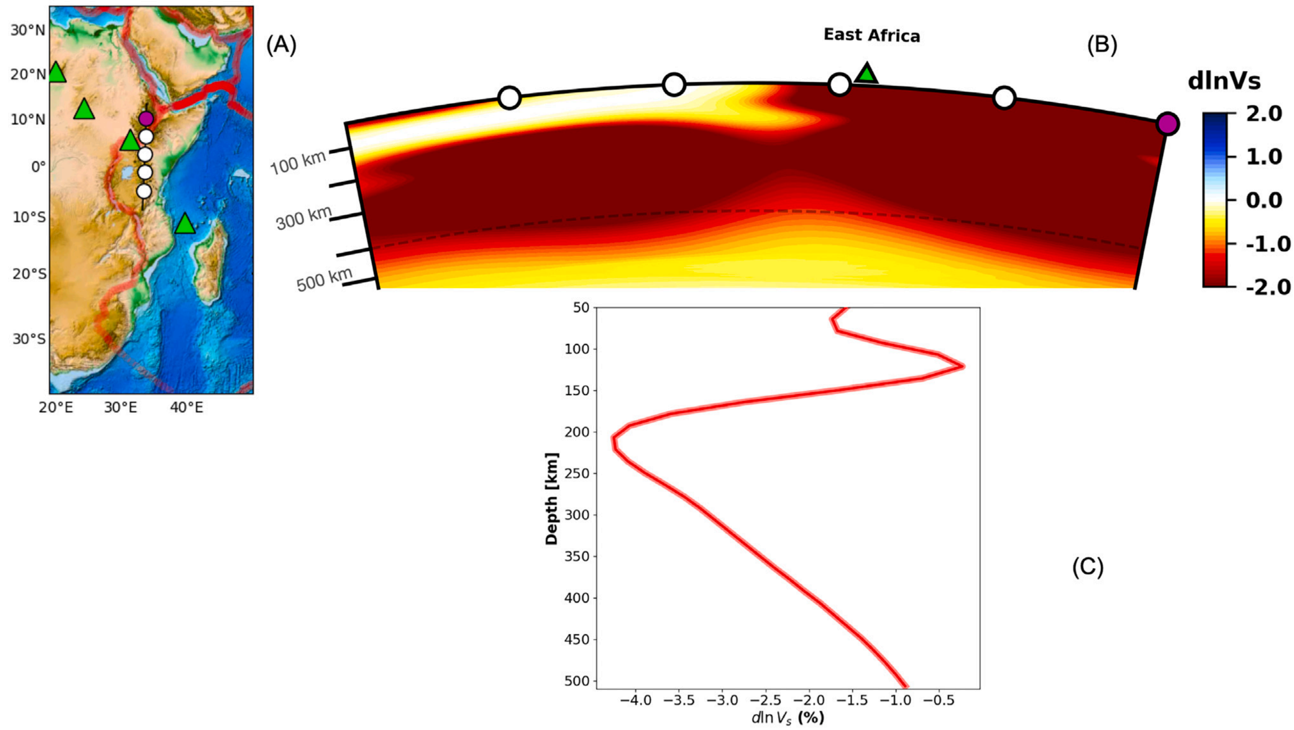

Fig. 3. (*Top*) Lithos-Asthenospheric low shear wave velocity anomaly reservoir beneath East-Africa. (*Bottom*) 1D shear wave velocity profile of low-velocity anomaly extracted along the cross-section and averaged at each depth. The profile only exhibits negative values (i.e., $d\ln V_s < 0$) since the extraction is performed only along the low-velocity anomaly. The positive values of the seismic shear wave velocity perturbation are set to zero. The geographical points on the cross-section are shown in the Table 1.

Table 1
Geographical points shown on the cross-section (from left to right in Fig. 3B) correspond to their representation in the inset map (from south to north) in Fig. 3A. These target points are the geographical localization of regions with potentially larger heat reservoirs within the lithosphere beneath East Africa. The points P3, P4, and P5 (on the right of the cross-section) are likely more reliable since they lie directly on the low-velocity structure as shown in Fig. 3.

Target Points	Latitude	Longitude
P1	−4.0593	36.0733
P2	0.4135	36.6445
P3	4.8862	37.2162
P4	9.3584	37.7957
P5	13.8297	38.3903

the world. Having established the origin of the heat source deep within the Earth, we will focus our investigation on the asthenosphere, where it is more likely to impact the temperature gradient at the Earth's surface.

The concept of mantle potential temperature is critical in evaluating the temperature difference, ΔT_p, between the ambient mantle and the hotter body (i.e., the plume head). It represents the hypothetical temperature at which the mantle would arrive at the Earth's surface if it endured compression without melting on its way to the surface. The ambient temperature (potential) of the Earth's mantle is $T_p = 1380$ °C [25,26], which corresponds to the reference adiabat at the surface of ∼13,770 °C (1650 K). The recent regional tomographic model [8] is potentially more accurate in assessing recent temperature as it provides a current snapshot of the Earth's mantle beneath the target region. We set all positive values of the seismic shear wave velocity perturbation to zero along the cross section to more accurately assess the potential temperature anomaly beneath East Africa (Fig. 3). Only the low shear velocity anomaly is converted into the temperature. The composition of the mantle is assumed to be based on the depleted MORB mantle (DMM) [27] as shown in Fig. 4.

The plume rises from the core–mantle boundary, ponds in the lithosphere, and forms the lithosphere's heat reservoir (Fig. 2). As the plume ascends toward the surface, it loses heat (Fig. 5), and the potential temperature difference between the head of the plume and the ambient mantle, ΔT_p, decreases. It is estimated to be ∼125 °C in the lithosphere and ∼200 °C in the asthenosphere, we use $d\ln V_s = -3$ % for the evaluation of ΔT_p (Fig. 5). This result classifies the East-African plume as hot, with an excess asthenospheric temperature greater than 155°C—a value recently reported by [21] when categorizing hot ($\Delta T_p \geq 155$ °C) and cold ($\Delta T_p \leq 36$ °C) plumes. The heat flux evaluation (Fig. 6) emphasizes heat transport toward the Earth's surface. We will now discuss the economic implications of exploiting these untapped geothermal resources.

4. Economic implications

In the previous sections, we presented a sustainable geothermal energy source beneath East Africa derived from a recent regional tomographic model [8]. The geothermal energy potential of this region has been documented extensively in the existing literature with the International Geothermal Association (IGA) and the International Renewable Energy Agency (IRENA) [29] estimating it to exceed 20 gigawatts of power. Olusola et al. [30] argue that the available geothermal energy potential in the East African Rift System (EARS) can sufficiently meet the energy demand for the year 2030 and that the addition of a pumped storage energy system is required to meet the energy demand by 2040 and to achieve the Sustainable Development Goal of net zero energy. However, geothermal resources remain a largely untapped potential as shown in Fig. 8. Most electricity generation in East African countries comes from hydropower and fossil fuels, with the exception of Kenya, for which geothermal accounts for 47 % of electricity

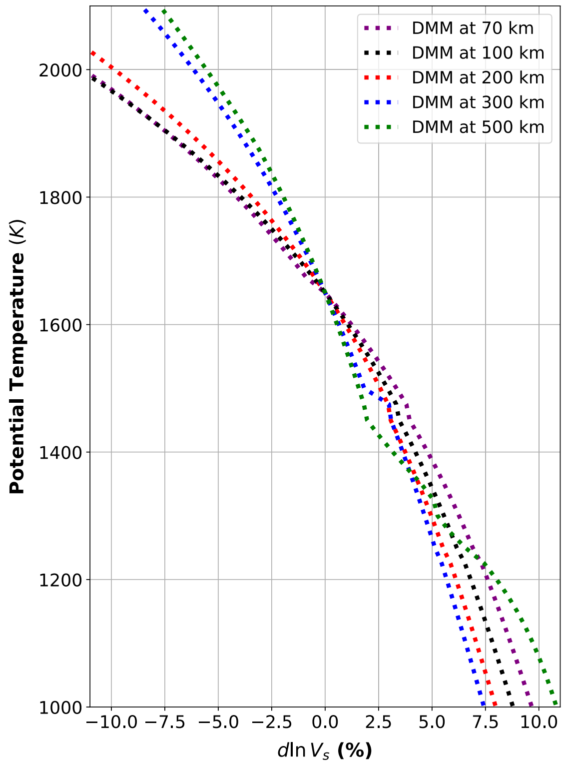

Fig. 4. Shear wave velocity perturbation (in percentage) as a function of temperature (in Kelvin) at different depths. The relationship between shear wave velocity anomaly and potential temperature is determined using the DMM [27].

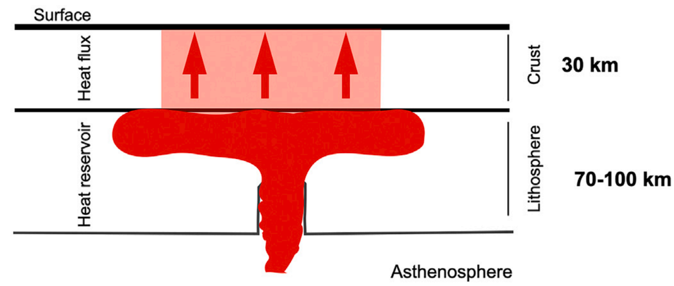

Fig. 6. Sketch illustrating the mantle's contribution to the lithosphere's heat reservoir and how the heat is radiated toward the Earth's surface. The radiated heat can be used for geothermal energy development. The generalized lower crustal rocks' thermal conductivity is ~2.6 W·m^{-1} K^{-1} [28]. The heat flux, Q is estimated to be ~40 mW/m^2 beneath East-Africa.

generation. The other country with installed geothermal capacity is Ethiopia (7.3 MW), which is negligible as 97 % of the country's electricity comes from hydropower. Amid hydropower tensions on the Nile, climate risks (droughts, floods), and geopolitical tensions affecting the production and distribution of fossil fuels, there is a need for rapid expansion of clean energy in East Africa, and geothermal energy can be the answer to this challenge. In fact, Idroes et al. [31] show that geothermal energy has a positive long-term impact on sustainable economic growth and greenhouse gas reduction by applying time series econometrics to a panel of developing and developed countries from 2000 to 2019.

Recent estimates of the capacity factor (CF), which measures how much electricity a plant produces relative to how much it can produce at peak capacity, show that geothermal plants can achieve an average CF of more than 80 %, which is higher than the CF of other renewable sources (hydro, solar, wind) except nuclear [32]. Therefore, geothermal plants can enhance energy security and grid stability to ensure reduced risk in electricity supply. Moreover, between 2021 and 2022, the global average levelized cost of electricity (LCOE) of newly commissioned geothermal projects fell by 22 % to USD$ 0.056 kWh according to IRENA [33]. In the context of these reduced costs, we discuss the economic and financial barriers that have prevented geothermal expansion in East Africa and some potential solutions. One of the main barriers to geothermal development is the high early-stage financial risk associated with years of geothermal energy exploration and drilling. The slow pace of geothermal energy development in EARS is attributed to the high initial capital required to drill wells, which can cost more than

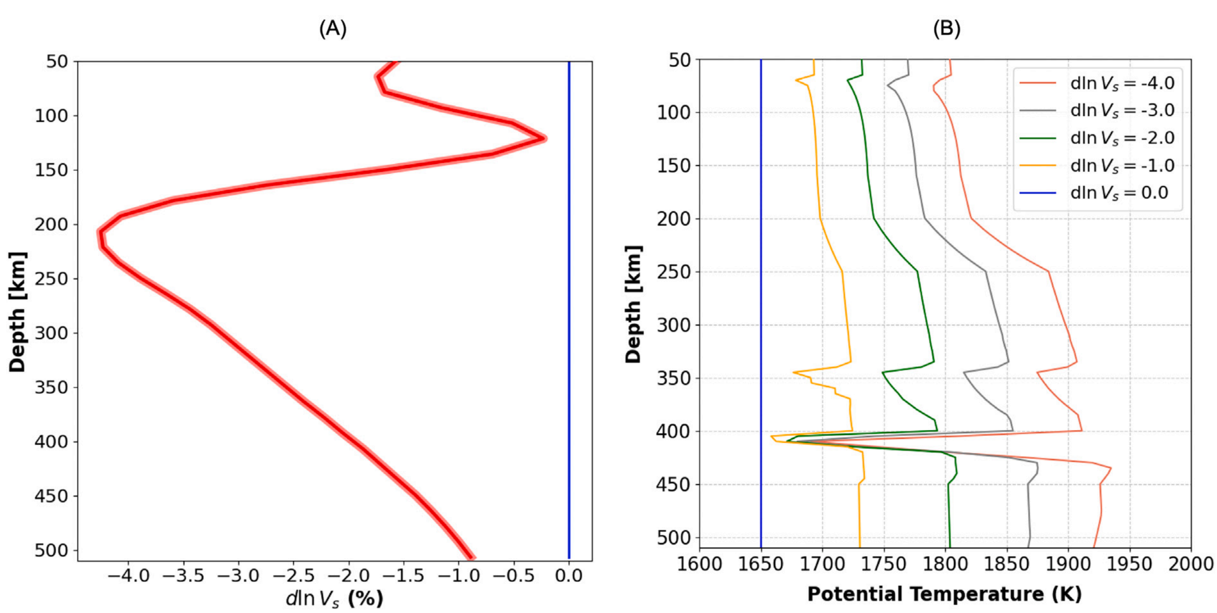

Fig. 5. Conversion of seismic low-shear-velocity perturbation derived from seismic tomography model, SEMINDO-WM3 [8], into 1D temperature profile as function of depth. Each profile corresponds to a particular seismic low-velocity perturbation. Zero perturbation (i.e., d$\ln V_s$ = 0) corresponds to referent temperature, 1650 K (in blue on the graph). Each color corresponds to a particular shear wave velocity perturbation.

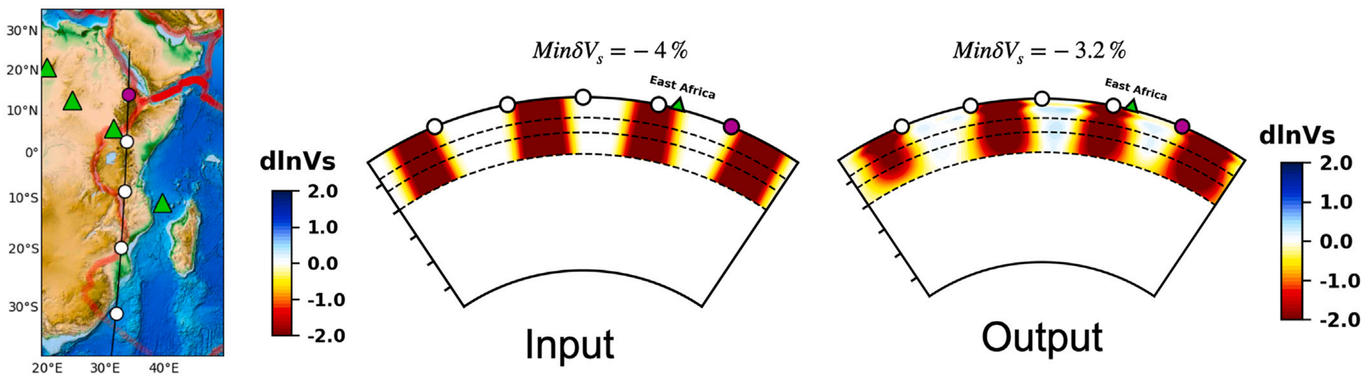

Fig. 7. Resolution test performed in tomographic model SEMINDO-WM3 [8]. The cross-section is the same as that in Fig. 2. We chose four input synthetic thermal plumes (*left*) along the shear wave low-velocity structure shown in Fig. 2, with a width of ~600 km and applied the resolution matrix to retrieve the output (*right*).

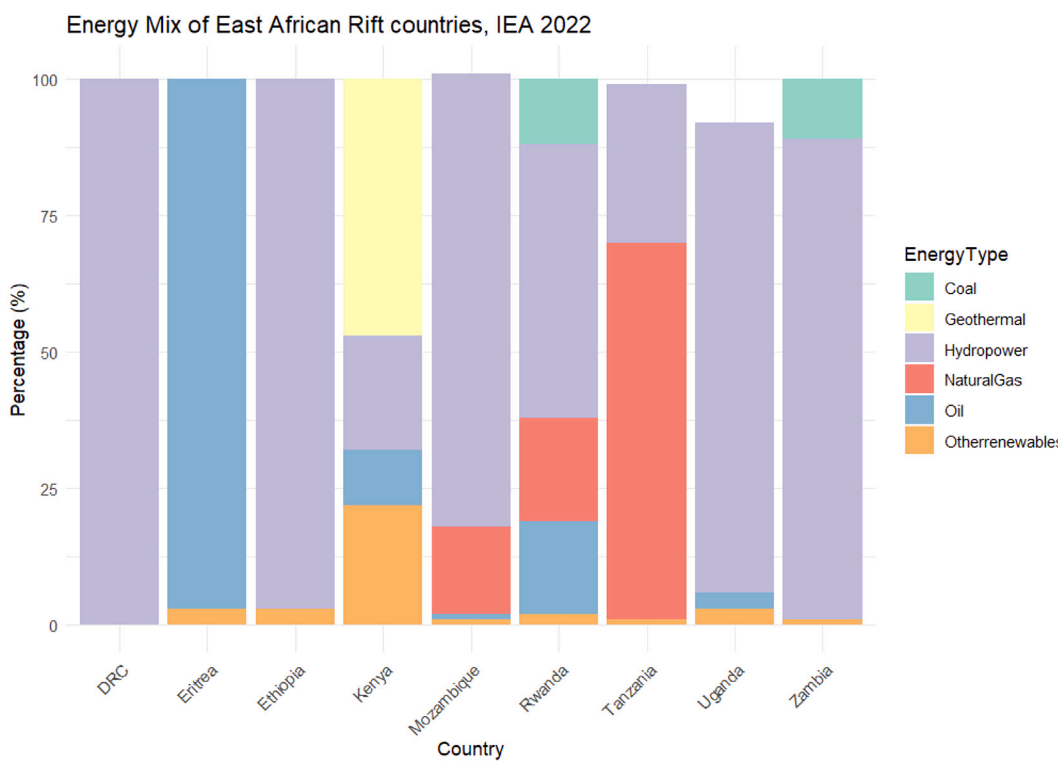

Fig. 8. Energy Mix in East African Rift Countries. DRC stands for the Democratic Republic of Congo. Other renewables include solar, wind, and biofuels.

US $5 million for a single test well [34], with no guarantee of success. Our deep seismic imaging approach offers a practical solution to this concern since we can geolocate positions with long-term high-heat reservoirs beneath the Earth's crust (Fig. 3), thus increasing the likelihood of successful explorations. This can be combined with the latest developments in geothermal power plant technology to further reduce the financial risk and optimize the economic benefits.

There are four main types of geothermal power plant technologies depending on the type and the temperature of the fluid used: dry steam, flash steam, binary cycle or organic Rankine cycle (ORC) and enhanced geothermal systems (EGS) [35]. EGS uses geothermal resources from deeper reservoirs where there is no hydrothermal fluid in the underlying rock structure so that none of the other technologies can be implemented. As shown in Table 2, flash steam and binary cycle plants are the two technologies in use for installed geothermal capacity in East Africa. Another major advantage of geothermal energy over other renewable sources is its multiple applications including electricity generation and direct use such as space heating/cooling, domestic hot water, greenhouse heating, agricultural drying, aquaculture, industrial processes (fermentation, pasteurization), and recovery of chemicals (hydrogen, carbon dioxide, minerals) [36]. The direct use of geothermal energy has several socioeconomic and environmental benefits, including employment, poverty reduction, food security, reduction of greenhouse gas emissions, and reduction of deforestation. To date, Kenya is the only country in the region with direct use of geothermal energy, mainly in the agricultural, aquaculture and tourism sectors. To accelerate the direct use of geothermal energy in the region, the African Union's Geothermal Risk Mitigation Facility (GRMF) launched the GRMF HEAT program in 2022. It provides grants to support public and private sector projects for the direct use of geothermal energy and has so far funded five projects in Kenya (2), Rwanda (1) and Tanzania (2) [37].

Wellhead plants, which are smaller, modular power plants that generate electricity using steam from a single well, are an important part of the installed geothermal capacity in both Ethiopia and Kenya. Wellhead

Table 2
Installed geothermal capacity in East African rift countries.

Country	Capacity installed	Technology	Location	Number of active wells	Maximum well depth
Ethiopia	7.3 MW	Binary cycle	Aluto-Langano	4	2500 m
Kenya	35 MW	Binary cycle	Menengai	27	3000 m
Kenya	2.44 MW	Single flash	Eburru	6	2500 m
Kenya	720 MW	Binary/Single flash	Olkaria	59	3000 m
Kenya	3.2 MW	Binary/Back pressure	Oserian	3	2500 m

plants could be the solution to the massive exploitation of geothermal resources in the EARS countries, as they have been successfully implemented in both Ethiopia and Kenya and offer several economic, financial, and technical advantages. First, they allow developers to achieve a return on investment sooner than in conventional development schemes and eliminate the need for a large steam collection system, reducing costs and pressure drops in the piping system. Second, they can serve as an initial phase in the construction of larger geothermal projects, and they improve reliability because a problem at one wellhead facility does not affect the entire geothermal field. This proposal is consistent with the literature comparing the economics of a wellhead geothermal plant to a conventional plant, which finds that wellhead plants have higher net power production and are more profitable as measured by net present value (NPV) [38]. There are also recent developments in traditional geothermal plant technologies that further reduce installation and operating costs. The techno-economic analyses of these new technologies whether for electricity use, direct heat use, a cascade of uses, or for a combination of geothermal and solar, all show that high capital costs can be overcome and that geothermal plants are now more energy-efficient and economically profitable both in the short and the long term [39–45].

Finally, the tomographic model assessment reveals a large-scale deeper source of underground clean thermal energy beneath the EARS region. Therefore, EARS countries can take advantage of recent technological advances in deep geothermal research and enhanced geothermal systems (EGS) to develop their long-term geothermal energy sectors. In China, for example, the potential of deep geothermal resources has been documented with proposed applications including geothermal power generation combined with cooling/heating and carbon dioxide sequestration, industrial and agricultural use, and multi-mineral resources extraction [46]. Due to the technical challenges and associated exploration costs, there has been a debate in recent years about whether EGS is economically viable due to the lack of economic assessment studies. Recently, the economic viability of EGS has been demonstrated through techno-economic analysis in a growing body of literature. Roland et al. [47] argue that current advances in drilling technology will make EGS costs competitive with U.S. electricity market prices by 2027 with a plant capital cost of US $4,500 kWh and an LCOE of US$80 MWh. The technical and economic viability of horizontal well EGS is discussed by [48–51] and their techno-economic evaluation indeed concludes that it is viable given the appropriate choice of heat extraction technology. [52] proposes a new type of vertical well EGS that can provide cheap electricity (with low LCOE) while significantly reducing greenhouse gas emissions. Collaboration between EARS governments and industrialized countries with more advanced geothermal sectors can accelerate the implementation of these technologies in the region through capacity building of public institutions and the sharing of geothermal knowledge and skills.

5. Conclusions & recommendations

This study identifies a large-scale thermal anomaly (plume-like) beneath the crust in East Africa. The anomaly extends over approximately 4000 km and is sourced by hot material from the deep mantle. Such a large-scale thermal anomaly-like plume is likely to generate intense magmatism associated with heat and topographic uplift, ultimately leading to rifting, as observed today [53,54]. The excess temperatures range from ∼100°C to 146°C at ∼50 km depth, evaluated using the DMM [27], and potential temperature corresponding to the shear wave low-velocity anomaly ($\delta \ln V_s$) ranges from −3 % to −4 % (Fig. 5). The heat flux at the bottom of the crust is ∼40 mW/m^2 (Fig. 6). It can contribute significantly to thermal processes, especially when combined with other factors such as mantle convection or magma intrusion. Although this study did not fully investigate the thermal anomalies within the crust beneath East Africa due to the resolution limitations of the tomographic model, we provide targeted geographical points (Table 1), located above mantle plume-like hot material, where subsurface imaging can be performed for future explorations of geothermal reservoirs.

Given these facts, we recommend that geothermal technology research be associated with pilot tests (wellhead plants) and that large-scale economic exploitation of deep geothermal resources be coordinated and planned in cooperation with all EARS countries. The financing of the geothermal expansion plan in the EARS region is now discussed. As highlighted in [29], the installed geothermal capacity in the region has been mainly financed by the public sector directly or indirectly through public–private partnership (PPP) initiatives. The EARS region needs alternative financing options in the context of economic slowdown and limited public financial resources. At COP29, an agreement was reached to triple climate finance for developing countries, committing to provide $300 billion per year by 2035, to reach a total of $1.3 trillion per year in climate finance from public and private sources. EARS countries can create a regional geothermal development plan to access these funds. An alternative source of financing is China's Belt and Road Initiative (BRI). Through the BRI, China has invested over $700 billion in infrastructure projects (ports, railways, roads, and power plants) in Africa between 2013 and 2023, with East Africa being the main recipient of these investments. One example of the green finance component of the BRI in the region is the Karuma hydropower plant in Uganda. In the geothermal sector, the BRI committed $244.8 million in foreign investment loans to construct the 244 MW Sorik Marapi geothermal power plant in Indonesia [55]. The green financing framework and governance structure of the Sorik Marapi project are excellent templates for EARS countries to follow in their geothermal development journey. To achieve this, they will need to invest in developing local expertise in geothermal science, engineering, and infrastructure project management, since low governance capacity has been identified as a key factor hindering the development of renewable energy in East African countries participating in the BRI [56].

CRediT authorship contribution statement

M.D. Wamba: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karim Nchare**: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Software

Python: https://www.python.org.
R: https://www.r-project.org/.
Operating systems: Windows, Mac, Linux.
Cost: Free.

Data availability

Data will be made available upon request.

References

[1] IEA. The future of geothermal energy; 2024 https://www.iea.org/reports/the-future-of-geothermal-energy.
[2] Ragnarsson Á. Geothermal development in Iceland 2010-2014. Fish Farming 2015;4(9).
[3] Jones DJR, A summary of the East Africa rift temperature and heat flow model (earth): 2020, British Geological Survey.
[4] Wamba M-D, Simons FJ, Irving JCE. Data-space cross-validation of mantle structure in global tomographic models underneath the Pacific Ocean. Geophys J Int 2025:ggaf044.
[5] French SW, Romanowicz B. Broad plumes rooted at the base of the earth's mantle beneath major hotspots. Nature 2015;525(7567):95–99.
[6] Lei W, Ruan Y, Bozdağ E, Peter D, Lefebvre M, Komatitsch D, et al. Global adjoint tomography model GLAD-M25. Geophys J Int 2020;223(1):1–21.
[7] Cui Y, Zhu C, Qiu N, Tang B, Guo S, Lu Z. The heat source origin of geothermal resources in Xiong'an New Area, North China, in view of the influence of igneous rocks. Front Earth Sci 2022;10:818129.
[8] Wamba M-D, Montagner J-P, Romanowicz B. Imaging deep-mantle plumbing beneath La Réunion and Comores hot spots: vertical plume conduits and horizontal ponding zones. Sci Adv 2023;9(4):eade3723.
[9] Koptev A, Cloetingh S, Ehlers TA. Longevity of small-scale ('baby') plumes and their role in lithospheric break-up. Geophys J Int 2021;227(1):439–71.
[10] Pasqua C, Chiozzi P, Verdoya M. Geothermal play types along the East Africa rift system: examples from Ethiopia, Kenya and Tanzania. Energies 2023;16(4):1656.
[11] Elbarbary S, Abdel Zaher M, Saibi H, Fowler A-R, Saibi K. Geothermal renewable energy prospects of the African continent using GIS. Geotherm Energy 2022;10(1):8.
[12] Elbarbary S, Zaher MA, Saibi H, Fowler A-R, Ravat D, Marzouk H. Thermal structure of the African continent based on magnetic data: future geothermal renewable energy explorations in Africa. Renew Sustain Energy Rev 2022;158:112088.
[13] Civiero C, Goes S, Hammond JOS, Fishwick S, Ahmed A, Ayele A, et al. Small-scale thermal upwellings under the northern East African rift from S travel time tomography. J Geophys Res: Solid Earth 2016;121(10):7395–408.
[14] Schmelzbach C, Greenhalgh S, Reiser F, Girard J-F, Bretaudeau F, Capar L, et al. Advanced seismic processing/imaging techniques and their potential for geothermal exploration. Interpretation 2016;4(4):SR1–18.
[15] O'Reilly SY, Griffin WL. 4-D lithosphere mapping: constructing stratigraphic sections of the lower crust and upper mantle in space and time. In: International Kimberlite Conference: Extended Abstracts, vol. 6. 1995. p. 407–09.
[16] O'Reilly SY, Griffin WL. 4-D lithosphere mapping: methodology and examples. Tectonophysics 1996;262(1–4)3–18.
[17] Sobolev SV, Zeyen H, Stoll G, Werling F, Altherr R, Fuchs K. Upper mantle temperatures from teleseismic tomography of French massif central including effects of composition, mineral reactions, anharmonicity, anelasticity and partial melt. Earth Planet Sci Lett 1996;139:147–63.
[18] Sobolev SV, Zeyen H, Granet M, Achauer U, Bauer C, Werling F, et al. Upper mantle temperatures and lithosphere-asthenosphere system beneath the French Massif Central constrained by seismic, gravity, petrologic and thermal observations. Tectonophysics 1997;275:143–64.
[19] Goes S, Govers R, Vacher P. Shallow mantle temperatures under Europe from P and S wave tomography. J Geophys Res: Solid Earth 2000;105(B5):11153–69.
[20] Jaupart C, Mareschal JC, Schubert G. Heat flow and thermal structure of the lithosphere. Treatise Geophys 2007;6:217–52.
[21] Bao X, Lithgow-Bertelloni CR, Jackson MG, Romanowicz B. On the relative temperatures of earth's volcanic hotspots and mid-ocean ridges. Science 2022;375(6576):57–61.
[22] Mazzullo A, Stutzmann E, Montagner J-P, Kiselev S, Maurya S, Barruol G, et al. Anisotropic tomography around La Réunion Island from Rayleigh waves. J Geophys Res: Solid Earth 2017;122(11):9132–48.
[23] Tsekhmistrenko M, Sigloch K, Hosseini K, Barruol G. A tree of Indo-African mantle plumes imaged by seismic tomography. Nat Geosci 2021;14(8):612–19.
[24] Wamba M-D, Montagner J-P, Romanowicz B, Barruol G. Multi-mode waveform tomography of the Indian Ocean upper and mid-mantle around the Réunion hotspot. J Geophys Res: Solid Earth 2021;126(8) e2020JB021490.
[25] Courtier AM, Jackson MG, Lawrence JF, Wang Z, Lee C-TA, Halama R, et al. Correlation of seismic and petrologic thermometers suggests deep thermal anomalies beneath hotspots. Earth Planet Sci Lett 2007;264(1–2):308–16.
[26] Dalton CA, Langmuir CH, Gale A. Geophysical and geochemical evidence for deep temperature variations beneath mid-ocean ridges. Science 2014;344(6179):80–83.
[27] Workman RK, Hart SR. Major and trace element composition of the depleted MORB mantle (DMM). Earth Planet Sci Lett 2005;231:53–72.
[28] Chapman DS. Thermal gradients in the continental crust. Geol Soc Lond Spec Publ 1986;24(1):63–70.
[29] IRENA. Geothermal development in eastern Africa: recommendations for power and direct use; 2020.
[30] Bamisile O, Cai D, Adun H, Taiwo M, Li J, Hu Y, et al. Geothermal energy prospect for decarbonization, EWF nexus and energy poverty mitigation in East Africa; the role of hydrogen production. Energy Strategy Rev 2023;49:101157.
[31] Idroes GM, Hardi I, Hilal IS, Utami RT, Noviandy TR, Idroes R. Economic growth and environmental impact: assessing the role of geothermal energy in developing and developed countries. Innov And Green Devel 2024;3(3) 100144.
[32] Bolson N, Prieto P, Patzek T. Capacity factors for electrical power generation from renewable and nonrenewable sources. Proc Natl Acad Sci USA 2022;119(52):e2205429119.
[33] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2020. eBook Partnership; 2022.
[34] Kombe EY, Muguthu J. Geothermal energy development in East Africa: barriers and strategies. J Energy Res Rev 2018;2(1):1–6.
[35] Benti NE, Woldegiyorgis TA, Geffe CA, Gurmesa GS, Chaka MD, Mekonnen YS. Overview of geothermal resources utilization in Ethiopia: potentials, opportunities, and challenges. Sci Afr 2023;19:e01562.
[36] Sharmin T, Khan NR, Akram MS, Ehsan MM. A state-of-the-art review on geothermal energy extraction, utilization, and improvement strategies: conventional, hybridized, and enhanced geothermal systems. Int J Thermofluids 2023;18:100323.
[37] Mahamoud Abdi A, Murayama T, Nishikizawa S, Suwanteep K. Social acceptance and associated risks of geothermal energy development in East Africa: perspectives from geothermal energy developers. Clean Energy 2024;8(5):20–33.
[38] Geirdal CAC, Gudjonsdottir MS, Jensson P. Economic comparison of a well-head geothermal power plant and a traditional one. Geothermics 2015;53:1–13.
[39] Ayub M, Mitsos A, Ghasemi H. Thermo-economic analysis of a hybrid solar-binary geothermal power plant. Energy 2015;87:326–35.
[40] Rubio-Maya C, Martínez EP, Romero CE, Díaz VMA, Pacheco-Ibarra JJ. Techno-economic assessment for the integration into a multi-product plant based on cascade utilization of geothermal energy. Appl Therm Eng 2016;108:84–92.
[41] Ezekiel J, Vahrenkamp V, Hoteit HA, Finkbeiner T, Mai PM. Techno-economic assessment of large-scale sedimentary basin stored–CO2 geothermal power generation. Appl Energy 2024;376:124270.
[42] Hu T, Zhang J, Su L, Wang G, Yu W, Su H, et al. Performance optimization and techno-economic analysis of a novel geothermal system. Energy 2024;301:131715.
[43] Li T, Zhang Y, Li X, Yuan Y. Techno-economic comparison of organic fluid between single-and dual-flash for geothermal power generation enhancement. Renew Energy 2024;231:120917.
[44] Budisulistyo D, Krumdieck S. Thermodynamic and economic analysis for the pre-feasibility study of a binary geothermal power plant. Energy Convers Manag 2015;103:639–49.
[45] Wang L, Li H, Bu X. Thermo-economic investigation of binary flashing cycle for enhanced geothermal system. Geothermics 2021;89:101951.
[46] Ma Y. Deep geothermal resources in China: potential, distribution, exploitation, and utilization. Energy Geosci 2023;4(4) 100209.
[47] Horne R, Genter A, McClure M, Ellsworth W, Norbeck J, Schill E. Enhanced geothermal systems for clean firm energy generation. Nat Rev Clean Technol 2025:1–13.
[48] Xue Z, Ma H, Wei Y, Wu W, Sun Z, Chai M, et al. Integrated technological and economic feasibility comparisons of enhanced geothermal systems associated with carbon storage. Appl Energy 2024;359:122757.
[49] El-Sadi K, Gierke B, Howard E, Gradl C. Review of drilling performance in a horizontal EGS development. In: Proceedings, 49th Stanford workshop on geothermal reservoir engineering; 2024.
[50] Xie J, Wang J. Compatibility investigation and techno-economic performance optimization of whole geothermal power generation system. Appl Energy 2022;328:120165.
[51] Xiao D, Liu M, Li L, Cai X, Qin S, Gao R, et al. Model for economic evaluation of closed-loop geothermal systems based on net present value. Appl Therm Eng 2023;231:121008.
[52] Yuan Y, Xu T, Jiang Z, Feng B. Prospects of power generation from the deep fractured geothermal reservoir using a novel vertical well system in the Yangbajing geothermal field, China. Energy Rep 2021;7:4733–46.
[53] Corti G. Continental rift evolution: from rift initiation to incipient break-up in the main Ethiopian rift, East Africa. Earth Sci Rev 2009;96(1–2):1–53.
[54] Michon L, Famin V, Quidelleur X. Evolution of the east African rift system from trap-scale to plate-scale rifting. Earth Sci Rev 2022;231:104089.
[55] Goodman S, Zhang S, Malik AA, Parks BC, Hall J. Aiddata's geospatial global Chinese development finance dataset. Sci Data 2024;11(1):529.
[56] An Y, Tan X, Gu B, Zhu K, Shi L, Ding Z. An assessment of renewable energy development in belt and road initiative countries: an entropy and topsis approach. Energy Rep 2023;10:3545–60.