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EDITED BY
Solomon Giwa,
Olabisi Onabanjo University, Nigeria

REVIEWED BY
Godwin Norense Osarumwense Asemota,
University of Rwanda, Rwanda
Samson Aasa,
University of Ibadan, Nigeria

*CORRESPONDENCE
Degfie Teku,
degfie2023@gmail.com

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Geology in renewable energy development in Ethiopia: potentials, challenges, and future directions

Degfie Teku*

Department of Geology, Mekdela Amba University, Tulu Awuliya, Ethiopia

Ethiopia possesses vast geological resources that present significant opportunities for renewable energy development, particularly in geothermal, hydropower, and wind energy. This review explores the role of geology in harnessing these resources, evaluating geological conditions, resource availability, and the feasibility of scaling up renewable energy projects. Ethiopia's geothermal potential is largely attributed to its location within the tectonically active East African Rift System, which provides abundant geothermal anomalies. Similarly, the country's river systems, shaped by geological formations, offer extensive hydropower capacity, while its wind corridors, particularly in the Somali and Afar regions, hold promise for wind energy generation. Despite these opportunities, geological factors pose notable challenges to renewable energy development. Seismic activity, sedimentation, and site accessibility can complicate exploration and infrastructure development. Furthermore, gaps in geological data, limited investment, and inadequate policy frameworks hinder effective resource utilization. Addressing these challenges requires integrated geological surveys, enhanced research, and coordinated policy efforts. The review highlights key barriers, including technical constraints, financial limitations, and regulatory hurdles that impede the expansion of renewable energy projects. Successful case studies demonstrate that overcoming these obstacles necessitates strategic public-private partnerships, improved policy support, and advancements in geological research. The role of geology extends beyond resource identification to influencing the sustainability and efficiency of renewable energy projects, underscoring the importance of comprehensive geological assessments in decision-making processes. Future efforts should focus on improving geological research, expanding data availability, and implementing robust policies that support sustainable energy development. Strengthening public-private collaboration and investing in capacity-building initiatives will be essential in addressing technical and financial limitations. By leveraging its geological advantages, Ethiopia can advance its renewable energy agenda, enhance energy security, and contribute to economic growth. This review provides insights for policymakers, industry stakeholders, and researchers seeking to optimize Ethiopia's renewable energy potential in alignment with national development objectives. The findings emphasize the need for a holistic approach that integrates geology with technological and economic considerations to ensure the long-term sustainability of Ethiopia's renewable energy sector.

KEYWORDS

energy, Ethiopia, geology, geothermal, hydropower, renewable energy, sustainability, wind energy

1 Introduction

Renewable energy development has seen significant global momentum, driven by the urgent need to mitigate climate change, reduce dependency on fossil fuels, and enhance energy security (Gielen et al., 2019). Globally, the share of renewables in electricity generation has steadily increased, with solar and wind power leading the charge due to their rapidly decreasing costs and technological advancements. By 2022, renewables accounted for nearly 29.0% of global electricity generation, reflecting the growing investment in sustainable energy sources (Hassan et al., 2024). In particular, regions such as North America, Europe, and Asia have witnessed substantial growth in renewable energy capacities, driven by technological advancements, policy support, and international collaborations (International Renewable Energy Agency, 2022). Africa, with its abundant renewable energy resources particularly solar, wind, and hydro has immense potential for renewable energy development. The continent has seen a remarkable increase in renewable energy capacity, particularly in North and South Africa, where countries like Morocco and South Africa have implemented large-scale solar and wind projects (Al-Shetwi, 2022). These projects, such as Morocco's Noor Ouarzazate Solar Complex and South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), highlight the continent's potential to transition toward sustainable energy systems (Awuku et al., 2021). However, despite these strides, Africa still faces challenges in scaling up renewable energy, including infrastructural limitations, financing hurdles, and regulatory barriers. Addressing these challenges is critical to harnessing the continent's full potential and ensuring access to clean, affordable, and reliable energy for its growing population (Owusu-Manu et al., 2021). The push towards renewable energy in Africa is not only essential for environmental sustainability but also for economic development, as it presents opportunities for job creation, industrial growth, and improved energy access. Consequently, global and regional partnerships, investments, and policy frameworks are pivotal in accelerating the renewable energy transition across Africa (Amir and Khan, 2022).

Ethiopia, endowed with abundant renewable energy resources, including geothermal, hydroelectric, solar, and wind energy, stands as a prime example of a country with immense untapped potential. The country's geological landscape plays a pivotal role in shaping its renewable energy prospects, particularly in geothermal and hydroelectric power generation (Endaylalu and Arsano, 2023). Ethiopia is part of the East African Rift System (EARS), a tectonically active region characterized by significant geothermal anomalies, making it one of the most promising areas for geothermal energy development globally (Kebede, 2015). Ethiopia's burgeoning demand for energy, driven by rapid economic growth and a growing population, underscores the critical need for sustainable and reliable energy sources (Mohapatra, 2019). As the country seeks to diversify its energy portfolio, renewable energy has emerged as a central component of its energy strategy (Endaylalu and Arsano, 2023). Notably, Ethiopia possesses substantial renewable energy potential, particularly in geothermal, hydropower, wind, and solar energy (Rodrigues et al., 2022). These resources are crucial not only for meeting domestic energy needs but also for fostering economic development and reducing dependence on imported fossil fuels (Iwuji et al., 2016). The role of geology in renewable energy development is pivotal. Geological assessments provide essential data for the exploration and exploitation of renewable energy resources (Joel and Oguanobi, 2024). For geothermal energy, geological studies help identify heat sources and assess geothermal gradients, while hydropower projects benefit from understanding river systems and geological formations that impact water flow and dam stability (Tiruye et al., 2021). Similarly, geological surveys contribute to wind and solar energy projects by evaluating land suitability and identifying optimal locations for energy generation (Desalegn et al., 2022).

The geological factors influencing renewable energy development in Ethiopia extend beyond geothermal resources. The country's diverse topography, including highland plateaus, volcanic formations, and sedimentary basins, contributes to the availability of hydropower potential, while wind corridors, such as those in the Somali and Afar regions, present significant opportunities for wind energy generation (Tiruye et al., 2021). Moreover, the presence of crystalline basement rocks and sedimentary basins offers potential for critical mineral exploration, essential for renewable energy technologies, such as batteries and photovoltaic systems (Wolde-Ghiorgis, 2002). Despite these geological advantages, Ethiopia faces challenges in fully utilizing its renewable energy potential. These include limited exploration and resource assessment, inadequate infrastructure for energy transmission and distribution, and insufficient investment in technology and capacity-building (Tiruye et al., 2021). While previous studies have extensively examined the technological and economic aspects of renewable energy development in Ethiopia (Tesfaye et al., 2021; Kebede, 2015), they often overlook the critical geological factors that underpin resource availability and project feasibility. For instance, studies by Mulugeta et al. (2021) and Tiruye et al. (2021) primarily focus on infrastructural challenges and investment barriers without detailed consideration of how geological formations influence site selection and energy output. This gap in understanding limits the effectiveness of resource exploration, planning, and utilization. Moreover, while some research highlights Ethiopia's geothermal potential, such as the works by Asres (2021), comprehensive assessments of geological constraints and site-specific challenges remain limited. This review addresses these gaps by integrating geological perspectives into the renewable energy discourse, emphasizing how factors like tectonic activity, volcanic formations, and mineral distributions directly impact renewable energy prospects. Such insights are crucial for policymakers, investors, and researchers seeking to maximize Ethiopia's renewable energy potential through well-informed decision-making and resource allocation.

Moreover, this review examines the vital role of geology in Ethiopia's renewable energy sector, focusing on the potential of geological resources, associated challenges, and future development directions. It aims to assess the current state of geological knowledge in renewable energy resource assessment, highlight challenges in harnessing geological resources, and offer recommendations for research and policy improvements. By synthesizing geological data on formations, mineral resources, and geothermal potential, the review underscores how Ethiopia's unique geological landscape shaped by the Great Rift Valley, volcanic activity, and mineral wealth affects the viability, efficiency, and sustainability of renewable energy projects. Unlike traditional studies that focus on technological or economic factors, this work highlights the often-overlooked geological perspective, providing crucial insights for policymakers, investors, and researchers seeking to maximize Ethiopia's renewable energy potential.

2 Methodology

This study employs a systematic review approach to examine the role of geology in renewable energy development in Ethiopia. A comprehensive literature search was conducted to identify relevant studies, including peer-reviewed journal articles, reports, and gray literature published between 2012 and 2024. The search was performed across multiple academic databases, institutional repositories, and government publications to ensure a diverse and representative dataset. Inclusion criteria focused on studies that directly address geological influences on renewable energy resources such as geothermal, hydropower, wind, and solar energy in Ethiopia. Key search strategies included Boolean search techniques, keyword-based searches, and citation tracking. Boolean operators such as "AND," "OR," and "NOT" were used to refine search results and ensure comprehensive coverage. Keywords and search terms included "geology and renewable energy in Ethiopia," "geothermal energy potential Ethiopia," "hydropower geological assessments Ethiopia," "wind energy geology Ethiopia," "solar energy geological suitability Ethiopia," "tectonic activity and energy resources Ethiopia," and "mineral resources for renewable energy Ethiopia." Searches were conducted in databases such as Scopus, Web of Science, Google Scholar, and institutional archives, ensuring a wide range of relevant literature was captured.

The review process involved a structured screening and selection procedure. Initially, titles and abstracts were reviewed to assess their relevance to the study objectives. Selected studies were then subjected to a full-text analysis to extract key geological insights related to renewable energy development. Special attention was given to studies discussing tectonic activity, geological formations, resource distribution, and site-specific challenges in energy project implementation. To enhance the robustness of the findings, cross-referencing was conducted to identify additional sources that contribute to the understanding of Ethiopia's geological landscape and its impact on renewable energy. Data extraction and synthesis were conducted to categorize findings based on themes such as geological assessments for geothermal energy, hydropower feasibility linked to geological formations, wind corridor assessments, and the role of mineral resources in energy technologies. Thematic analysis was employed to identify patterns, trends, and knowledge gaps in the existing literature. Furthermore, the review considered case studies of specific renewable energy projects to illustrate practical applications of geological principles in site selection and resource utilization. To ensure the credibility and reliability of the review, only studies from reputable sources, including international energy agencies, Ethiopian government reports, and academic institutions, were included. The synthesis of findings was aimed at providing a balanced perspective on both the opportunities and challenges presented by Ethiopia's geological characteristics in renewable energy development. This approach allows for a holistic understanding of the interplay between geology and renewable energy, offering insights for future research and policy formulation.

3 Geology and renewable energy resources

3.1 Geothermal energy

Ethiopia's geothermal resources are notably abundant due to its strategic position within the East African Rift System (EARS), a geologically active zone rich in volcanic and geothermal activity (Benti et al., 2023). The Rift Valley, which spans Ethiopia, offers ideal conditions for geothermal energy development, providing a stable renewable energy source that can complement the country's heavily relied-upon hydropower, which is increasingly susceptible to climate variability (Burnside et al., 2021). Recognizing this potential, the Ethiopian government has integrated geothermal energy into its energy diversification strategy, with estimates from the Geological Survey of Ethiopia (GSE) placing the country's geothermal potential at over 10,000.0 MW, primarily concentrated within the Rift Valley (Guangul and Chala, 2021). Despite this significant potential, Ethiopia's current geothermal output is modest, with only a few sites like the Aluto-Langano plant, producing approximately 7.3 MW (Solomon et al., 2020).

Ethiopia's geothermal potential is primarily shaped by its unique geological structures, including active rift zones, volcanic formations, and fault lines. These features influence the availability, temperature, and accessibility of geothermal resources across different locations. For instance the geological conditions within the Rift Valley are highly favorable for geothermal development, thanks to the region's active tectonic and volcanic activity (Guangul and Chala, 2021). Key features that enhance geothermal potential include active volcanism, extensive fault systems, and thermal manifestations. Active and dormant volcanoes, especially around the Aluto-Langano, Tendaho, and Corbetti areas, indicate high geothermal potential due to their high heat flow and shallow magma chambers (Benti et al., 2023). Fault systems in the rift facilitate fluid circulation through the crust, which transfers heat from deeper layers to accessible depths, ideal for harnessing geothermal energy (Solomon et al., 2020). Additionally, surface manifestations such as hot springs and fumaroles serve as indicators of underlying geothermal activity and guide site exploration for future geothermal projects (Burnside et al., 2021). These favorable geological features position Ethiopia as a prime candidate for expanding its geothermal energy sector. Table 1 below details the geological structures associated with key geothermal sites and their impact on energy development. This overview provides insight into the country's progress in harnessing its vast geothermal potential, which is integral to its renewable energy strategy and sustainable development goals. Moreover, the table illustrates how Ethiopia's diverse geological structures such as volcanic complexes, fault zones, and caldera systems directly influence geothermal resource availability. Rift faulting enhances permeability, volcanic activity elevates heat flow, and caldera systems create ideal conditions for geothermal reservoirs. Understanding these relationships is crucial for effective site selection, reservoir management, and sustainable energy production.

3.2 Hydropower

Ethiopia, often called the "water tower" of Africa, holds abundant water resources that make hydropower the backbone of its energy sector. With major rivers like the Blue Nile, Omo, and Awash, Ethiopia's hydropower potential is estimated at around 45,000.0 MW, yet only a fraction of this capacity is currently tapped (van der Zwaan et al., 2018). Hydropower generates over 90.0% of the country's electricity, establishing it as Ethiopia's leading renewable energy source (U.S. Department of Commerce, 2024). These resources underscore Ethiopia's capacity for significant expansion in hydropower, a key component of its future energy strategy. The unique geological conditions across Ethiopia amplify this hydropower potential. The Ethiopian Highlands, with elevations exceeding 4,000.0 m, form steep river gradients that create rapid water flows ideal for generating energy (Eldardiry and Hossain, 2021). The rugged terrain and deep river basins found in regions like the Blue Nile Basin offer excellent sites for large-scale hydropower development, capitalizing on the kinetic energy produced by these elevations (Bombelli et al., 2021). Additionally, the presence of stable, crystalline basement rocks, such as granite and gneiss, provides solid foundations for dam structures, supporting the reservoirs necessary for hydropower generation (Orkodjo et al., 2022).

Several geological factors are crucial for determining the feasibility of hydropower projects. Rock type and stability are essential to ensuring the safety and longevity of dams, with hard rocks like granite and basalt ideal for foundation stability (Eldardiry and Hossain, 2021). However, Ethiopia's location within the seismically active East African Rift System necessitates careful site assessments to ensure structures can endure seismic events (van der Zwaan et al., 2018). Erosion and sedimentation in river catchments also influence reservoir storage capacity and operational efficiency. High sedimentation can reduce reservoir capacity over time, impacting long-term power generation and requiring ongoing management strategies (Bombelli et al., 2021). Geological features such as fault lines, fractures, and underground water channels can further influence dam stability and water flow dynamics. Faults and fractures may lead to water seepage, potentially undermining dam integrity. The Grand Ethiopian Renaissance Dam (GERD), for instance, was strategically sited where minimal faulting was detected, minimizing the risk of structural compromise. In contrast, sites affected by volcanic ash layers or fault lines require specialized engineering measures like grouting or additional barriers to control water flow and reinforce stability (International Hydropower Association, 2022). Table 2 provides a snapshot of Ethiopia's major hydropower sites, highlighting the diversity of projects across regions and at various stages of development. Operational sites like the Grand Ethiopian Renaissance Dam (GERD) exemplify Ethiopia's high-capacity projects, while under-construction and planned sites reflect a strong commitment to expanding renewable energy production. Each project harnesses Ethiopia's topographical advantages, further establishing hydropower as the country's leading renewable energy resource. Furthermore the table clearly presents the hydropower projects, their locations, geological structures, and how these structures influence hydropower development in each area.

3.3 Wind energy

Ethiopia holds considerable promise for wind energy generation due to its diverse topography and favorable climatic conditions. The country's geographical location within the Horn of Africa places it within key wind corridors, with strong seasonal winds, particularly across high-altitude plateaus and ridges (Chen, 2018). Studies estimate Ethiopia's wind energy potential at approximately 1,350.0 GW, with wind speeds surpassing 7.0 m per second in several regions, including the Rift Valley and eastern escarpment (Knight, 2016). These areas, characterized by their distinct wind patterns, present an excellent opportunity for harnessing wind power to meet the country's growing energy demands (Asress et al., 2013). The geological landscape of Ethiopia significantly contributes to the viability of wind energy projects. The country's varied topography, from high plateaus and rift valleys to mountainous terrains, creates ideal wind corridors that can enhance wind energy generation (Gaddada and Kodicherla, 2016). Stable geological formations in these regions provide a solid base for wind turbine installation, while the elevated terrains naturally increase wind speeds, making these areas suitable for large-scale wind farms (Gebreslassie, 2021). Additionally, the minimal seismic activity in many parts of Ethiopia reduces the risk of structural damage to turbines, ensuring the reliability and longevity of wind energy infrastructure. Table 3 provides a summary of Key Geological Structures and Their Influence on Wind Energy in Ethiopia.

In northern Ethiopia, including the Ashegoda Wind Farm in Tigray, the presence of stable Precambrian basement rocks and highland plateaus facilitates consistent wind flow and secure turbine foundations. Similarly, the Adama Wind Farm in Oromia benefits from the Rift Valley's geological structure, where escarpments channel winds into concentrated corridors, significantly enhancing turbine efficiency (Desalegn et al., 2022). The Rift Valley's volcanic formations, characterized by basalt and tuff, play a crucial role in wind energy development across sites like Metehara and Aysha. These formations not only create narrow wind channels that amplify wind speeds but also provide stable ground conditions for turbine installation. The absence of significant faulting and seismic activity further enhances the suitability of these regions for long-term energy projects (Negash et al., 2020). In the highlands of Debre Berhan, the presence of elevated ridges and stable crystalline bedrock ensures

TABLE 1 Geological structures associated with key geothermal sites and their impact on energy development (Boke et al., 2022).

Geothermal site	Location	Status	Capacity	Geological structures	Influence on geothermal development
Operational sites					
Aluto-Langano Power Plant	Near Lake Ziway, Central Ethiopia	Operational	7.3 MW (expansion to 70.0 MW)	Aluto volcanic complex, Rift Valley faults	High heat flow from volcanic activity and fault structures facilitates steam production for power generation
Under-Development Sites					
Aluto-Langano Expansion	Near Lake Ziway, Central Ethiopia	Under Development	Planned: 70.0 MW	Aluto volcanic complex, Rift Valley faults	Expanding capacity by tapping additional high-temperature reservoirs linked to volcanic and tectonic activity
Tulu Moye Project	Near Lake Koka, Central Ethiopia	Under Development	Phase 1: 50.0 MW (520.0 MW total)	Silicic volcanic rocks, faulted rift zones	Rift fractures allow deep circulation of geothermal fluids, enhancing reservoir productivity
Corbetti Project	Near Shashamane, Southern Ethiopia	Under Development	Initial: 50.0 MW (500.0 MW total)	Corbetti Caldera, Quaternary volcanic rocks	Presence of a caldera system enhances heat accumulation and fluid movement for geothermal production
Potential and Exploration Sites					
Abaya Field	Near Lake Abaya, Southern Ethiopia	Exploration Ongoing	Potential: 100.0 MW	Rift Valley faults, volcanic structures	Faulted zones increase permeability, allowing for efficient heat transfer
Dofan Field	Near Dofan, Northeastern Ethiopia	Exploration Ongoing	Potential: 60.0 MW	Quaternary volcanic rocks, fault zones	Volcanic activity contributes to high subsurface temperatures suitable for geothermal production
Fentale Field	Near Mount Fentale, Central Ethiopia	Exploration Ongoing	Potential: 100.0 MW	Fentale volcano, Rift Valley faults	Volcanic heat sources and extensive faulting enhance fluid circulation and geothermal gradient
Alalobeda Field	Afar Region, Northeastern Ethiopia	Exploration Ongoing	Potential: 50.0 MW	Rift Valley faults, volcanic formations	Active rifting increases subsurface permeability and heat accumulation
Meteka Field	Afar Region, Northeastern Ethiopia	Exploration Ongoing	Potential: 100.0 MW	Rift Valley faults, Quaternary volcanic rocks	Fault intersections enhance geothermal fluid flow and heat retention
Tendaho Field	Afar Region, Northeastern Ethiopia	Exploration Ongoing	Potential: 100.0 MW	Rift faults, basaltic volcanic formations	Basaltic formations act as heat reservoirs, while rift structures facilitate fluid movement
Explored and Unconfirmed Sites					
Debre Zeyt Field	Near Debre Zeyt (Bishoftu), Central Ethiopia	Exploration Ongoing	Potential: TBD	Volcanic craters, rift fractures	Geothermal potential linked to volcanic craters and heat from recent volcanic activity

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TABLE 1 (*Continued*) Geological structures associated with key geothermal sites and their impact on energy development (Boke et al., 2022).

Geothermal site	Location	Status	Capacity	Geological structures	Influence on geothermal development
Boku Field	Rift Valley, Ethiopia	Exploration Ongoing	Potential: TBD	Rift faults, volcanic rocks	Faulting and volcanism contribute to elevated subsurface temperatures
Aleta Field	Southern Ethiopia	Exploration Ongoing	Potential: TBD	Rift escarpments, faulted volcanic rocks	Rift escarpments enhance heat flow and fluid circulation
Other Prospective Sites					
Dallol Geothermal Area	Afar Region, Northeastern Ethiopia	Prospective	Challenging site	Rift Valley, hydrothermal deposits	Extreme geothermal gradient due to shallow heat sources and hydrothermal activity
Gedemsa Field	Near the Great Rift Valley, Central Ethiopia	Prospective	Potential requires further exploration	Rift faults, volcanic structures	Rift faults enhance permeability, while volcanic heat sources provide thermal energy

consistent wind exposure while minimizing the risks associated with ground instability. Moreover, the highland plateaus, formed through tectonic uplift, create expansive areas where wind turbines can be strategically placed for optimal energy capture (Alemu and Tegegne, 2024).

Wind energy potential varies across Ethiopia, primarily influenced by geological and topographic conditions. The northern and eastern regions, including Tigray, Afar, and Oromia, exhibit the highest wind potential due to elevated terrains, escarpments, and their proximity to major wind corridors (Zegeye, 2021). These regions consistently experience strong winds, making them ideal for large-scale wind farms. Conversely, the western lowlands, characterized by sedimentary basins and dense vegetation, demonstrate lower wind speeds due to reduced elevation and less favorable topographic conditions (Knight, 2016). Additionally, areas with loose alluvial deposits and unconsolidated sediments pose challenges for turbine foundation stability, increasing construction costs and maintenance requirements. In general, Ethiopia's geological landscape plays a pivotal role in shaping its wind energy potential. The presence of stable bedrock, high-altitude plateaus, rift valleys, and volcanic formations not only enhances wind flow but also ensures the structural integrity of wind energy infrastructure. Future wind energy development in Ethiopia will continue to rely on comprehensive geological assessments to identify optimal sites, mitigate potential risks, and maximize energy generation.

3.4 Solar energy

The role of geology in solar energy development is significant, as factors such as land use, terrain, soil types, and geological stability directly impact site selection, construction feasibility, and long-term efficiency. Ethiopia's varied geological landscape including high plateaus, rift valleys, and arid lowlands presents both opportunities and challenges for large-scale solar energy projects (Tiruye et al., 2021). Table 4 summarizes key geological parameters and their specific impact on solar energy development across Ethiopia's major regions.

Moreover, geological stability is essential for ensuring the longevity of solar infrastructure (Benti et al., 2022). Regions prone to seismic activity or land subsidence may be less suitable for solar farm development, as these factors can increase the risk of damage to infrastructure. Ethiopia's Rift Valley, however, offers a relatively stable foundation for solar projects, providing a reliable base for long-term installations (Mulatu et al., 2023). Table 5 highlights how geological conditions influence solar energy potential across key Ethiopian regions:

In general, Ethiopia's geological features offer substantial potential for solar energy development, particularly in flat, stable regions such as the Rift Valley and Afar Depression. However, challenges such as land use conflicts, soil instability, and rugged terrains in the highlands must be addressed through advanced site assessment techniques, including Geographic Information Systems (GIS) and remote sensing technologies (Tiruye et al., 2021). Integrating solar energy with other renewable sources, such as wind and geothermal power, will further enhance energy reliability while maximizing Ethiopia's renewable energy capacity.

3.4 Potentials of geology in renewable energy development

Ethiopia's renewable energy resources are substantial, and the role of geology in harnessing these resources is crucial for effective development. As a country endowed with diverse geological formations and unique topographical features, Ethiopia's potential for renewable energy, especially geothermal, hydropower, wind, and solar energy, is enormous. Understanding the geological context of

TABLE 2 Major hydropower projects, their locations, geological structures and their influence on hydropower development in each area (Kruger et al., 2019).

Hydropower project	Status	Location	Region	Capacity (MW)	Geological features	Influence on hydropower development
Grand Ethiopian Renaissance Dam (GERD)	Operational	Blue Nile River	Benishangul-Gumuz	6,450.0	Precambrian basement complex with granitic and metamorphic rocks	Strong bedrock provides foundation stability and reservoir integrity
Gilgel Gibe III	Operational	Omo River	SNNPR	1,870.0	Volcanic rocks (basalt and tuff)	High runoff and steep topography enhance water storage and energy output
Gilgel Gibe II	Operational	Omo River	SNNPR	420.0	Volcanic and sedimentary formations	High flow gradient facilitates efficient energy generation
Tekeze Hydroelectric Power Station	Operational	Tekeze River	Tigray	300.0	Precambrian basement rocks and deep river gorge	Narrow gorge and stable bedrock enable dam height and high water head
Gilgel Gibe I	Operational	Omo River	SNNPR	184.0	Volcanic formations and alluvial deposits	Favorable topography enhances water flow and storage
Fincha Hydroelectric Power Plant	Operational	Fincha River	Oromia	134.0	Volcanic rocks with highland plateau	Plateau aids reservoir formation and efficient water flow
Tana Beles Hydroelectric Power Plant	Operational	Beles River	Amhara	460.0	Volcanic and sedimentary formations	Stable geology supports underground tunnels and reservoir formation
Koka Dam	Operational	Awash River	Oromia	43.2	Volcanic rocks and alluvial deposits	Stable volcanic formations provide foundation for dam structure
Awash I, II, III Hydropower Stations	Operational	Awash River	Oromia	110.0 (combined)	Volcanic and sedimentary formations	Geological stability ensures long-term sustainability
Melka Wakena	Operational	Wabe Shebele River	Oromia	153.0	Volcanic highlands with basaltic formations	High-gradient river enhances energy generation capacity
Sor Hydroelectric Power Station	Operational	Sor River	Oromia	5.0	Volcanic formations with stable bedrock	Geological stability supports small-scale energy generation
Dire Dawa Hydroelectric Power Station	Operational	Dechatu River	Dire Dawa	7.0	Volcanic formations and alluvial deposits	Stable geology supports infrastructure development
Koysha Hydroelectric Power Plant	Under Construction	Omo River	SNNPR	2,160.0	Volcanic rocks and sedimentary deposits	Steep gradient enhances energy potential

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TABLE 2 (*Continued*) Major hydropower projects, their locations, geological structures and their influence on hydropower development in each area (Kruger et al., 2019).

Hydropower project	Status	Location	Region	Capacity (MW)	Geological features	Influence on hydropower development
Genale Dawa III Hydropower Project	Under Construction	Genale Dawa River	Somali	254.0	Volcanic and Precambrian basement complex	Geological stability enables large reservoir formation
Chemoga Yeda Hydroelectric Power Plant	Planned	Chemoga and Yeda Rivers	Amhara	280.0	Volcanic and sedimentary formations	Favorable topography supports dam and reservoir construction
Halele Werabessa Hydroelectric Power Plant	Planned	Halele and Werabessa Rivers	SNNPR	426.0	Volcanic formations and river gorges	Steep gorges provide high head for energy generation
Karadobi Hydroelectric Power Plant	Planned	Abay River (Blue Nile)	Amhara	1,600.0	Precambrian basement rocks and deep gorge	Narrow gorge enhances water pressure and energy generation
Baro 1 and 2 Hydropower Projects	Planned	Baro River	Gambella	800.0 (combined)	Sedimentary formations and river floodplains	Favorable topography facilitates large reservoir formation
Geba Hydroelectric Power Plant	Planned	Geba River	Oromia	385.0	Volcanic and sedimentary formations	Geological stability ensures dam construction and energy output
Tams Hydroelectric Power Plant	Planned	Baro River	Gambella	1,200.0	Sedimentary formations and river valley	River valley supports large reservoir development
Dabus Hydroelectric Power Plant	Planned	Dabus River	Benishangul-Gumuz	168.0	Precambrian basement rocks and volcanic formations	Stable bedrock ensures dam strength and reservoir sustainability

TABLE 3 Key geological structures and their influence on wind energy in major locations across Ethiopia.

Location/Project	Geological structure	Influence on wind energy development
Ashegoda Wind Farm (Tigray)	Precambrian basement rocks and highland plateau	Elevated terrain enhances wind acceleration; stable bedrock supports turbine foundations.
Adama Wind Farm (Oromia)	Rift Valley escarpment and volcanic formations	Rift corridor channels strong winds; volcanic bedrock ensures structural stability.
Aysha Wind Farm (Somali Region)	Rift Valley margins with volcanic plains	Plains promote steady wind flow; stable formations minimize ground instability.
Metehara Wind Farm (Oromia)	Rift Valley floor and volcanic escarpments	Narrow valley accelerates wind speeds; solid volcanic substrate supports infrastructure.
Debre Berhan (Amhara Highlands)	Precambrian highland plateau and ridges	Elevated plateau enhances wind exposure; low seismicity ensures long-term stability.

TABLE 4 Key geological parameters and their specific impact on solar energy development across Ethiopia.

Geological feature	Region	Impact on solar energy	References
Topography	Rift Valley, Afar	Flat terrain facilitates easy installation and maintenance.	Tiruye et al. (2021)
	Ethiopian Highlands	Mountainous areas complicate installation and increase costs.	Mulatu et al. (2023)
Soil Composition	Rift Valley	Stable, firm soils support solar panel foundations.	Kebede (2015)
	Western Lowlands	Loose, sandy soils require additional structural support.	Benti et al. (2022)
Geological Stability	Rift Valley, Afar	Minimal seismic activity ensures infrastructure longevity.	Getnet et al. (2024)
	Northern Highlands	Moderate seismic risk increases maintenance costs.	Mulatu et al. (2023)
Land Use	Afar Depression	Arid, unshaded lands ideal for solar farms.	Benti et al. (2022)
	Oromia and Amhara	Competing agricultural land use limits availability.	Tiruye et al. (2021)

TABLE 5 Highlights how geological conditions influence solar energy potential across key Ethiopian regions.

Region	Solar radiation ($kWh/m^2/day$)	Geological advantage	Challenges	References
Rift Valley	5.5–6.5	Flat terrain, stable soils, low seismic activity	Competition with agricultural land use	Getnet et al. (2024)
Afar Depression	6.0–7.0	Arid climate, expansive unshaded lands	Harsh climate increases panel maintenance	Tiruye et al. (2021)
Ethiopian Highlands	5.0–6.0	High solar radiation	Rugged topography complicates infrastructure setup	Mulatu et al. (2023)
Western Lowlands	4.5–5.5	Expansive lands	Loose, sandy soils increase installation costs	Benti et al. (2022)

each resource is essential for ensuring the technical and economic feasibility of renewable energy projects.

3.6 Geothermal potential

Ethiopia is situated along the East African Rift Valley, one of the most geothermal-active regions globally, with abundant potential for geothermal energy. Geothermal energy relies heavily on geological features, particularly geothermal gradients and heat flows, which are critical for identifying areas where heat from the Earth's interior, can be harnessed. In Ethiopia, high geothermal gradients areas where the temperature increases rapidly with depth are concentrated around the Rift Valley, which is a hotspot for geothermal potential (Benti et al., 2023). This geological phenomenon indicates that the country is well-suited for geothermal energy exploitation, with the potential to produce large-scale electricity and provide direct heating applications. In terms of economic and technical feasibility, geothermal energy in Ethiopia faces both opportunities and challenges. On one hand, the vast geothermal resources, such as those found in the Aluto-Langano, Tendaho, and Dallol fields, offer long-term, sustainable energy solutions. However, the technical feasibility of drilling deep enough to access these resources and the initial high capital costs for geothermal power plant construction are major challenges. Geological studies, including mapping heat flow and assessing subsurface structures, are essential for identifying the most productive geothermal wells and ensuring that the projects are economically viable (Burnside et al., 2021). Moreover, such studies can help mitigate risks related to well interference, reservoir management, and environmental impact.

3.7 Hydropower potential

Ethiopia's river systems, notably the Blue Nile and its tributaries, offer significant hydropower potential, making hydropower the cornerstone of the country's energy strategy. Geological and sedimentological studies are pivotal in optimizing the location and design of hydropower plants (Bombelli et al., 2021). River systems, such as the Blue Nile and the Omo River, have vast catchment areas that contribute to their large flow volumes, making them ideal candidates for hydropower development. However, understanding the sedimentological characteristics of these riverbeds, including sediment transport and deposition, is crucial for optimizing the construction and lifespan of hydropower dams (van der Zwaan et al., 2018). Sediment accumulation behind dams can reduce the storage capacity and efficiency of hydropower plants, making sediment studies a key component of site selection. Geological studies also help in assessing the stability of dam sites and ensuring the integrity of dam structures. The strength and stability of underlying bedrock are essential for ensuring the long-term security of the hydropower installations. For instance, understanding fault lines, seismic risks, and soil stability at potential dam sites is critical for safeguarding the infrastructure and preventing costly failures (Eldardiry and Hossain, 2021). Geological surveys, including subsurface investigations, offer insights into the type and depth of bedrock, aiding in the optimal placement of dams and turbines. In Ethiopia, projects such as the Grand Ethiopian Renaissance Dam (GERD) have benefited greatly from these studies, ensuring a design that accommodates the specific geological and hydrological conditions of the Blue Nile River basin.

3.8 Wind and solar potential

The evaluation of wind and solar energy potential in Ethiopia also relies heavily on geological and topographical assessments (Gebreslassie, 2021). Geological studies of terrain and wind corridors are essential for optimizing the siting of wind farms. Ethiopia's high plateaus, escarpments, and valleys, particularly in the Rift Valley, offer excellent wind speeds, making them prime locations for wind power development (Desalegn et al., 2022). Geological surveys that map wind flow patterns in these areas allow for a more precise assessment of wind energy potential, improving the overall efficiency and cost-effectiveness of wind energy projects (Asress et al., 2013). Additionally, the stability of the underlying rock formations and the absence of seismic hazards are important considerations for the long-term durability of wind turbines in these areas. Similarly, solar energy development in Ethiopia depends on geological factors such as land suitability and terrain. Areas with flat, unshaded terrain, such as parts of the Afar Depression and the Rift Valley, offer excellent conditions for solar farms. Geologic surveys of soil stability, land use, and the potential for land subsidence are critical for ensuring the feasibility of solar installations (Getnet et al., 2024). The country's high levels of solar irradiance make it an ideal candidate for solar power, but effective planning, informed by geological data, is necessary to avoid areas where terrain or soil characteristics could hinder installation (Benti et al., 2022). Moreover, geological factors such as soil erosion, particularly in areas prone to landslides or flooding, need to be carefully considered to avoid long-term operational disruptions for solar farms.

4 Ethiopia's geological potential in a global context

The geological characteristics of Ethiopia, primarily shaped by the East African Rift Valley, play a crucial role in the development of geothermal energy. The Rift Valley is characterized by active tectonic movements, volcanic activity, and high subsurface heat flow, making it one of the most promising geothermal regions globally. However, the development of geothermal energy in Ethiopia remains underexplored compared to countries like Kenya, Iceland, and Turkey, which have leveraged their geological advantages more effectively. To provide a broader perspective on Ethiopia's renewable energy potential, it is essential to compare its geological features and challenges with those of other regions that share similar geological characteristics. Table 6 compares Ethiopia's geological features and challenges with those of Kenya, Iceland, and Turkey, countries with similar geological formations. The aim is to provide a broader perspective on Ethiopia's Geothermal Energy Development, offering insights into opportunities and challenges from a global viewpoint.

5 Challenges in harnessing geological resources for renewable energy

As Ethiopia continues to explore and expand its renewable energy potential, geological resources such as geothermal, hydropower, wind, and solar energy offer tremendous promise. However, the development of these resources is fraught with challenges rooted in the country's geological and environmental contexts (Sawo, 2024). The interplay of technical, environmental, and geological factors presents obstacles that must be addressed to ensure the long-term success of renewable energy projects. This review highlights the key challenges in harnessing geological resources for renewable energy in Ethiopia, focusing on geothermal, hydropower, wind, and solar energy.

5.1 Geothermal challenges

Geothermal energy, with its substantial potential in Ethiopia, particularly within the East African Rift Valley, presents significant technical and environmental challenges (Pasqua et al., 2023). One of the primary difficulties in geothermal development is the drilling process (Tiruye et al., 2021). Drilling deep enough to access geothermal reservoirs often involves high upfront costs and complex technical requirements. In Ethiopia, regions with geothermal potential are often characterized by challenging terrain, which adds further complexity to drilling operations. The depth of geothermal wells, often exceeding 2.0–3.0 km, requires advanced drilling technologies and specialized equipment, making the process both costly and technically demanding (Benti et al., 2023). Environmental concerns related to geothermal resource management also pose challenges. Geothermal fields, while generally considered sustainable, can face issues such as the depletion of shallow geothermal reservoirs if not managed carefully. In some cases, excessive extraction can lead to the reduction of pressure within the reservoir, ultimately diminishing the energy output. Furthermore, geothermal power plants require significant water usage, which can be a concern in Ethiopia's arid and semi-arid regions, where water resources are limited (Mohamed and Kassim, 2024). Effective management of geothermal reservoirs to maintain pressure and minimize environmental impact requires sophisticated geological monitoring and regulation (Sawo, 2024).

5.2 Hydropower challenges

Hydropower has been a major focus of Ethiopia's energy strategy, particularly with the construction of large dams such as the Grand

TABLE 6 Comparative analysis of geological features and challenges for renewable energy development.

Criteria	Ethiopia	Kenya	Iceland	Turkey
Geological Features	East African Rift Valley, volcanic activity, river systems (Blue Nile, Omo River)	East African Rift Valley, volcanic activity, geothermal resources (Rotich et al., 2024)	Volcanic geology, active tectonic plates, high geothermal potential (Alghasi and Althafzufar, 2024)	Western Anatolian region, active fault zones, significant geothermal fields (Melikoglu, 2017)
Geothermal Potential	High potential in Rift Valley and Afar Depression, but still underexplored (Benti et al., 2023)	Over 800.0 MW geothermal power capacity developed (Rotich et al., 2024)	Global leader in geothermal energy, ~25.0% of energy from geothermal (Alghasi and Althafzufar, 2024)	Nearly 2,000.0 MW installed capacity, successful integration with energy policy (Melikoglu, 2017)
Geothermal Development Status	Relatively nascent sector with limited capacity (e.g., 7.0 MW from Aluto-Langano plant) (Burnside et al., 2021)	Established sector, with rapid expansion in recent years (Rotich et al., 2024)	Advanced, with deep drilling and direct-use applications (Mikhaylov, 2020).)	Developed sector with high installed capacity and continuous expansion (Melikoglu, 2017)
Investment and Infrastructure	Limited technological capacity and investment in geothermal exploration (Guangul and Chala, 2021)	Strong government support and foreign investment in geothermal energy (Rotich et al., 2024)	Highly advanced infrastructure for deep drilling, innovative geothermal technology (Alghasi and Althafzufar, 2024)	Robust investment in geothermal infrastructure, government incentives (Melikoglu, 2017)
Policy Framework	Developing, with emerging policies but lacking full integration with geological opportunities (Benti et al., 2023)	Strong policy alignment, government incentives for geothermal energy (Rotich et al., 2024)	Well-established policy support for geothermal, high energy independence (Mikhaylov, 2020)	Comprehensive policy framework integrating geology with energy sector development (Bilgili et al., 2018)
Wind Energy Potential	Moderate, with potential in the Ethiopian Highlands and Rift Valley (Gaddada and Kodicherla, 2016)	High, particularly in the Rift Valley region (Ndi, 2024)	Moderate, with coastal wind potential (Hassanian et al., 2023)	Significant, with wind farms in coastal and mountainous areas (Kaplan, 2015).
Solar Energy Potential	High, particularly in the Afar Depression and Rift Valley (Tiruye et al., 2021)	High, especially in the northern regions (Mukoro et al., 2022)	Moderate, limited by cloudy conditions in some areas (Alghasi and Althafzufar, 2024)	High, with a focus on solar projects in the south and central regions (Stritih et al., 2013)
Hydropower Potential	Significant, with major river systems (Blue Nile, Omo River) and existing large-scale dams (e.g., GERD) (Orkodjo et al., 2022)	Significant, with major rivers like the Tana River supporting large dams (Chemengich and Masara, 2022)	Limited due to Iceland's small rivers and geographic size (Voegeli and Finger, 2021)	Extensive, with several large dams and projects on major rivers (e.g., Ataturk Dam) (Bilgili et al., 2018)
Challenges	Limited technology for deep drilling, infrastructure deficits, policy misalignment (Sawo, 2024)	Overcoming issues of land acquisition and environmental concerns (Chemengich and Masara, 2022)	Remote location, high drilling costs, maintaining efficiency in volcanic areas (Mikhaylov, 2020)	Seismic risks, land acquisition challenges, balancing geothermal with other energy sources (Melikoglu, 2017)
Key Lessons for Ethiopia	Focus on increasing investment, technological capacity, and international collaboration	Emulate Kenya's success in geothermal development through improved exploration and infrastructure	Leverage Iceland's advanced geothermal technologies and experience in high-temperature resources	Integrate geological potential with stronger policy frameworks and incentives, learn from Turkey's experience in aligning energy policy with resource development

Ethiopian Renaissance Dam (GERD). However, geological risks related to dam construction, seismic activity, and sedimentation remains significant challenges. One of the most pressing issues in hydropower development is the stability of dam sites, especially in regions prone to seismic activity (Tiruye et al., 2021). Ethiopia's geological landscape is characterized by fault lines and tectonic movements, especially in the Rift Valley, which can affect the integrity of dam structures. Earthquakes or minor seismic shifts can lead to dam destabilization, potentially causing catastrophic failures. For example, studies have shown that seismic activity in the Blue Nile basin has raised concerns over the long-term stability of large hydropower projects in the region (Degefu et al., 2015). Sedimentation is another challenge that significantly impacts the lifespan and efficiency of hydropower dams. The accumulation of sediment behind dams reduces their storage capacity and can interfere with the proper functioning of turbines (Bombelli et al., 2021). In Ethiopia, the sediment load in rivers like the Blue Nile and Omo River is high due to the country's topography and climate, which is marked by heavy rainfall and erosion in the catchment areas (Orkodjo et al., 2022). Over time, sedimentation leads to reduced efficiency, necessitating costly dredging and maintenance operations. Geological surveys and sedimentology studies are therefore essential in selecting optimal dam sites and designing projects that minimize sedimentation risks and ensure long-term viability (Abebe et al., 2024).

5.3 Wind energy challenges

Wind energy in Ethiopia has substantial potential, particularly in the Rift Valley and the highland plateaus. However, the development of wind energy faces challenges related to the availability and accuracy of wind resource data, which is influenced by geological and topographic factors (Boadu and Otoo, 2024). Wind speeds can vary significantly across the country, and localized geological features such as valleys, ridges, and plateaus can either enhance or reduce wind flow patterns (Adenle, 2020). These topographical variations make it challenging to obtain accurate, high-resolution wind data needed to optimize the placement of wind farms. For instance, in areas with complex terrain, such as the Ethiopian Highlands, the topography can cause wind patterns to be highly localized, leading to inconsistent wind resource assessment (Bekele and Tadesse, 2012). Additionally, the lack of comprehensive, long-term wind data in some regions hinders the proper evaluation of wind energy potential. While some wind farms, such as the Ashegoda Wind Farm and Adama Wind Farm, have shown success, further expansion requires more accurate and consistent wind resource mapping (Woldegiyorgis et al., 2024). The challenge of gathering reliable wind data in Ethiopia is compounded by logistical and financial constraints, which limit the ability to conduct extensive site assessments (Adenle, 2020). Therefore, addressing the gap in wind data through enhanced geological surveys and meteorological studies is critical to expanding wind energy capacity in Ethiopia.

5.4 Solar energy challenges

Solar energy in Ethiopia is increasingly seen as a viable solution, thanks to the country's high levels of solar irradiance. However, several geological factors pose challenges to the widespread deployment of solar installations. Land suitability for solar farms is one of the most significant constraints, as Ethiopia's landscape is marked by diverse terrains, including rugged highlands and expansive lowlands (Tiruyeet al., 2023). The presence of steep slopes and unstable soils can complicate the construction of large-scale solar farms. Additionally, areas prone to soil erosion or landslides, particularly in the highland regions, may not be suitable for solar installations, as the land may not provide the necessary stability for the installation of solar panels (Adenle, 2020). Soil composition also plays a crucial role in land suitability. In regions where the soil is prone to subsidence or shifting, it may not be able to support the heavy infrastructure of solar panel installations (Getnet et al., 2024). Furthermore, areas affected by flooding or poor drainage conditions may pose additional risks for solar farm sustainability (Mulatu et al., 2023). A thorough understanding of the geological properties of potential solar farm sites is essential to avoid these issues. While Ethiopia's large areas of sun-rich terrain in places like the Afar Depression and the Rift Valley are well-suited for solar energy, local geological surveys are necessary to assess land stability and mitigate risks associated with construction and long-term operation (Benti et al., 2023).

6 Case studies and examples

6.1 Geothermal projects: notable geothermal projects and their geological assessments

Ethiopia's geothermal potential ranks among the highest in Africa, primarily due to its location along the tectonically active East African Rift Valley. This geological setting has created significant geothermal reservoirs, making the region highly suitable for geothermal energy development. Notable projects include the Aluto-Langano and Tendaho geothermal fields, both of which have undergone extensive geological assessments to facilitate successful exploration and development. The geothermal energy development process in Ethiopia follows a structured operational procedure, beginning with site selection and geological assessments, followed by exploratory drilling, reservoir evaluation, and finally, energy production and distribution. The following key steps outline this process:

1. Geological and Geophysical Survey:
    - Conducting remote sensing and field-based geological mapping to identify geothermal surface manifestations, such as fumaroles and hot springs.
    - Fault mapping to determine subsurface fractures and heat flow paths.
    - Geophysical surveys, including magneto telluric (MT) and gravity studies, to assess subsurface structures and reservoir boundaries.
2. Thermal Gradient and Hydrogeological Analysis:
    - Measuring temperature variations at shallow depths to identify heat anomalies.
    - Analyzing hydrogeological conditions to understand groundwater flow and its role in geothermal reservoir recharge.
3. Exploratory Drilling and Reservoir Assessment:
    - Drilling exploratory wells to collect subsurface temperature, pressure, and fluid samples.
    - Conducting well-logging and permeability tests to assess the reservoir's capacity and sustainability.
    - Estimating potential energy outputs based on reservoir temperature and flow rate.

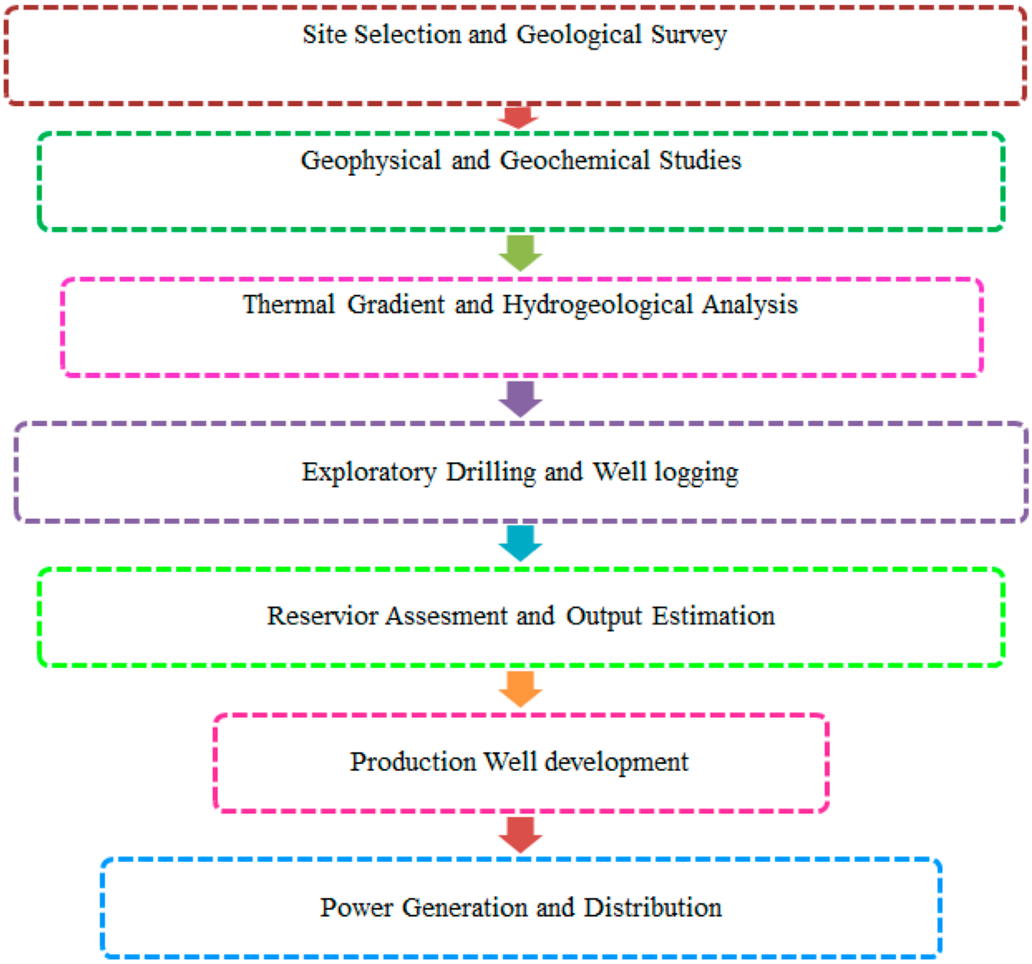

FIGURE 1
A schematic flow diagram of the geothermal development process.

4. Production and Power Generation:

- Developing production wells and re-injection wells to sustain reservoir pressure.
- Converting geothermal energy into electricity using steam turbines and power plants.
- Distributing the generated electricity to the national grid or local energy systems.

The Aluto-Langano geothermal field serves as a prime example of this structured approach. Extensive geological assessments, including fault mapping, thermal gradient studies, and subsurface reservoir evaluations, have been conducted to identify optimal drilling targets, estimate energy outputs, and minimize exploratory risks (Benti et al., 2023). Similarly, the Tendaho geothermal field has undergone detailed geological and hydrogeological analyses to assess reservoir potential and inform development strategies. However, challenges remain, including the complexity of subsurface structures, resource accessibility, and reservoir sustainability. Addressing these challenges requires continued geological assessments, advanced geophysical modeling, and adaptive drilling technologies to enhance project success and long-term energy production. A schematic flow diagram of the geothermal development process (Figure 1), illustrates the step-by-step energy generation pathway from site exploration to power generation and distribution.

6.2 Hydropower projects: examples of hydropower projects influenced by geological studies

Ethiopia's hydropower capacity is also significant, benefiting from its highland topography and extensive river systems. The Grand Ethiopian Renaissance Dam (GERD) is a prime example of how geological studies can influence project outcomes. Geological investigations revealed key insights into bedrock stability, sediment deposition rates, and seismic activity, which were essential for dam site selection, structural integrity, and risk assessment. These studies informed engineering designs to enhance dam stability while accounting for geological hazards such as landslides and sedimentation (Bombelli et al., 2021). Similar geological

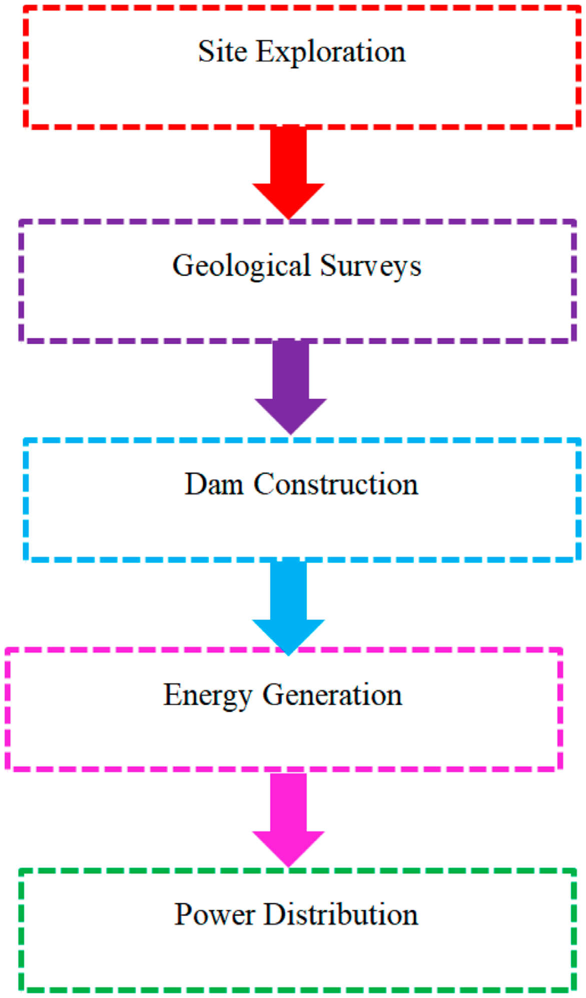

FIGURE 2
A schematic flow diagram of the Hydropower development process.

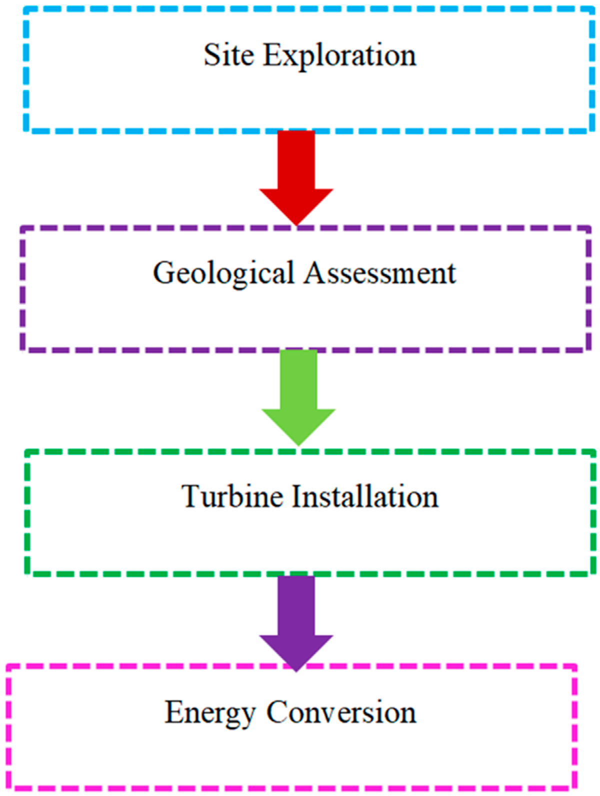

FIGURE 3
A schematic flow diagram of the Hydropower development process.

evaluations have supported projects like the Gibe III Dam, where assessments of riverbed geology and fault lines helped optimize construction and operational efficiency (Abebe et al., 2024). The schematic flow diagram (Figure 2), illustrates hydropower development process, from site exploration to power generation and distribution.

6.3 Wind and solar projects: case studies highlighting the impact of geological factors on project outcomes

Although wind and solar projects are often less directly influenced by subsurface geology, geological factors like terrain stability, soil composition, and wind channeling effects are critical for infrastructure stability and efficiency. Ethiopia's Aysha Wind Farm is a case in point, where geological studies helped identify wind patterns influenced by the country's mountainous topography, thus optimizing turbine placement for maximum output. In the case of solar projects, such as the Metehara Solar Power Plant, geological assessments were essential for site preparation, ensuring stable soil foundations to support photovoltaic (PV) installations. This attention to geological conditions has minimized land degradation and ensured efficient operation (Mulatu et al., 2023). The schematic flow diagram (Figure 3), illustrates the wind energy development process, from site exploration to power generation and distribution. Each step, from geological assessments to turbine installation and energy conversion, is depicted with arrows to show the progression of the energy generation pathway.

7 Future directions and recommendations

7.1 Technological innovations: emerging technologies for better geological assessment and resource utilization

Innovative technologies in remote sensing, seismic imaging, and geochemical analysis are revolutionizing geological assessments for renewable energy. Remote sensing tools, for instance, enable rapid geological mapping, especially in inaccessible regions. Advances in 3D seismic imaging have also improved subsurface characterization, critical for geothermal exploration. Furthermore, machine learning algorithms are increasingly being applied to geological data to predict resource availability, which could enhance the accuracy and efficiency of exploration activities. These technological innovations have the potential to reduce costs, minimize environmental impacts, and support the sustainable development of Ethiopia's renewable energy sector (Kebede and Mitsufuji, 2017).

7.2 Policy and regulatory framework: recommendations for improving policies and regulations

To effectively leverage geological resources for renewable energy, Ethiopia requires a robust policy framework that integrates geological insights into project planning and development. Policymakers should prioritize creating incentives for renewable energy projects with a strong geological foundation, such as tax credits for geothermal and hydropower investments. Additionally, regulations should encourage comprehensive geological assessments as part of the permitting process for energy projects. Streamlining regulatory processes to facilitate easier access to geological data would also support private sector investment. These policy changes could accelerate renewable energy development while ensuring environmental and social sustainability (Sawo, 2024).

7.3 Research and development: areas where further research is needed

Several areas of research remain critical to advancing the role of geology in Ethiopia's renewable energy sector. Firstly, improved models for predicting geothermal and hydropower potential could enhance resource utilization, particularly in underexplored regions of the Rift Valley. Research into the impacts of geological variability on solar and wind projects would also provide valuable insights for infrastructure stability and long-term project efficiency. Furthermore, interdisciplinary studies examining the interplay between geology, climate, and renewable energy output would support adaptive planning in the face of climate change, allowing Ethiopia to harness its resources sustainably (Yalew, 2022).

7.4 Community and environmental considerations: balancing renewable energy development with environmental and community impacts

Ethiopia's renewable energy projects must be developed with careful consideration of community and environmental impacts. Strategies to mitigate these impacts include involving local communities in project planning and establishing frameworks for environmental stewardship. For instance, geothermal and hydropower projects can lead to ecosystem alterations; thus, conducting environmental impact assessments (EIAs) is essential. Community engagement is equally vital, as it fosters local support and mitigates social disruptions. Compensation for affected communities and the promotion of local employment opportunities within renewable energy projects can foster community acceptance and long-term project success. These strategies will help balance the socio-environmental aspects of energy development with Ethiopia's sustainable energy goals (Sawo, 2024).

8 Conclusion

This review underscores the pivotal role of Ethiopia's geological resources in advancing the country's renewable energy sector, particularly in geothermal, hydropower, and wind energy. Ethiopia's diverse geology offers substantial potential for energy production, yet significant challenges remain in harnessing these resources. Geological factors such as seismic risks, site accessibility, and the variability of geothermal and hydropower sites must be carefully addressed through comprehensive resource assessments and improved site characterization. Despite these challenges, Ethiopia's renewable energy potential is vast, and the successful development of geothermal fields, hydropower dams, and wind farms demonstrates the feasibility of scaling up renewable energy production. To overcome existing barriers, it is essential to invest in advanced geological research, improve technical capabilities, and establish robust regulatory frameworks. Further, multi-stakeholder collaboration, including public-private partnerships, will be key to overcoming financial and logistical challenges. The review also highlights the urgent need for more localized geological data and the integration of these findings into national energy strategies to optimize resource use. Moving forward, Ethiopia's energy development efforts should focus on building sustainable, long-term capacity, with measurable goals to increase the share of renewable energy in the national grid. Timely policy reforms, coupled with targeted investments in research and development, will be crucial to unlocking the full potential of Ethiopia's geological resources for renewable energy generation.

Author contributions

DT: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review and editing.

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References

Abebe, N., Maitra, S., Esayas, B., and McDermott, R. (2024). A hydraulic mission for whom? A critical examination of Ethiopia's Gibe III hydropower dam. *Energy Res. & Soc. Sci.* 115, 103660. doi:10.1016/j.erss.2024.103660

Adenle, A. A. (2020). Assessment of solar energy technologies in Africa-opportunities and challenges in meeting the 2030 agenda and sustainable development goals. *Energy Policy* 137, 111180. doi:10.1016/j.enpol.2019.111180

Alemu, Y. B., and Tegegne, E. B. (2024). "Wind as a promising alternative energy source in Ethiopia: feasibility analysis for wind farm Establishment and investigation of wind energy potential in the Upper Blue Nile River basin," in *Land and water degradation in Ethiopia: climate and land Use change Implications* (Cham: Springer Nature Switzerland), 229–258.

Alghasi, M. A., and Althafzufar, M. A. (2024). Comparative Legal analysis of renewable energy utilization regulations between Iceland and Indonesia. *Policy, Law, Notary Regul. Issues* 3 (2), 333–341. doi:10.55047/polri.v3i2.1235

Al-Shetwi, A. Q. (2022). Sustainable development of renewable energy integrated power sector: trends, environmental impacts, and recent challenges. *Sci. Total Environ.* 822, 153645. doi:10.1016/j.scitotenv.2022.153645

Amir, M., and Khan, S. Z. (2022). Assessment of renewable energy: Status, challenges, COVID-19 impacts, opportunities, and sustainable energy solutions in Africa. *Energy Built Environ.* 3 (3), 348–362. doi:10.1016/j.enbenv.2021.03.002

Asres, G. A. (2021). "Renewable energy potential, energy access, and climate change mitigation in Ethiopia, "in *Handbook of Climate Change Management: Research, Leadership, Transformation*. Cham: Springer International Publishing, 2603–2625.

Asress, M. B., Simonovic, A., Komarov, D., and Stupar, S. (2013). Wind energy resource development in Ethiopia as an alternative energy future beyond the dominant hydropower. *Renew. Sustain. Energy Rev.* 23, 366–378. doi:10.1016/j.rser.2013.02.047

Awuku, S. A., Bennadji, A., Muhammad-Sukki, F., and Sellami, N. (2021). Promoting the solar industry in Ghana through effective public-private partnership (PPP): some Lessons from South Africa and Morocco. *Energies* 15 (1), 17. doi:10.3390/en15010017

Bekele, G., and Tadesse, G. (2012). Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. *Appl. Energy* 97, 5–15. doi:10.1016/j.apenergy.2011.11.059

Benti, N. E., Aneseyee, A. B., Asfaw, A. A., Geffe, C. A., Tiruye, G. A., and Mekonnen, Y. S. (2022). Estimation of global solar radiation using sunshine-based models in Ethiopia. *Cogent Eng.* 9 (1), 2114200. doi:10.1080/23311916.2022.2114200

Benti, N. E., Woldegiyorgis, T. A., Geffe, C. A., Gurmesa, G. S., Chaka, M. D., and Mekonnen, Y. S. (2023). Overview of geothermal resources utilization in Ethiopia: Potentials, opportunities, and challenges. *Sci. Afr.* 19, e01562. doi:10.1016/j.sciaf.2023.e01562

Bilgili, M., Bilirgen, H., Ozbek, A., Ekinci, F., and Demirdelen, T. (2018). The role of hydropower installations for sustainable energy development in Turkey and the world. *Renew. Energy* 126, 755–764. doi:10.1016/j.renene.2018.03.089

Boadu, S., and Otoo, E. (2024). A comprehensive review on wind energy in Africa: challenges, benefits and recommendations. *Renew. Sustain. Energy Rev.* 191, 114035. doi:10.1016/j.rser.2023.114035

Boke, M. T., Moges, S. A., and Dejen, Z. A. (2022). Optimizing renewable-based energy supply options for power generation in Ethiopia. *Plos one* 17 (1), e0262595. doi:10.1371/journal.pone.0262595

Bombelli, G. M., Tomiet, S., Bianchi, A., and Bocchiola, D. (2021). Impact of prospective climate change scenarios upon hydropower potential of Ethiopia in GERD and GIBE dams. *Water* 13 (5), 716. doi:10.3390/w13050716

Burnside, N., Montcoudiol, N., Becker, K., and Lewi, E. (2021). Geothermal energy resources in Ethiopia: Status review and insights from hydrochemistry of surface and groundwaters. *Wiley Interdiscip. Rev. Water* 8 (6), e1554. doi:10.1002/wat2.1554

Chemengich, S. J., and Masara, D. O. (2022). The state of renewable energy in Kenya with a focus on the future of hydropower. *Afr. Environ. Rev. J.* 5 (1), 246–260.

Chen, Y. (2018). Comparing North-South technology transfer and South-South technology transfer: the technology transfer impact of Ethiopian Wind Farms. *Energy Policy* 116, 1–9. doi:10.1016/j.enpol.2017.12.051

Degefu, D. M., He, W., and Zhao, J. H. (2015). Hydropower for sustainable water and energy development in Ethiopia. *Sustain. Water Resour. Manag.* 1, 305–314. doi:10.1007/s40899-015-0029-0

Desalegn, B., Gebeyehu, D., and Tamrat, B. (2022). Wind energy conversion technologies and engineering approaches to enhancing wind power generation: a review. *Heliyon* 8 (11), e11263. doi:10.1016/j.heliyon.2022.e11263

Eldardiry, H., and Hossain, F. (2021). Evaluating the hydropower potential of the Grand Ethiopian Renaissance dam. *J. Renew. Sustain. Energy* 13 (2). doi:10.1063/5.0028037

Endaylalu, G. A., and Arsano, Y. (2023). Ethiopia: an emerging renewable energy power Hub of Africa. *Ethiop. J. Water Sci. Technol.* 6, 38–74.

Gaddada, S., and Kodicherla, S. P. K. (2016). Wind energy potential and cost estimation of wind energy conversion systems (WECSs) for electricity generation in the eight selected locations of Tigray region (Ethiopia). Renewables: wind. *Water, Sol.* 3, 1–13. doi:10.1186/s40807-016-0030-8

Gebreslassie, M. G. (2021). Development and manufacturing of solar and wind energy technologies in Ethiopia: challenges and policy implications. *Renew. Energy* 168, 107–118. doi:10.1016/j.renene.2020.11.042

Getnet, A., Getnet, T., Beyene, A., Nallamothu, R. B., Semeneh, T., and Mulugeta, H. (2024). Assessment of solar energy potential for Bahir Dar city, Ethiopia. *Sci. Rep.* 14 (1), 22750. doi:10.1038/s41598-024-74433-1

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., and Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy strategy Rev.* 24, 38–50. doi:10.1016/j.esr.2019.01.006

Guangul, F. M., and Chala, G. T. (2021). Geothermal power potential in Ethiopia. *Clean Energy Oppor. Trop. Ctries.*, 197–216. doi:10.1007/978-981-15-9140-2_10

Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M., et al. (2024). The renewable energy role in the global energy Transformations. *Renew. Energy Focus* 48, 100545. doi:10.1016/j.ref.2024.100545

Hassanian, R., Helgadóttir, Á., and Riedel, M. (2023). Iceland wind farm assessment case study and development: an empirical data from wind and wind turbine. *Clean. Energy Syst.* 4, 100058. doi:10.1016/j.cles.2023.100058

International Hydropower Association (2022). *Hydropower Sustainability Standard: Technical Guidance*. London, United Kingdom

International Renewable Energy Agency (2022). Renewable capacity Statistics 2022. Available online at: https://www.irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022.

Iwuji, C. C., Okeke, O. C., Ezenwoke, B. C., Amadi, C. C., and Nwachukwu, H. (2016). Earth resources exploitation and sustainable development: geological and engineering perspectives. *Engineering* 8 (1), 21–33. doi:10.4236/eng.2016.81003

Joel, O. T., and Oguanobi, V. U. (2024). Geological survey techniques and carbon storage: optimizing renewable energy site selection and carbon sequestration. *Open Access Res. J. Sci. Technol.* 11 (1), 039–051. doi:10.53022/oarjst.2024.11.1.0054

Kaplan, Y. A. (2015). Overview of wind energy in the world and assessment of current wind energy policies in Turkey. *Renew. Sustain. Energy Rev.* 43, 562–568. doi:10.1016/j.rser.2014.11.027

Kebede, K. Y. (2015). Viability study of grid-connected solar PV system in Ethiopia. *Sustain. Energy Technol. Assessments* 10, 63–70. doi:10.1016/j.seta.2015.02.003

Knight, O. (2016). Ethiopia Wind Mapping: Mesoscale Modeling Report. *World Bank*. Available online at: https://thedocs.worldbank.org/en/doc/960001461946242687-0010042016/Ethiopia-Wind-Mapping-Mesoscale-Modeling-Report-Feb2016

Kebede, K. Y., and Mitsufuji, T. (2017). Technological innovation system building for diffusion of renewable energy technology: a case of solar PV systems in Ethiopia. *Technol. Forecast. Soc. Change* 114, 242–253. doi:10.1016/j.techfore.2016.08.018

Kruger, W., Fezeka, S., and Olakunle, A. (2019). *Ethiopia country report*. Report 5: Energy and Economic Growth Research Programme. Oxford, United Kingdom: Oxford Policy Management. (W01 and W05) PO Number: PO00022908.

Melikoglu, M. (2017). Geothermal energy in Turkey and around the World: a review of the literature and an analysis based on Turkey's Vision 2023 energy targets. *Renew. Sustain. Energy Rev.* 76, 485–492. doi:10.1016/j.rser.2017.03.082

Mikhaylov, A. (2020). Geothermal energy development in Iceland. *Int. J. Energy Econ. Policy* 10 (4), 31–35. doi:10.32479/ijeep.9047

Mohamed, K. I., and Kassim, S. (2024). Challenges of geothermal energy development in east afican countries: case of djibouti geothermal projects. *Int. J. Soc. Sci. Res.* 6 (2), 1–13.

Mohapatra, D. K. (2019). Analysis of Ethiopian energy system transition towards renewable energy sector expansion (Doctoral dissertation, Hochschulbibliothek der Technischen Hochschule Köln).

Mukoro, V., Sharmina, M., and Gallego-Schmid, A. (2022). A framework for environmental evaluation of business models: a test case of solar energy in Kenya. *Sustain. Prod. Consum.* 34, 202–218. doi:10.1016/j.spc.2022.09.007

Mulatu, A. B., Negash, W. A., and Teshome, M. (2023). The Status of solar energy utilization and development in Ethiopia. *Am. J. Appl. Sci. Res.* 9 (3), 97–108. doi:10.11648/j.ajasr.20230903.13

Mulugeta, M., Abi, M., and Mekonnen, T. (2021). Analysis of Opportunity Factors for Economic Development in Ethiopia: A Commentary. *Ethiop. J. Health. Dev.* 43 (2), 147–170.

Ndi, F. A. (2024). Justice concerns in large-scale renewable energy projects: a case study echoing the importance of procedural justice in wind energy development in Kenya. *Energy, Sustain. Soc.* 14 (1), 47. doi:10.1186/s13705-024-00482-z

Negash, T., Möllerström, E., and Ottermo, F. (2020). An assessment of wind energy potential for the three topographic regions of Eritrea. *Energies* 13 (7), 1846. doi:10.3390/en13071846

Orkodjo, T. P., Kranjac-Berisavijevic, G., and Abagale, F. K. (2022). Impact of climate change on future availability of water for irrigation and hydropower generation in the Omo-Gibe Basin of Ethiopia. *J. Hydrology Regional Stud.* 44, 101254. doi:10.1016/j.ejrh.2022.101254

Owusu-Manu, D. G., Mankata, L. M., Debrah, C., Edwards, D. J., and Martek, I. (2021). Mechanisms and challenges in financing renewable energy projects in sub-Saharan Africa: a Ghanaian perspective. *J. Financial Manag. Prop. Constr.* 26 (3), 319–336. doi:10.1108/jfmpc-03-2020-0014

Pasqua, C., Chiozzi, P., and Verdoya, M. (2023). Geothermal play types along the East Africa rift system: examples from Ethiopia, Kenya and Tanzania. *Energies* 16 (4), 1656. doi:10.3390/en16041656

Rodrigues, C., Pinheiro, H., and De Sousa, M. L. (2022). Clean energy transition challenge: the Contributions of geology. *Afford. Clean Energy* 47. doi:10.3390/books978-3-03897-777-3

Rotich, I. K., Chepkirui, H., Musyimi, P. K., and Kipruto, G. (2024). Geothermal energy in Kenya: evaluating health impacts and environmental challenges. *Energy Sustain. Dev.* 82, 101522. doi:10.1016/j.esd.2024.101522

Sawo, B. A. (2024). Prospects and challenges of renewable energy in Ethiopia with special focus on trends and Practices. *JIM J. Ilm. Mhs. Pendidik. Sej.* 9 (2), 651–664. doi:10.24815/jimps.v9i2.30105

Solomon, K., Fikru, W., Tesfaye, K., and Ababa, P. O. B. A. (2020). "Status of geothermal exploration and development in Ethiopia," in *Proceedings World geothermal Congress* (Iceland: Reykjavic), 1.

Stritih, U., Osterman, E., Evliya, H., Butala, V., and Paksoy, H. (2013). Exploiting solar energy potential through thermal energy storage in Slovenia and Turkey. *Renew. Sustain. Energy Rev.* 25, 442–461. doi:10.1016/j.rser.2013.04.020

Tesfaye, M., Moges, S., Melesse, A. M., and Agide, Z. (2021). Long-term water–energy–food security and resources sustainability: a case study of Ethiopia by 2030 and 2050. *International Journal of Energy and Water Resources* 5, 343–356.

Tiruye, G. A., Besha, A. T., Mekonnen, Y. S., Benti, N. E., Gebreslase, G. A., and Tufa, R. A. (2021). Opportunities and challenges of renewable energy production in Ethiopia. *Sustainability* 13 (18), 10381. doi:10.3390/su131810381

U.S. Department of Commerce (2024). *Ethiopia - Energy. International Trade Administration*. Available online at: https://www.trade.gov/country-commercial-guides/ethiopia-energy

van der Zwaan, B., Boccalon, A., and Dalla Longa, F. (2018). Prospects for hydropower in Ethiopia: an energy-water nexus analysis. *Energy Strategy Rev.* 19, 19–30. doi:10.1016/j.esr.2017.11.001

Voegeli, G., and Finger, D. C. (2021). Disputed dams: mapping the divergent stakeholder perspectives, expectations, and concerns over hydropower development in Iceland and Switzerland. *Energy Res. & Soc. Sci.* 72, 101872. doi:10.1016/j.erss.2020.101872

Wolde-Ghiorgis, W. (2002). Renewable energy for rural development in Ethiopia: the case for new energy policies and institutional reform. *Energy Policy* 30 (11-12), 1095–1105.

Woldegiyorgis, T., Benti, N. E., Habtemicheal, B. A., and Jembrie, A. A. (2024). Unleashing the power of artificial neural networks: accurate estimation of monthly averaged daily wind power at Adama wind farm I, Ethiopia. *Environ. Res. Commun.* 6, 075010. doi:10.1088/2515-7620/ad592f

Yalew, A. W. (2022). The Ethiopian energy sector and its implications for the SDGs and modeling. *Renew. Sustain. Energy Transition* 2, 100018. doi:10.1016/j.rset.2022.100018

Zegeye, A. D. (2021). Wind resource assessment and wind farm modeling in Mossobo-Harena area, North Ethiopia. *Wind Eng.* 45 (3), 648–666. doi:10.1177/0309524x20925409