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Mini Review

Unlocking Ethiopia's Renewable Energy Potential: Pathways into a Sustainable Future

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Abstract

The global energy transition necessitates a shift to renewables to mitigate climate change and ensure energy security. For developing nations like Ethiopia, this presents a critical opportunity to leverage abundant domestic resources for suitable development. Ethiopia, with over 45% of its population lacking electricity, faces a paradox of energy poverty and immense renewable potential. Its grid is 90% hydropower-dependent, making it vulnerable to climate-induced droughts. Previous studies have individually assessed Ethiopia's hydropower, geothermal, wind, and solar potential. However, a holistic analysis integrating all sectors with current policy and investment frameworks is needed. This article provides a comprehensive analysis of Ethiopia's renewable energy landscape. We synthesize the potential of hydropower, geothermal, wind, and solar resources, and propose integrated policy and investment pathways to achieve universal electrification by 2030 and position Ethiopia as a regional renewable energy exporter.

Introduction

The modern world is undergoing an unprecedented energy transformation, driven by the urgent need to alleviate climate change, enhance energy security, and achieve universal electricity access. According to the International Energy Agency (IEA), renewable energy must account for over 60% of global electricity generation by 2030 to meet the Paris Agreement's 1.5°C. For developing nations, particularly in Africa, this transition presents both a challenge and an opportunity, balancing rapid industrialization with sustainable energy transition. A way to figure out how to balance fast industrialization with long-term energy growth is required. Ethiopia, the second-most populous country in Africa, stands at the forefront of this transition. Ethiopia's energy needs are growing quickly because its GDP grew by an average of 9% a year from 2010 to 2020 [1]. However, the country faces a critical paradox: despite possessing some of Africa's most abundant renewable energy sources, over 45% of its population still lacks electricity access [2]. This energy poverty stifles economic growth, limits healthcare and education, and exacerbates rural-urban disparities. Unlike many African nations reliant on fossil fuels, Ethiopia's energy mix is already 90% renewable, primarily due to its vast hydropower capacity [3]. As the non-renewable energy sources are environmentally unfriendly due to emissions and too large for small customers, the huge opportunities of renewables in Ethiopia address these issues.

Currently, the inauguration of the Grand Ethiopian Renaissance Dam (GERD) -Abay, necessitates an urgent action of electricity generation for the whole population in Ethiopia. In the year 2025 (2017 E.C.), with the inauguration of the Grand Ethiopian Renaissance Dam, we do not just open the gates of a dam; we open the gates to a new era for Ethiopia. This is more than a monumental feat of engineering; it is the ignition of our national potential. Every megawatt of electricity generated by GERD is a shining hope, flowing into the lifeblood of our nation. What does this mean for our people? It means light where there was darkness. This is about more than just power; it is about empowerment. The reliable, affordable electricity from GERD is the foundation upon which we will build a modern, diversified economy. It means light where there was darkness, power for industries that will create millions of jobs, and the energy needed to unlock the nation's human capital, allowing its doctors, engineers, artists, and scientists to thrive and compete on a global stage. The distribution of this power, reaching every town, village, and home, is the next great national mission, a promise that the benefits of this national achievement will be shared by all and that no Ethiopian will be left in the dark. It is a rejoice with a hope of a bright future for the whole nation. GERD is a testament to what we can achieve through unity, determination, and self-reliance. It is a source of immense national pride. Its true legacy will be written in the lit-up faces of our generation, in the hub of new industries, and in the improved quality of life for every citizen. Let us celebrate this historic milestone not as an end, but as a brilliant beginning. The power is now in our hands. Let us use it wisely, distribute it justly, and together, build a brighter, more electrified future for Ethiopia.

The successful completion of our Great Dam is more than a national achievement; it is a powerful declaration of Ethiopia's commitment to a future built on clean, sustainable, and self-reliant energy. It marks the pivotal moment we begin to fully harness our greatest natural resources, not just the mighty Blue Nile, but the abundant sun and wind that grace our lands. GERD is the mighty heart of our new energy system. Its vast, consistent generation provides the stable, baseload power that forms the backbone of a modern smart grid. This stability is crucial because it enables the next phase of our energy revolution: the seamless integration of other renewable sources. This is the dawn of a true renewable energy ecosystem: with a stable grid powered by GERD, we can now deploy large-scale solar farms across our sun-drenched plains without fear of instability. When the sun shines brightest, solar power can soar, and hydropower from GERD can be stored, creating a perfect balance. This synergy ensures that our lights, factories, and homes are powered 24/7 by the cleanest sources available. Due to intermittency issues, relying on a single source, even a green one, carries risk. By building a diversified portfolio of renewable energy sources, such as hydropower, solar, and wind, we can create a resilient national grid. On days with less sun or wind, GERD provides the power. During dry seasons, solar and wind can supply the load. This diversification is the key to long-term energy security and price stability, ensuring a resilient and expanded grid.

The conventional analysis of the Grand Ethiopian Renaissance Dam (GERD) focuses on its monumental electricity generation capacity. However, a more profound and strategic insight lies in reconceptualizing the GERD as the foundational regulator for a climate-resilient Water-Enegy-Food (WEF) nexus across the Eastern Nile Basin. While its primary mandate is energy, the GERD's massive reservoir introduces an unprecedented capacity for multi-annual water storage in a region increasingly plagued by climate volatility. This function is a game-changer for systematic resilience. By strategically retaining water during periods of extreme rainfall and managed release during prolonged droughts, the GERD can mitigate the flood-drought cycle that has historically crippled hydropower generation and agricultural productivity downstream. This creates a novel opportunity for "Transboundary Load-Following." Instead of operating solely for Ethiopia's peak energy demand, the GERD's output can be dynamically dispatched to complement the energy profiles of neighboring nations. For instance, it can supply peak power to Sudan and South Sudan when their demand spikes, while they potentially develop cheaper base-load solar, keeping its major domestic relevance. This turns the GERD from a point of geopolitical contention into a source of grid stability for the entire region, creating mutual interdependence and economic incentive for cooperation. Furthermore, the regulated flow of the Blue Nile enabled by the GERD can significantly enhance downstream agricultural certainty in Sudan. A more predictable water supply, facilitated by the GERD's regulatory function, can reduce crop failure risk, enable multi-cropping seasons, and improve the efficiency of irrigation schemes. This directly enhances regional food security. Therefore, the true value of the GERD extends beyond its megawatt power supply. It is the key infrastructural asset that can decouple the Eastern Nile Basin's economic development from climate variability. The future challenge and opportunity lie in establishing a "Nexus Governance Framework", a cooperative institution between Ethiopia, Sudan, and Egypt to jointly optimize the GERD's operations for shared benefits across the water, energy, and food sectors, transforming a national project into a pillar of regional climate adaptation and sustainable development. Leaving this to the corresponding areas of study, we will turn our discussion into energy generation.

This article explores Ethiopia's renewable energy potential, analyzing how the country can leverage its hydropower, geothermal, wind, and solar resources to achieve universal electrification, energy security, and economic growth. We also examine the policy, financial, and technological barriers that must be overcome to position Ethiopia as a renewable energy leader in Africa. The article examines Ethiopia's renewable energy landscape, focusing on four key sectors: 1) Hydropower, where the Grand Ethiopian Renaissance Dam (GERD) presents both opportunities and geopolitical complexities; 2) Geothermal energy, and underutilized yet stable baseload source with 10 GW potential in the Rift Valley [4]; 3) Wind power, where Ethiopia ranks second in Africa for capacity but has developed less than 1 % of its 1,350 GW potential [5]; and 4) Solar energy, critical for rural electrification through decentralized mini-grids and pay-as-you-go (PAYG) systems. Additionally, the paper examines the policy and investment frameworks required to accelerate Ethiopia's energy transition, including public-private partnerships (PPPs), feed-in-tariffs, and cross-border energy trade within the African Continental Free Trade Area (AfCFTA). Lessons from Kenya's successful geothermal expansion and Morocco's solar initiatives provide actionable insights for Ethiopia's path forward. This study asserts that Ethiopia can achieve its goal of universal electricity access by 2030 through coordinated policy initiatives, increased foreign investment, and technological progress, while positioning itself as a renewable energy exporter in East Africa. The study is relevant for policymakers, investors, and development agencies seeking sustainable energy solutions in emerging economies.

Literature review

The scholarly and institutional discourse on Ethiopia's energy sector is vast, evolving from early resource assessments to contemporary analyses of integrated policy, market, and technological frameworks. This review synthesizes this body of work, categorizing it into thematic areas to clearly identify the research gap. The initial ideas of the literature focused primarily on quantifying Ethiopia's immense renewable energy potential. Wolde-Ghiorgis [6] was among the first to systematically document the country's energy resources in a clear and organized way, highlighting the disparity between potential and development and calling for new policies focused on rural renewable energy deployment. This foundational work has been consistently updated by international agencies. The Ethiopian Electric Power (EEP) and the Ministry of Water and Energy (MoWE) regularly publish master plans and national electrification programs [7] that provide official government estimates, placing hydropower at 45 GW, wind power at 1,350 GW, solar radiation at 5.2–6 kWh/m^2/day, and geothermal power at 10 GW.

The Global Wind Energy Council [5,8] confirms Ethiopia has the second-best wind potential in Africa, predominantly concentrated in the Somali and Oromia regional highlands. Their reports detail the exact wind corridors and provide estimates of the capacity factor, which makes Ethiopian wind projects highly competitive. IRENA's reports from 2022 and 2023 also give the most thorough technical assessments of the potential for geothermal and solar energy. IRENA's [9] "Geothermal Development in Eastern Africa" status report benchmarks how Ethiopia's progress compares to Kenya's, noting that Ethiopia's Corbetti and Tulu Moye fields are geologically similar to Kenya's Olkaria, but progress has been slow because of financial and regulatory hurdles. Solargis [10] built high-resolution solar maps identifying the best regions in the country to use photovoltaic (PV) power, which are in the east and north, ideal for both utility-scale plants and decentralized systems.

A considerable amount of recent literature investigates the essential paradox of Ethiopia's energy sector: its renewable yet precarious hydropower-dependent system. Bekele [11] and Williams [12] provide thorough analyses of the direct relationship between climate change-induced variations in rainfall patterns and power crises, as evidenced by the severe droughts of 2015, 2019, and 2023. Their research models future climate scenarios, predicting increased volatility in hydropower output and emphasizing the essential need for diversification. The Grand Ethiopian Renaissance Dam (GERD) is a focal point of study in both policy and academia. While much of the literature focuses on how it affects the countries downstream on the Nile [13], more work is looking at how it affects people in Egypt. Mulat [14] argues that GERD's 6.45 GW capacity will make it much easier to get energy and industrialize, but it will also make the system more vulnerable unless it is paired with other sources. The IEA [15] Electricity Market Report backs this up by showing that the drought in 2023 caused a 40% drop in hydropower generation. This made Ethiopia spend hundreds of millions on diesel imports and power rationing. This event has become a case study in the literature for the risks of over-reliance on a single renewable source, even if it is green.

There has been a lot more research on non-hydro renewables because costs are going down all over the world, and Ethiopia has specific needs. Literature on Ethiopian geothermal energy consistently describes it as the ideal complement to hydropower—a stable, baseload, and climate-resilient resource. Matek [4] and IRENA [9] provide thorough technical and economic assessments of the Rift Valley's potential. Mwakirani et al. [16] is particularly influential; their study of Kenya's Olkaria PPP model is presented as the definitive blueprint for de-risking geothermal exploration in Ethiopia. They explain what made the project successful: a government-led initial resources assessment, shared infrastructure development, and standardized Power Purchase Agreements (PPAs) that attract experienced international developers. The primary issue identified in all studies is the substantial cost and risk associated with exploratory drilling, necessitating government intervention [4,17]. The literature on wind energy focuses on a unique set of challenges. The resource is world-class [8], but progress has been slow. Gebreslase [18] and the African Development Bank [19] identify the main problems as: a lack of robust wind resource data at a granular level to attract financiers; (2) transmission bottlenecks, as the best wind sites are often remote from the grid; and (3) competition from historically cheap hydropower, which has historically set a low benchmark for tariff expectations. The Ashegoda (120 MW) and Adama (153 MW) wind farms are well-documented as proof of concept. However, the literature agrees that a more strategic approach to zoning and expanding the grid is needed to unlock the remaining potential. Utility-scale systems and decentralized systems are the two main areas of solar research. The literature for utility-scale is still emerging, as Ethiopia's large-scale PV sector is still in its infancy. The IRENA [20] and IEA (2022) reports focus on a dramatic reduction in global solar PV costs all over the world, emphasizing that Ethiopia can now build gigawatt-scale plants with tariffs lower than \$0.04/kWh by using auctions. Their annual reports show us that Pay-As-You-Go (PAYG) solar home systems (SHS) are helping to make solar energy more affordable. Decentralized solar for rural electrification is the most interesting area of research. GOGLA's [21] work is seminal as it looks at the global off-grid solar market. Kemenke [22] and Getu & Makeyaw [23] use this framework to analyze how PAYG models can help the National Electrification Program 2.0 [7] reach its last-mile connectivity goals in Ethiopia. The identified challenges include consumer awareness, last-mile distribution logistics, and the integration of these systems into broader mini-grid frameworks.

A consistent theme across the literature is that technical potential is meaningless without frameworks that make it easier to use. The World Bank's "Doing Business" reports (and subsequent investment climate assessments) have consistently highlighted regulatory impediments. The World

Bank [17] explicitly notes that Ethiopia's process for approving Independent Power Producers (IPPs) is one of the longest in Africa. It takes 2 to 3 years, while it only takes 6 to 9 months in Kenya and Senegal. This is attributed to bureaucratic fragmentation, lack of a single authority for renewables, and legacy policies that favored a state-owned monopoly (EEP). Financial barriers are equally well-documented. The "Global Landscape of Renewable Energy Finance" report from IRENA [20] identifies a critical gap in project financing for emerging economies. This is even worse for Ethiopia because it doesn't have enough foreign exchange and a difficult macroeconomic environment, which makes foreign direct investment (FDI) less attractive. Research indicates various methods to address the issue. Getu and Makeyaw [23] advocate that development partners should set up a separate fund for renewable energy development. The AfDB [24] and the IEA (2022) are two other groups that back using de-risking tools like guarantees (like partial risk guarantees) and selling sovereign green bonds to get money from international capital markets for green projects. Serious discussions have been conducted about feed-in tariffs (FiTs) and auctions as policy tools. Early literature from a decade ago strongly advocated for FiTs to kickstart the market, strongly supported FiTs as a way to get the market going [6]. Recent research, particularly from the IEA [25], indicates a global shift towards competitive auctions, akin to those in Morocco and South Africa, which have significantly reduced costs. Recent research concurs that Ethiopia ought to implement a technology-specific auction system to ensure transparency and minimize costs [20,25].

Research is increasingly focusing on the potential for Ethiopia to emerge as a regional power exporter. The Eastern Africa Power Pool's (EAPP) annual reports for 2022 explain the plans for the physical infrastructure that will be needed for cross-border interconnectors. Cervigni's (2023) research shows that Ethiopia's hydropower, geothermal, and wind energy could provide cheap, clean power to Sudan, South Sudan, Kenya, and Djibouti, fostering regional economic integration. In general, comparative studies with other African nations provide critical lessons. Mwakirani et al. [16] discuss that the "Kenyan model" for geothermal development is the most frequently cited example for Ethiopia. Kenya has been successful because the Kenya Electricity Generating Company (KenGen) took on the initial risk of exploration and then worked with private companies. The IEA [20] also pointed out that Morocco's Noor solar complex is a great example of how to use well-structured auctions and government-backed offtakers to attract massive investment in concentrated solar power (CSP) and PV.

- The existing literature provides significant insights into multiple aspects of Ethiopia's energy landscape, encompassing hydropower vulnerability, geothermal potential, and solar pay-as-you-go systems; nevertheless, a considerable gap remains. There is no comprehensive, current analysis that integrates the following components:A holistic view of all renewable sectors (hydro, geothermal, wind, and solar) under a unified framework.
- A critical analysis of policy and investment barriers, using the most recent reports from the World Bank, IEA, and IRENA (2022–2023) as examples.
- An actionable roadmap that synthesizes lessons from Kenya (geothermal PPPs) and Morocco (solar auctions) into a coherent strategy tailored to Ethiopia's specific political and economic context.
- A clear articulation of how decentralized renewables can achieve universal electrification through decentralized renewables and establish a regional export strategy.

This study aims to rectify this gap. It goes beyond separate analyses to give a full evaluation that clearly connects resource potential with modern policy tools and investment models. This gives Ethiopia a real plan for becoming a leader in renewable energy.

Ethiopia's Energy Landscape: Current Status and Challenges

Ethiopia's energy sector is a complex tapestry of significant achievement juxtaposed with profound challenges, characterized by rapid demand growth, a precarious generation mix, deep infrastructural inequities, and a regulatory environment in transition. A detailed, multi-faceted examination is crucial to understand the starting point for any sustainable energy pathway. The rate of electrification in the country has shown a remarkable improvement, from 5% in 2000 to about 54% in 2024, connecting more than 60 million people [2,24]. The government's National Electrification Program (NEP 2.0), which includes both grid expansion and off-grid solutions, is mostly to attribute this progress. But this aggregate figure obscures severe and long-lasting differences. Most cities, about 85% to 90%, with major cities like Addis Ababa nearing full access. In stark contrast, rural electrification languishes at around 30-35%, leaving nearly 55 million people in the dark [2]. This urban-rural divide perpetuates a cycle of poverty, limiting access to education (e.g., inability to study after dark), hindering economic productivity (e.g., no power for agro-processing), and compromising healthcare services (e.g., lack of refrigeration for vaccines and medicines). Beyond the urban-rural split, significant regional disparities exist [27]. The primary energy source of these off-grid populations remains traditional biomass (wood, charcoal, dung), used for cooking and heating by over 90% of the rural population. This reliance leads to severe health issues from indoor air pollution (a leading cause of mortality in Ethiopia) and environmental degradation through deforestation and soil erosion (IEA, 2022).

Hydropower accounts for approximately 90% of Ethiopia's installed capacity, which is around 5.3 GW, and an even greater percentage of the energy generated [3,28]. The main part of this system is a series of big dams on the Omo and Abbay (Blue Nile) rivers. Some of the most important operational facilities are Gilgel Gibe III (1,870 MW), Tekeze (300 MW), Gilgel Gibe II (420 MW), Melka Wakena (153 MW), and Fincha (134 MW). Recently, the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile has been completed. With an installed capacity of 6.45 GW, it will more than double the country's generation capacity. This reinforces that Ethiopia appears as a country that uses renewable energy, but it also brings systemic risk. Because the system relies so heavily on hydropower, it is very sensitive to the acute vulnerability of climate variability. The El Niño Southern Oscillation (ENSO) has a big impact on Ethiopia's climate, making floods and droughts happen in cycles. The levels in the reservoirs went down a lot during the very dry years of 2015–2016 and, more recently, 2022–2023. The 2023 drought, which was found to be the worst due to climate change, cut hydropower generation by 40% - 50%. This caused rolling blackouts across the country that lasted for months, power rationing for industrial customers, and a significant drop in economic activity [12,15].

To compensate for this shortfall, the government was forced to activate expensive diesel-powered generation plants. The cost of diesel generation is exorbitant, estimated at $0.25-$0.30 per kWh, which is 5-6 times the cost of hydropower generation ($0.05-$0.06 per kWh). In 2023, this emergency measure cost the national utility, Ethiopian Electric Power (EEP), hundreds of millions of dollars in fuel imports, straining foreign exchange reserves and contributing to a fiscal deficit [2,28]. Furthermore, Ethiopia resorted to importing power from neighboring Djibouti and Sudan, albeit in limited quantities due to constrained interconnection capacities, highlighting a lack of self-sufficiency despite abundant resources. The Ethiopian electricity transmission and distribution network is very extensive, but it is plagued by critical deficiencies. It is primarily managed by Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU). The national grid has 90,000 kilometers of distribution lines and 18,000 kilometers of transmission lines. The majority of the transmission lines operate at 230 kV and 400 kV. However, its reach is uneven, heavily biased towards the north and central parts of the country, while the vast lowland regions in the east and south remain largely unconnected [24]. A primary challenge is the high technical and non-technical losses, which average 15-17% across the system. Technical losses are attributed to overloaded transformers, outdated switchgear, and long, inefficient distribution lines in rural areas. Non-technical losses, including commercial losses from inadequate metering, billing inefficiencies, and electricity theft, further erode the financial viability of the utility companies, reducing revenue available for reinvestment in maintenance and expansion [17,29]. For rural electrification, the cost of grid extension is prohibitively high, often exceeding $8,000-$10,000 per km in rugged terrain, for communities with low population density and low initial energy demand. This means that a purely grid-based approach to getting 100% access is not cost-effective, so we need to rely more on decentralized renewable energy solutions [7]. The grid's design and operation are not yet optimized to handle variable renewable energy (VRE) inputs from large-scale solar and wind farms. This is because the grid isn't balanced. After all, it doesn't have enough smart grid technologies, automation, or energy storage systems [23].

The policy and regulatory environment, while improving, remains a significant barrier to investment and development. The energy sector has historically been a state-owned monopoly. Although the government has opened the door for Independent Power Producers (IPPs) since 2013, the implementation has been slow and cumbersome. The process for approving IPP projects is notoriously protracted, taking an average of 2-3 years from proposal to financial close, compared to 6-9 months in more agile markets like Kenya or South Africa [17]. This is due to bureaucratic fragmentation, requiring approvals from multiple agencies (MoWE, EEP, EEU, Ethiopian Investment Commission, National Bank), often with unclear timelines and overlapping mandates. Land acquisition for energy projects is another major hurdle. Geothermal exploration in the Rift Valley and wind farm expansions are just two examples of projects that have been put on hold because of complicated land tenure systems, conflicts with local communities, and inadequate compensation mechanisms [4,8]. The state-owned utilities have limited capital expenditure capacity and struggle with low cost-recovery tariffs. The country faces a severe foreign exchange shortage, making it difficult for international investors to repatriate profits. While Ethiopia has immense potential for green finance, it has yet to tap into international climate funds (e.g., Green Climate Fund) or issue sovereign green bonds at scale. Geothermal development, in particular, is stalled by the high upfront capital required for exploratory drilling, which carries a high risk of failure, deterring private investors without robust public risk-sharing mechanisms [16,20].

Most importantly, a less discussed but equally critical challenge is the shortage of skilled human resources. The energy sector is growing quickly, but the number of human resources who can work in it is not significant. There aren't enough skilled engineers and technicians for new technologies like geothermal drilling, solar PV installation and maintenance, grid modernization, and energy efficiency. Vocational schools and colleges still aren't producing enough graduates with the practical skills required by the industry. To the government, the energy sector, and academic institutions, we want to put our outlook here: our nation stands at a pivotal moment. With ambitious goals for universal electrification, the integration of renewable energy, and the operation of monumental projects, the demand for a highly skilled, innovative, and readily employable electrical engineering workforce is a significant need. A critical gap threatens to undermine this progress: the misalignment between our academic output and the practical, evolving needs of the energy sector. We must act with urgency and unity to transform our educational system. The future of our energy security and economic development depends on it. This is not merely an educational issue; it is a national economic imperative. Here is what must be done: to the Colleges and Universities, curricula must be dynamically updated to include hands-on training in smart grids, renewable energy integration, power electronics, grid cybersecurity, and digital twin technologies. We need problem-solvers, not just memorizers. They need to establish deep, structural partnerships with energy companies. This means every student must complete at least one significant internship, gaining real-world experience before graduation. Practicing engineers must regularly teach specialized courses and labs, provide students with access to and skills to the same tools and technologies used in the field. To the government, it is not enough to produce graduates; there should be a plan to employ them. The government must create and fund a "Graduate Engineering Corps" to deploy new graduates into critical national projects, from rural electrification to grid maintenance and renewable energy plant operation. Besides, the government should provide tax incentives and subsidies for private companies that hire and mentor fresh graduates, and tie public funding for universities to key performance indicators like employment rates and industry satisfaction with graduates. To the Energy Sector Companies and Organizations, there should be a proactive engagement with universities to clearly articulate the specific skills needed today and in the future. They should fund specialized labs, sponsor capstone projects based on real company challenges, and offer apprenticeship programs. This is not charity; it is a strategic investment in their own future workforce. Besides, there is a need for a permanent seat at the table in the university accreditation and review boards to ensure educational outcomes are directly relevant. The synergy among a robust education system, a proactive government, and an engaged industry is non-negotiable. We must break down the silos between academia and the workplace. Without this framework, the plan for renewable energy and rural electrification is a superficial strategy and can't be addressed practically. This "skills gap" threatens to derail ambitious projects and increase dependence on expensive foreign expertise [23] (Table 1).

This comparison shows Ethiopia's unique position. It has a 90% share of renewable energy, which is higher than that of most African countries and is impressive. It is a critical weakness that it hasn't used a lot of different renewable technologies, though. Kenya, on the other hand, has built a successful multi-technology renewable system. The grid system in South Africa is stronger and more industrialized than it used to be, and the country has made a lot of progress in integrating utility-scale wind and solar through its successful auction programs. Ethiopia's challenge is thus twofold: to rapidly expand access while simultaneously diversifying its generation mix to enhance resilience, a task that requires addressing the deep-rooted infrastructural, financial, and regulatory challenges detailed above.

Ethiopia's Untapped Renewable Energy Potential for Clean Energy

Ethiopia's renewable energy resources are not merely abundant; they are on a scale that could potentially reposition it as a global green energy powerhouse and the primary engine for decarbonization in the Horn of Africa. This section provides a meticulous, resource-by-resource breakdown of this huge potential, examining specific projects, technological problems, and the exact reasons why this treasure hasn't been used yet.

Hydropower: Beyond the GERD Monolith

The conventional estimate of Ethiopia's hydropower potential is 45 GW, but recent basin-wide studies incorporating advanced digital elevation models and flow data suggest a technically feasible potential could be as high as 60 GW under optimized, cascaded development scenarios [17,27]. Currently, only about 4.5 GW (10% of the conservative estimate) is operational. The Grand Ethiopian Renaissance Dam (GERD) has begun initial turbine testing. It is more than 90% finished and has begun testing its first turbines. However, an exclusive focus on mega-dams exacerbates climate vulnerability. A diverse portfolio is the key to the future of Ethiopian hydropower:

- **Mega-Dams for Baseload and Export:** The main mega-dam for baseload and energy export is GERD. It is built for energy generation, regional flood management, and ensuring water security. Its annual energy generation is projected at 15,692 GWh. The planned 2.1 GW Koisha Dam on the Omo River is the next mega-project in the pipeline.
- **Cascade and Run-of-River (ROR) Projects for Resilience:** A strategic shift towards smaller, cascaded systems and ROR projects is critical. These projects have significantly smaller reservoirs, reducing evaporation losses and social displacement, and are less vulnerable to multi-year droughts. Identified sites for such development include the Genale Dawa III (254 MW), Halele Werabesa (422 MW), and the Border (1,200 MW) projects, which collectively could add over 2 GW of more resilient capacity [28].

Table 1: Comparative Energy Snapshot: Ethiopia and Regional Peers (2023).

Indicator	Ethiopia	Kenya	South Africa
Population (Millions)	123	55	60
Electrification Rate	54%	75%	85%
Installed Capacity (GW)	~5.3	~3.1	~58
Renewable Share of Grid	90% (mostly hydro)	90% (Geothermal, Wind, Hydro)	25% (wind, solar, and water)
Key Generation Mix	Hydro (4.5 GW op.)	Wind (0.4 GW) and geothermal (0.9 GW)	Coal (38 GW), Wind (3.4 GW), Solar (2.6 GW)
Avg. Gen. Cost ($/kWh)	(Hydro) $0.05–0.08	$0.07–0.10 (Geothermal)	$0.10–0.15 (Wind)
Major Challenge	Climate vulnerability & Grid Access	High upfront costs (Geothermal).	Grid integration & Coal dependency

Sources: (IEA, 2022; World Bank, 2023 [2]; IRENA, 2023a [20]; National Utilities Data).

- **Pumped Storage Hydropower (PSH) for Grid Stability:** It will be very important to keep the grid stable as more solar and wind power plants will become paramount. Ethiopia's topography is ideal for PSH. Preliminary feasibility studies have identified several sites, including a potential 1,000 MW facility near the Tis Abay waterfalls, which could serve as the country's extensive battery, storing excess solar energy during the day for use at night [9].

Geothermal: The Sleeping Giant of the Rift Valley

The Ethiopian Rift Valley, part of the larger East African Rift System, holds a conservatively estimated geothermal potential of 10 GW, with some experts projecting it could exceed 15 GW [4,9]. This is Ethiopia's most important energy security asset because it is a clean, baseload, and climate-resilient power source that can run at 90% - 95% capacity. Still, the pilot Aluto Langano plant has only reached 7.3 MW of capacity, which is less than 0.1% of what it could be. The development is mostly in high-temperature fields (>200 °C), which are ideal for power generation:

- **Corbetti Caldera:** One of the biggest calderas in the world is the Corbetti Caldera. It is to the south of Addis Ababa. Estimates of resources suggest a range of 500 to 1,000 MW. Corbetti Geothermal PLC, a partnership between Berkeley Energy and Iceland Drilling, has finished exploring and signed a 500 MW PPA. The project is in the advanced stage of securing financing for full-scale development.
- **Tulu Moye:** This is next to the Corbetti field and is estimated to produce 150 MW of power. Tulu Moye Geothermal Operations S.A., Meridiam, and Reykjavik Geothermal are progressing with drilling and aim for an initial 50 MW by 2026.
- **Other Proven Fields:** The Aluto Langano (70 MW more than the pilot), Dofan (200 MW), and Abaya (100 MW) fields are all very promising. Exploration is also ongoing in the Dallol and Danab fields in the Afar region.

The primary barrier remains the high capital intensity and risk of the initial exploration phase. Drilling one exploratory well costs $5-$7 million, with a 20-40% risk of failure. This necessitates a public-private partnership (PPP) framework wherein the government or other public entities assume the risk of initial exploration, as evidenced by successful implementation in Kenya [16].

Wind Power: A Resource of Global Significance

Ethiopia's wind energy potential is not only the second-largest in Africa, but it is of world-class quality. The GWEC [8] estimates 1,350 GW is a theoretical potential. The technically feasible potential is thought to be between 30 and 50 GW, which is still enormous [5,18]. This is because of land use restrictions, distance to the grid, and wind class. The resource is concentrated in specific corridors:

- **The Somali Regional State Corridor:** This includes the areas around Aysha, Dewele, and Shinile, with average wind speeds exceeding 9.5 m/s at 100m hub height and capacity factors of over 50%.
- The South-Eastern Corridor (Oromia): Areas around Mega, Yirgalem, and Negele, with wind speeds of 8.5-9.0 m/s.
- The Tigray Corridor: Areas around Mekele and Adigrat, with speeds of 7.5-8.5 m/s.

The Ashegoda (120 MW), Adama I (51 MW), and Adama II (153 MW) farms together can produce 324 MW of power. The 100 MW Assela wind farm is under development. The gap between potential and developed capacity is arguably the largest of any resource. Key barriers include the need for detailed, bankable wind resource measurements, high upfront costs for building transmission lines to remote, high-wind sites, and the need for a regulatory framework that values the complementary nature of wind and solar generation profiles.

Solar Energy: The Key to Universal Access and Diversification

Ethiopia receives between 5.2 and 6 kWh/m^2/day of solar radiation. The Afar, Somali, and Oromia areas get the most, up to 6.5 kWh/m^2/day. This is more significant than the average for many European countries that use solar power (for example, Germany uses 2.9 kWh/m^2/day) [10]. Despite this, the grid-connected solar contribution is negligible (<1%). The potential is bifurcated:

A. Utility-Scale Solar PV: The technical potential for ground-mounted PV is vast, estimated at over 50 GW. The first major project, the 250 MW Metehara PV plant, is under construction. The government has identified and prioritized sites for development through the "Solar Energy Development Roadmap," including areas in Afar (Logya, 500 MW), Somali (Fafan, 300 MW), and Oromia (Babile, 200 MW). The Levelized Cost of Energy (LCOE) for large-scale solar in Ethiopia is now highly competitive, estimated at $0.035-$0.055 per kWh, making it the cheapest source of new generation capacity [20].

B. Distributed and off-grid solar: This is the most critical segment for achieving universal access. Solar Home Systems (SHS): Pay-As-You-Go (PAYG) SHS have emerged as the dominant solution for tier 1 and 2 electrifications (basic lighting and phone charging). Companies like D. and SunFunder Light have deployed hundreds of thousands of units. GOGLA [21] discussed that the market is growing by more than 25% every year. The Solar Mini-Grids (for clusters of households and productive uses (e.g., rural clinics, schools, small businesses), solar-diesel or solar-wind-battery hybrid mini-grids) are the optimal solution. Ethiopia can build more than 2,000 mini-grids to serve remote communities. The AfDB-funded "National Electrification Program 2.0" aims to develop 200 pilot mini-grids by 2026 [7].

Synthesis: An Integrated Renewable Energy Portfolio

The real potential lies not in examining these resources individually, but in leveraging their synergies (Table 2). A diverse mix has strategic advantages, like making systems more reliable. Geothermal energy, for example, provides a steady supply of energy all day and night. Hydropower reservoirs can be used to store energy and meet peak demand. Wind generation is often highest at night, which works well with solar. The national grid is strong and can handle challenges because it has so many different types of power. Second, economic optimization lowers the overall cost of electricity by using the cheapest resource available at any given time. For example, solar energy during the day, wind energy at night, or hydro/geothermal energy for baseload. This makes businesses more competitive. Finally, Ethiopia's export revenue, which comes from a variety of surplus generation capacity, makes it a reliable energy exporter to Sudan, South Sudan, Kenya, and Djibouti through the Eastern Africa Power Pool (EAPP). This is important for the country's foreign exchange [30]. To turn this integrated potential into a reality, the next sections will discuss how to solve the problems of grid modernization, strategic investment, and regulatory reform. The issue is not the resource base; rather, it is the environment that facilitates possibilities.

Policy and Investment Pathways for a Renewable Future

We need to change our policies and get a lot of money to work together to make Ethiopia's huge potential for renewable energy into a real, climate-resilient energy system. This section gives a detailed, multi-level plan of actions that goes beyond general suggestions to include specific tools, changes to institutions, and a sequence of actions.

Foundational Policy and Regulatory Overhaul

The current regulatory labyrinth is the single greatest impediment to investment. A root-and-branch reform is necessary to create a transparent, efficient, and investor-friendly environment. Establishing a Renewable Energy Development Authority (REDA) helps to create a powerful, centralized, one-stop-shop agency to streamline the entire investment cycle for renewable projects. REDA would consolidate currently fragmented functions from the MoWE, EEP, EEU, and Ethiopian Investment Commission. Its mandate would include: project pre-feasibility and land banking, managing competitive auctions, coordinating environmental and social impact assessments (ESIAs), and serving as the single point of contact for all permitting, aiming to slash approval timelines from 2-3 years to under 12 months [17]. Modernizing the Legal and Tariff Framework will also enact a Renewable Energy Act to provide a stable, long-term legislative foundation, superseding outdated proclamations. This act should enshrine principles of open access to the grid for IPPs, priority dispatch for renewables, and clear rules for wheeling and banking. Transition from a state-led model to a competitive reverse auction system for utility-scale solar, wind, and geothermal. Following the successful models of Morocco (MASEN) and South Africa (REIPPPP), this will drive down costs through competition and ensure transparency. Initial auctions should be technology-specific (e.g., a 500 MW solar round, a 300 MW wind round) to build a diverse portfolio [20,25]. The national utility also needs to have a tariff structure that reflects costs. These subsidized tariffs are bad for the economy and stop private investment because they make it hard for EEU to be a reliable buyer. The utility's finances and creditworthiness will get better if tariffs are changed in stages and low-income households get direct subsidies.

De-risking Investments and Mobilizing Finance

The estimated $40 billion needed by 2030 won't be enough from public funds alone. We need to use a complicated mix of public, private, and international climate finance, with a focus on using public capital to de-risk and crowd in private investment. By 2025, the government should issue Ethiopia's first sovereign green bond. This will help the government set up a clear framework that follows international standards like the ICMA Green Bond Principles. The fund should be used to build strategic transmission infrastructure and to lower risk. To help with this, it might be helpful for Ethiopian banks to issue corporate green bonds that can be used to lend money to projects that use renewable energy [31-34].

The National De-risking Facility will help raise capital through the sale of sovereign green bonds, concessional loans from development partners like the World Bank and AfDB, and climate finance from the Green Climate Fund. This facility would offer a variety of tools, such as Partial Risk Guarantees (PRGs) that protect against political risks like currency inconvertibility and transfer restrictions, which are significant uncertainties for foreign investors; Viability Gap Funding (VGF), which gives capital grants to make pioneering projects (especially geothermal) financially viable until

Table 2: Ethiopia's Integrated Renewable Energy Potential Portfolio.

Resource	Theoretical Potential	Technically Feasible Potential (2035 Target)	Current Capacity (2024)	Key Projects in Pipeline	LCOE Range (USD/kWh)	Primary Application
Hydropower	45 - 60 GW	15 GW	4.5 GW	GERD (6.45 GW), Koisha (2.1 GW)	0.05 - 0.07	Baseload, Peak Load, Export
Geothermal	10 GW	5 GW	7.3 MW	Corbetti (500 MW), Tulu Moye (150 MW)	0.07 - 0.10	Climate-Resilient Baseload
Wind Power	1,350 GW	30 GW	324 MW	Assela (100 MW), Aysha (500 MW)	0.04 - 0.06	Bulk Generation, Complement to Solar
Utility Solar	> 50 GW	15 GW	~5 MW	Metehara (250 MW), Fafan (300 MW)	0.035 - 0.055	Daytime Baseload, Peak Shaving
Biomass & Other	1.5 GW (waste)	500 MW	Negligible	Waste-to-Energy in Addis Ababa	0.08 - 0.12	Waste Management, Distributed Gen.

Sources: IRENA [20], GWEC [8], EEP [28], MoWE [27], and Author's Synthesis.

economies of scale are reached; First Loss Capital, which takes a junior equity position in projects to attract senior commercial debt; and Tapping into Carbon Markets, which lets Ethiopia's renewable projects earn carbon credits under Article 6 of the Paris Agreement. If developers register their projects with systems like VERRA or the Gold Standard, they can sell Emissions Reduction (ER) certificates and make more money. This helps the project's money situation. The government needs to set up a strong national carbon registry and authorization framework for this to happen [2]. Foreign Exchange Solutions also needs to set up a separate forex escrow account for IPPs to deal with the important forex shortage. A percentage of revenue from power exports (e.g., from GERD to Sudan) and from domestic tariff payments in ETB could be pooled into this account, which is then used to guarantee forex availability for debt servicing and profit repatriation for renewable energy investors.

Technology-Specific Development Strategies

Each renewable technology faces unique challenges requiring tailored policy approaches.

Geothermal: Adopting the Kenyan PPP Model is valuable. The government should be in charge of the first resource assessments and the first high-risk exploration wells, which should be done through the proposed REDA or EEP. Once a resource is confirmed, private developers who are experts in that area are invited to bid on the construction and operation of the power plant. This model, which was perfected at Olkaria, directly addresses the main risk of exploration that stops investment [16].

Solar and wind: Should focus on integrating and hybridizing with the grid. The government should pay for and require research on how to use variable renewable energy (VRE). This includes spending significant capital to strengthen and expand the grid so that high-potential wind corridors in the Somali region can connect with solar sites in Afar; testing battery energy storage systems (BESS) at key substations to deal with intermittency; and giving incentives to hybrid power plants (like solar-wind, solar-diesel-battery) for off-grid mini-grids to make them more reliable and cheaper.

Distributed renewables for rural electrification: Start a Mini-Grid Acceleration Program that gives developers standard, pre-approved technical designs, easier permits, and financing based on results (for example, $/customer connected).

Implement a PAYG Solar Tax Holiday: Exempt import duties and value-added tax (VAT) on certified SHS and their components for 5-10 years to lower the end-consumer price and accelerate market penetration [21].

Regional Integration and Market Creation

The idea that Ethiopia could become a regional power exporter is a significant reason why renewable energy is growing so quickly. It will be easier to do this if we speed up the building of important cross-border transmission interconnectors, like the Ethiopia-Kenya High Voltage Direct Current (HVDC) line, which is needed to send hydro, geothermal, and wind power to a market that needs a lot of power. It is also very helpful to make sure that the rules and standards for the grid in the Eastern Africa Power Pool (EAPP) are the same as those in other countries. This will make it easier to trade electricity across borders. Furthermore, active engagement in the African Single Electricity Market (AfSEM) initiative, leveraging anticipated export revenues as collateral, is crucial for securing financing for domestic generation projects [19,21].

Human Capital and Institutional Development

Policies are ineffective without the capacity to implement them. So, it's important to start a national program to train employees in the skills of renewable energy. Partner with universities (like Addis Ababa University, Arba Minch University, and all the other universities in the country) and vocational colleges to develop specialized classes in geothermal engineering, solar PV technology, grid management, and energy economics, as addressed before in this article. It looks good to set up special training centers at important project sites, like in the Rift Valley for geothermal. The goal should be to train and certify a specific number of technicians and engineers by 2030. This will really help the country move toward a Golden Age. Most importantly, fund post-doctoral research programs and partnerships with top institutions in Iceland (geothermal), Denmark (wind), China, and Germany (solar) to help build local research and development (R&D) capacity. Ethiopia must implement policy reforms and strategic investments to establish itself as a leader in renewable energy.

A Roadmap for Ethiopia's Renewable Energy Leadership

Ethiopia needs a ten-year plan that runs from 2025 to 2035 and should be broken down into three ambitious phases in order to become a leader in renewable energy. By 2030, the main goal is to have the country with a green energy economy that can handle climate change and give everyone access to electricity. By 2035, it will be the largest exporter of renewable energy in East Africa. The main phases that will guide this change are diversification, decentralization, strategic investment mobilization, regional integration, and inclusive growth.

The first phase needs to focus on creating an environment for rapid scale-up. This critical period requires enacting a comprehensive Renewable Energy Act and establishing a powerful, streamlined Renewable Energy Development Authority (REDA) to serve as a one-stop shop for investors. Concurrently, the government should launch the first technology-specific auctions for solar and wind power, implement a phased cost-reflective tariff adjustment to improve utility finances, and issue Ethiopia's inaugural sovereign green bond to seed a national de-risking facility. Getting the Corbetti and Tulu Moye geothermal fields financially closed, starting up the Metehara solar and Assela wind farms, and starting a faster "Light for All" program that uses decentralized solar to connect millions of new customers are all important steps in this phase of the project. Using real Key Performance Indicators (KPIs) to see how well this phase goes is helpful. These include raising the national electrification rate above 70%, getting more than $3 billion in private investment commitments, and increasing renewable capacity to over 2 GW. The second phase will build on this base and will prioritize deep diversification and the sophisticated integration of variable renewables into the national grid. During this phase, the commissioning of the first major geothermal plants and the initial wave of auctioned solar and wind projects necessitating the introduction of a modernized Green Grid Code and the piloting of utility-scale battery storage to ensure system stability should be conducted. The Ethiopia-Kenya HVDC interconnector will be a big step forward in this phase. It will let Ethiopia export a lot of renewable energy and solidify its regional role. By the end of this phase in 2030, Ethiopia should have reached its goal of providing electricity to its domestic and neighbors, built more than 10 GW of renewable capacity, cut its annual CO_2 emissions by more than 5 million tons, and set up a strong baseload. The last phase is meant to keep Ethiopia at the forefront of new technologies and a regional center for green energy. The main part of a carbon-neutral power system will be the fully diversified and resilient grid, which will have 10 GW of solar and wind power and 5 GW of geothermal power. This extra clean energy will not only help the Eastern Africa Power Pool meet long-term export contracts, but it will also help start a green hydrogen economy that will export fertilizer and make it for use at home. Building large-scale pumped storage hydro will also help keep the grid in balance. When this strategic roadmap is done, Ethiopia will be able to export more than $1 billion worth of goods every year, create more than 200,000 jobs in the renewable energy sector, and make the nation a center for clean energy finance and innovation.

The successful execution of this complex roadmap hinges on a robust implementation framework and proactive risk mitigation. Governance must be led by a high-level National Energy Council, chaired by the Prime Minister, to ensure cross-ministerial coordination, with REDA serving as the operational secretariat. Transparency will be maintained through a public dashboard tracking all KPIs. Critical risks, including political volatility, macroeconomic instability, social discontent, and climate change itself, must be actively managed through cross-party policy endorsements, a functional forex escrow mechanism for investors, comprehensive community benefit-sharing schemes, and climate-resilient infrastructure design. Through this coordinated and steadfast approach, Ethiopia can successfully translate its immense natural potential into enduring energy security, economic prosperity, and regional leadership. Hence, Ethiopia's renewables could power not just its industrialization, but also a clean energy corridor across East Africa. The time for decisive action is now.

Limitations and Future Research Directions

This study provides a comprehensive analysis and strategic framework for Ethiopia's transition to renewable energy; however, it is crucial to acknowledge its inherent limitations, which concurrently delineate a robust agenda for future academic and practical inquiry. The outcomes and projections articulated in this article are primarily constrained by their reliance on secondary data obtained from international organizations and national reports, in conjunction with the authors' imperative for prompt action on the issue. Despite reliable sources, they may vary in methodological assumptions, update frequencies, and contextual applicability, potentially introducing biases or gaps that affect the precision of resource assessments and economic forecasts. Moreover, the proposed pathways, though informed by global best practices and lessons from regional peers, are ultimately contingent upon political stability, sustained macroeconomic health, and consistent policy implementation, variables that are inherently dynamic and challenging to model with certainty over a decadal horizon. The analysis also operates at a macro-level, which may overlook micro-level complexities such as localized land tenure disputes, community-specific social acceptance, and hyper-localized environmental impacts that could significantly alter project feasibility and timelines.

A critical, overarching limitation lies in the prerequisite of stable and secure governance across all regions for the successful execution of this energy vision. The government's primary mandate extends beyond energy policy to encompass the fundamental responsibility of ensuring national security and the safety of citizens. Present regional instabilities and conflicts pose a profound risk to the development and operation of large-scale energy infrastructure, potentially deterring investment, disrupting supply chains, and delaying timelines. Hence, a paramount critique and essential precursor to the entire renewable energy transition is the urgent need for the government to intensify its efforts in correctly managing internal security. This involves impartially addressing the root causes of regional conflicts through inclusive dialogue, upholding the rule of law, and ensuring the protection of all communities. Without a secure and stable environment, the massive public and private investments required for this energy transformation become exceedingly vulnerable, and the overarching goals of universal access and economic development remain unattainable. The government must therefore pivot towards a development-centric governance model that prioritizes human security, transparent institutions, and the creation of a predictable environment conducive to long-term capital investments over political expediency.

Consequently, these limitations reveal numerous essential and interconnected avenues for future investigation. Future research should prioritize the acquisition of high-fidelity, primary data through extensive, site-specific feasibility studies for hybrid renewable systems, particularly in Ethiopia's remote and conflict-prone regions, to generate detailed data essential for reducing investment risks and guiding implementation strategies. There is an urgent need for advanced, multi-sectoral economic modeling that goes beyond simple cost comparisons to look at the full range of social, economic, and political effects of the energy transition. This includes its potential to promote peace or, if not managed well, to make resource-based conflicts worse. This includes precise projections of job creation, GDP growth, public health enhancement, and the impact of distributed versus centralized generation models on national security. Furthermore, comprehensive research is essential to develop and assess novel financial and governance mechanisms tailored for fragile and emerging state contexts. This includes making good blended finance models that include peacebuilding metrics, setting up local currency guarantee facilities, making frameworks for community equity participation, and putting in place third-party monitoring protocols for projects in high-risk areas to make sure that benefits are shared fairly and openly. The most important area for future research is to create integrated frameworks that connect energy planning with conflict sensitivity and stability operations in a way that ensures that the search for a renewable future helps rather than hurts the basic goals of national security, social cohesion, and sustainable development for all Ethiopians.

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