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East Africa's Renewable Energy Diversity Landscape: A case of Kenya's Potential, Progress and Future Prospects

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

East Africa holds enormous renewable energy (RE) resources, including solar, wind, geothermal, hydroelectric power and green hydrogen, yet there remains a substantial gap in harnessing these resources to meet rising energy demands and mitigate climate change. This study focuses on Kenya, aiming to assess its renewable energy potential, examine current infrastructure, and chart future paths for sustainable development. Geothermal energy makes up 28.8% of Kenya's total installed capacity (3,264.42 MW), with hydro, wind, solar, and bio-energy contributing 25.5%, 13.3%, 7.4%, and 0.1%, respectively, accounting for about 75% of the total generation. Despite

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this, utilization rates are low: hydro at 10.7%, geothermal at 9.4%, wind at 7.3%, solar at 1.6%, and bio-energy at 1.5%, revealing substantial underutilization. Kenya currently generates 2453.9 MW of RE, with ongoing projects poised to raise this capacity to 3982.9 MW, inclusive of those under development. Compared to other East African countries, Kenya leads, with Uganda at 1,245.5 MW, Tanzania at 848 MW, Burundi at 46.7 MW, Rwanda at 166.7 MW, and South Sudan at 74 MW. By 2032, Kenya aims to add 350–450 MW of Green Hydrogen power and 150–250 MW of electrolyzer capacity to replace 50% (300,000–400,000 tonnes annually) of nitrogen fertilizer imports. The study underscores the need for greater investment in infrastructure, research, and capacity building to unlock East Africa's renewable energy potential, highlighting that strategic partnerships and investor collaboration are crucial for closing the capacity-to-use gap and achieving a sustainable energy future for the region and globally.

Keywords: East Africa; renewable energy; potential; sustainable.

1. INTRODUCTION

Across Sub Saharan Africa region, East African countries possesses abundant RE resources [1,2], such as solar [3] and wind [4,5], geothermal [6], hydroelectric power [7], biomass [8] and green hydrogen [9], yet to be fully exploited [10] to meet the rising energy demands and mitigate climate change effects [1,11]. This suggests that East Africa's RE resources have not progressed as much as expected in recent decades. This review aims to evaluate Kenya's RE potential and prospects within East Africa, highlighting investment opportunities to support sustainable energy growth in the region. Globally, there are now 3,146 gigawatts of renewable energy capacity installed across 135 countries, and 156 countries have enacted laws to regulate the RE sector [12,13], while wind energy and solar energy having capacities of 564 GW and 480 GW respectively [14,15]. Numerous nations have already achieved impressive milestones, with RE contributing more than 20% of their total energy supply, and some surpassing the remarkable feat of generating over half of their electricity from renewable sources. For successful CO_2 emissions mitigation and well-informed policy formation, it is imperative to leverage insights into Kenya's large RE contribution. Studies have also shown that CO_2 emissions are increasing rapidly at a rate of 6.5% per year [16], stressing the crucial need to transition to RE sources.

Table 1 presents an overview of the East Africa energy sector, highlighting the untapped resources within the region. The findings shows that many East African nations, including South Sudan (SS) have not harnessed their wealth of renewable energy resources, which include biomass, solar, wind, and hydropower. The country is largely dependent on fossil fuels for power generation and currently 7.75% of people have access to electricity [17]. The country has an installed generation capacity of just 221.5 MW, which signifies less than the demand of over 300 MW. This indicate that a large portion of this capacity is either non-operational or devoted to the oil fields of the nation, leaving less than 70 MW available to the general people. To exacerbate the situation, over half of this capacity is centered in Juba.

Table 1. An Overview of East Africa energy sector

No			Kenya	Uganda	Tanzania	Burundi	Rwanda	South Sudan	Authors
1	Hydro power	Status	838.5	1,072.90	581	35.2	104.6	42	[18-21]
		Potential	7812	2200	4700	1700	672	5,583	
2	Wind	Status	436.1	-	2	-	-	-	[18]
		Potential	6,000	-	-	-	-	19,757.8	
3	Solar	Status	212.6	60.93	2	7.5	12.1	32	[18,19]
		Potential	15000	5000	-	-	-	-	
4	Geothermal	Status	940	-	200	-	50	-	[22-24]
		Potential	10000	450	650	18	170	-	
5	Bioenergy	Status	2	111.743	63	4	-	-	[25]
		Potential	131	1650	-	-	-	-	
	Total renewable		**2429.2**	**1245.5**	**848**	**46.7**	**166.7**	**74**	
6	Non-Renewable		810.52	101.08	1171	30.5	58.8	147.5	
	Total		**3239.72**	**1346.58**	**2019**	**77.2**	**225.5**	**221.5**	
7	Electricity Access (%)		76.54	45.2	37.7	10.2	48.7	7.75	[26]

Additionally, Table 1 highlights Kenya as a key case study of East Africa's diverse RE landscape, standing out for its broad range of RE sources, high installed capacity and more electricity-accessible population compared to other nations in the region [27, 28]. According to the data, there is a lot of room for investment, especially in the fields of hydro, wind, solar, geothermal, and biofuels [29]. Therefore, the research seeks to untie the complex dynamics underlying the energy shift in the region by evaluating Kenya's potential, scrutinizing its growth, and examining its future prospects. This study purposes to provide important insights into the opportunities influencing Kenya's renewable energy trajectory and further deepen the understanding of the changing dynamics of renewable energy distribution and investment prospects in East Africa and beyond by placing Kenya's experiences within regional and global frameworks.

2. CURRENT RE STATUS IN KENYA

2.1 Solar Energy

Recently, the Kenyan government, led by the Ministry of Energy, has intensified investments in solar energy, targeting rural schools and health facilities with solar systems and distributing solar-powered laptops [30,31]. The initiative includes offering tailored solar solutions such as home systems, lanterns, and appliances, as well as retrofitting diesel mini-grids with solar hybrids and creating new solar mini-grids for remote areas [32]. Currently, solar energy represents only 2.4% of Kenya's energy supply [33]. Research indicates that solar PV modules can convert 10-14% of solar energy into electricity, potentially generating around 23,046 TWh/year and meeting the country's electricity needs [34]. Kenya's total installed and developing solar capacity is 372.6 MW, with Garissa Solar leading at 55 MW, and the Nakuru Solar Park in Mogotio, featuring about 150,000 solar panels on a 400-acre site as shown on Table 2.

The Alten solar facility, with 928 single-axis trackers supporting 103,936 panels, aligns with the sun to increase overall efficiency, yielding a capacity of 123,000 MWh annually. Similarly, the 651-acre Malindi Solar PV Park, with 157,000 modules, offsets 44,500 tons of CO2 emissions and powers 250,000 households. Strathmore University's 600 kW solar system saves Kshs. 2 million monthly on electricity bills, showcasing the economic and environmental benefits of solar energy [36,37,41]. These examples highlight investment potential in solar plants and components. Further research is needed to enhance solar energy conversion and storage efficiency [42], with over 35 projects approved under the Feed-in-Tariff and six currently under construction [43].

2.2 Wind Energy

With an estimated wind power potential of 346 W/m², Kenya ranks among Africa's top countries for wind energy. Its land wind speeds range from 3.26 to 8.11 m/s, exceeding the global average of 3.28 m/s at ten meters above ground [44], giving the country the capacity to meet its electricity needs. Kenya has about 90,000 square kilometers of land with wind speeds averaging 6 m/s or higher, ideal for wind power generation [34]. A 2013 study by WinDForce Management Services estimated Kenya's wind power potential at 4,600 MW [45], with projections to install 2,036 MW by 2030.

The nation benefits from advantageous wind conditions, with 73% of the country experiencing wind speeds of 6 m/s or more at 100 meters above sea level, particularly in counties like Marsabit, Turkana, and Meru. Wind speeds are classified from Class I (over 8.5 m/s) to Class IV (6 to 6.5 m/s), covering 28,228 km² with speeds between 7.5 and 8.5 m/s and 2,825 km² between 8.5 and 9.5 m/s at 100 meters. By 2022, Kenya's wind capacity reached 336.05 MW, primarily from the 310 MW Lake Turkana Wind Farm and the 25.5 MW Ngong Hills project [46]. The Lake Turkana facility, with 365 turbines, is projected to generate 1,400 GWh annually, offsetting 16 million tonnes of CO_2 emissions over its 25-year lifespan. Marsabit offers the highest wind potential, with speeds of 9.27 m/s across 75,596 km², while Turkana covers 61,353 km².

Despite Kenya's vast wind energy potential, only about 16% of its total electricity is currently generated from wind [47]. This gap highlights the need for targeted research to boost wind energy adoption. To promote sustainable growth, it is crucial to address infrastructure, policy, and technological barriers hindering wind power development [48]. According to Table 3, there are currently 435.5 MW of existing capacity and 361 MW of planned capacity. In the near future, this is expected to translate into a total capacity of 796.5 MW.

Table 2. Commissioned Solar power projects in Kenya [35-40]

S/N	Plant	Capacity (MW)	Year commissioned	County
1.	Garissa	55	2018	Garissa
2.	Radiat	40	2019	Uasin-Gishu
3.	Eldosol	40	2019	Uasin-Gishu
4.	Alten	55	2022	Eldoret
5.	Strathmore University	0.6	2014	Nairobi
6.	Malindi	52	2022	Kilifi
Total installed		**242.6**		
7.	Kopere	50	Under construction	Nandi
8.	WITU	40	Under development	Lamu
9.	Migotiyo	40	Under development	Nakuru
Total under development		**130**		
Projected Total		**372.6**		

Table 3. Commissioned and under development wind power projects [46,49,50]

S/N	Plant	Capacity (MW)	Year commissioned	County
1	Ngong wind	25.5	1993	Kajiado
2	Turkana wind Power	310	2019	Marsabit
3	Kipeto Wind	100	2020	Kajiado
	Sub Total	**435.5**		
Wind power projects under development				
4	Ngong Wind farm III	11	2021	Kajiado
5	Chania Green	50	2021	Kajiado
6	Meru (Isiolo) wind farm	100	2023	Meru
7	Ol-Ndanyat Power	10	2023	Kajiado
8	Aperture Green power	50	2024	Kiambu
9	Prunus	50	2023	Ngong, Kajiado
10	Baharini Wind Farm	90	2020 (Expected)	Lamu
	Sub Total	**361**		
	Total	**796.5**		

This research sheds light on key areas for strategic development, offering valuable insights into maximizing Kenya's wind energy potential for efficient and sustainable power generation.

2.3 Geothermal Energy

As of 2019, Kenya has 891.8 MW of installed geothermal capacity, primarily in the Rift Valley, with an estimated total potential of 7,000 to 10,000 MW across 14 sites [34,51]. Geothermal energy offers several advantages: it is unaffected by drought or climate variability, has over 95% availability, is environmentally friendly, and is locally available [52,53]. This makes it ideal for base-load power generation, potentially reducing greenhouse gas emissions by 14 metric tons of CO2 equivalent. Exploration has occurred at various sites, with 59 production wells drilled at Olkaria and 51 wells at Menengai and Baringo-Silali, identifying 170 MW of steam for power. Reviewing the current development status of these fields is crucial for informed resource allocation, investment, and policy decisions. Table 4 presents the Kenya's geothermal installed capacities' which is estimated at 1496 MW. Organizations and governments may efficiently prioritize projects, maximize resource usage, and promote sustainable growth in certain sectors by carefully analyzing the potential and problems linked with each field [54]. Gaining knowledge about the state of growth also makes it easier to spot gaps, roadblocks, and opportunities for improvement. This makes it easier to put customized interventions and strategies into place to help these fields reach their full potential.

2.4 Hydro Power

Kenya's total hydropower technical potential is estimated at 7,812.70 MW, with half attributed to small rivers [55]. The installed hydro capacity is 833.8 MW, contributing about 30% of the national energy mix. By 2019, small hydropower schemes had a capacity of 11.7 MW, with commercial developers operating 8.3 MW [34]. Five key locations hold an estimated 1,484 MW of potential. Large hydropower contributes 826.23 MW, while the untapped small hydro potential is around 3,000 MW, though less than 60 MW has been exploited, with only 53.651 MW connected to the grid as shown in Table 5. Recent oil price increases have made previously uneconomical sites more viable, including Mutonga on the Tana River, which has a projected capacity of 60 MW and an annual generation of 336 GWh.

Table 4. Geothermal plants in Kenya (installed and expected) [37]

Station	Licensee	Installed capacity (MW)	Status
Olkaria I	KenGen	185	Generation and Production drilling
Olkaria II	KenGen	105	Generation & production drilling
Olkaria III	Orpower 4	136	Generation & production drilling
Olkaria IV	KenGen	140	Generation & production drilling
Olkaria V	KenGen	170	Generation & production drilling
Olkaria IV	KenGen	140	Surface exploration & production drilling
Modular Units	KenGen	85	Generation & production drilling
Suswa	CYRQ	330	Surface exploration & production drilling
Eburu	Kengen	25	Generation & piloted generation
Akira	AGIL	70	Exploration and surface studies
Oserian	ODGL	5	Production under steam sale
Menengai	GDC	105	Production and exploration drilling
Total		**1496**	

Table 5. Installed Small, Mini & Pico Hydropower plants in Kenya [59,60]

Small Hydropower	Installed Capacity (MW)	Year
Nzoia II	20	Not Completed
Gitungi	7.51	Not Completed
Virunga	7.56	Not Completed
Total not completed	**35.07**	
Gura Power station	5.8	2022
Mutunguru	7.8	2019
Imenti	0.9	2009
Kathamba	0.001	2001
Thima	0.01	2001
Tungu - Karibu	0.01	2000
Mujwa	0.01	NA
Tenwek	0.32	NA
Diguna	0.4	1997
Savani	0.09	1927
Brook bond 4	0.24	NA
Brook bond 3	0.18	NA
Brook bond 2	0.1	NA
Brook bond 1	0.09	NA
James Finlays 5	1.1	1999
James Finlays 4	0.3	1984
James Finlays 3	0.1	1980
James Finlays 2	0.4	1934
James Finlays 1	0.3	1934
Sosiani	0.4	1955
Wanji 3 & 4	2	1952
Wanji 1 & 2	5.4	1952
Tana 5	4	1955
Tana 4	4	1954
Tana 3	2.4	1952
Tana 1 & 2	4	1932
Gogo falls	2	1958
Sagana falls	1.5	1955
Selgy falls	0.4	1952
Mesco	7.4	1933
Ndula	2	1925
Total completed	**53.651**	

The estimated construction cost for Mutonga is US$ 270 million. Downstream, the Lower Grand Falls has a capacity of 140 MW, generating 715 GWh annually. While several projects are planned, like the HPP Karura and the 700 MW High Land Falls on the Tana River [56], no systems are currently operational. Modernizing existing facilities could add 120 MW. However, high installation costs (US$ 2,500 per kW), limited hydrological data, climate change impacts, and a lack of local manufacturing capacity hinder small-scale hydropower development [57,58]. Phased feasibility studies are needed to assess the potential of hydro power sites nationwide.

2.5 Bio-energy

2.5.1 Biogas

Though the potential for biogas is far higher [2], the uptake still represents a small fraction of about 11.4 to 14.6% of the energy mix at household level in peri urban [29]. Additionally, it is estimated that Kenya has the capability to leverage biogas mechanisms to generate 624 GWh of electricity from agro-industrial waste and wastewater [40, 41]. Moreover, the nation possesses the capacity to generate biogas from sources such as dung, sisal, municipal waste, coffee, and other agricultural residues [13, 14, 42]. It has also been found that alternative substrates like water hyacinth, food waste, slaughter waste, and molasses distillery waste serve as effective biogas sources [43,44]. It's crucial to recognize that diverse waste materials can act as substrates for the anaerobic digestion process [45].

Kenya currently has around 20,000 biogas systems, reflecting substantial progress. The Kenya Biogas Program, supported by the Dutch government, has facilitated the installation of about 17,000 digesters across 36 counties [61]. Additionally, several institutions have successfully established commercial biogas plants, contributing approximately 15.155 MW of electricity, as detailed in Table 6.

The Baringo Biogas Power Plant, utilizing plant material from the Prosopis juliflora tree, has an installed capacity of 12 MW, contributing 8.4 MW to the grid. In addition, biogas plants have been installed at various schools, including Siana Boarding Primary School (120 m³), Kaimosi Teachers' College (200 m³), Jomo Kenyatta University of Science and Technology (385 m³), and College of Agriculture and Veterinary Sciences (120 m³). These installations aim to reduce fuel costs and provide biogas technology training, highlighting a commitment to sustainability [2, 39]. Research could evaluate the financial, environmental, and educational benefits of these biogas systems, including cost savings, greenhouse gas reductions, and the effectiveness of training programs. Additionally, studying the challenges and best practices for setting up biogas plants in educational settings could offer valuable insights for future projects.

Table 6. Kenya's smaller commercial biogas plants installed

NO	Company	Location	Bio waste	Size (m^3)	Capacity (MW)	Reference
1	Gorge Farm – Biojoule	Naivasha	Flower waste	5000	2.2	[30,31]
2	James Finlay Ltd	Kericho	Flower and tea wastes	1,700	0.16	[32]
3	**Keekonyokie**	Kajiado	Slaughter waste	248	0.06	[33]
4	Pine power	Kilifi	Sisal waste and cow dung	750	0.15	[25,34]
5	Isinya - Dave Flower Farms Ltd	Kajiado	Flower waste	400	0.1	[35]
6	Afrisol	Chaka, Nyeri	Slaughter waste	372	0.06	[25]
7	Sagana Oilvado Company	Murang'a	Avocado waste	1,400	0.34	[36]
8	Ereka Holdings Ltd	Simbi Roses	Flower waste	200	0.055	[25]
9	Dagoretti Slaughterhouse	Nairobi	Slaughterhouse waste	60	0.03	[37,38]
10	Baringo Thermal Power Station	Baringo	Prosopis Juliflora	-	12	[62]
Total					**15.155**	

2.5.2 Biomass

Biomass encompasses energy derived from various solid, liquid, and gaseous sources, including fuel wood, charcoal, ethanol, bio-diesel, biogas and briquettes [63]. In Kenya, biomass accounts for 70% of the final energy demand, satisfying over 90% of rural household energy needs, mainly sourced from charcoal, wood-fuel, and agricultural waste [64]. In addition, the collective sources have an installed electric capacity potential ranging from 29 to 139 MW [65], constituting approximately 3.2% to 16.4% of the total electricity generated. The government acknowledges substantial potential for power generation using forestry and agro-industry residues, notably bagasse, with a total cogeneration potential of 193MW, although the utilization remains untapped [55]. The Mumias Sugar Company, functioning as an Independent Power Producer [66], has faced closure due to challenges such as outdated technology, financial mismanagement, and fluctuating world sugar prices, despite its 35MW energy production capacity [67]. The closure has led to job losses, economic instability, and disruptions in fuel and sugar supply, underscoring the need for collaborative efforts among government, stakeholders, and the business sector to devise sustainable solutions.

Under the Feed-in Tariff [68] policy, biomass energy resources for electricity generation can fetch a fixed tariff not exceeding US Cents 10 per Kilowatt-hour, facilitating the approval of an 18MW cogeneration project using cane bagasse in Kenya's coastal region. Opportunities for biofuel production and processing, particularly from Jatropha and sweet sorghum, exist in various regions, including Galana and provinces like Eastern, North-Eastern, Rift-Valley, and Nyanza. Moreover, consultancy prospects are available for research and capacity building in bio-technology and related industrial potentials. Exploiting opportunities within other sugar factories, estimated at up to 300MW, remains an untapped potential awaiting exploration and utilization.

2.6 Tidal Energy and WAVE Power

Kenya's tidal energy resources offer great potential for electricity generation with proper site planning and optimized ocean energy converters. Characterization and mapping of tidal resources reduce uncertainties, boosting investment in green energy initiatives. Theoretical estimates suggest around 1.9 GW (16.5 TWh annually) could be extracted, with more potential through advanced deployment. However, no tidal or wave energy systems are currently installed. A study identified potential in Mombasa and Lamu but highlighted challenges like high capital costs, political instability, and energy density fluctuations [69]. Addressing these issues requires strategic actions, including creating supportive networks and regulations to promote ocean energy development.

Wave energy, though undeveloped in Kenya, has potential. Blackbird International plans a 100 MW wave farm, and the Uppsala University study in Kilifi demonstrated the feasibility of wave energy converters (WECs) for off-grid desalination, with 10 WECs potentially supplying freshwater for 5,000 coastal residents [70]. To overcome barriers like high costs and political instability, further research should focus on innovative finance, technological advancements, and human capital development to fully tap Kenya's tidal and wave energy potential.

2.7 Hybrid Renewable Energy

Kenya is developing hybrid renewable energy (HRE) facilities. Meru County Energy Park is the only hybrid project in the country. The combination of wind, solar PV, and battery storage is used in this substantial installation. The facility is expected to generate 80MW of power when completed. Up to 20 wind turbines and more than 40,000 solar panels are anticipated to be used in the project. Its renewable energy is planned to power more than 200,000 homes [71,72].

In addition, another notable development in the area's energy environment is the Gitwamba Hydro Hybrid Power Plant, which is located in Kirinyaga. Designed to accommodate the varying river flow rates throughout the year, this cutting-edge plant combines solar and hydro power technology. When it rains, the hydro plant provides extra capacity, and during the dry season, the solar system augments power generation. Day or night, Kirinyaga County consumers are guaranteed a steady base load supply thanks to this dual strategy. The Gitwamba hydropower plant has a total capacity of 170 kW and is composed of a hydro component that can generate 50 kW when designed for a design flow of 0.65 m^3/s [73]. This dynamic configuration highlights the region's dedication to sustainable and dependable electricity generation while also enhancing energy resiliency.

Inspiring further investment and cooperation for a cleaner future, these projects demonstrate Kenya's commitment to renewable energy and energy resilience. In order to electrify remote areas—which frequently lack dependable power—research on HRE systems is crucial [74, 75]. An energy source that is reliable and sustainable can be provided by HRE systems. Research may be done to optimize these systems so that distant communities can obtain robust, affordable, and environmentally friendly electricity, hence spurring growth.

2.8 Green Hydrogen

Kenya has made notable strides in renewable energy development, yet its potential for green hydrogen production remains largely untapped [66]. Research is needed to fully understand and harness this potential to diversify energy sources, improve energy security, and support global decarbonization efforts [76]. Green hydrogen, produced from renewable energy sources like solar and wind [77], is a clean and versatile fuel that can power various applications including vehicles, industrial processes, and electricity generation. Namibia is already advancing in this area by leveraging its solar and wind resources for green hydrogen production [78, 79]. Kenya plans to initiate its green hydrogen program in phases, aiming to significantly reduce nitrogen fertilizer imports and enhance energy capacity. Phase I (2023–2027) will focus on installing 150 MW of energy and 100 MW of electrolyzers, aiming to cut nitrogen fertilizer imports by 20%. Phase II (2028–2032) will expand capacity to 350–450 MW and 150–250 MW of electrolyzers, with a goal of replacing 50% of nitrogen fertilizer imports, and the government will explore export opportunities post-2032.The potential benefits of green hydrogen include economic growth through reduced import dependency, enhance power storage, improved food security via locally produced fertilizers, and the promotion of green industrialization. Additionally, this sector could attract substantial investments and create new job opportunities, reinforcing Kenya's position in the global green economy and contributing to sustainable development. The successful implementation of Kenya's Green Hydrogen Plan and Execution Strategy requires a clear, focused, and supportive atmosphere built on strong, well-aligned pillars to establish a prosperous green hydrogen industry as shown in Fig. 1.

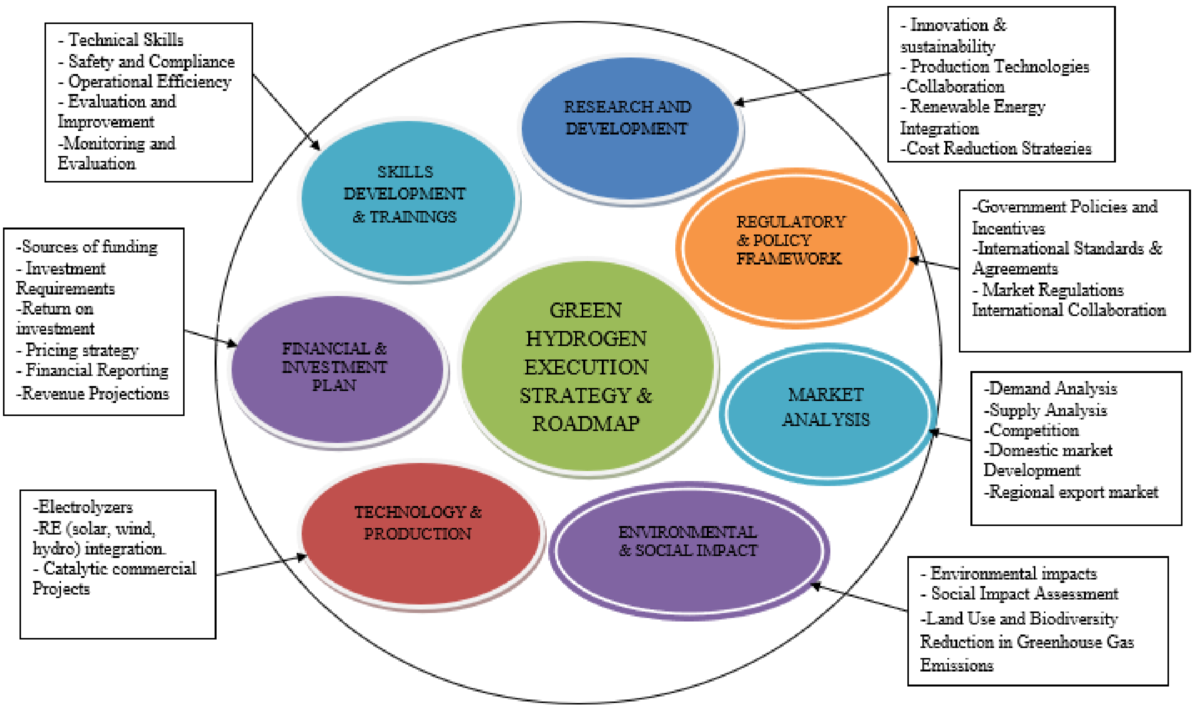

Fig. 1. Kenya's Green Hydrogen Plan and Execution Strategy (Author's 2024)

Table 7. Energy mix, degree of development, potential capacities and % exploited (Author's 2024)

Energy Source	Current Status				Installed and Underdevelopment		
	Potential (MW)	Capacity (MW)	Percentage Contribution	Percentage Exploitation	Capacity (MW)	Percentage Contribution	Percentage exploitation
Hydro	7812	833.8	25.5	10.7	1026.23	21.4	13.1
Solar	15,000	242.6	7.4	1.6	372.6	7.8	2.5
Wind	6,000	435.5	13.3	7.3	996.5	20.8	16.6
Geothermal	10,000	940	28.8	9.4	1496	31.2	15.0
Hybrid	-	0	0.0		80	1.7	
Bio Energy	131	2	0.1	1.5	11.6	0.2	8.9
Total RE		**2453.9**	**75.2**		**3982.9**	**83.1**	
Thermal	-	810.52	24.8		810.52	16.9	-
TOTAL		**3264.42**	100		**4793.45**	100.0	

2.9 Percentage of Renewable Energy Sources Installed and in Development in Kenya

Table 7 presents a summary of the national energy mix, including development stages, potential capacities, current statuses, and the extent of resource utilization. The data indicates significant underutilization of resources such as hydro, geothermal, wind, solar, and bioenergy, suggesting that their full potential is not being exploited. These findings align with previous studies [34] but contradict the EPRA reports [21].

2.10 Challenges and Future opportunities to Renewable Energy

a) **Energy Policy:** Kenya has made strides in renewable energy policy, notably with the Energy Act No. 1 of 2019 and the establishment of the EPRA to streamline energy projects and promote investment. However, challenges persist, including complex licensing processes, limited local production capacity, and delays in financing. Additionally, the shift from the Renewable Energy Feed-in Tariff to the Renewable Energy Auction Policy (REAP) has raised concerns about potentially slowing investment and hindering progress toward renewable energy targets [80].

b) **Disputes and Conflict:** Conflicts and disputes are preventing Kenya from developing its renewable energy industry and creating serious obstacles to its expansion [81]. Also, the policy transition from FiT to REAP has sparked disputes over power purchase agreements (PPAs) and project selection criteria, leading to delays and legal challenges. Local concerns about environmental impacts and land use further complicate project development, creating an unstable investment climate and impeding progress in RE.

c) **Environmental Issues:** Renewable energy sources in East Africa face environmental challenges such as water variability affecting hydroelectric power [5-7] and potential impacts from geothermal [82], solar, and wind energy on groundwater and wildlife [83]. Addressing these issues requires careful planning [84], environmental assessments, and mitigation strategies to ensure sustainable development.

d) **Energy Storage:** Integrating energy storage systems with renewable sources offers significant benefits but faces challenges such as maximizing storage capacities, ensuring compatibility with various power generation technologies [85], and managing the intermittency of renewable energy. Research should focus on optimizing storage solutions and improving grid reliability [86].

e) **Renewable Energy Integration:** Increasing renewable energy integration into power systems is crucial for sustainable energy solutions [87, 88], yet it brings challenges like managing intermittency, improving grid stability, and refining policy frameworks [33]. Addressing these challenges is essential for advancing toward a more sustainable energy future.

3. CONCLUSION

East Africa has significant, underutilized RE resources, particularly wind and solar, making investment reporting essential for leveraging regional opportunities. The review reveals that Kenya's energy mix in 2023 comprises about 75.2% green energy, including geothermal, hydro, wind, solar, and bioenergy, contrasting with EPRA reports. This suggests that thermal energy and imports make up the remaining portion, with thermal energy being constant in this analysis. As investment shifts away from costly hydro plants and reduces dependence on hydroelectricity, geothermal energy and green hydrogen are projected to grow, especially given hydroelectricity's vulnerability to droughts. Establishing research facilities like the African Renewable Energy Research Institute could support renewable energy initiatives [89].

In Kenya and other East Africa, efforts must focus on building a resilient and sustainable energy landscape to bridge the gap between available and utilized capacity. Additionally, improved information accessibility could drive broader adoption of RE by influencing policy decisions and public awareness. Moreover, addressing the complex links between sustainable development and renewable energy requires comprehensive policies, cross-sectoral collaboration, and greater transparency. Enhanced research can also help dispel myths about renewable energy sources, facilitating a more informed and confident transition.

4. RECOMMENDATIONS

To fully leverage East Africa's abundant renewable energy resources and address the underutilization of hydro, geothermal, wind, solar, and bioenergy, it is crucial to improve information transparency, review and strengthen policy frameworks, and foster public-private investment partnerships. Aligning with initiatives like Kenya's Vision 2030 and the Climate Change Act of 2016 can boost public awareness, education, and institutional capacity in renewable energy. Enhanced research efforts are essential to clarify uncertainties and facilitate a smooth transition to sustainable energy, positioning East Africa as a leader in creating a resilient, environmentally sustainable energy landscape that supports global climate goals and the SDGs.

For green hydrogen, Kenya and East African countries can capitalize on their strong solar resources and growing renewable energy infrastructure [90, 91]. It is important to conduct a comprehensive techno-economic evaluation of solar green hydrogen production, including cost benefits from commercializing byproduct oxygen. This involves assessing solar potential using satellite data and field measurements, comparing various solar-powered electrolysis technologies for cost, efficiency, and scalability, and studying solar energy's impact under different conditions to improve output and storage. Additionally, developing a conceptual design for a hydrogen production system with solar panels, electrolyzers, and storage infrastructure is essential [92]. Research should also explore using fruits like tomatoes and pineapples as electrolytes in bioelectrolytic reactions to generate electricity for remote areas [93, 94].

Enhancing the reliability of renewable energy sources through energy storage solutions, such as pumped hydro storage [95, 96], is vital for improving power output dispatchability and scheduling. Evaluating East Africa's renewable energy policies and their impact on the private sector, exploring community involvement strategies, and assessing the effects of foreign direct investment on local economies are also crucial. Finally, fostering global collaboration and knowledge transfer mechanisms will support these efforts.

5. FUTURE PROSPECTS

Based on the untapped RE sources, East African countries such Kenya have significant potential for scaling its RE sources. The countries are well-positioned to advance its solar, wind, geothermal, and bioenergy sectors through scientific innovations and enhancements. New innovations and improvements to current technology have the potential to boost significant expansion in the renewable energy industry. Future expansion is anticipated to be driven by continuing research and the creation of more economical and efficient energy systems, opening the door for Kenya and East Africa at large to have a more sustainable energy environment.

Kenya's future in renewable energy is bright, especially with green hydrogen, especially considering its vast solar resources. Kenya has to do thorough investigation of the technical and financial feasibility of producing green hydrogen in order to fully realize this promise. This entails evaluating the infrastructure needs, advantages, and expenses associated with creating, storing, and delivering hydrogen. At the same time, it will be essential to update energy policies and regulatory frameworks to ensure that they meet global standards and offer the required incentives to assist this developing industry.

The RE sector in Kenya and other East Africa will also need to disclose investment opportunities and attract both local and foreign investment in order to fund the start-up of new projects. Also, through streamlined resource usage and the development of a more integrated energy market, cooperation among East African nations might enhance the energy security of the region. Additionally, integrating the community and building its ability will be essential to the efficient administration and implementation of renewable energy projects. Kenya can play a significant role in promoting public awareness, education, and stakeholder involvement regarding sustainable development goals and climate action by fortifying its RE sector.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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