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Review

Ethiopia hydropower development and Nile basin hydro politics

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Abstract: Ethiopia, one of the countries in the Horn of Africa, has an abundance of hydroelectric resource potential that can meet the country's energy demand. However, this energy resource has been underutilized, and the country has one of the lowest per capita consumption rates of electricity. Recognizing that energy access and security are critical factors in economic growth, the country has launched a number of hydroelectric projects to meet rising energy demand, as well as a plan to export electricity to neighboring countries. As a result, this paper provides an in-depth review of the country's hydropower potential and current development status. The article then discusses hydro-politics in the context of the construction of the Grand Ethiopian Renaissance Dam (GERD). Finally, it discusses the role of hydropower in meeting energy needs.

Keywords: energy potentials; hydropower; Ethiopia; rural energy supply

1. Introduction

Access to modern energy services plays a critical role in nations' socioeconomic development by raising the standard of living and the quality of life [1]. However, we live in a paradoxical world where there are abundant resources but insufficient energy, particularly in developing countries such as sub-Saharan Africa. Despite the region's vast energy potential, more than 620 million people lack access to electricity, and nearly 730 million rely on risky, inefficient cooking methods, a dependency that disproportionately affects women and children. Meanwhile, those who do have access to modern energy will pay exorbitant prices for insufficient and unreliable supplies [2].

Ethiopia, a sub-Saharan African country, has an abundance of renewable energy resources, including hydro, wind, geothermal, solar, and biomass [3]. Despite the abundance of available potential, the country has one of the lowest levels of clean energy access in the world, and the

country relies largely on biomass energy as a source of energy, primarily for household use [4]. According to a 2017 report from Ethiopia's ministry of water, irrigation, and electricity, household connectivity is only about 25% while access to the electric grid is around 56 percent [5]. Hydropower generates the majority of the electricity that is integrated into the national grid, accounting for about 87 percent of the country's total 4,674 MW of energy production capacity [6]. The country's hydroelectric resource potential is estimated to be up to 45,000 MW, ranking it in second place in Africa behind the Democratic Republic of Congo [7]. Table 1 shows the country's exploitable energy potential and the percentage exploited. Based on the estimated hydropower potential, approximately 30,000 MW of hydropower production at various sizes is estimated to be economically feasible [8], generating 162 TWh of electricity [3]. However, the country produces only about 14.29 TWh of hydroelectric power, which is only about 10% of the country's economically feasible hydropower generation potential. Given the country's energy resource potential for hydroelectric power utilization, this capacity is clearly insufficient to serve a population of more than 105 million people [3].

As a result, the Ethiopian government is currently working extensively in exploiting the country's energy resource potential in order to address the issue of energy access in society. They are also working to become a major power exporter in the Horn of Africa, thereby creating new economic opportunities and improving energy security through cooperation and collaboration in the development of a green economy. Therefore, the goal of this study is to examine the country's hydropower development in order to meet society's energy demand while also boosting the country's socioeconomic development. Furthermore, in the context of the construction of the Grand Ethiopia Renaissance Dam, this research helps to the updating of current information and understanding about the hydropower geopolitics of Nile basin countries (GERD).

Table 1. Ethiopia's exploitable energy potential and the percentage exploited [9–11].

No.	Source	Unit	Exploitable potential	Exploited amount	Percentage exploited (%)
1	Hydropower	MW	45,000	4,063.6	<10
2	Solar (day)	KWh/m^2	5.2	14 MW	<1
3	Wind	GW m/s	1350	0.324	<1
4	Geothermal	GW	5–7	0.0073	<1
5	Wood biomass	Million Ton	1120	560	50
6	Agricultural waste	Million Ton	15–20	~6	30
7	Municipal solid waste	Million Ton	2.8–8.8	0.001	<1
8	Biogas	Household	1–3 million	17,869	<1

2. Methodology

This article is based on a review of the most recent scientific literature presented in journals, books on hydropower development, internet sources, and country data obtained from Ethiopia's ministries of water, irrigation, and energy, as well as international organizations such as the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and World Bank reports to collect qualitative and quantitative data. A thorough review of the literature on Ethiopia's hydropower development and Nile basin hydro-politics has been conducted. The article is

divided into six sections: section 1 contains an introduction and a literature review on the status of hydropower development in Ethiopia, and section 2 discusses methodology parts. Section 3 provides a brief overview of Ethiopia's current energy consumption status. Section 4 examines the country's hydropower potential and development status, while section 5 reviews about construction of controversial Grand Ethiopia Renaissance Dam (GERD) and the Nile basin's hydro-politics. Finally, section 6 provides a thorough conclusion to this article.

3. Current status of energy consumption in Ethiopia

Ethiopia is one of the countries in the Horn of Africa with underutilized energy resources. The majority of Ethiopia's energy supply, like that of many other African countries, comes from waste and biomass fuel, accounting for up to 86.48 percent of the total 1,878,972 TJ primary energy supply, followed by oil at 9.99 percent, hydropower at 2.79 percent, and the remainder from solar and coal [12]. Figure 1 shows the country primary energy supply by source.

Based on sector energy consumption in Ethiopia household sector consumes about 88.2 percent of total energy supply, followed by the transportation sector (8.4 percent) and 3% by industry [3,12]. However, the majority of energy supply in household sector thereby is covered by bio-energy while a transport sector is predominantly run by imported petroleum [3,13]. In 2020, total electricity generation capacity of the country was 4,713 MW with 86 percent produced from hydro, 6 percent from bio-energy, 7 percent from wind and 1 percent from non-renewable sources [14]. According to the IEA report in 2019, the country's national electrification rate is still very low, at around 48.3 percent [12]. Furthermore, there is a stark differences in the rate of electricity access between urban and rural areas; in urban areas, 92.8 percent of the population has access to electricity, whereas in rural areas, access to electricity remains extremely low at around 36.3 percent [12,15]. As a result, the vast majority of the population lives in rural areas and relies heavily on traditional biomass energy sources for cooking and heating [1,15].

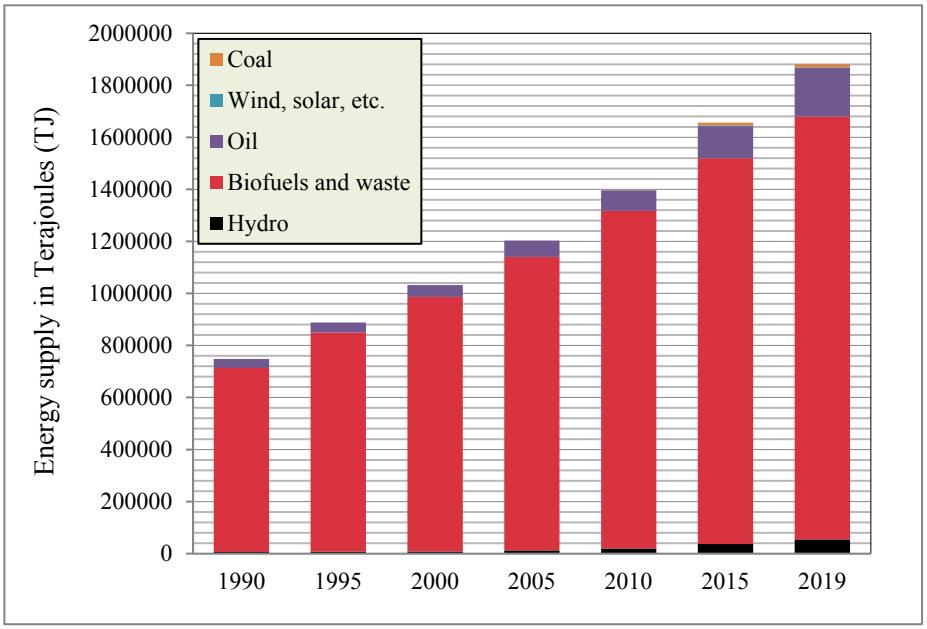

Figure 1. Primary energy supply of Ethiopia [16].

The estimated electricity consumption per capita of the country by 2017 was 100 kWh and increased to about 130 kWh by 2019 [17]. However, this capacity is certainly too small considering energy resource potential of the country for both conventional and renewable energy utilization [3]. As a result, this study provides relevant information on hydroelectric power development as well as the current state of the energy sector. Furthermore, it reviews the hydro-political crisis between Nile river basin countries towards the construction of GERD.

4. Ethiopia hydropower potential and development status

Hydropower can serve as a bridge into a transition to more sustainable sources of energy due to its large potential development scale, environmentally friendly nature, and lower average cost of electricity generated than any other energy generation technology [18]. The technical hydropower potential in Africa is estimated to be around 283 GW and capable of generating close to 1200 TWh per year, accounting for 8% of the global technical potential. It is estimated that 90% of hydropower potential in the continent is still untapped [3,15]. In 2018, nearly half of Africans (600 million people) lacked access to electricity, and roughly 80% of sub-Saharan African businesses experienced frequent power outages, resulting in economic losses. Furthermore, more than 70% of the population, or approximately 900 million people, lack access to clean cooking fuel [19].

Table 2. Hydropower production potential of Ethiopia's river basins [20,21].

No.	River Basin	Number of potential sites				Annual runoff (Billion meter cube)	Gross hydroelectric production potential (Gwh/year)
		Small scale (<40 MW)	Medium scale (40–60 MW)	Large scale (>60 MW)	Total		
1	Tekeze	11	1	8	20	8.2	5,980
2	Abbay	74	11	44	129	54.8	78,820
3	Baro-Akobo	17	3	21	41	23.6	13,765
4	Omo-Ghibe	4	-	16	20	16.6	36,560
5	Rift Valley	7	-	1	8	5.6	800
6	Mereb	-	-	-	-	0.65	-
7	Afar/Denakil	-	-	-	-	0.86	-
8	Awash	33	2	-	35	4.9	4,470
9	Ayisha	-	-	-	-	-	-
10	Ogaden	-	-	-	-	-	-
11	Wabi-Shebelle	9	4	3	16	3.16	5,440
12	GenaleDawa	18	4	9	31	5.88	9,270
	Grand Total	173	25	102	300	124.25	155,105

Ethiopia, one of East Africa's countries, is well-known for its abundant water resources. There are twelve river basins in the country. The total annual mean surface runoff from all twelve river basins is estimated to be 124 billion cubes [8,22]. Eight of Ethiopia's twelve river basins have been identified for their hydroelectric power production potential. Table 2 depicts Ethiopia's river basins' hydropower production potential. Around 300 hydropower plant sites have been identified in those eight river basins, with 102 large-scale (more than 60 MW) and 198 small-scale (less than 40 MW)

sites [3]. The economically feasible estimated potential of Ethiopia is approximately 30,000 MW, but only 8.82% of this potential is exploited [3,8]. Given Ethiopia's hydropower potential, this capacity is insufficient to meet the country's energy demands. As a result, developing the country's abundant hydropower resources in all schemes holds the key to meeting energy demand in various sectors such as agriculture, transportation, industries, and services, as well as contributing to the country's socioeconomic development. With this understanding, the country has initiated a plan to develop a number of hydroelectric projects, including the 2,160 MW Gilgel Gibe IV hydropower project and the massive 6000 MW GERD being built on the Abbay (Blue Nile) River, with the goal of meeting the growing energy demand, as well as a plan to export electric power to neighboring countries [8].

4.1. Small hydropower development in Ethiopia

Table 3. The list of small-scale hydroelectric power plant in Ethiopia [23].

No.	Small hydroelectric power plant	Operational since	Drainage Basin	Type	Installed capacity (kW)
1	Aba Samuel	1932	Afar Triangle	-	6600
2	Sor 2	1990	Nile	run-of-river	5,000
3	Dembi	1991	Nile	run-of-river	800
4	Yadot	1990	Jubba	run-of-river	350
5	Tis Abbay I	1953	Abbay	Weir	12,000
6	Awash 2	1965	Awash	Weir	32,000
7	Awash 3	1971	Awash	Weir	32,000
Grand Total					88,750

Small hydropower technology is best suited for rural areas with no grid access. Small hydropower is regarded as more environmentally friendly because it avoids the significant environmental impacts associated with large-scale hydro, such as habitat loss, water quality changes, and siltation. Small hydropower, also known as mini and micro hydropower, refers to the harnessing of power from water on a small scale (capacity of less than 40 MW) [24]. Small hydropower has multiple applications, including energy generation, irrigation, and water supply, and it is also a very reliable technology. The majority of the untapped potential for small hydro is in remote areas. Eastern and Southern Africa has a large number of permanent streams, rivers, and tributaries with excellent hydropower development potential [25]. Ethiopia, one of East African countries, has a total theoretical potential for small hydropower schemes of about 100 MW [26]. Despite this enormous potential, the country has only used a small portion of it through small hydropower plants. Table 3 shows a list of Ethiopia's small-scale hydroelectric power plants. The majority of Ethiopians, particularly in rural areas, rely heavily on traditional forms of energy such as biomass, kerosene, charcoal, and so on. For example, approximately 99 percent of rural households use biomass for cooking and heating [27]. Small hydropower plants are well-known for their ability to provide electricity to rural areas in developing countries [28]. Small hydroelectric projects are a safer choice than large hydroelectric projects for controlling and using water supplies in a sustainable manner with minimal socioeconomic and environmental impact [24]. Small hydropower plants will reduce energy imbalances, and they are simple to build, inexpensive, and environmentally safe [29]. As a

result, given that the majority of the Ethiopian community lives in remote areas, constructing such standalone electricity supply facilities will address the society's energy demand in a more sustainable manner.

4.2. Large hydropower development in Ethiopia

Hydropower is a renewable energy source that harnesses the energy of moving water from higher to lower elevations. Hydropower can provide a significant and consistent supply of electricity by utilizing an indigenous and renewable energy source and relying on well-established, low-carbon technology. In Africa, hydropower is the most cost-effective option for large-scale electricity generation [15,30].

Table 4. Currently installed Mega hydroelectric power plant in Ethiopia [3,8].

No.	Power plant	Date of completion construction	Catchment area(Sq.km)	Dam height (m)	Installed capacity (MW)	Average energy production (GWh)
1	GenaleDawa III	2020	10,445	110	254	
2	Gilgel Gibe III	2016		243	1870	6,500
3	Beles	2010	14,200	35	460	1867
4	Tekeze	2009	30,390	188	300	1393
5	Gibe II	2009	Weir	46.5	420	1635
6	Gibe I	2004	51	41	184	722
7	MelkaWakena	1988	5300	42	153	543
8	Fincha	1972	170	22.2	134	760
9	FinchaaAmertiNeshe	2011	29.5	38	97	
10	Tis Abay II	2001	15,300	Weir	73	359
11	Koka	1960	200	23.8	43.2	110
	Grand Total				3,988.2	13,889

Ethiopia, an East African country, has the world's second largest hydropower potential, trailing only the Democratic Republic of the Congo, with an estimated annual theoretical energy potential of 954 TWh [31]. The country has approximately 11 large hydropower dams with an annual energy production capacity of 14,296.7 GWh. Hydropower is currently the most important renewable energy source that is integrated into the national grid, accounting for approximately 87 percent of the country's total energy production capacity, making it the primary energy source [6]. Table 4 presents data on the catchment area, elevation, and energy potential of large hydropower plants in the country by 2020. The country has begun construction on a number of large hydroelectric projects, including the Gilgel Gibe IV (Koysha) hydropower project and the massive Grand Ethiopian Renaissance Dam being built on the Abbay (Blue Nile) River, which when completed will be Africa's largest dam and the world's sixth largest [8]. However, plans to build a large hydroelectric dam to meet the country's energy demand are unfeasible given that the majority of Ethiopia's population lives in rural, dispersed areas. Furthermore, because of the large sums of money involved in large-scale hydro projects, these projects are hindered by allegations of corruption. Another disadvantage of

hydropower development is dam silting, which reduces the amount of electricity that can be generated over time and will be affected by drought, resulting in huge shortfalls in electricity generation. To meet the universal electrification plan, the country should shift its energy policy toward small-scale and standalone renewable energy technology development, as well as diversifying its power mix and supplementing it with intermittent sources such as wind and solar to meet peak demand.

5. Construction of grand Ethiopia renaissance dam and Nile basin hydro politics

Nile is probably the longest international river in the world, with a length of 6670 km. Before reaching the Mediterranean Sea, the Nile River flows through 11 African countries [32]. The Nile's two main tributaries are the White Nile and the Blue Nile. The White Nile begins in Burundi and flows through the Equatorial Lakes before entering Sudan's Sudd swamps. The Blue Nile, the major water supplier, however, originates in the Ethiopian highlands. The Ethiopian highlands account for 86 percent of Nile flow, while the Equatorial Lakes region contributes only 14 percent. Ethiopia is the source of three of the four major tributaries: the Blue Nile, the Sobat, and the Atbara. As a result, Ethiopia is classified as an upstream riparian state, whereas Egypt and Sudan are classified as downstream riparian countries [33]. In recent years, the Nile basin countries, particularly Ethiopia, Sudan, and Egypt, have seen massive population growth [34]. Sudan built the large Merowe Dam (1250 MW) in 1936 and later Roseires Dam was begun in 1950 to add additional 420,000 hectares of irrigated land while, Egypt built the Aswan High Dam (2100 MW) to control the flow of the Nile in the 1960's, resulting in increased agricultural production, employment, and electricity [35,36]. The Ethiopian government has planned to construct a mega hydroelectric dam on the Abbay (Nile) river since the 1960's [36]. Since then, Nile basin countries have been engaged in open conflict on water sharing issues. Egypt, one of the downstream riparian countries, has imposed its control on the Nile since historical times, granted through 1902, 1929, and 1959 colonial agreements over Ethiopia and other Nile Basin nations [37]. However, the establishment of the Nile Basin Initiative (NBI) in 1999 brought a certain shift in the bilateral relationships among the basin countries [34]. Table 5 shows the treaties that have been made on Nile water sharing.

On the other hand, the controversial Grand Ethiopian Renaissance Dam on the Blue Nile River has heightened tensions among Nile basin countries, particularly between Ethiopia, Sudan, and Egypt. Despite the fact that the Ethiopian government had planned the GERD project since the 1960s, it was not officially launched until April 2011 [36]. With this in mind, Egypt has successfully persuaded international and regional financial institutions, such as the World Bank, the European Investment Bank (EIB), and the Asian Development Bank (ADB), not to finance Ethiopia's construction of hydropower generation infrastructure projects on Nile tributaries, including the construction of GERD, which the World Bank has expressed reluctance to fund [38]. As a result, Ethiopia has been unable to make significant use of the Nile River's water. However, due to Ethiopians' ability and willingness to invest in the dam project both at home and abroad, the government was able to raise a significant portion of the funds required to begin construction of the GERD. GERD, which is scheduled to be completed by 2025, will be Africa's largest, with a capacity of about 6,000 megawatts [39]. This dam will create a reservoir with a volume of more than 74 billion cubic meters, or roughly 1.3 times the annual flow of the Blue Nile [40]. Figure 2 depicts the Nile river basin and the location of the GERD.

Table 5. The treaties that have been made on Nile water sharing.

Name of treaty	Treaty year	Treaty made between	Main agreement of treaty	References
Anglo-Ethiopia treaty	May 15,1902	Great Britain and Ethiopia	This treaty prohibits any construction work along the Blue Nile. It aimed to create the border between Ethiopia and Sudan.	[41]
Agreement between Belgium and Great Britain	May 9, 1906	Britain and Belgium	Prohibit Congo not to build projects along the Nile River. Favored only downstream states of Nile River basins.	[38]
Tripartite Treaty	December 13, 1906	Britain-France-Italy	It tries to protect the interests of the Great Britain and Egypt in the Nile Basin. Ethiopia was denied its sovereign right to use its own water.	[38,42]
Anglo-Egyptian Treaty	May 7, 1929	Egypt and Anglo-Egyptian Sudan	Egypt has been granted exclusive use of the Nile's water during the dry season. Egypt reserves the right to monitor the availability of Nile water in upstream countries. Egypt agreed to veto any Nile River-related construction projects proposed by upstream countries.	[43]
Nile Water Treaty	1959	Sudan and Egypt	Allotment of the Nile's annual flow 55.5BCM for Egypt, 18.5BCM for Sudan and 10BCM for evaporation and seepage. Egypt and Sudan was granted the right to build the Aswan High Dam and Rosaries Dam on the Blue Nile.	[44]
Nile Basin Initiative Agreement	1999	Nine member nations	A permanent commission was formed to manage water resources and work toward equitable water allocation.	[45–47]
Cooperative Framework Agreement	2010	Ethiopia, Kenya, Uganda, Rwanda, Burundi and Tanzania	Seeks more water shares. It emphasizes each basin country's right to use the Nile's waters in an equitable manner. Egypt and Sudan both strongly opposed the agreement.	[48–50]

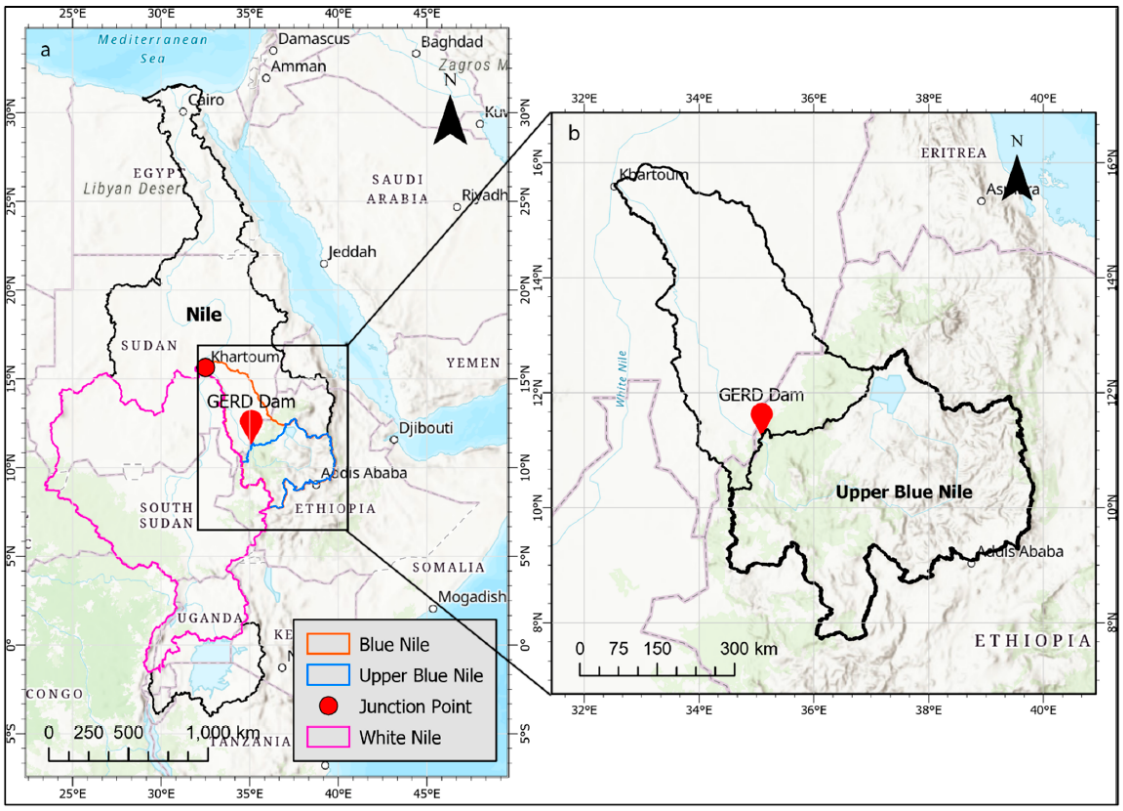

Figure 2. Nile river basin and location of the GERD [51].

According to the Ethiopian government, GERD will become a symbol of national pride and recent progress. Ethiopia claimed that GERD could benefit everyone [52]. They claim that storing water in the Blue Nile Gorge reduces evaporation and increases downstream water flow. It will provide hydroelectric power to the entire region as well as manage flood control and siltation. Egypt's and Sudan's claims to historic water rights, on the other hand, will be speculative. Furthermore, Egypt has historically justified its water share by claiming that Ethiopia receives a lot of rain and owns a lot of rivers, whereas Egypt is completely reliant on the Nile River [38].

Negotiations on filling strategies and long-term operations began in 2011, about a decade after Ethiopia announced the dam's construction, as the dam's development sparked heated disagreement among Ethiopia, Sudan, and Egypt. The negotiations, however, failed and came to a halt since the three countries were unable to achieve an agreement [53]. Table 6 depicts the filling rules and long-term operation of GERD that were negotiated. Ethiopia unilaterally filled the reservoir with 4.9 billion m^3 and 13.5 billion m^3 in the summers of 2020 and 2021, respectively, due to the difficulty in reaching mutually acceptable agreements [11,32]. On February 20, 2022, Ethiopia officially began producing 375 MW of electricity from GERD with single turbine.If it’s completed, GERD will turn Ethiopia into a net exporter of electricity to plenty of regional buyers, including Djibouti, Kenya, Somalia, Sudan, Uganda, and possibly Egypt.

Table 6. Negotiations on filling policies and long-term operations of GERD [54,55].

Name of negotiation	Year	Main agreement of negotiation
International Panel of Experts (IPoE)	2012	It was the first step in the negotiation process. Three parties agreed to establish an international expert panel. Its mission was to determine the negative impact of GERD and develop strategies to mitigate it. Recommends additional research to be conducted on its impact on Egypt and Sudan.
Tripartite National Council (TNC)	2014	The TNC was formed from members of three countries and was tasked with selecting international consulting groups to carry out the IPoE-recommended studies. TNC failed due to disagreements over the selection of international consultants. Egypt demanded that the GERD construction be halted until the studies were completed, which Ethiopia rejected.
Declaration of Principles (DoP)	2015	DoP reiterates the necessity of implementing the IPoE studies. Commits all parties to peacefully resolve the conflict and To not cause significant harm and to equitably and reasonably utilize Nile waters.
National Independent Research Scientific Group (NIRSG)	2018	NIRSG was a nine-party mechanism, created to select international consultancy groups. NIRSG made significant progress for the first filling. However, the scientific group did not agree on baseline scenarios for the studies. Also three countries unable to reach a compromise on the long-term operation and coordination mechanisms of the dam.
Washington Round	2019	Egypt invited the United States and the World Bank to the negotiations process. Ethiopia withdrew from the process in 2020 and refused to sign the final US-proposed agreement. The agreement sketches out the technicalities of the filling and the operations of the dam. Ethiopia later claimed it was technically impracticable and would severely limit the energy-generation capacity of the GERD.
Process led by the African Union (AU)	2020	In this time Egypt brought the dam issue to the United Nations Security Council (UNSC) and Ethiopia proceeded with the first filling. AU-led round of negotiations between the three parties was launched, ending in a deadlock in 2021. The same chain of events took place in the second half of 2021, when Egypt again brought the issue to the UNSC. While, Ethiopia unilaterally proceeded with the second filling. UNSC session urged the three parties to restart talks within the AU's framework.

As a result, rather than escalating conflict and potential war between the three riparian countries, the construction of GERD could be a great opportunity for cooperation and development if they can agree on a cooperative framework that benefits each country while not harming the interests of the other countries [53]. Furthermore, poverty alleviation, which is a major concern for all Nile Basin countries, and collaborative research, particularly in areas such as climate change, terrorism, and extremism, could serve as the foundation for a cooperative arrangement among all Nile Basin countries.

6. Conclusions

Ethiopia has a lot of hydropower potential, with plenty left over to sell to other countries, which will bring in a lot of money. The vast majority of the country's population, however, lives in rural areas with limited access to electricity. Ethiopia currently produces approximately 4 GW of electricity from 11 large and 7 small hydropower plants. However, when compared to the country's hydroelectric resource potential, this amount is extremely small. As a result, in order to achieve universal electricity supply, the country's energy policy should favor the development of small-scale hydroelectric power, which could be a better option for meeting rural energy demand while also improving rural society's economic development by improving water supply for irrigation development and fish production. Furthermore, Ethiopia should initiate and expand collaborative research with all Nile basin countries on natural resource utilization, climate change, food security, and poverty reduction in order to achieve mutual development and resolve the hydro-political crisis. As a result, this paper provides a brief overview of Ethiopia's hydropower potential and current development status. The article then discusses hydropower politics in the context of the GERD construction. Finally, it discusses the role of hydropower in meeting the energy demands of nations.

Conflict of interest

The author declares no conflict of interest.

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