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Sustainability challenges of hydropower and its implication on Ethiopia's economy

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ABSTRACT

Ethiopia has the potential to be 100% renewable. Its renewables are capable to solve its energy poverty and energy shortage in East Africa. The country's climate resilient green economy strategy considers energy as key enabler for vibrant economy. The objective of this paper is to identify key challenges of the energy sector by studying 12 years of electricity generation data, 2012 to 2023, and to analyze the sector's performance with a special emphasis on hydropower. In this study, both quantitative and qualitative methods were employed to draw performances indicators. The quantitative results showed that the country achieved 30% of its energy development plan with a deteriorating performance from 94% to 40%. This performance works for hydropower too, which dominants the electricity development and supply. The declining performance comes from government's monopoly in the sector, financial deficit due to ongoing internal crises and technical unavailability of power plants. This performance has greatly influenced expansion of industries, access to electricity, unemployment, and other economic activities. The authors advise the government, stakeholders, and development partners to consider the recommendations given in this paper to boost the energy sector development and keep the country in healthy economic pace by all measures.

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Energy development; hydropower performance; wind energy development; environmental impact of hydropower; renewable energy mix; UN SDG

1. Introduction

The growing population and economy of Ethiopia, escorted by an influx of local and foreign investments, has substantially increased the demand for dependable electricity supply. The government devised and implemented different energy policies that promote energy accessibility. The climate resilient green economy (CRGE) strategy is one of the grand strategies that aspire to transform the country from low income country to middle-income country by 2025. This strategy mainly accentuated on development of diversified energy mix, improved energy efficiency and increased off grid electrification as means to grow the countries macro and micro-economy (FDRE 2011). Subsequently, it has implemented cascaded plans such as the first growth and transformation plan (GTP I) (FDRE 2011), second growth and transformation plan (GTP II) (FDRE 2016) and national electrification program (MoWIE 2019). In addition, the launch of the united nations sustainable development goals (UN SDG) added the government's leverage to implement these ambitious plans. The CRGE strategy goes in agreement with the SDG-7 and SDG-13 target of 2030 (UN 2015).

Based on reports from Ethiopian electric power, the average implementation performance of the energy plans, GTP I (2011–2015) and GTP II (2016–2020), were 57% and 52%, respectively. This has generally affected the planned anticipated economic growth, the energy sector's 2025 plan to become major power exporter in East Africa, and to generate income from selling electricity to neighbouring countries. The particular impact is observed in terms of limited expansion of high-power consuming industries, reduced foreign direct investment, increased youth unemployment, limited expansion of small and medium enterprises (SMEs), which are key drivers of economic growth. The national electrification program (NEP 2) is the successor of GTP I and GTP II, that aspired to achieve universal electricity access by 2025 through 65% grid and 35% off-grid energy systems expansion (MoWIE 2017, 2019). Given the diverse terrain and scattered settlements of the country, promoting off-grid energy systems is considered cost-effective. Despite all these ambitious plans and efforts, the generation capacity of the country stands at 5.3 TW by 2022 (EEP 2022a) with remarkable growth from 3.4 in 2018 to 15.2 in 2020 and 15.5 TWh in 2022 (National Bank of Ethiopia 2020, 2022). This slower development pace of the power sector is influencing the country's economic and social development including but not limited to education, health, employment, entrepreneurship, investment and others not to grow as planned (National Bank of Ethiopia 2018, 2020, 2022).

The planning, development and distribution of the power sector in Ethiopia is owned by a state entity and it was continuously restructuring since its establishment in the 1960s. Consequently, the council of ministers issued a regulation, No. 302/2013 and No. 381/2016, to restructure the Ethiopian electric power corporation (EEPCO) to Ethiopian electric power (EEP) and Ethiopian electric utility (EEU). EEP is responsible to:

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(i) Undertake feasibility studies, design and survey of electricity generation in integrated national grid, construction of transmission lines and substation over 66kV and outsource such activities as required;
(ii) Commence construction and upgrading power plants that are integrated to the national grid, construction and upgrading of transmission lines and substations over 66kV, subcontract such works to third parties as required;
(iii) Administer, operate and maintain electricity generation in the integrated national grid and transmission lines and substation of over 66kV;
(iv) Sell and purchase bulk electric power on transmission lines above 66kV;
(v) Lease transmission lines above 66kV;
(vi) Submit electricity tariff proposals with respect to power sales and implement upon approval;
(vii) In line with directives and policy guidelines issued by the ministry of finance and economic cooperation to sell and pledge bonds and to negotiate and sing loan agreements with locale and international finance institutions; and
(viii) Engage any other related activities necessary for the attainment of its purposes.

Currently, EEP manages 22 power plants out of which 16 are hydropower plants with a generation capacity of 5 TW. High voltage transmission lines and substations were developed alongside power plant projects to transfer the generated power to national grid and provide quality electricity throughout the country. In that aspect, over 17,000 km of high voltage transmission lines ranging from 132kV to 500kV and 163 substations ranging from 132kV to 500kV were established (EEP 2022c). It is also mandated to provide electricity to large industries and neighbouring countries such as Djibouti and Sudan that use 132 kV and above. As a result, it is generating an average income of $70 million annually. Moreover, it aspires to play a vital role in the east African power pool and beyond by developing bilateral relations with Somali Land, Kenya, Tanzania and South Sudan (EEP 2022b).

Similarly, the EEU is established by the regulation No. 303/2013 (Ethiopian Electric Utility 2013) with the purpose to:

(i) Construct and maintain electric distribution networks, contract out the distribution networks construction to contractors as required,
(ii) Administer electric distribution networks, purchase bulk electric power and sell electric energy to customers;
(iii) Initiate electric tariff amendments and upon approval to implement it
(iv) In line with directives and policy guidelines issued by the Ministry of Finance and Economic Development, to sell and pledge bonds and to negotiate and sign loan agreements with local and international financial sources, undertake any other related activities necessary for the attainment of its purposes.

Despite the huge investment, Ethiopia's energy sector pace is slow to achieve national and international goals. It achieved only 51% access to electricity and 8% access to clean cooking with renewable energy makes up 89% of total final consumption (I. E. A. IRENA, UNSD, and WHO 2022). Ethiopia still has one of the lowest per capita energy supply and consumption rates in the world (IEA 2019; I. E. A. IRENA, UNSD, and WHO 2022). The country's performance indicators highlighted the need for improvement in order to achieve the expected targets. In addition, the tracking SDG 7 2022 report raised concerns that Ethiopia might not reach its targets due to lack of success in implementing national and international plans (I. E. A. IRENA, UNSD, and WHO 2022; Helen Mountford et al., 2021; Razzaq et al., 2023). On the other hand, sustainability of electricity generation from developed power plants show a frustrating trend as there is frequent blackouts and shedding that is heavily influencing the economy.

The main purpose of this study is to highlight the sustainability challenges faced by Ethiopia's power sector in general and hydropower in particular by examining generation data from 2011–2023 and site investigation in one of the power plants. The study draws a full picture of the nature of actual power generation against the expected plans through these years and the corresponding economic impact of the country. It also identified the key challenges of the sector and produced recommendations to overcome these challenges in the future. The results indicated the technical unavailability influence of the energy sector on the economic growth, investment payback and expansion. The findings show huge implications for policy makers and other stakeholders where to focus in order to solve the technical challenges of existing power plants while planning to expand. Moreover, this study will contribute to the hardly published scientific work and motivate different research and academic institutions, scholars to engage further studies to improve the deteriorating performance of the energy sector and its trade-off influences. The uniqueness of this paper is its focus on the technical challenges of the energy sector, which anchored the countries transformation journey. However, it did not get attention to be considered as one of the prime movers for health growth. In this perspective, the paper will serve as a baseline for future works to deal with the following gaps: first, there has not been any attention on sustainability of power generation and its impact on the country's macroand micro-economic growth. Second, the influence of government's monopoly on the sector and quality of service. Third, main policy bottlenecks for private sectors to invest in the energy sector and implication. Fourth, the trade-off between sustainable availability of electricity and economic transformation.

The paper is structured in six sections. Section 1 introduces the general energy development activities in Ethiopia. Section 2 describes the study area and the methodology employed in the study. Section 3 gives the overall picture of the power generation capacity in Ethiopia. Section 4 discusses the challenges of Ethiopia's power sector and main focus on hydropower. Section 5 provides actionable recommendations and section 6 give concluding remarks.

2. Methodology

In this study, primary and secondary data were used for analysis purpose. The primary data are actual electricity generation data collected from Ethiopian electric power. The secondary data were collected from official reports and scientific articles. Quantitative and qualitative analysis of the collected data together with field investigation methodology was used to draw the actual electricity generation nature, performance of the generation capacity, performance of hydropower plants and its inference to social and economic development. From the bigger picture of the energy sector status, various policy recommendations were produced to improve energy service and boost economic growth.

2.1. Description of the study area

Ethiopia locates in the north-eastern part of Africa commonly called as the Horn of Africa. It shares borders with Sudan in the west, Somalia and Djibouti in the east, Eritrea in the north and Kenya in the south. It covers a total area of about 1.13 million km^2 (Zelelew, Gebre, and Wasihun 2022). It implemented CRGE strategy in 2011 and started to substitute its conventional power plants with renewables. Table 1 presents the renewable energy potential of the country, which can be harnessed to develop the economy. Currently, the country has the highest installed hydropower capacity in Africa (IHP 2022) and the ninth top in the world in creating job opportunities in hydropower (IRENA 2022).

3. Power generation

3.1. Total power generation in Ethiopia

Ethiopia is endowed with abundant renewable energy resources, see Table 1, with a potential to generate over 60 GW of electric power from hydropower, wind, solar and geothermal. This potential could give the country a good opportunity and leverage to grow its economy and play vital role to supply electricity to neighbouring countries. However, taping all these resources demands huge capital investment beyond the country's capacity. Accordingly, the country should revise its long-term planning to utilise and strengthen its energy security, economy and stability. At the present, the country faces big energy shortage and load shedding to serve its about 126 million people (UNFPA 2023). This shortage is as a result of low generation performance, planning, failure in implementation scheme, lack of finance, conflict and other factors.

Table 1. Ethiopia's energy resource potential (Ethiopia - Energy 2023).

Resource	Unit	Exploitable potential	Exploited %
Hydropower	MW	45,000	<5%
Solar/day	kWh/m^2	4–6	<1%
Wind: Power	GW	100	<1%
Speed	m/s	>7	
Geothermal	MW	<10,000	<1%
Wood	Million tons	1120	50%
Agricultural waste	Million tons	15–20	30%
Natural Gas	Billion m^3	113	0%
Coal	Million tons	300	0%
Oil shale	Million tons	253	0%

Only 45GW from hydropower, 5GW from solar, 5GW from wind and 5GW from geothermal is consider in long term planning as generation capacity.

The CRGE strategy fits to SDG-7 and SDG-13 and it shows a significantly headway in many activities. Yet it fell far short of what is expected to achieve. One reason to drag its full implementation is due to its capital intensiveness and a missed promise from Paris agreement [COP26 2021]. On the other hand, the intensive hydropower development in the country raised environmental concerns that delay the development of some hydropower projects. As a result, the country's development capacity is falling short of its ambitious energy plans outlined in its GTP I and GTP II. This has challenged the country's macroeconomic growth, trade and investment (National Bank of Ethiopia 2022). Because of this, The plan to achieve 100% electrification is now in jeopardy (MoWIE 2019). Ethiopia's electric power development was mainly dependent on hydropower. The hydropower was known for its significant power blackout and shedding due to lower reservoir volume, especially in the dry season. Rarely published researches show substantially reduce generating capacity of many power plants during the dry season (Chen 2016). This problem was addressed by implementing renewable energy mix based on studies that shown the complement of wind energy during the dry season (Embassy of Japan in Ethiopia 2008). Today, the small mix of wind energy shows significant contribution into the overall generation capacity of the country since 2013 see Figure 1(a). The share is slowly increasing and reached around 7% by 2023 as shown in Figure 1(b). This share is expected to increase upon the completion of undergoing wind farm projects and execution of pipeline plans.

Figure 2 shows the country's 12-year generation trend. It clearly highlights how the energy sector is facing a new and unrecognised challenge. Despite the highest volume of water in the reservoirs during the rainy season, June to September, the hydro-dominated generation trend is declining (Figure 2(a)). This decline in generation capacity is not due to water shortage, but availability challenges of the power plants. The power plants are generating considerably less power far below their optimal operating capacity. The performance declined rapidly from 94% in 2012 to 40% in 2023. Due to this performance deterioration and dependability challenges, many development activities including expansion of industrial parks, job creation and access to electricity was diminished. As a result, several industrial parks with greater job creation potential are forced to postpone their launch or operate under capacity that in return exacerbated the growing unemployment rate in the country.

3.2. Power generation from Hydro

Ethiopia's power system expansion master plan forecasted, energy requirements within Ethiopia and potential exports to neighbouring countries. The forecast showed that the total energy generation of 147TWh by the year 2037 (EEPCO 2013a, 2013b). This forecast considered an average of 13% and 12.4% annual generation and power demand growth, respectively. This forecast targeted to satisfy 22GW and 5GW peak demand for Ethiopia and export correspondingly. It further indicated that several hydropower plants would

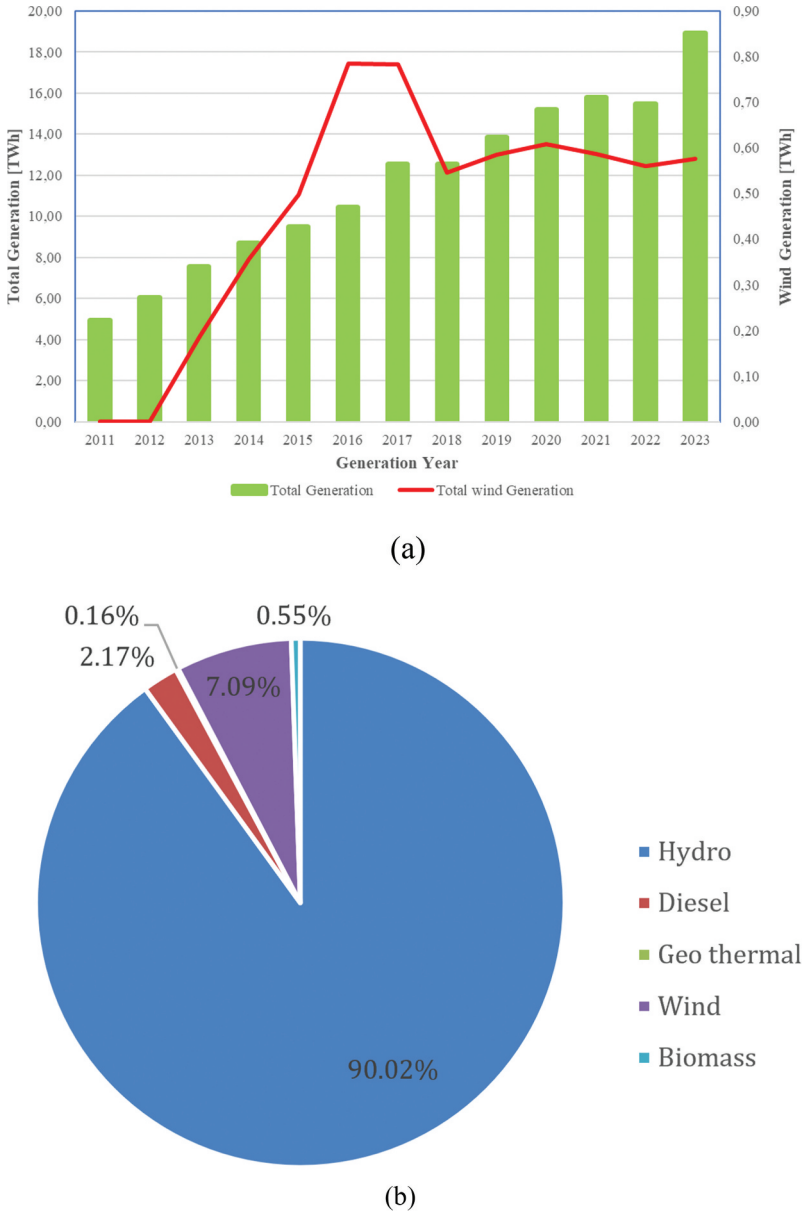

Figure 1. Ethiopia's power production trend: a) contribution of wind and b) utilized resource.

develop in the coming 10 to 15 years as shown in Figure 3. It also gives the clue for domination of hydropower in the electricity supply until 2037. In addition, it also indicated that the share of wind, solar, geothermal and bioenergy will also increase. The growing energy mix strategy would contribute to assure increased access, stable and reliable energy system, grow the economy.

Despite the increasing generation capacity, people connected to the grid remained to suffer from undependable electricity supply and people expecting to get electricity access are forced to wait longer than the planned time. since recently, the frequent power interruptions become common throughout the year. Most of the time this happens without schedule and notification spontaneously. Such unstable availability of power caused serious damage to individual, institutional properties and to the economy at large. For example, after every interruption reconnecting to the internet network is taking from minutes, hours and even days. This challenge greatly influences financial institutions such as banks and micro enterprises and the service sector in general.

The power blackouts become serious when it happened as a result of fluctuated generation due to technical unavailability of units on top of overloaded transmission lines, transformers and substations. The main cause for this is lack of proper maintenance and operation, shortage of spare parts, ageing, delayed management decisions, long and tedious procurement system, inefficient centralised maintenance management system and others.

The reduced generation performance during the rainy season shown in Figure 2(a) is an indication to question if the investment on wind power is right or not. Another indication for technical unavailability, is the climate impact study of international energy agency (IEA) on hydropower generation. It showed that Ethiopia's hydro powers would not experience shortage of water

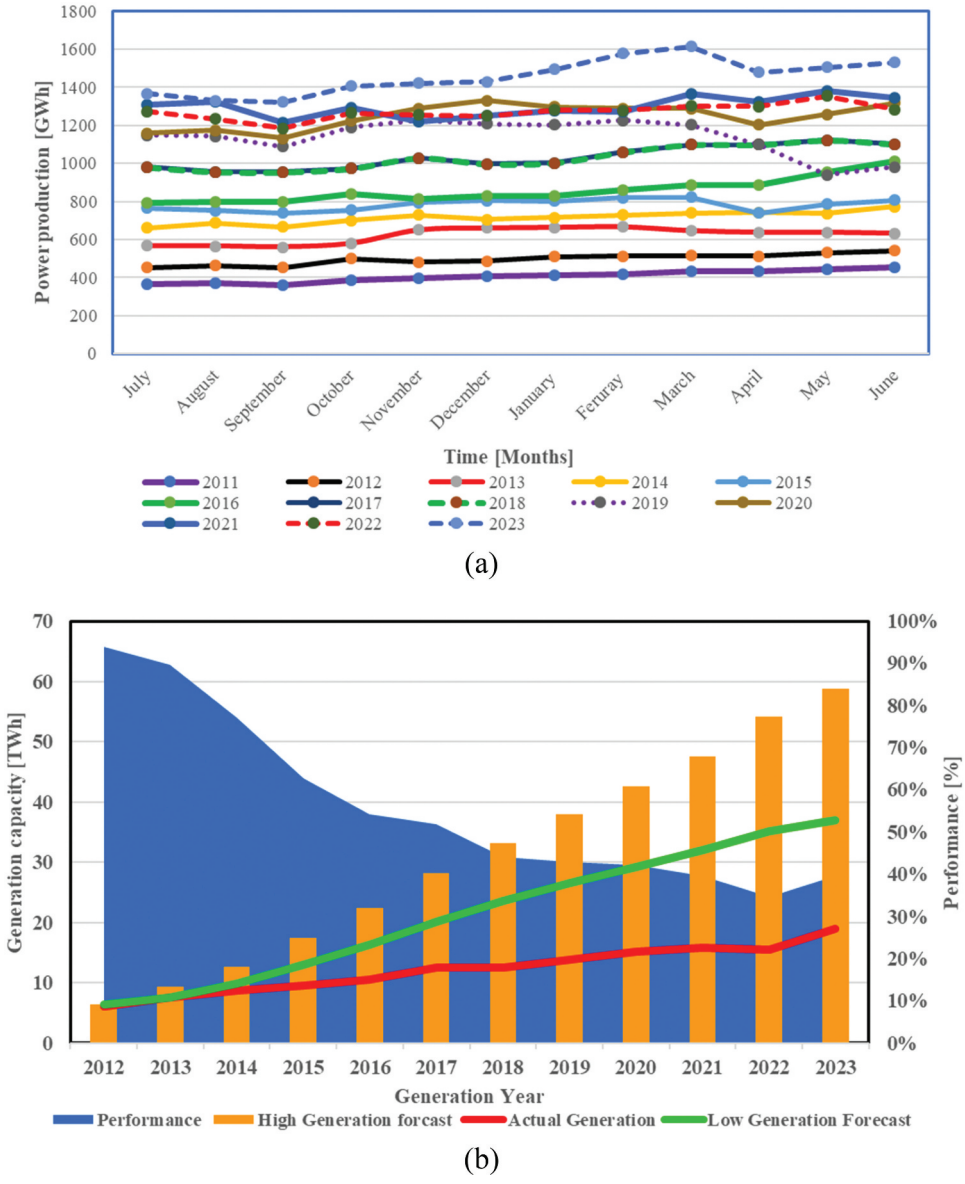

Figure 2. Ethiopia's generation trend a) monthly and b) generation performance.

due to the slightly increase in rainfall (IEA 2020). The continuously falling generation capacity observed in Figure 1, Figures 2 and 5, indicates the alarming unhealthy availability of power plants that in return influences the electricity supply, developing demand of electricity, transportation, industries productivity, raising unemployment rate, inflation and so on. Similarly, the wind power plants are also facing availability challenge. For example, the 120 MW Ashegoda wind farm is found at its critical stage to refunction. The long idle time of the farm would demand significant finance for maintenance, spare parts and refurbishment if not complete upgrading.

In 2022, Ethiopia ranked first in Africa by having highest installed hydropower capacity (IHP 2022). The contribution of hydropower in the country's electricity generation capacity is enormos as shown in Figure 4. Many of the hydro powers are storage type with four run-of-the-river (Open Infra Map 2023). The dominance of hydropower will also continue in the future; however, the low generation performance in general and the performance of certain hydropower plants in particular seeks attention for healthy availability and planning alongside to expansion works. Expansion without proper planning for technical availability is a zero-sum game investment. In addition, hydropower development has controversial environmental impact issues globally and studies show there is no agreed positive or negative environmental impact of growing hydroelectricity consumption (Adebayo, Kartal, and Ullah 2023). However, development of Ethiopia's hydropower was considered as a swift means to get dependable electricity, strengthen the economy, substitute any imported fossil fuels and take mitigation to any environmental impacts (Estifanos 2019). Nevertheless, the environmental impact and water politics issue has influenced the development of large hydro powers of the country and requires good handling prior to any development.

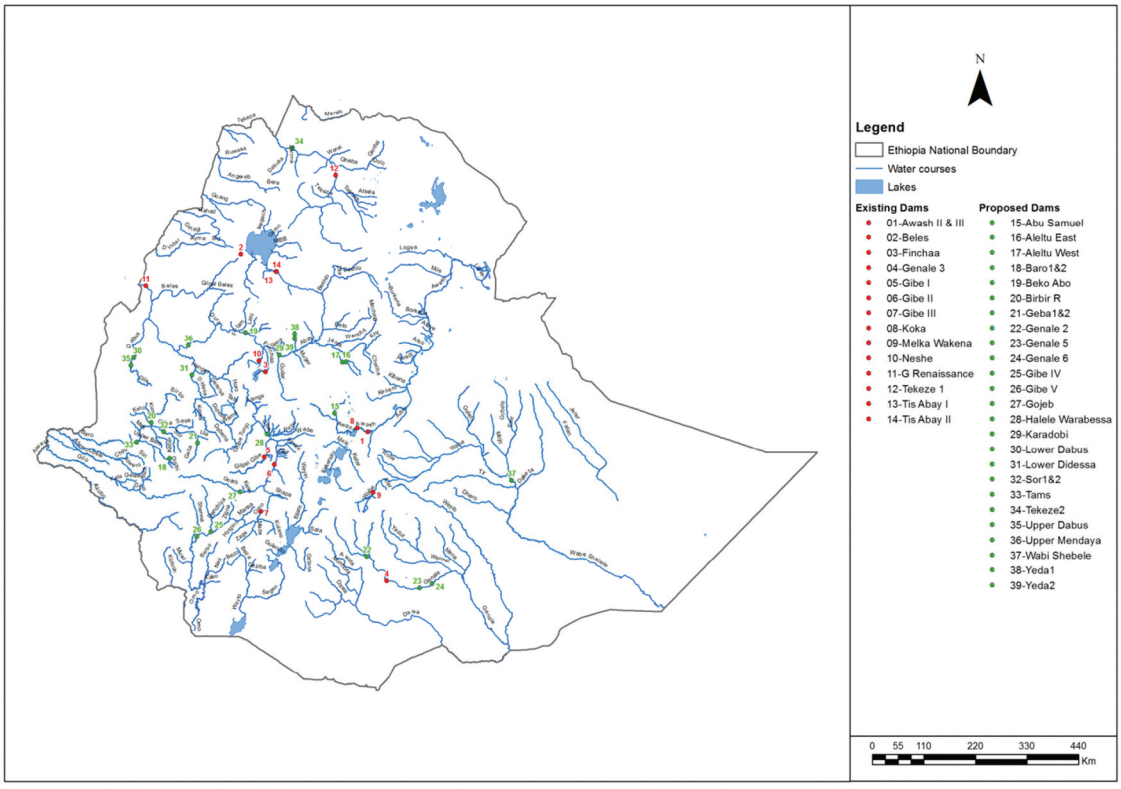

Figure 3. Existing and planned hydroelectric developments in Ethiopia (EEPCO 2013b).

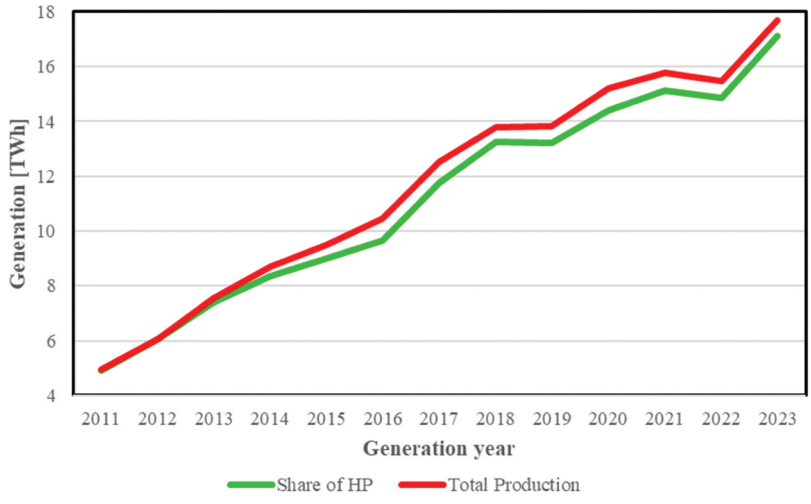

Figure 4. Ethiopia's hydropower production behaviour.

3.3. Power generation from other energy sources

Ethiopia's ambitious electricity development plan did not only focus on hydropower and wind but it tried to mix all possible sources of renewables including solar, geothermal and bioenergy. EEP planned the developments of solar power projects for Metehara (100 MW), Metema (125 MW), Mekelle (100 MW) and Humera (100 MW) through public private partnership (PPP) and independent power producer (IPP) scheme. The development of these projects is delayed due to the peace and insecurity crisis in the country. Since recently, the impact of COVID-19 and the Tigray war in the north has left the country at high risk to perform any developmental activities and growth as before (Ayele et al. 2023a). However, in normal circumstances the contribution of such generation mixes would expect to grow by type and capacity as the country's commitment to invest on geothermal, sugar industries and waste to energy continues. In this view, the potential of wind and solar integration by 2025 was estimated as 2GW and 3.44GW with a potential to increase into 3.6GW and 5.3GW by 2030 respectively (RES4Africa 2019). At this time, a very small contributions from geothermal and waste to energy conversion were integrated to the power mix. With continued implementation

of the CRGE strategy to decommission non-renewable power plants, it would also open doors for increased integration of the available renewables.

4. Challenges of the power sector

Ethiopia's state-owned electricity sector underwent continuous reform following electricity sector liberalisation experiences of other countries. The reform targeted to reduce public finance deficit due to huge investment on energy development, enable the government to invest on other development projects, diversify the generation capacity to withstand drought and climate impacts and to satisfy a pressing need for clean and affordable energy supply. Following the reform, different policies and proclamations were exercised. These policy reforms narrated today's mixed generation capacity and access targets (Girma 2020). Nevertheless, the delayed development projects of wind and solar plans gave the energy sector a bigtime to realise its energy mix targets. Table 2 shows the execution performance of the country's grand energy development plans. The hydro-dominating generation capacity of the country need to address key challenges detailed in the subsequent sections is essential for sustainable and responsible development.

4.1. Technical challenges of the hydropower sector

This study examined six representative hydropower plants, listed in Table 3, to explore the main technical issues for their underperformance. These plants represent about 33% of the entire hydropower plants in the country. Figure 5 (a and b) indicates how the power plants are straggling with availability. The below-average annual performance shown in Figure 5(b) depicts the behaviour of the other power plants as well.

The individual generation details of the power plants revealed their lower performance profile except for Finchaa power plant. Finchaa is the oldest HP in the group and it was refurbished in 2003 after 30 years of service. The power plant performed better compared to the other five power plants. Its 10-year generation performance indicated that the power plant has a good availability reputation. On the other hand, Tekeze HP has experienced inconsistent availability that indicates the actual poor maintenance practice.

4.2. Performance of Tekeze hydropower plant

Tekeze hydropower plant has four 75 MW turbines and it has entered into commercial operation in 2009. It was jointly operated for two years by the contractor, HARZA Engineering Com. Intel., and the client, Ethiopian electric light and power authority, EELPA. Later, it was handed over to the client for full operation and maintenance. The power plant contributed greatly in electricity supply significantly from the date of its commencement. Its share when the country was in a critical power shortage was so incredible and it was named as 'Fetno Derash' meaning a fast helper. However, shortly its performance was deteriorated to highly stochastic nature as shown in Figure 6. Since 2013, the power plant was stressed by sever technical challenges. Client's technical reports show that the plant's units (unit 2, 3 and 4) were experiencing exceptional vibrations and they were forced to stop in 2015. This technical status led the power plant not only to be scheduled for extended maintenance but also proposed for rehabilitation options. While the process for extended maintenance and procurement of spare parts were under way, a war crisis broke out in Tigray on 4 November 2020.

During the war period, the power plant was lounging and giving service in its limited capacity in an off-grid modality separated from the centralised national grid system. The government bombed the power plant's substation by air and drones amid to toughened the siege situation in Tigray. The consecutive air and drone strike cause partially damaged to the control room and completely damage to one of the transformers shown in Figure 7. During this very critical crisis

Table 2. Summary of Ethiopia's GTP I &II energy development performance.

	GTP I			GTP II		
Activities	Planned	Achieved	Performance	Planned	Achieved	Performance
Generation [MW]	10,000	2,221	22%	17,346	4516	26%
HV transmission line [km]	17,174	12,825	75%	21,728	20,803	96%
MV Transmission line [km]	110,000	88,266	80%	120,699	64,000	53%
LV transmission line [km]	148,038	100,939	68%	175,240	62,690	36%
Electricity access %	61	53	87%	90	60	67%
number of customers connected [million]	1.97	0.22	11%	2.96	0.95	32%
	Average Performance		57%	**Average Performance**		52%

The implementation success of the country's national electrification plan is highly dependent on this performance.

Table 3. Selected hydropower plants.

Power plant	Installed capacity [MW]	minimum Energy [GWh year]	Average Energy [GWh/year]	Average plant Factor	Investment [$million]	Year of commencement
Tana Beles	460	1357	2749	0.68	500	2010
Tekeze	300	782	1400	0.53	400	2009
Finchaa/refurbished	128	422	615	0.55	NF	1973/2003
Gibe I	210	610	882	0.48	331	2004
Gibe II	420	1400	2030	0.55	600	2010
Melka Wakena	153	325	556	0.42	NF	1988
Total	1671	4896	8232			

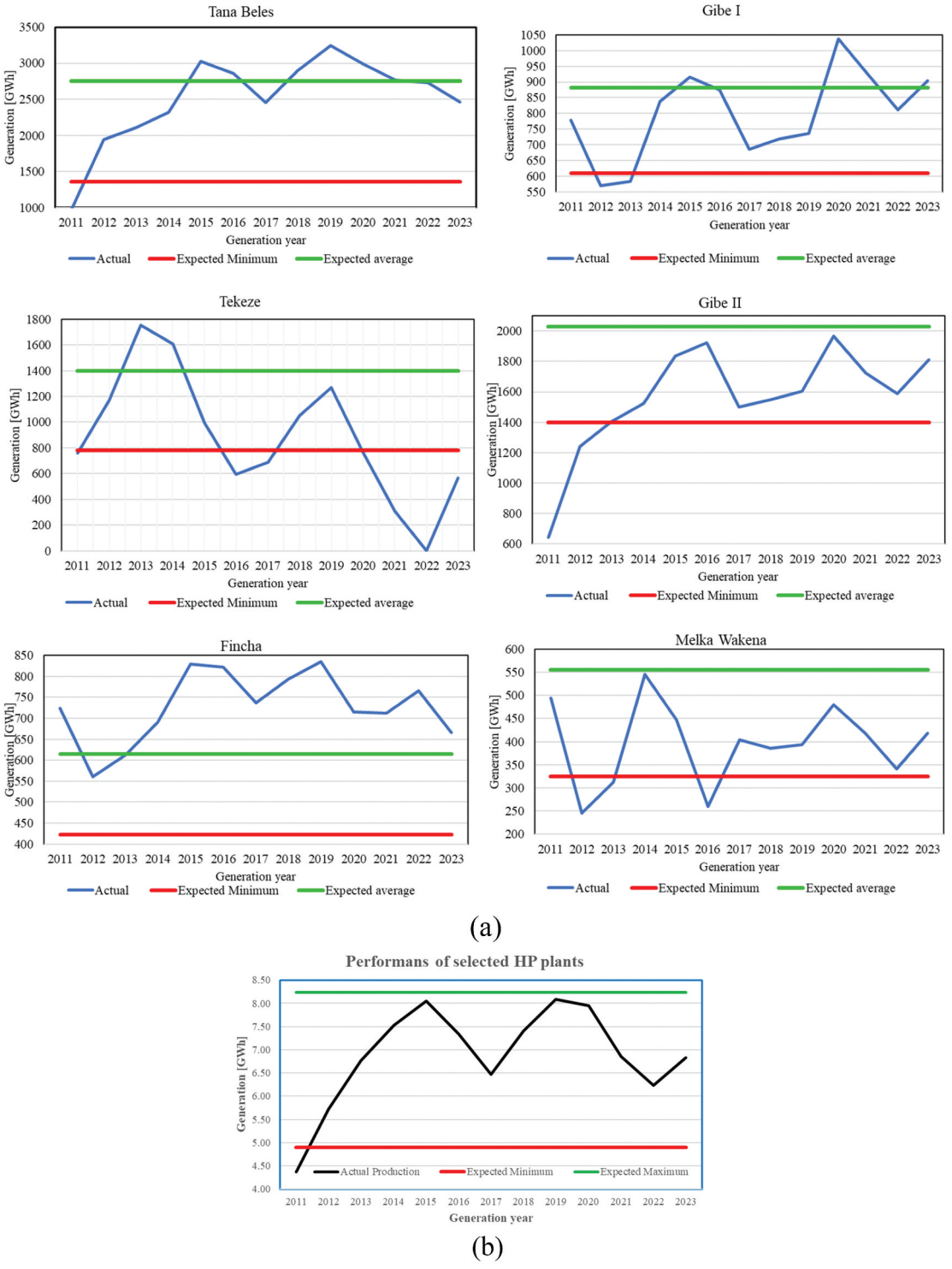

Figure 5. Performance of selected hydropower power plants in Ethiopia (a) individual behaviour and (b) average performance.

situation, the authors pay frequent visit to the power plant to contribute technical support, troubleshooting, perform root cause analysis and supervised ongoing maintenance activities.

The desk review and site investigation of the power plant showed the power plant has experienced inflated maintenance cost, acute shortage of spare parts, untimely worn-out of components, visible and unavoidable units' vibration, malfunctioning of unit components and systems, especially monitoring, communication and instrumentation that made operation and management risky. On the other hand, the power plant was used to spill water on scheduled timeframes with prior preparation and awareness. At times the power plant was connected to the national grid the impact of its unavailability during spilling was not well recognised. However, during the war time availability of the power plant become a means of life and death for the people of Tigray. Nevertheless, the power plant was forced to spill very large amount of water during the summer of 2021 and 2022. The amount of the spilled water was almost equivalent to its annual water requirement for normal full capacity generation. The

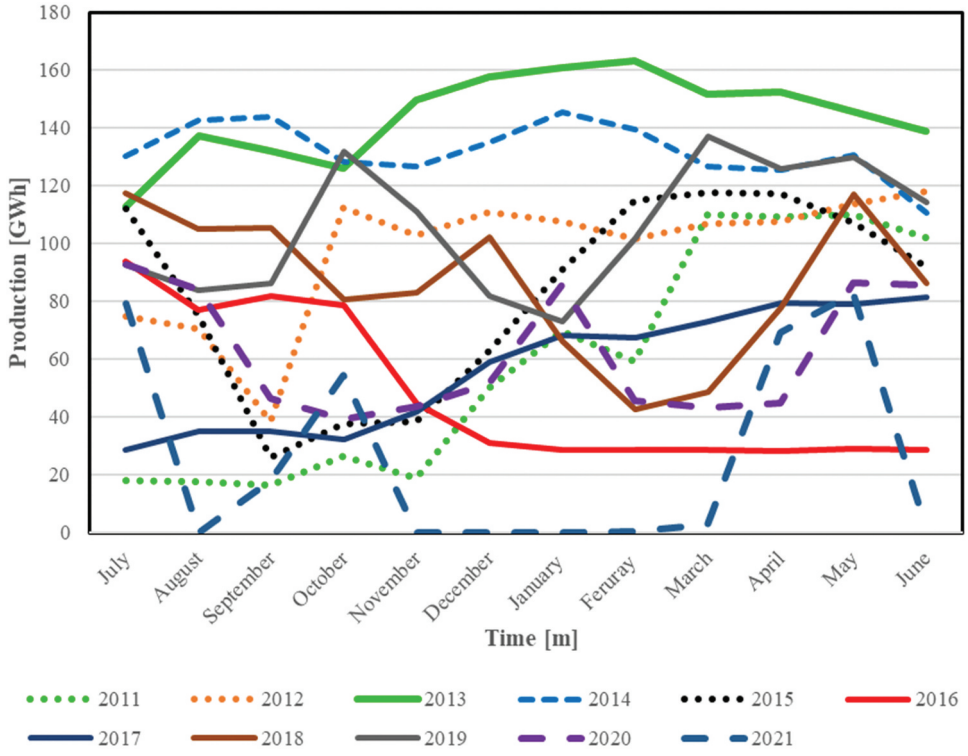

Figure 6. Monthly performance of Tekeze hydropower.

Figure 7. Tekeze transformer burned by drone.

spilling was performed to protect reservoirovertopping. The level increment comes as a result of low performance nature of the power plant, regular spilling communication was interrupted due to the war situation and heavy rainy season in the catchment.

During spilling, the flowing water was usually causing big damage to agricultural properties of downstream farmers. The extent of damage was expected to worsen during the war period as spilling was made without any prior notification to downstream communities due to communication obstruction and siege. In addition, the power plant's design made it impossible to generate power while spilling. This challenge became bold as the power plant became the only power source to the people of Tigray who was under a complete siege.

Throughout the spilling period, the power plant became under 100% forced shutdown condition as power transformation cables and is powerhouse covered by a continuously varying direction of water shower. The corona effect on the transmission cables and highest water jet covering the transformers in the partially opened transformer house, see Figure 8, made generation impossible. The transmission cables were not only under corona effect but experienced a lateral turbulent water jet that skewed and disturbed their normal insulation gap. In addition, the water jet approaching the transformer house was leaking to the powerhouse that created

(a) (b)

Figure 8. Power house and transmission cables of Tekeze hydropower a) during spilling and b) normal operation.

other challenges in the generation units. Moreover, the spilled water caused higher erosion and sliding with high material transport on the left abutment of the dam. This material entered the draft tube forcefully through tailrace gates and caked up. In addition, this would compromise the safety of the arc dam greatly. The leaked water in the power house and deposited material in the draft tube all the way to tail race required additional working days to dry and clean the power house to restart.

In Ethiopia, households consume about 85% of the total supplied electricity. The households typically use more energy during the day and less at night that made generation units to operate at fluctuating and lower capacities than their optimal generation capacity, especially at night. In addition, the load demand profile of the neighbouring countries to which the country sells electricity is similar.

Particularly, at Tekeze, it was observed that units were generating very low power during night time that influenced units to operate at extended cavitation zone that produced higher vibration in the draft tube and in the units in addition to the inherited vibrations. As part of the investigation, shifting of all higher power demanding activities such as milling, bakery, household intensive cooking and all industrial duties to night time was practiced to narrow the day and night time demand gap. This created some stability on the units to operate at their lowest safe marginal generating capacity. In addition, it was suggested direction change to the transmission line and building appropriate shade to the transformers that enable the power plant to operate while spilling. The later recommendations would address the design short comings of the power plant.

Normally, hydropower plant maintenance in Ethiopia is handled centrally. This method has shown inefficient and slow reputation. Moreover, it doesn't develop local capacities such as spare part manufacturers, industries to hand maintenance work, skilled labour and it did not invest in academic and research to assure sustainability. The industrial experience at Tekeze revealed that there is local capacity, manufacturing, maintenance and skilled labour, that can excel if opportunity is created. This also highlighted the timely need for intervention of continuous research and development, continued short and long-term capacity building, partnership development, spare part indigenisation and public awareness in the sector.

Allowing Tekeze and the other power plants to continue with their present performance trend will not only shorten their lifespan but also lead to reduced and/or no investment payback potential of the sector and economic disaster in the country. Allowing this means giving assurance to worsen sediment accumulation, dead storage volume reduction and reduced generation capacity than they are designed for. This would affect the country's economic growth, environmental safety, power sector sustainability and others. In return, it would directly influence the investment to expand the energy sector and energy system. Indirectly, low energy investment would lead to step back the access to affordable and clean energy plans, limit industrial expansion, slow or halted the country's transformation journey that aspired to become middle income economy by 2025 or so.

4.3. Hydropower dominance and financing challenges

Regardless of the beautiful energy mix planning, Ethiopia's electricity falls under hydropower full dominance with the government remained as the sole actor in the sector's transformation. The multipurpose development potential of hydropower will also enable it to continue as an important key player in the water-energy-food and environment nexus (A. D. Hailu 2022; Jima et al. 2022). However, the project execution period of many developed and undergoing HP projects consumed extended project time, which ended up at higher project cost than planned investment margins. In addition to the prolonged project execution period, the performance of the installed hydro power plants exhibited lower performance that further prolong the payback period of their investment. This investment trend limits the financing capacity of the government to expand the electricity sector and other development projects. Furthermore, added collateral damages attributable to recent peace crises worsen the maintenance and investment efficiency of the sector.

As Ethiopia aspires to become a middle-income country, its big challenge was getting finance for its ambitious plans including for building large hydropower projects as they

need multi-trillion financing. In addition, studies suggest the government to consider environmental, geopolitical and social factors for implementing long term plans (van der Zwaan, Boccalon, and Dalla Longa 2018). The development of the great Ethiopian renaissance dam (GERD) can be seen as example how international donors and lenders were hesitant to support its development. The country's right to develop GERD and unsettled diplomatic relation with downstream countries led to development of new policies in order to avoid potential conflicts (Abebe et al. 2023; Tefera and Sterk 2008; You 2023). The geopolitical issues and concerns of international actors on the country's interest to develop large hydropower project was hindering the country's ability to utilise its resources and meet its increasing electricity demands. In this condition, creating conducive environment for accelerable execution of IPP and PPP is the way forward to speed up the development of planned hydropower projects.

4.4. Climate change, environmental and social impacts

Hydropower might cause negative environmental and social impacts. Building big dams can force people to leave their homes and harm the environment. It is tough to balance these impacts while promoting sustainable development. However, proper strategic planning to reduce land use land cover impacts on the environment and local community believed to improve this condition (Soressa and Gebre-Egziabher 2023). Similarly, hydropower developments have potential variabilities due to climate change that would strongly influence water level, agricultural productivity and energy generation. Studies indicate that Ethiopia would have a slightly increase precipitation until the end of the 21st century (M. B. Hailu et al. 2023; IEA 2020). Accordingly, climate change poses a threat drought and flood on the country due to changes in rainfall patterns. This could affect the hydropower by disrupting its water flow, availability, sediment accumulation as well dam failures. In this regard, the country should conduct thorough assessment, protection procedures and tabled approved assessment reports of potential harm before starting new hydropower development would normalise any cross-border misunderstandings and climate change predictions. This would also help the country to get support from global development partners.

4.5. Local capacity

Looking at the available resources, history of development and global contribution, hydropower in Ethiopia remained with undeveloped local capacities. Specialized technical expertise together with robust technological capacities are crucial for proper development and operation of the sector. However, Ethiopia faces critical skilled gap particularly in project planning, design, manufacturing, safety, management, maintenance and operation to satisfy its striving HP development. To fill this gap, the country highly relied on foreign capacities. One factor that contributed to this challenge is the limited knowledge and technology transfer strategy exercised during project planning, development, execution and very poor skill retention mechanism.

4.6. Regional and local conflicts

Ethiopia shares river basins, including the Blue Nile basin, with neighbouring countries. The question for equitable water share has been raised when hydropower development was initiated. In this regard, continued research on mutual economic and social developments of shared water resources would be instrumental to narrow misunderstanding, have effective negotiation and to resolve potential conflict (Getahun, Wakjira, and Nyingi 2020; Sallam 2014; Veilleux 2018). On the other hand, the extended intensive civil wars, such as the Tigray war erupted in 2020, recent crises in the Amhara and Oromia region, are diverting government and stakeholders' attention from development engagements in general and hydropower development in particular. The impact of the Tigray war on Ethiopia's economy is very huge and it has diminished the countries capacity to convene any development projects (Ayele et al. 2023b; UNDP 2021). Moreover, international investors and development partners are also hesitant to support endeavours in conflict areas, including development of HP in trans-international river projects.

5. Actionable recommendations

5.1. Government-led intervention

Hydropower will continue as lead electricity supplier in Ethiopia. To assure its sustainable development, the government needs to create transparent policies and regulations including but not limited to investment, licencing, environmental protection and social impacts. Expansion of IPP and PPP policies and proclamations would contribute to ensure public interest protection to leverage expertise, capital and technology for hydropower projects. In addition, the government should focus to invest in the necessary infrastructures such as roads and robust grid infrastructures to facilitate fast development and integration of hydropower projects. Moreover, government direction and efforts to create local capacities in hydropower design, planning, operation, management, skill development, research and development strategies would be paramount important.

5.2. Private sector intervention

The implementation of IPP and PPP policies and collaboration between the government and private sector are very important mechanisms for successful and sustainable hydropower developments. In this view, the government should incentivise private investment through tax breaks, subsidies, finance access mechanisms, guarantees and risk-sharing mechanisms. This will encourage the involvement of foreign and local private sectors that have advanced technologies and innovative solutions in the sector. In addition, it would be helpful to promote partnerships with private companies that have the expertise, advanced equipment and practices. Private sector involvement would bring efficiency and innovation to project

development, construction, quality of service, operation and marketing in the sector. To successfully implement this, the government should ensure the following: the participation of experienced and qualified private developers through competitive bidding and monitor for compliance with environmental and social safeguards and compliance with global standards for environmental and social impact evaluations, relocation procedures and community engagements.

5.3. Data availability

Generally, countries without robust systems have poor data handling. However, Ethiopia's data handling, openness and availability represents one among the worst. Most important data of the country are found in the hands of individuals not in the system of institutions. This made it data collection is a time taking and tedious process in the way it causes data adulteration and greatly influence the credibility of many plans. In addition, it becomes very difficult to deal with the relation of one sector with others as this study is trying to solve. Accordingly, the government should build centralised data hubs which are open to research institutions, private sectors and the public.

6. Policy consideration recommendations

To expand hydropower development in Ethiopia, the authors propose the following policy considerations:

(a) Develop a comprehensive energy strategy that clearly outlines goals, necessary steps, timeline, actors and investments for increasing hydropower capacity.
(b) Create a transparent and efficient permitting process to reduce delays in project approvals and encourage private sector investment in new hydropower projects.
(c) Offer investment incentives, including tax breaks, subsidies and financial support, to attract private sector funding for hydropower projects and accelerated development,
(d) Encourage and support collaborations between government and private investors in hydropower development and operation. This approach enables sharing of resources, risks and expertise, leading to quicker project implementation.
(e) Promote water-energy-food- environment nexus projects.
(f) Invest in capacity building programs that train local institutions and individuals, including project planning, construction, operation and maintenance. The programs should also cover research and technology development, test and verification, environmental and social impact management schemes that enhance skills and knowledge in hydropower development.
(g) Create renewable energy market mechanisms, like feed-in tariffs or power purchase agreements to offer long-term price certainty and market stability for hydropower producers. This will enhance the investment climate and appealing to both local and international investors.
(h) Develop strong environmental and social safeguards for hydropower projects to ensure sustainable development. This includes impact assessments, engaging stakeholders and mitigating negative impacts on local communities and ecosystem.
(i) Maximize the use of hydropower resources by exploring regional cooperation for power trading through interconnecting power grids and macroeconomic integration with neighbouring countries.
(j) Develop appropriate water-energy-food-environment nexus strategy with neighbouring countries to utilise fair water share equity. In this way, the country can attract investment and meet its energy and economic development needs while ensuring sustainability and social inclusions for sustainable hydropower development.
(k) Consider multipurpose hydropower development projects with in the country and collaborative project with neighbouring countries to harmonise water politics.
(l) Consider multipurpose long duration energy storage planning to boost electricity trade, sustainable integration of other renewables and sustainable food supply.
(m) Develop capacities in dam operation and dam safety with short and long capacity building schemes.

7. Conclusions

Ethiopia's energy sector development can be categorised as a slowly peaking process looking at its age and development performance. Since recently, many projects such as hydropower, wind, solar, geothermal, bioethanol, waste to energy and others experienced either delay or exclusion from development plans. This is due to the continuously decreasing leverage of the government to continue as key player in the sector. Today the country's installed energy generation capacity is below 30% of its plan and below 40% generation performance. This also applies to the hydropower sector, which currently is the backbone of the electricity supply and the economy. The hydropower sector is also having the lion share to drag the country's overall development and economic vibrancy. It's under performance is primarily related to technical unavailability. Unless the technical unavailability challenges are solved properly, the present trend of the sector could cause catastrophic economic collapse in the country and neighbouring countries that purchase electricity from Ethiopia. The sluggish development pace and dwarfed performance nature of the energy sector has contributed to the overall limited economic development of the country particularly: delay of projects, termination of different projects, shift the plan and budget of prioritised projects, increased youth unemployment, education and pressure on biomass resource and ecosystem. This deters the country's transformation target and step back from achieving its CRGE target and the UN SDGs.

Nomenclature

CRGE	Climate resilient green economy
EELPA	Ethiopian electric light and power authority
EEP	Ethiopian electric power
EEPCO	Ethiopian electric power corporation
EEU	Ethiopian electric utility
FDRE	Federal democratic republic of Ethiopia
GERD	Great Ethiopian renaissance dam
GTP	Growth and transformation plan
GTP I	First growth and transformation plan
GTP II	Second growth and transformation plan
GWh	Giga Watt hour
HP	Hydropower
HV	High Voltage
kV	Kilo Volt
kWh	Kilo Watt hour
LV	Low voltage
MoWIE	Ministry of water irrigation and energy
MV	Medium Voltage
MW	Mega Watt
MWh	Mega Watt hour
NEP	National Electrification Plan
NF	Not find
SDG	Sustainable development goal
UN SDG	United Nations sustainable development goal

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Data availability statement

The data used in this research will be available based on request.

Dedication

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