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Unlocking wind power potential to improve energy security in Ethiopia

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Abstract

Ethiopia possesses abundant wind resources that have the potential to revolutionize its energy sector by providing reliable and sustainable electricity through wind power. Despite the presence of a few operational wind farms, the country is facing challenges in generating sustainable electricity. The slow progress in wind power development raises concerns, as the impact of declining power generation from existing wind farms on economic development and return on investment remains insufficiently examined. The research paper aims to examine the status, challenges, and opportunities in developing, deploying, and sustaining wind power generation. This was accomplished through qualitative and quantitative analysis using 11 years of power generation data from operational wind farms and field research. Data sources include Ethiopian Electric Power, wind power operation reports, official government reports, field observations and discussions with wind power operators. The study reveals that challenges such as intermittent wind resources, high initial investment costs, inadequate transmission infrastructure, limited skilled workforce, and environmental concerns hinder the realization of wind energy's full potential. The article provides evidence-based recommendations for policymakers and the wider stakeholders to address the challenges and maximize benefits of wind energy in Ethiopia. This contributes to understanding the current situation and necessary actions to harness the country's abundant wind power potential.

Keywords Wind power, Renewable energy, Energy security, Ethiopia, Sustainable development

Introduction

Ethiopia's expanding population and economy has led to a higher demand of power for the last three decades. The country designed different energy policies and plans that address the growing demand and promote accessibility. The base for all on going grand development plans is the climate resilient green economy (CRGE) strategy. This strategy aims to transform Ethiopia from low income to a middle-income country by 2025 by developing diversified energy mix and improved energy efficiency (FDRE, 2011). Subsequently, the country implemented cascaded plans of its CRGE as the first growth and transformation plan (GTP1) (FDRE, 2010), the second growth and transformation plan (GTP2) (FDRE, 2015), and National Electrification Program (MoWIE, 2019). These plans were complementarily supported by the UN's 17 Sustainable Development Goals, including SDG 7 for clean and affordable energy (UN, 2030). SDG 7 intends to achieve six goals by 2030: ensuring everyone has access to energy, increasing the use of renewable energy in the world's energy mix, doubling the rate of global energy efficiency improvement, encouraging international collaboration for clean energy research and technology access, expanding infrastructure, and upgrading technology for modern and sustainable energy services (UN, 2030)

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Irrespective of all the ambitious plans and efforts, the country's combined installed generation capacity from hydropower, wind, solar, geothermal and few diesel based generators reach 5,273.77 MW by 2022 (EEP, 2022). A recent study by (Tesfay et al., 2024), contains detailed share of each power generations in the Ethiopian power sector. Even at a slower development rate, the power sector is still contributing significantly to the country's economic and social development. The electricity access rate is currently at 51% and clean cooking access is only at 8%, despite the fact that 89% of total final consumption comes from renewable energy (Gebreslassie & Bahta, 2023). However, despite efforts to expand access to electricity and clean cooking, Ethiopia still has one of the lowest per capita energy supply and consumption rates in the world (IEA, 2019) (IEA & Tracking SDG, 2020) (ESMAP , 2022). The performance indicators of the country highlight the need for improvement in achieving the expected targets. Similarly, the tracking SDG 7, 2022 report expressed its concern that Ethiopia, along with other countries, may not reach their 2030 targets due to lack of success in implementing national and international plans (WHO, 2022).

Ethiopia aims to diversify its energy sources with wind energy considered as a sustainable way to meet the increasing energy demands and complement its hydropower during dry seasons. Using wind power has multiple benefits, including being a renewable and clean energy source that helps reduce greenhouse gas emissions and mitigate climate change (Dong et al., 2023; Kammen, 2006; Mammadov et al., 2022). Wind power also has a short construction period, making it a quick solution to meet energy demands and creating stable jobs and contribute to local economic growth (Enel, 2023) (Loomis et al., 2016) (Simas & Pacca, 2014). Despite Ethiopia's abundant wind resources in regions such as the Rift Valley and highlands, the country has few wind farms, such as Ashegoda Wind Farm, Adama I and II, and Aysha II with several other wind farms planned for development. The government has made a strong effort to support wind power generation by implementing policies and strategies to attract both local and foreign investors. Additionally, international organizations and financial institutions have extended financial and technical support to facilitate the growth of wind power projects in the country.

However, generating sustainable electricity from the few established wind farms is becoming a growing concern in the country, and the pace of wind power development has been slow. The decline in power generation trend from the existing wind farms and its consequences on the country's economic development and return on investment has not been thoroughly studied. The aim of this paper is therefore to examine these by addressing three main questions: (1) how has power generation evolved since the inception of wind farm development in Ethiopia? (2) What are the main causes for discrepancies between predicted and actual power generation and expansion of the wind energy sector? (3) Which policies would effectively address these challenges and harness Ethiopia's abundant wind energy potential? To answer these questions, we gathered primary and secondary quantitative and qualitative data by conducting field visits, observations, discussions with Ethiopian electric power officials, recording historical power generation data from official documents, and reviewing recent publications. By employing these methods, this study identifies the main challenges contributing to discrepancies in power generation forecasts, their impact on investment returns, and the low pace of wind farm development. It also suggests proven policy recommendations to address these challenges. The outcome of this study will be significant for policy makers and stakeholders in solving existing power plants' technical issues, local capacity building, improve research, technology development and planning for expansion.

The paper has 7 sections. Sect. "Methods and materials" describes the research methods used. Sect. "Power generation in Ethiopia" shows the trend of wind power generation in Ethiopia over almost 11 years. Sect. "Challenges of wind power generation" discusses the challenges in the sector including discussions on its consequence to the economic development. Sect. "Opportunities for wind power development" details the wind power opportunities with Sect. "Policy recommendations" providing evidence-based recommendations for policy makers. Sect. "Conclusions" provides concluding remarks.

Methods and materials

This research paper uses data spanning 11 years and field research from one of the wind farms to analyse power generation. The data were collected from various sources including Ethiopian Electric Power, official reports, and scientific articles. The goal of the assessment is to provide an accurate representation of electricity generation in Ethiopia, as well as evaluate the performance of wind power plants and their impact.

Description of the study area

Ethiopia has been making efforts to harness its wind energy potential. As part of these initiatives, the country has developed four wind farms namely Ashegoda Wind Farm (120 MW), Adama I Wind Farm (51 MW), and Adama II Wind Farm (153 MW), and Aysha II (current initial generation at 80 MW) (EEP, 2022). These projects have contributed to the overall energy generation capacity growth and expanding wind power in the country that is paving the way for further development in the sector. As indicated in Fig. 1, location of these wind farms is in the Tigray, Oromia and Somalia regions with further developments planned within these and other regions of Ethiopia.

Data sources and collection methods

This study uses both primary and secondary data as shown in Fig. 2. The primary data come from Ethiopian Electric Power focusing on wind power generation from 2013 to 2021, field observations and discussions with wind power operators. The authors were part of a consulting forum that supported Ethiopian Electric Power

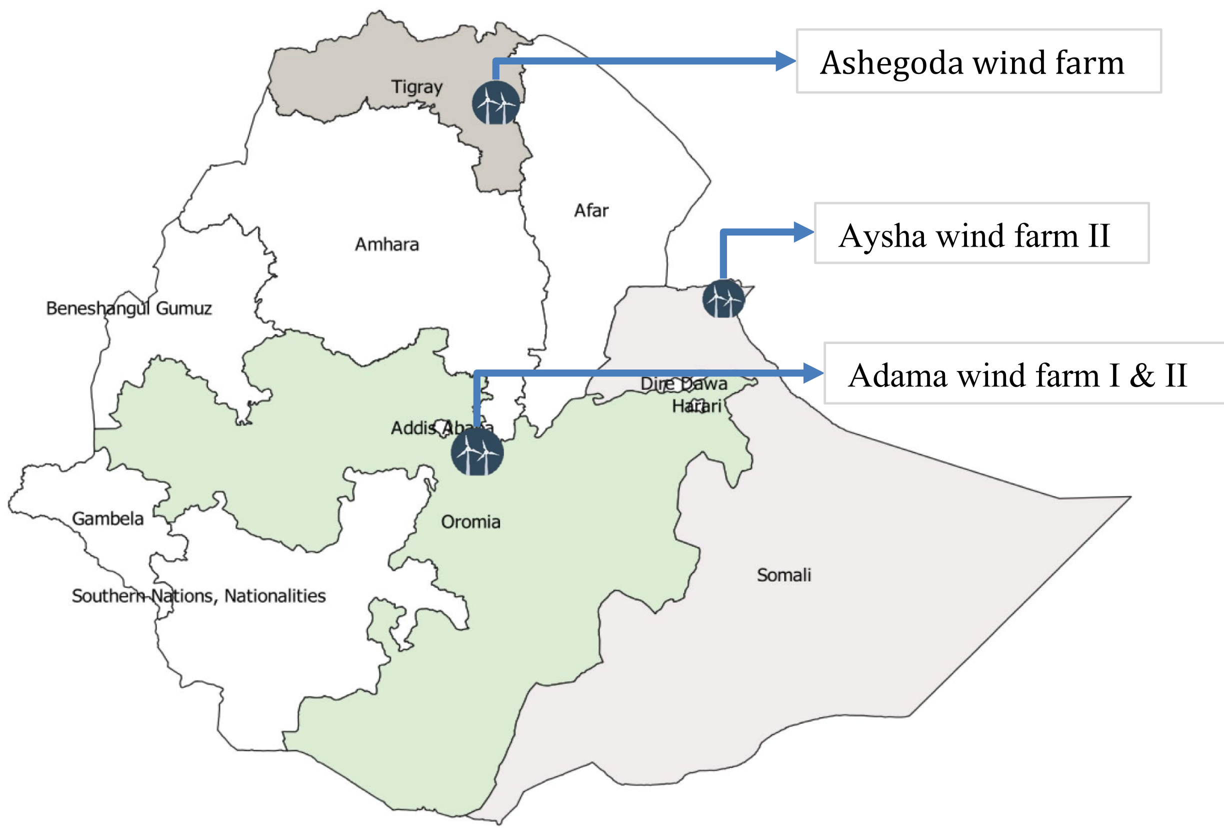

Fig. 1 Location of the existing three wind farms in Ethiopia

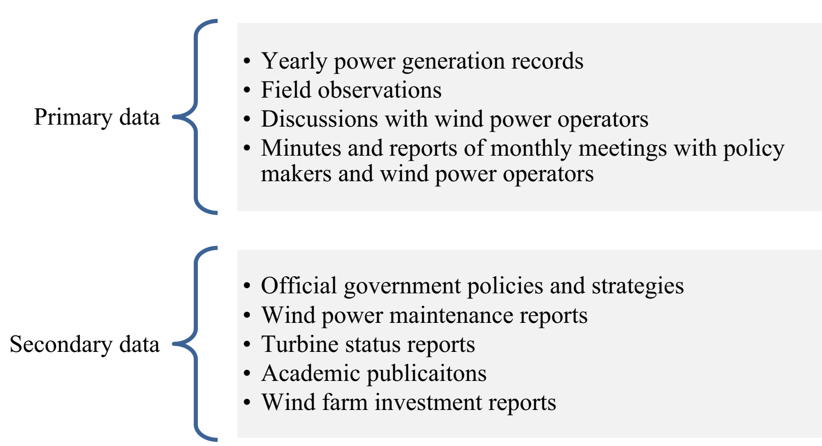

Fig. 2 Data sources and collection methods

and Ethiopian Electric Utility regional offices from July 2021 to November 2022. The forum met weekly to address challenges at power generation plants in the Tigray region, including the Ashegoda wind farm. The meetings provided detailed primary quantitative data and discussions among industry experts, higher education institutions, policy makers, and representatives from the Ethiopian Electric regional office responsible for operating the Ashegoda wind farm. During this time, we conducted monthly field observations at the wind farm. Data on the power generation were gathered from the official records of the Ethiopian Electric Power regional office, which maintains the country's power generation data.

The secondary data come from reviewing recent academic and policy publications, regional and national policies, wind power operation reports, and strategic government documents. The key documents reviewed were the Ethiopian Energy Policy, the flagship plan for universal access called "National Electrification Programme 2″ (MoWIE, 2019), yearly plans from Ethiopian Electric offices, and other academic policy publications.

The power generation and investment of wind farms are considered quantitative data, while the rest is qualitative data, which guided the analysis process.

Data analysis procedures

Both the qualitative and quantitative data were analysed in detail based on the data analysis steps given in Fig. 3.

The statistical results provide opportunities for interpretations and conclusions. This thorough analysis offered insights into the challenges and opportunities of wind power farms. It presented both quantitative and qualitative data on the contribution and challenges of wind power generation. The study analysed reasons for the lack of sustainable wind power generation and its impact on economic development. The findings informed evidence-based recommendations for addressing challenges and enhancing future development in wind energy.

Power generation in Ethiopia

Ethiopia, along with other African countries, struggles with significant interrelated energy security challenges. Ethiopia's heavy dependence on hydropower makes the country vulnerable to droughts and fluctuating rainfall patterns, impacting electricity generation and grid stability. The on-grid infrastructure related to hydropower also leaves significant portion of the population, particularly in rural areas, lacking access to electricity. The country also lacks technical and institutional capacity and financial resources making it difficult to develop large-scale energy projects. To successfully oversee a complex energy system, trained local staff and strong institutions are essential, but the country is fully dependant on foreign experts for its energy infrastructure development. It is critical to upkeep current power infrastructure for dependable electricity provision. Encouraging energy

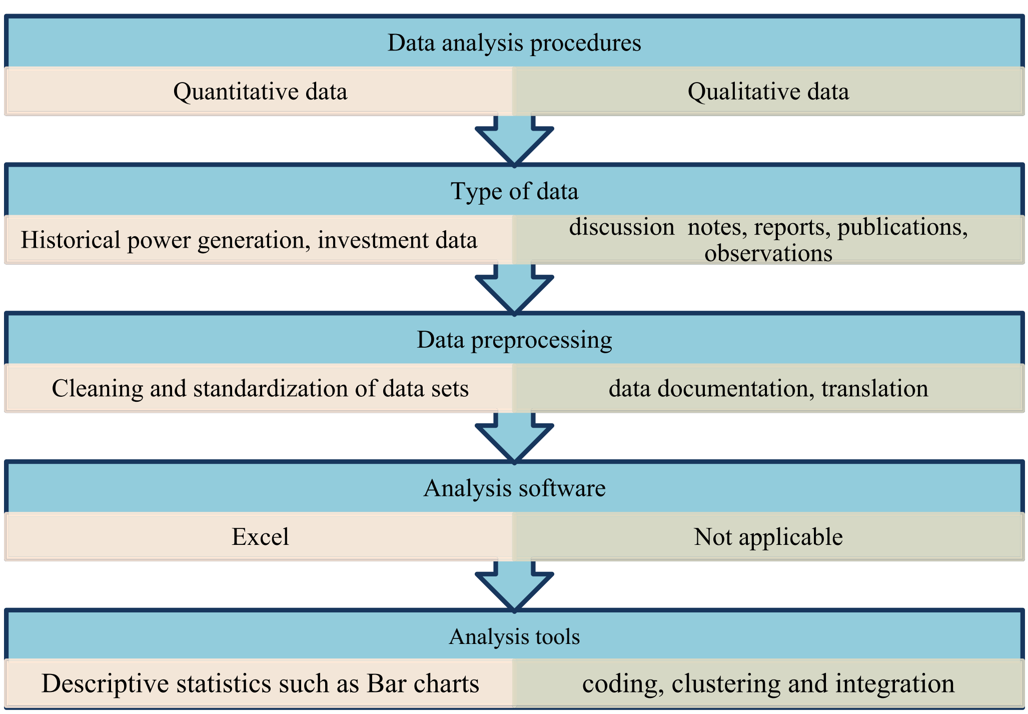

Fig. 3 Step-by-step data analysis procedures

efficiency and deploying demand-side management programs are key to curbing consumption and easing strain on the grid. Addressing these challenges demands a comprehensive strategy to bolster energy security. Including wind, solar, and geothermal power can strengthen energy production and reliability by diversifying the energy sources for a more robust generation capacity.

Ethiopia's wind power potential

Ethiopia's geography and topography provide great potential for wind power generation (Hameer & Ejigu, 2020). With abundant wind resources in regions such as the Rift Valley and highlands, both local and global investors have recognized the importance of wind power as a key part of the country's renewable energy strategy. The Hydrochina Corporation report found that Ethiopia has 6,720 MW of potential sites for wind power development (Jiangtao et al, 2012). This is supported by studies conducted by Ethiopian Electric Power, which projects a capacity of over 10,000 MW. However, except few wind resource assessments on certain sites (Jiangtao et al, 2012; Mulugetta & Drake ,1996 ; Wolde-Ghiorgis , 1988), wind resource estimates in the country rely on satellite data that are unreliable for investors. There is a lack of detailed mapping of wind resources, with scattered studies only indicating some key potentials. The existing wind resource data collected by the National Meteorological Service Agency (NMSA) do not follow the standard for wind speed measurements needed to determine wind power potential as its for aviation purposes (Asress et al., 2013). Therefore, in order to attract potential investors and fully utilize the abundant wind resources, the country needs extensive wind resource assessment and mapping. This will require significant investment requiring commitment from the government and other stakeholders. Detailed mapping can attract investors to feasible wind power sites, which has huge potential to make Ethiopia a top destination for wind power investments in Africa.

Status of wind power generation

Wind power generation began in 2013, and data were collected to track the power generation trend for 11 years. At the present, the country has few operational wind farms, such as Ashegoda Wind Farm, Adama I and II, and Aysha II with several other wind farms planned for development. Wind trends at the site show that March has the highest wind resources, resulting in maximum power generation. In contrast, August experiences the lowest wind resources and minimum power generation, as depicted in Fig. 4. It is important to note that power generation is affected not only by wind availability, but also by turbine downtime due to maintenance issues. From 2013 to 2017, the farm's power production gradually increased after an initial period of commissioning. However, there was a decline in power generation from 2018 to 2021 due to disputes between the Ethiopian Electric Power, owner of the wind farm, and the company that developed the wind farm. Originally, the company was supposed to take over operation and maintenance after commissioning, with the owner paying for the services. However, a dispute between them led the developer to abandon the wind farm. This caused significant disruptions in maintenance and operation, impacting power generation. In November 2020, a war started between the Ethiopian Government and regional forces in the Tigray region. This conflict literally halted the operation of the

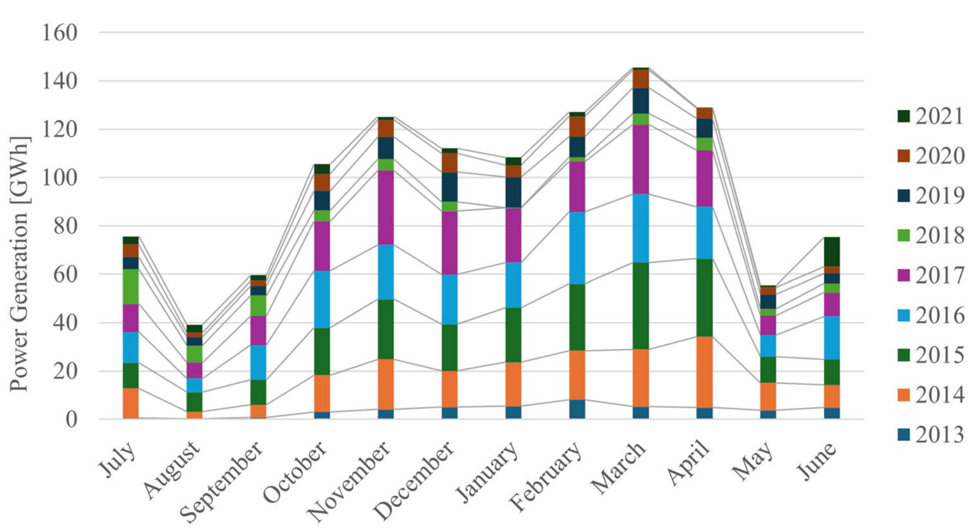

Fig. 4 Monthly power generation from Ashegoda wind farm (Own elaboration using data from Ethiopian Electric Power)

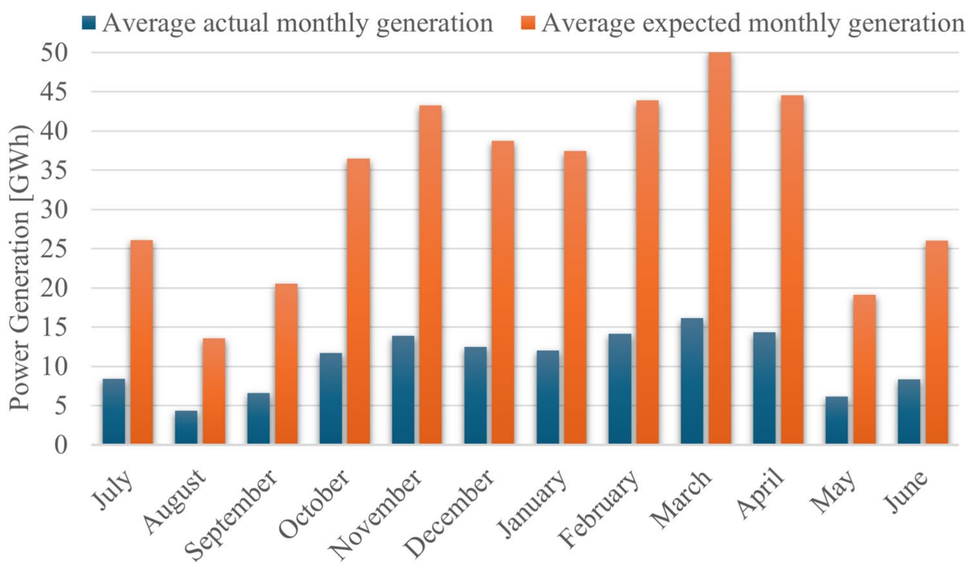

Fig. 5 Average monthly power generation from Ashegoda wind farm from 2013 to 2021 (Own elaboration using data from Ethiopian Electric Power)

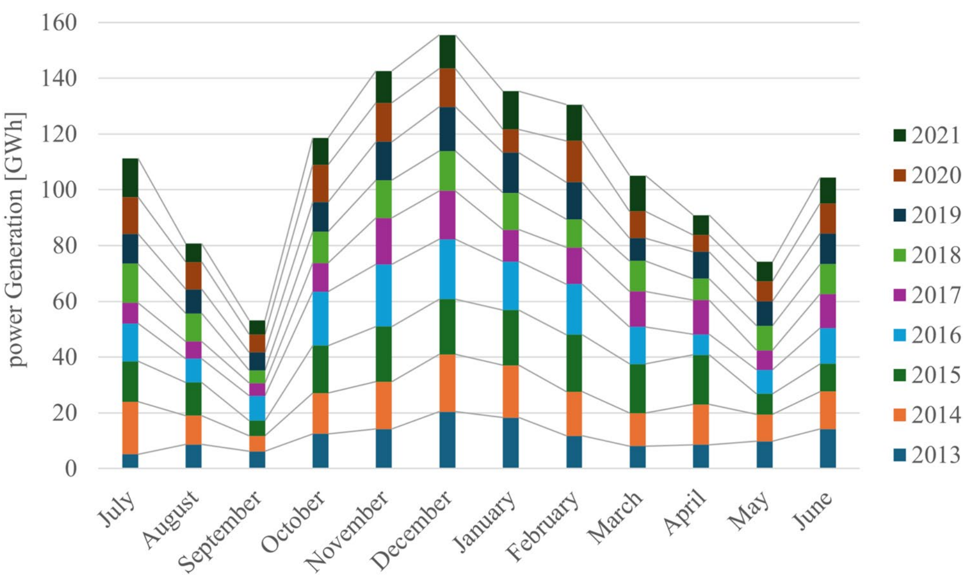

Fig. 6 Monthly power generation from Adama I wind farm (Own elaboration using data from Ethiopian Electric Power)

wind farm located in the region for a specified period, resulting in minimum power generation from the farm.

The Ashegoda power plant was expected to generate 400 GWh, but it fell short even during its peak power generation periods from 2014 to 2017. Monthly average generation from 2013 to 2021 showed a total of 129 GWh power, just 32.3% of the expected amount as shown in Fig. 5. This significantly impacted the plant's return on investment.

Wind data from the site indicate that December has the highest wind resources, while September has the lowest. The other months show varying levels of wind resources, resulting in fluctuating power generation trends as depicted in Fig. 6. Adama I wind farm has maintained consistent power generation since its inception, in contrast to the Ashegoda wind farm which has experienced fluctuations. Power generation was slightly higher from 2013 to 2016 compared to 2017 onwards due to maintenance challenges.

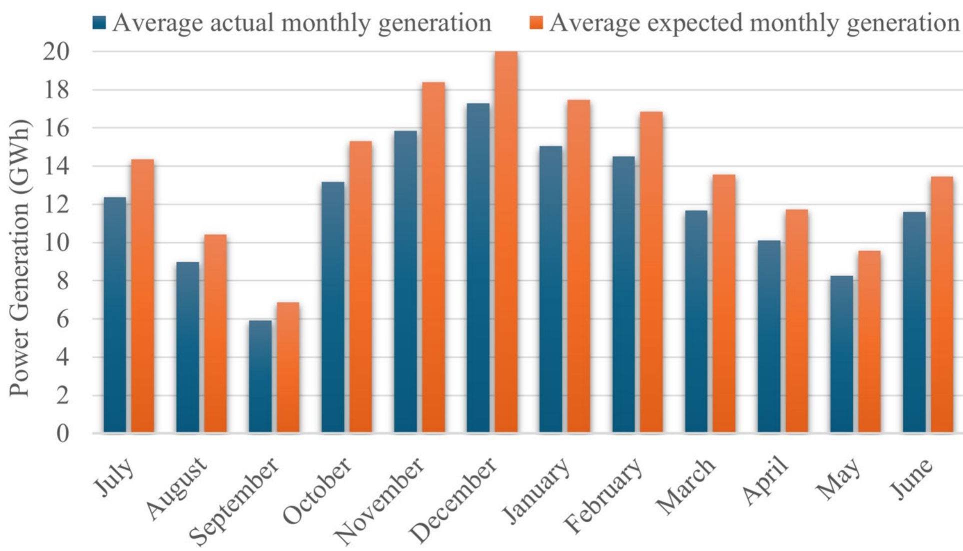

Fig. 7 Average monthly power generation contribution of Adama I wind farm from 2013 to 2021 (Own elaboration using data from Ethiopian Electric Power)

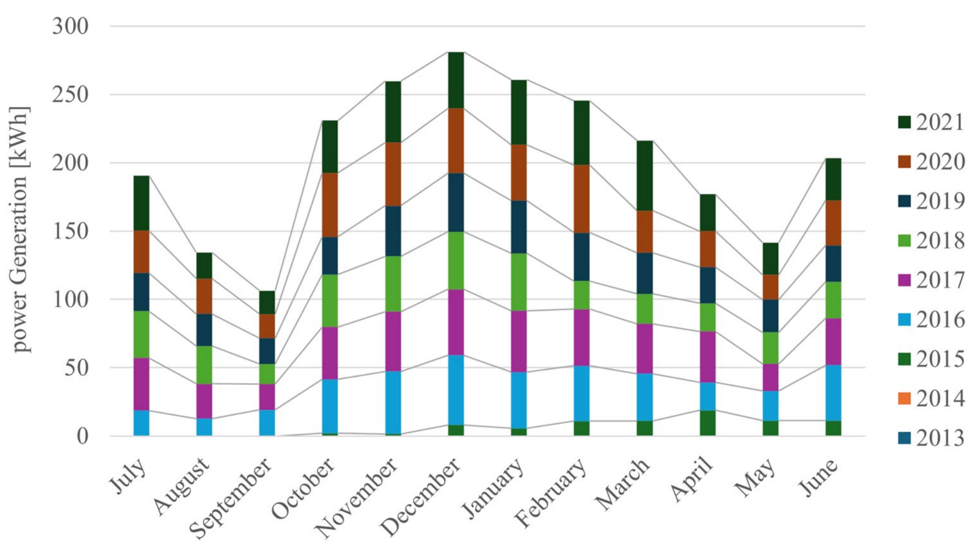

Fig. 8 Monthly power generation contribution of Adama II wind farm (Own elaboration using data from Ethiopian Electric Power)

The Adama I wind farm is expected to generate 168 GWh yearly. Analysis of its monthly power generation from 2013 to 2021 shows the plant is operating at around 86% capacity (as in Fig. 7). Adama I wind farm outperforms Ashegoda and Adama II wind farms due to better power generation rates, thanks to the majority of units functioning as expected.

Both Adama I and Adama II have similar wind resource trends, with December having the highest and September the lowest availability (Refer to Fig. 8). Adama II outperforms Ashegoda and Adama I as the best-performing wind farm in terms of similarity in generating electricity through the years. Since its commissioning in 2007, the Adama II wind farm has consistently generated electricity with minor fluctuations throughout the years. However, there are distinct patterns in power generation each month. For instance, the highest power output occurred in July 2021, while in June 2016, the peak power generation was observed. These fluctuations are primarily attributed to turbine maintenance challenges rather than resource availability.

Adama II wind farm is expected to generate 479 GWh annually, but in reality, it only achieves 56.8% of this expected output, as indicated in Fig. 9.

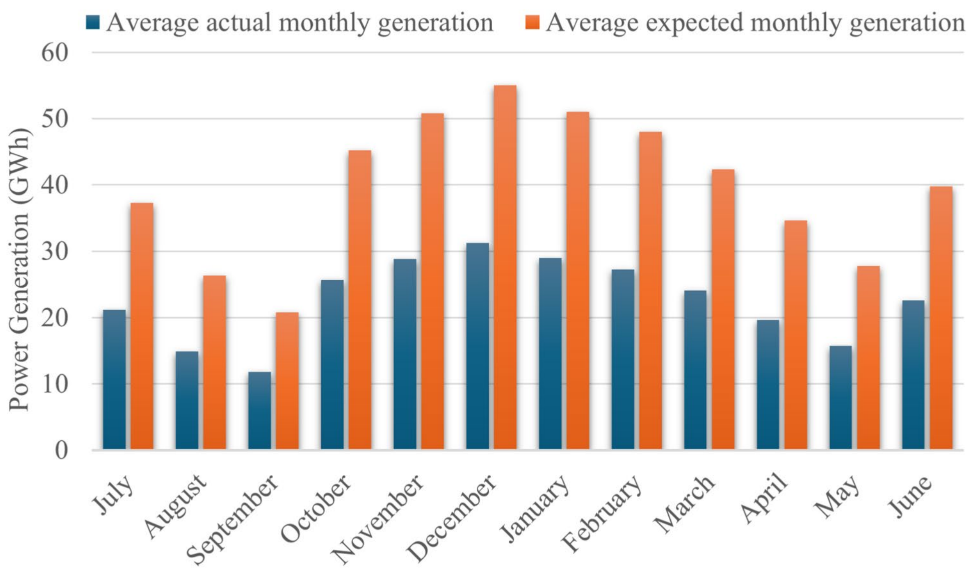

Fig. 9 Average monthly power generation contribution of Adama II wind farm from 2013 to 2021 (Own elaboration using data from Ethiopian Electric Power)

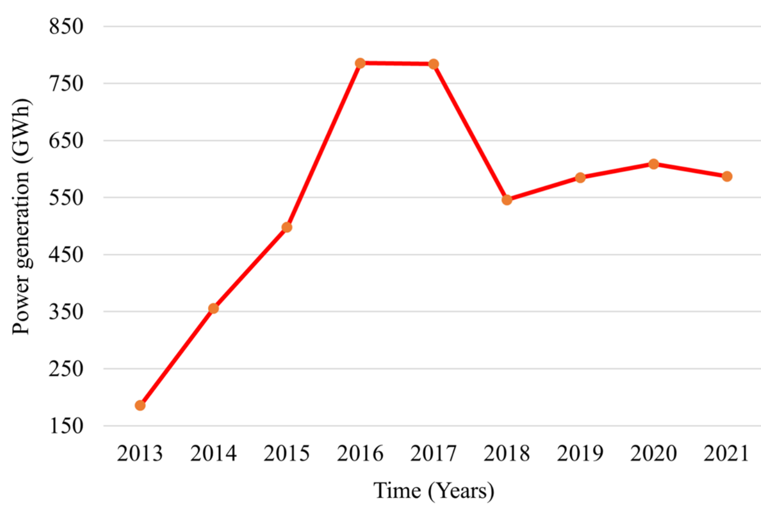

Fig. 10 Ethiopia's wind power generation trend (Own elaboration using data from Ethiopian Electric Power)

Figure 10 shows the average annual power generation trend from wind farms for better understanding of the yearly power generation. The highest point of wind power generation occurred in 2016, coinciding with the operation of the three wind farms (Ashegoda, Adama I and Adama II). Power generation consistently rose from 2013 to 2016, ultimately reaching 786 GWh. The power generation was expected to be steadily increasingly with all turbine units being commissioned. However, since 2017, power generation has been declining due to operational challenges highlighted in Sect. "Challenges of wind power generation". These challenges include conflicts such as the Tigray war, affecting the operation of the Ashegoda wind farm. The Adama wind farms (Adama I & II) are generating power consistently, albeit at a lower capacity than anticipated. However, the Ashegoda wind power plant began experiencing a power generation decline in 2017 and has been completely inactive since the start of the Tigray war in 2020. This was caused by a combination of the war and pre-existing operational difficulties. This reveals the functionality challenges of the wind power plants regardless of the expansion efforts.

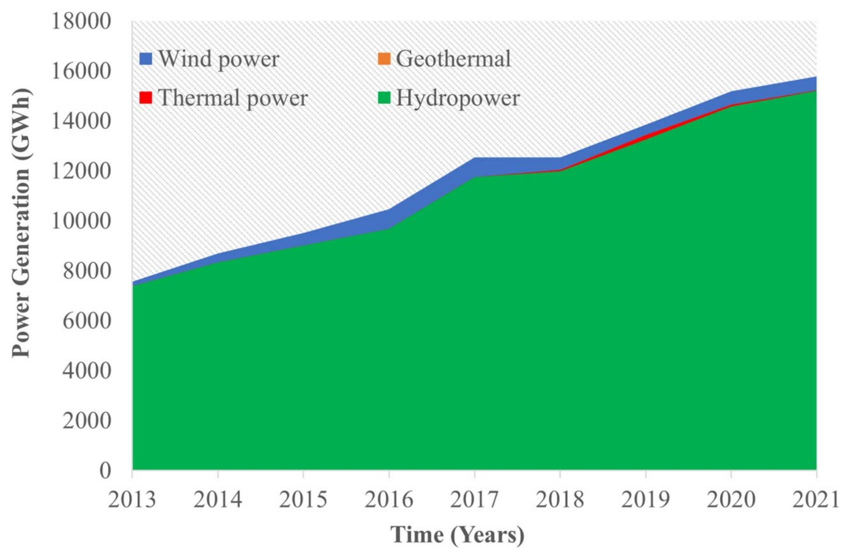

Fig. 11 Share of Ethiopia's wind power against total power generation trend (Own elaboration using data from Ethiopian Electric Power)

Share of wind power generation in Ethiopia's power sector

The up-to-date data showed that the share of wind power generation in Ethiopia's total electricity generation is relatively small. According to the Ethiopian Electric Power, as of 2023, wind power accounted for approximately 404 megawatts (MW) of installed capacity, representing around 7.7% of the country's total installed capacity but the actual generation from the wind farms represents around 2% only (EEP, 2022). Biomass and geothermal power generation units are also part of the utility-scale power sources, but they contribute minimally due to maintenance challenges, often remaining idle as shown in Fig. 11. Ethiopia does not have utility-scale solar power generation. Solar energy is mainly used in rural areas through off-grid energy systems to improve energy access. This share is very small compared to the untapped wind energy potential, which is highly expected to contribute to the government's ambitious targets to achieve 17,300 MW generation capacity from renewable energy mix by 2030. The government's focus on renewable energy development, combined with the country's wind resource potential, indicates a positive outlook for the future share of wind power generation in Ethiopia. Figure 11 indicates the dominance of hydropower contribution and the pace of wind power development and its contribution to the overall electricity generation capacity of the country. Ethiopia's dominance in hydropower is primarily due to its abundant water resource and elevated topography. It has a vast network of rivers, including the Blue Nile, which originates in Lake Tana and carries significant volume of water, making Ethiopia the second country in hydropower potential from the African continent (Mohammed, 2024). The strong water flow in the highlands of the country, along with steep gradients and elevation drops, created perfect conditions for generating hydroelectric power. Additionally, the technology is matured and its industrial use has started since 1880 (Killingtveit, 2019). The mature technology and ample water resources is making hydropower the dominant force in the country's power generation mix.

However, there have been various factors impacting the sustainability of hydropower generation in Ethiopia, such as droughts, siltation, and rising power demand due to population growth and industrialization. Therefore, to address these challenges, Ethiopia is actively engaging in diversifying its power sources by incorporating wind, solar, biomass and geothermal energy resources. Wind energy is considered an attractive option due to its abundant resources and increasing competitiveness with traditional power technologies.

Challenges of wind power generation

While wind power presents promising opportunities, there are also challenges to its widespread adoption in Ethiopia. These include the intermittent nature of wind resources (Ren et al., 2017), the need for adaptable and reliable transmission infrastructure, and high upfront costs (Mukasa et al., 2015). Wind speeds can vary significantly and are not constant throughout the year. This intermittency makes it difficult to ensure a consistent and reliable electricity supply causing problems to the existing grid (Ayodele & Ogunjuyigbe, 2015) (Perez-Arriaga & Batlle, 2012) (George et al., 2010).

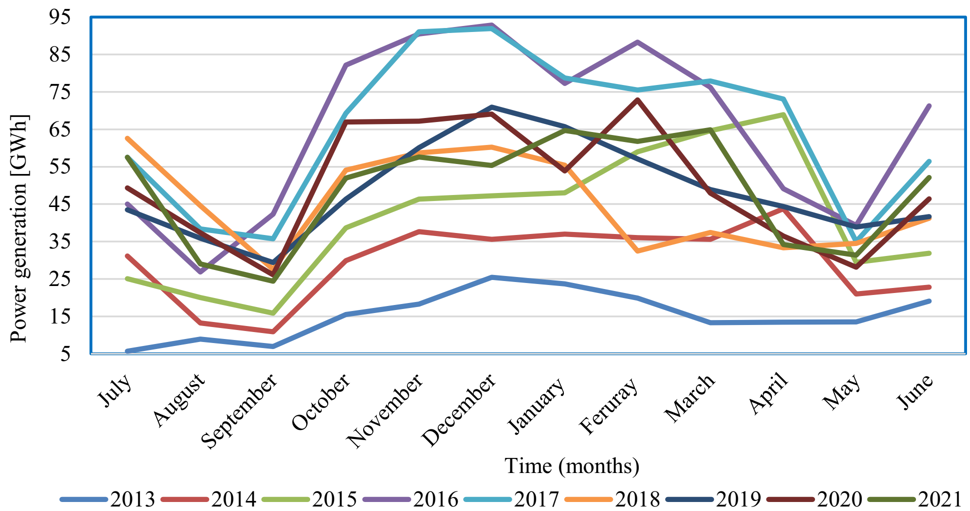

Fig. 12 Ethiopia's wind power monthly generation behaviour (Own elaboration using data from Ethiopian Electric Power)

Operational challenges

Intermittency of wind

Power generation from wind is typically lower from May to September, during the rainy season of the country, compared to the other months that are considered as dry, as indicated in Fig. 12. From October to April, there is a steady trend with December typically having the highest peak in most years. However, even with such variable resources, wind energy is seen as a promising addition to hydropower because they complement each other well: in rainy seasons, hydropower is strong while winds are weak, and in the dry season, hydropower is weak while winds are strong.

Maintenance of turbines

The wind power sector faces challenges beyond just intermittent wind sources. Maintenance of wind turbines is a major issue for wind farms. Two main reasons contribute to this problem. Firstly, there is a lack of skilled maintenance experts in the Ethiopian power sector, leading to delays as foreign experts are often brought in to address key faults. An example highlighting this challenge is the situation at the Ashegoda wind farm. The Ethiopian government, represented by Ethiopian Electric Power, entered into an agreement with the developer of the wind farm. The agreement aimed to develop the wind farm and manage its operations and maintenance post-commissioning. Nonetheless, a dispute arose between the parties after a few years of operation, prompting the developer to abandon the wind farm. The Ashegoda wind farm experienced significant disruptions due to the reliance on foreign skilled workers for operation and maintenance by the Ethiopian Electric Power. This dependency highlights the broader issue of the country's reliance on foreign manpower across the wind energy sector. While the other wind farms may not have the same contractual agreements, they also rely on foreign skilled workers for their operation and maintenance. This overall sector reliance is a key factor contributing to increased downtime of turbine units. In order to fully harness the vast wind energy potential in Ethiopia, a skilled local workforce is needed to regularly maintain and troubleshoot wind turbines. Developing wind farms alone is not enough to ensure uninterrupted power supply, so having trained professionals is essential for reliable power generation in the country (refer to Sect. "Focus on the capacity building of human power"). Secondly, Ethiopia relies entirely on imported technologies and spare parts. The wind industry is facing delays in supply chain due to the challenge of acquiring enough foreign currency to purchase these spare parts. This is exacerbated by inadequate advance planning and a scarcity of locally available spare parts. The country must focus on developing local technologies to tackle these challenges (refer to Sect. "Invest in wind power R&D"). These challenges are causing a decrease in power generation from the current wind farms, as depicted in Fig. 10.

Expansion challenges of wind farms

High upfront cost

The high upfront costs associated with establishing wind farms become another challenge to the expansion of wind energy development as planned. The initial investment required for infrastructure development, including the purchase and installation of wind turbines, transmission lines and substations is substantially high. This is

Table 1 Summery of investment and capacity of wind farms in Ethiopia (EEP, 2022) (Chen, 2016)

No	Name of wind farm	Investment (USD)	Capacity (MW)	Inauguration
1	Ashegoda wind farm	$290 million	120	2013
2	Adama I wind farm	$117 million	51	2013
	Adama II wind farm	$345 million	153	2015
3	Aysha I	$257 million	120	Not started
	Aysha II			2022
Total		$1.009 billion	404 MW	

mainly because of the lack of local manufacturing capability making Ethiopia wholly dependent on imported technologies (Gebreslassie, 2021). This cost may deter potential investors and hinder the expansion of wind power development in the country. Thus, the country needs to diversify its financial resources to address this challenge (refer to Sects. "Improve project funding" and "Improve community engagement and environmental considerations"). In addition, the existing transmission infrastructure cannot handle new wind farms without upgrades. Wind resources are typically in remote locations, which limits access to the national grid. This insufficient infrastructure makes it difficult to transport and distribute wind power to high-demand areas. Expanding and upgrading the transmission network is crucial to effectively harness and distribute wind energy across the country (refer to Sect. "Strengthen grid infrastructure").

Lack of detailed wind resource map

The country relies heavily on satellite mapping for wind resources due to inadequate detailed mapping. Wind resource assessments are typically done at specific sites only when necessary for wind power projects. This hinders the growth and speed of wind power development, as there are no easily accessible wind resources for investors to evaluate investing in the country. A key focus for all stakeholders should be investing in a comprehensive assessment and mapping of the wind resources (refer to Sect. "Conduct comprehensive wind resource mapping").

Economic consequences

Ethiopia has invested more than $1 billion in wind power development, creating a total generation capacity of 404 MW as indicated in Table 1. This investment is expected to boost economic development by providing consistent power, diversifying energy resources, and enhancing energy security.

In reality, there is a significant discrepancy between the actual power generation from existing wind farms and their expected capacity, as shown in Figs. 5, 7 and 9.

This is a significant economic setback for the country that invested huge money into the wind farm developments, and it is already struggling to fulfil its increasing energy needs. Additionally, it could have generated income from selling electricity to neighbouring countries. All these economic related challenges make wind farms less reliable and increases the time it takes for them to pay off their investment. To maximize return on investment in current and future wind power plants, stakeholders must address the key challenges identified in this research before investing in new developments to avoid wasting a significant amount of investment.

Opportunities for wind power development

Ethiopia has great potential for wind power generation, especially in the highlands and along the Rift Valley where there are high and consistent winds. This untapped resource can help the country to diversify its energy mix and reduce dependence on a single energy source as it has historically relied heavily on hydropower for its electricity needs. Table 2 shows viable locations for wind power development. These sites have an average wind speed of 5–10 m/s at 50 m Above Ground Level (AGL), suitable for generating wind power (Jiangtao et al, 2012). Developing these opportunities would enhance the country's electricity capacity and sustainability, potentially improving economic growth within the country and through power sales to neighbouring nations. Investing in diverse sources of energy improves energy security and reduces vulnerability to climate change impacts and hydrological variations (Chen, 2016). Wind power can aid Ethiopia in meeting its national renewable energy goals and decreasing greenhouse gas emissions, aligning with global efforts to transition to cleaner and more sustainable energy systems (UN, 2030). Developing wind farms in Ethiopia can create huge job opportunities, boost local economies, and encourage industrial growth (IRENA & World, 2022). This can also lead to create additional employment opportunities in manufacturing, construction, and operation and maintenance sectors.

Wind power is also useful for remote and off-grid areas that conventional energy sources cannot reach. Small-scale wind power projects can enhance energy access and reduce poverty in Ethiopia's rural communities. However,

Table 2 Potential wind development sites (Jiangtao et al, 2012)

No	Name of site	Capacity (MW)	Area (km^2)	Domicile	Altitude (m)	Wind speed 50 m AGL (m/s)
1	Nazret wind farm	300	254	Oromiya	1904	6
2	Mek'ele South wind farm	100	77	Tigray	2231	9
3	Sheno wind farm	100	56	Oromiya	2847	7
4	Ch'ach'a wind farm	100	56	Amhara	2786	8
5	Phase I wind farm in Iteya	100	66	Oromiya	2063	7
6	Sulalta wind farm	100	60	Oromiya	2955	7
7	Gondar West wind farm	50	49	Amhara	2474	7
8	Imdibir wind farm	50	47	SNNP	2191	5
9	Dire Dawa wind farm	50	40	Dire Dawa	1156	7
10	Dilla East wind farm	300	268	SNNP	2323	7
11	Mek'ele North wind farm	200	185	Tigray	2134	7
12	Debre Markos East wind farm	200	143	Amhara	2230	5
13	Soddo wind farm	200	160	SNNP	1841	5
14	Sendafa North wind farm	100	70	Oromiya	3065	8
15	Sendafa South wind farm	100	70	Oromiya	2500	8
16	Gondar North wind farm	100	65	Amhara	2940	7
17	Phase II wind farm in Iteya	100	70	Oromiya	2017	7
18	Bu'i East wind farm	100	80	SNNP	2045	5
19	Aysha wind farm	100	60	Somali	726	9
20	Phase I wind farm in Bolo	100	60	Oromiya	2480	7
21	Diche Oto wind farm	50	100	Afar	556	7
22	Bahir Dar wind farm	50	80	Amhara	1975	5
23	Assela wind farm	50	71	Oromiya	1777	5
24	Jacho wind farm	600	330	SNNP	1481	5
25	Phase II wind farm in Bolo	500	300	Oromiya	2655	7
26	Hula wind farm	300	220	Oromiya	2300	5
27	Dilla West wind farm	300	230	SNNP	1386	5
28	Dangla wind farm	200	170	Amhara	2404	5
29	Debre Markos West wind farm	200	150	Oromiya	2186	5
30	Ambo wind farm	200	130	Oromiya	2124	5
31	Babile wind farm	200	130	Oromiya	1587	6
32	Dabat wind farm	100	61	Amhara	2610	7
33	Phase I wind farm in Weldiya	100	43	Amhara	3508	8
34	Phase II wind farm in Weldiya	100	40	Amhara	3450	8
35	Gondar East wind farm	100	76	Amhara	2563	7
36	Rufa'el wind farm	100	100	Amhara	2715	6
37	Debre Birhan wind farm	100	67	Amhara	3327	8
38	Bale wind farm	100	60	SNNP	1791	5
39	Harar West wind farm	100	90	Oromiya	1965	8
40	Harar Eest wind farm	100	75	Harar	1629	7
41	Jijiga wind farm	100	80	Somali	1919	8
42	Durame wind farm	100	65	SNNP	2478	6
43	Debre Sina wind farm	50	30	Amhara	3013	9
44	Bu'i West wind farm	50	40	SNNP	2602	7
45	Butajira wind farm	50	30	SNNP	3331	7
46	Fonka West wind farm	50	25	SNNP	2331	6
47	Fonka East wind farm	50	25	SNNP	2128	6
48	Yabelo wind farm	50	45	Oromiya	1635	10

Table 2 (continued)

No	Name of site	Capacity (MW)	Area (km^2)	Domicile	Altitude (m)	Wind speed 50 m AGL (m/s)
49	Mega East wind farm	50	30	Oromiya	1443	10
50	Mega West wind farm	50	30	Oromiya	1497	10
51	Wind energy and solar energy demonstration base in Addis Ababa	20	28	Oromiya	2995	

these developments are currently limited despite their potential for off-grid solutions to provide energy access to remote areas. Ethiopia could have multitude of benefits from wind power generation, such as utilizing plentiful wind resources, expanding energy sources, fulfilling renewable energy goals, generating employment, improving energy accessibility in distant regions, expanding export possibilities, and promoting knowledge transfer. These benefits can lead to sustainable development, energy security, and enhance Ethiopia's socio-economic progress.

Policy recommendations

Ethiopia has made significant progress in developing the necessary and supportive policy and regulatory frameworks for the wind power development. These frameworks include the development of feed-in-tariffs, power purchase agreements, renewable energy law, grid interconnection, the need for social and environmental assessment, and capacity building initiatives. In addition, the framework includes investment incentives that include tax holidays, import duty exceptions for machinery and equipment, and access to land for renewable energy projects. However, in practice, implementation of these supportive regulatory frameworks is flawed, and, in some cases, they are not yet implemented. Such challenges are affecting the development of the wind power sector. The regulatory framework should be transparent, stable, and uniform to promote consistency and encourage the development of wind power both by the government and the private sector. To address the key challenges of sustaining electricity supply from the wind farms and fully exploit Ethiopia's wind power potential, policymakers and stakeholders should consider the following key recommendations.

Focus on the capacity building of human power

Developing and managing a complex energy system requires skilled personnel and robust institutions. Strengthening technical expertise within the energy sector and improving regulatory frameworks are essential for efficient and sustainable energy development. Building local capacity through education and training programs can help address the lack of skilled human power and ensure the sustainable operation of wind power generators. The country should have a human power that have the skills and knowledge on resource assessment, project planning and management, turbine installation and maintenance, grid integration, and policy and regulatory frameworks. These necessary capacities can be achieved through technical training, hands on experience for trainees on existing wind power plants, fostering collaboration between national and international training institutions and the wind power industry, and establishing knowledge sharing platforms and continuous professional development. The knowledge sharing platforms could be used to organize conferences, seminars, workshops to bring wide range of expertise for knowledge sharing experiences and best practice to support the human capacity development of the country. These are considered effective way of knowledge transfer as proved in other countries such as in Kenya that fosters local learning and capacity building through experiences from local wind power projects (Gregersen, 2022).

Improve project funding

Developing large-scale energy projects requires substantial investment. There are several financing mechanisms that have been effective to mobilize financial resources for renewable energy development such as wind power projects. However, these financial mechanisms require conducive and effective policy supports. The public–private partnership (PPPs) is considered effective in mobilizing financing where the government can provide land and permits while the private sector could mobilize capital and expertise. Collaborating with international financial institutions such as world bank, African development bank, and international finance corporation, renewable energy funds, green funds, carbon financing through the Clean Development Mechanism (CDM) could support the wind power development but these needs conducive working environment including security guarantees. Developing competitive feed-in-tariffs is also effective way of attracting the private sector to invest in the wind power development as it gives long germ fixed rate guaranteed payments for their investments. Local financial institutions could also have huge impact in supporting the development of wind power projects. In order for these financial mechanisms to be effective, the government should provide guarantees or risk-sharing mechanisms to reduced perceived risks associate with the development of wind power projects. Developing and implementing of financial de-risking are considered effective in attracting the private sector and other financial institutions as indicated in studies Uganda (Wabukala et al., 2021).

Conduct comprehensive wind resource mapping

Ethiopia's wind resource potential estimations and maps are mostly developed by project developers at specific sites. However, developing a thorough wind resource maps by conducting detailed assessments throughout the country would increase the bargaining power of the country during development negotiations and planning. In addition, such maps will increase the confidence of the sector to highlight prioritized areas with greatest potential for development priority and search for loan to suitable wind farms, as well as project planning.

Strengthen grid infrastructure

The transmission infrastructures in Ethiopia were commonly developed without considering future expansions, but the integration of large-scale wind farms into the grid system can affect the power quality (Mahela et al., 2020). This is an indication that the power gird requires extensive rebuilding, upgrading and development of new infrastructures. Proper planning and development would improve grid infrastructure to support upcoming wind and other power integrations by upgrading transmission and distribution networks, implementing smart grid technologies, and establishing a reliable grid management system to enable smooth and dependable power delivery from wind farms.

Invest in wind power R&D

Provide resources for wind power technology research and development. This includes financing research institutions, working with global partners, and fostering innovation in wind power generation, storage, and grid integration. The authors home institution was pioneering in pushing forward to show the importance of engagement of local stakeholders, research and manufacturing, in developing windfarm projects. As a result, the university has supervised the development of Adama wind farm II and showed the government how local capacities can improve the delivery of projects, create remarkable local capacity, save finance and show the possibilities of local manufacturing by integrating research institutions, local manufacturer and a foreign technology provider. Ethiopia is lagging behind in developing the wind power technology manufacturing capability (Gebreslassie, 2021). The government and the energy sector should put efforts to encompass higher institutions and local industries to develop the necessary capacities for development of the wind power sector. Energy development generally boosts local economy during development of projects by creating various job opportunities for skilled and non-skilled workers. The job opportunity could expand by engaging local manufactures by means of joint engagement with foreign developers. This needs to be supported through policies that prioritize the use of local labour, materials, and services.

Improve community engagement and environmental considerations

Enforce stringent environmental and social regulations for wind power projects. Prioritize extensive assessments of potential environmental and social impacts before initiating projects and implement measures to lessen negative effects on communities and ecosystems. Environmental impact assessment and community engagement in terms of financial support and decision-making in the planning and operation of the power plants are essential in the development of wind power projects and their sustainability (Aitken, 2010; Hinshelwood, 2001; Hinshelwood & Tawe, 2000). It is crucial to assess the potential environmental and social impacts of wind farms and involve local communities in the decision-making process (Gebreslassie, 2020; Yiridoe, 2014). This helps address concerns related to land use, wildlife protection, and cultural heritage preservation.

Conclusions

Ethiopia could revolutionize its energy sector by utilizing wind power as a dependable and sustainable electricity source. However, tackling the challenges of intermittent wind resources, expensive initial investments, limited transmission infrastructure, skilled workforce requirements, and environmental concerns is crucial to fully realizing the potential benefits of wind energy in Ethiopia. To overcome the challenges, all stakeholders should implement the following recommendations: a) promote policy frameworks that incentivize private sector investment in wind power through tax breaks, feed-in tariffs, and simplified permitting processes; b) improve grid infrastructure and invest in energy storage technologies to manage the inconsistency of wind power; c) strengthen research and development efforts to improve the understanding of wind resources and optimize wind turbine technology suitable for Ethiopian conditions; d) encourage partnerships and collaborations with international organizations and experienced wind power developers to benefit from knowledge sharing and capacity building. The goal of these policy recommendations is to facilitate the growth of wind power in Ethiopia by creating a positive environment for investment, encouraging economic expansion, and advancing the country's shift toward sustainable energy. By implementing such effective policies and investments, Ethiopia can become a leader in wind power generation for the region.

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Author contributions
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References

Aitken, M. (2010). Wind power and community benefits: Challenges and opportunities. *Energy Policy, 38*(10), 6066–6075. https://doi.org/10.1016/j.enpol.2010.05.062

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

Ayodele, T., & Ogunjuyigbe, A. (2015). Mitigation of wind power intermittency: Storage technology approach. *Renewable and Sustainable Energy Reviews, 44*, 447–456.

Chen Y. (2016). A comparative analysis: the sustainable development impact of two wind farms in Ethiopia," Working Paper

Dong, Y., et al. (2023). Do natural resources utilization and economic development reduce greenhouse gas emissions through consuming renewable and Clean Technology? A case study of China towards sustainable development goals. *Resources Policy, 85*, 103921.

EEP, "Power Generation," Ethiopian Electric Power, 2022. https://www.eep.com.et/en/power-generation/. Accessed 25 Mar 2023

Enel, "All the benefits of wind power," https://www.enelgreenpower.com/learning-hub/renewable-energies/wind-energy/advantages-wind-energy#:~:text=Compared%20to%20other%20energy%20sources,the%20size%20of%20the%20plant. Accessed 17 Oct 2023

ESMAP, "Tracking SDG 7: The energy progress report," *Energy Sector Management Assistance Program*, https://trackingsdg7.esmap.org/country/ethiopia. Accessed 25 Oct 2023

FDRE. (2011). *Green economy strategy of Ethiopia; Ethiopia's climate-resilient green economy Addis Ababa, Ethiopia*. Ethiopia: Federal Democratic Republic.

FDRE. (2011). *Ethiopia's Growth and Transformation Plan I (2010/11–2014/15)*. Ethiopia: Federal Democratic Republic of Ethiopia.

FDRE, "Growth and Transformation Plan II (GTP II) (2015/16–2019/20) Volume I : Main Text," I, GTP II, 2015

Gebreslassie, M. G. (2020). Public perception and policy implications towards the development of new wind farms in Ethiopia". *Energy Policy*. https://doi.org/10.1016/j.enpol.2020.111318

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

Gebreslassie, M. G., & Bahta, S. T. (2023). Ethiopia needs peace to accelerate its SDG 7 achievements. *World Dev Perspect, 30*, 100507. https://doi.org/10.1016/j.wdp.2023.100507

George S. O., H. George, and S. V. Nguyen. (2010). Effect of wind intermittency on the electric grid: Mitigating the risk of energy deficits," ArXiv Prepr. ArXiv10022243

Gregersen, C. T. T. (2022). Local learning and capability building through technology transfer: Experiences from the Lake Turkana Wind Power Project in Kenya. *Innovation and Development, 12*(2), 209–230.

Hameer, S., & Ejigu, N. (2020). A prospective review of renewable energy developments in Ethiopia. *AAS Open Res., 3*, 64.

Hinshelwood, E. (2001). Power to the People: Community-led wind energy–obstacles and opportunities in a South Wales Valley. *Community Development J., 36*(2), 96–110.

Hinshelwood, E., & Tawe, A. A. (2000). Community funded wind power—the missing link in UK Wind Farm Development? *Wind Engineering, 24*(4), 299–305.

IEA, "Ethiopia energy outlook," International Energy Agency, 2019. https://www.iea.org/articles/ethiopia-energy-outlook. Accessed 11 Apr 2023

IEA (2020). Tracking SDG 7. The energy progress report. The World Bank, the International Energy Agency, the International Renewable Energy Agency

IRENA, World Energy Transitions Outlook 2022: 1.5°C Pathway. 2022. https://www.irena.org

Jiangtao M, Lushi X, Kai Z, Guo S, Xiaojun L, Chengzhi W, Bo Z. (2012). Master plan report of wind and solar energy in the federal democratic republic of Ethiopia. *Hydrochina Corporation, 1*, 236.

Kammen, D. M. (2006). The rise of renewable energy. *Scientific American, 295*(3), 84–93.

Killingtveit, Å. (2019). Hydropower. *Managing global warming.* Amsterdam: Elsevier.

Loomis, D. G., Hayden, J., Noll, S., & Payne, J. E. (2016). Economic impact of wind energy development in Illinois. *Jounal Business Valuation and Economic Loss Analysis, 11*(1), 3–23.

Mahela, O. P., Khan, B., Haes Alhelou, H., & Tanwar, S. (2020). Assessment of power quality in the utility grid integrated with wind energy generation. *IET Power Electron, 13*(13), 2917–2925.

Mammadov, N. S., Ganiyeva, N. A., & Aliyeva, G. A. (2022). Role of renewable energy sources in the world. *Journal Renewable Energy Electrical Computer Engineering, 2*(2), 63–67.

Mohammed, A. A. (2024). The strategic significance of Ethiopia's hydroelectric energy exports on Horn of Africa regional integration. *International Journal River Basin Management, 3*, 1–14.

MoWIE, "National electrification program 2.0: Integrated planning for universal access. Technical report." Ethiopian Ministry of Water, Irrigation and Energy, 2019.

Mukasa, A. D., Mutambatsere, E., Arvanitis, Y., & Triki, T. (2015). Wind energy in sub-Saharan Africa: Financial and political causes for the sector's under-development. *Energy Research & Social Science, 5*, 90–104.

Mulugetta, Y., & Drake, F. (1996). Assessment of solar and wind energy resources in Ethiopia. II. Wind energy. *Solar Energy, 57*(4), 323–334. https://doi.org/10.1016/S0038-092X(96)00074-6

Perez-Arriaga, I. J., & Batlle, C. (2012). Impacts of intermittent renewables on electricity generation system operation. *Economics of Energy & Environmental Policy, 1*(2), 3–18.
Ren, G., Liu, J., Wan, J., Guo, Y., & Yu, D. (2017). Overview of wind power intermittency: Impacts, measurements, and mitigation solutions. *Applied Energy, 204*, 47–65.
Simas, M., & Pacca, S. (2014). Assessing employment in renewable energy technologies: A case study for wind power in Brazil. *Renewable and Sustainable Energy Reviews, 31*, 83–90.
Tesfay, A. H., Gebreslassie, M. G., & Lia, L. (2024). Sustainability challenges of hydropower and its implication on Ethiopia's economy. *International Journal of Sustainable Engineering, 17*(1), 1–14.
UN, "Transforming our world: the 2030 Agenda for Sustainable Development," *U. N. N. Y. NY USA*, 2015.
Wabukala, B. M., Otim, J., Mubiinzi, G., & Adaramola, M. S. (2021). Assessing wind energy development in Uganda: Opportunities and challenges. *Wind Engineering, 45*(6), 1714–1732.
WHO. (2022). *Tracking SDG 7: the energy progress report 2022"*. Geneva: Wolrd Health Organisation.
Wolde-Ghiorgis, W. (1988). Wind energy survey in Ethiopia. *Solar and Wind Technology, 5*(4), 341–351. https://doi.org/10.1016/0741-983X(88)90001-X
Yiridoe, E. K. (2014). Social acceptance of wind energy development and planning in rural communities of Australia: A consumer analysis. *Energy Policy, 74*, 262–270.

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