AIMS Energy, 9(6): 1299–1320.
DOI: 10.3934/energy.2021060
Received: 12 October 2021
Accepted: 21 December 2021
Published: 27 December 2021

http://www.aimspress.com/journal/energy

Overview

Overview of hydropower resources and development in Uganda

Vincent Katutsi[1], Milly Kaddu[2], Adella Grace Migisha[3], Muhumuza Ezra Rubanda[4] and Muyiwa S Adaramola[5,*]

[1] Department of Economics Makerere University Business School, Kampala, Uganda
[2] Department of Economics Uganda Martyrs University, Nkozi, Uganda
[3] School of Management and Entrepreneurship Kyambogo University, Kampala, Uganda
[4] Faculty of Graduate Studies and Research Makerere University Business School, Kampala, Uganda
[5] Faculty of Environmental Sciences and Natural Resource Management Norwegian University of Life Sciences, Aas, Norway

* **Correspondence:** Email: muyiwa.adaramola@nmbu.no; Tel: +4767231793.

Abstract: Even though hydropower plants are currently the most dominant source of electricity in Uganda, the rate of development of these resources for power generation remains low. Using a semi-systematic review approach, this paper seeks to understand why there is a slow rate of hydropower development in Uganda (challenges) and thereby provide potential solutions to these challenges. With current total capacity of about 1011 MW, findings indicate that there is a higher future prospect for hydropower generation in Uganda, with an estimated potential of over 4500 MW. In terms of number of projects, small-scale hydropower plants dominate power plants in Uganda, currently accounting for 19 out of 35 grid-connected power plants. However, with 855 MW installation capacity, large hydropower plants dominate the power generation plants landscape in Uganda. This study found that the challenges to hydropower development in this country are multi-dimensional including technical, economic, environmental, and social factors, and shows that the cross-cutting challenge is lack of human capacity that possess adequate skills to handle hydropower projects in the country. Furthermore, this study discussed practical solutions to address the identified problems facing hydro power in Uganda.

Keywords: energy resources; hydropower resource; hydropower technology; hydropower policy; Uganda

Abbreviations: NPA: National Planning Authority; SHP: Small Hydropower plant; UBOS: Uganda Bureau of Statistics; IRENA: International Renewable Energy Agency; IHA: The International Hydropower Association; IEA: International Energy Agency; ERA: Electricity Regulatory Authority; LHP: Large Hydropower plant; MEMD: Ministry of Energy and Mineral Development; OPEX: Operation and Maintenance Expenses; IPPs: Independent Power Plants; DAP: Dynamic Adaptive Policy Pathways; PPPs: Public Private Partnerships; AA: Action Agenda; SE4ALL: Sustainable Energy for All; ADB: African Development Bank; DRC: Democratic Republic of Congo; NEMA: National Environment Management Authority; HYPSO: Hydropower solutions for developing and emerging countries; Mtoe: Million tonnes of oil equivalent

1. Introduction

1.1. Background

Generation, supply and use of electricity remains critical for Uganda to attain economic growth and socio-economic transformation of its growing population. Uganda is endowed with various electricity generating resources such as biomass, solar, geothermal, peat and fossil fuels, which are distributed throughout the country. Despite this, Uganda has not been able to provide reliable and cost-effective electricity to meet the demand of its growing population and economy. Access to electricity remains low (at 28% in 2019) compared with the sub-Saharan Africa average of 42% [1]. Consumption of electricity in Uganda (of 215 kWh per capita per year, which is less than half that of the sub-Saharan African average of 552 kWh) is among the lowest in the world [2].

Therefore, limited access and high cost of electricity has affected delivery of social services, constrained the development of small-scale industrial and commercial enterprises and disillusioned larger-scale industrial and commercial investment in the country. Uganda's Vision 2040 lays out the broad policy directives to improve electricity access and transform Uganda to a modern and prosperous country within the next 20 years [3] It aims to achieve an electricity access target of 80% by 2040. Furthermore, Uganda's National Development Plan (NDP II) highlights the urgent need to increase access and usage of electricity through investments in least cost power generation, promotion of renewable energy and energy efficiency as well as development and expansion of associated transmission and distribution infrastructure [4]. Hence, NDP III aims at making the generated energy more available to households and businesses [1]. Currently, energy mix in Uganda consists of 88% biomass resource (mainly derived from charcoal and firewood), 10% petroleum products (mainly use in transportation sector) and 2% electricity (dominated by hydropower generation) [5,6].

Cumulative installed power capacity increased from about 609.4 MW in 2011 to 1268.9 MW by the end of 2020, with an average of 65.95 MW increment per year from 2011 to 2020 [7]. The contribution of hydropower to installed capacity increased from 71.0% (in 20211) to 79.7% (2020) while that of solar energy (solar PV) increased from 0% in 2011 to 4.8% in 2020. However, contribution from both thermal (by Heavy Fuel Oil (HFO)) and cogeneration decreased between 2011 and 2020. With a projected national population of about 41.6 million in 2020 [8], power intensity in Uganda at the end of 2020 was 30.5 W/capita, hence Uganda could be considered as an energy poor country. With the government's power development plan, it is expected that hydropower will continue to dominate electricity generation in Uganda in the foreseeable future. In Uganda, hydropower is a major source of electricity, generating over 4911 GWh of electricity in 2019 [9] through both large hydropower plants (LHPs) and small hydropower plants (SHPs). In terms of number of power plants, there are currently 28 SHPS and 6 LHPs in operation in Uganda (see Table 3 and Table 4 for more information on these power plants).

1.2. Global hydropower development

Among the renewable energy resources, hydropower is the most matured technology and widely used globally. According to [7], hydropower accounted for 45.6% (1331.9 GW) of the global cumulative installed power capacity from renewable energy resources at the end of 2020, while wind energy, solar energy, bioenergy, and geothermal energy contributed 25.1%, 24.4%, 4.3% and 0.5%, respectively. The Asia region accounted for 42.6% (or 566.7 GW), while the Africa region accounted for 2.8% (or 37.3 GW) of global installed hydropower. Furthermore, Eurasia, Europe, North America, and South America respectively, contributed 6.7%, 16.7%, 14.8% and 13.4%. In terms of installed capacity, Ethiopia, with a capacity of 4074 MW, is the first ranked country, while Uganda ranked 13th in hydropower development in Africa (see Table 1). Overall, the thirteen top ranked countries accounted for 31.62 GW (81.9%) of the hydropower installed capacity in the continent in 2020.

Table 1. Cumulative installed hydropower in selected countries in Africa [12].

Country	Capacity (MW)	Proportion (%)
Angola	3836	10.0
DR of the Congo	2760	7.2
Egypt	2876	7.5
Ethiopia	4074	10.7
Ghana	1584	4.1
Morocco	1770	4.6
Mozambique	2216	5.8
Nigeria	2111	5.5
South Africa	3596	9.4
Sudan	1923	5.0
Uganda	1040	2.7
Zambia	2400	6.3
Zimbabwe	1076	2.8
Rest of Africa	6 912	18.1
Total (Top 13 countries)	31262	81.9

1.3. Purpose of this study

Several hydropower plants have been constructed and more are expected to be constructed in the future as Uganda aims at significantly improving electricity access by 2040. Therefore, the purpose of this paper is to review hydropower resources in Uganda with the goal of highlighting the status and the challenges facing its development. Relative to similar studies which focused on the renewable energy resources (such as [10]) and wind energy (such as [11]), this study presents comprehensive and updated status of hydropower projects specifically (operational, under-construction, proposed and granted licence not yet constructed) in Uganda. This paper is guided by the following specific objectives: (i) examine the available renewable energy resources in Uganda, (ii) identify the technologies used in the hydropower production in Uganda, (iii) identify the barriers to the development of hydropower resources in Uganda, and (iv) analyze the present energy related policies and how they address the challenges of hydropower resource exploitation in Uganda.

The rest of the paper is structured as follows: section 2 provides a brief approach employed in the paper; in section 3, overview of energy resources in Uganda and status of hydropower projects are presented, while in section 4 brief information about hydro power technology is presented. section 5 and section 6 respectively discussed main challenges facing hydropower development in Uganda and suggested solution ways to address these challenges. in section 7, provide brief discussion and conclusion on the work.

2. Research approach

The study adopted a semi-systematic review approach to highlight the overview of hydropower development overtime in Uganda, and identify challenges facing its development in this country. Relevant scientific and government documents related to hydropower projects in Uganda that are available in public domain are identified and reviewed. Furthermore, additional information is sought from the Electricity Regulatory Authority (ERA) of Uganda. Despite the useful information provided in this study, the limitations of the review approach used include challenges in access to recent and up to date (most public data are made available about 2 years lag) as well as accuracy of published data partly due to the less willingness of public agencies and power companies to share so-called ‘confidential data’.

3. Overview of energy resources and water resource in Uganda

3.1. Energy resources

Uganda is a land locked country that is endowed with renewable and non-renewable energy resources. The renewable energy resources in Uganda include biomass (firewood, charcoal, and cogeneration resources (such as sugarcane), hydropower (water) resource, solar energy, geothermal energy, and wind energy resources. The non-renewable energy resources include crude oil, peat, and nuclear energy. Table 2 shows the renewable and non-renewable potential in Uganda. As shown in Table 2, the minimum renewable power potential in Uganda is estimated to stand at 12700 MW.

According to Government of Uganda' Vision 2040 program [13], hydropower, solar PV, geothermal energy, and cogeneration (biomass) are expected to contribute 35.4%, 39.4%, 11.8% and 13.3%, respectively to renewable energy based-electricity power generation by 2040. It should be noted that wind energy potential has not been exploited partly due to lack of adequate wind energy resource assessment activities to generate reliable and accurate wind energy data, and that wind energy resource is overshadowed by the vast solar renewable energy potential available in almost all areas in Uganda [10,11].

Table 2. Energy resources potential in Uganda.

Energy resources	Potential	References
Renewable energy		
Hydropower (MW)	>4500 MW	NPA, 2013
Solar energy	Mean solar radiation of 5.1 kWh/m^2/day	ERA
	>5000 MW	NPA, 2013
Geothermal energy (MW)	>1500 MW	NPA, 2013
Biomass (cogeneration) (MW)	>1700 MW	NPA, 2013
Wind energy	2 m/s to about 4 m/s @ less than 10 m height	ERA
Waste residues		
Crop residues (selected crops)	148.67 PJ/year	
Animal manures (selected animals)	65.23 PJ/year	Okello et al., (2013)
Forest residues	44 PJ/year	
Fossil fuels		
Crude oil	Reserves: 6.5 billion barrels; 2.2 billion is recoverable	Patey, (2015)
Peat	6000 million m^3 (equivalent to 250 Mtoe) > 800 MW	ERA NPA, 2013
Nuclear energy	>24000 MW	NPA, 2013

*Note: Authors' compilation from different sources as indicated.

3.2. Water resource and hydropower potential

Uganda is endowed with water bodies, which are estimated at 66 km^3/year, which is equivalent to about 1586.5 m^3/person per year (using Uganda's population of about 41.6 million [8]. Major water bodies in the country are Lake Victoria, Lake Kyoga, Lake Albert, Lake George, and Lake Edward while major rivers are the Nile, Ruizi, Katonga, Kafu, Mpologoma and Aswa. The locations of these lakes and rivers are shown in Figure 1 and Table 3, respectively. A recent study has indicated that hydropower potential is about 4,137 MW in this country [14], with about 2000 MW concentrated on the Nile River, while the rest are scattered across the country [15]. However, based on the Government of Uganda Vision 2040 document target on power generation, it is reasonable to assume that hydropower potential in Uganda is over 4500 MW (as shown in Table 2).

Figure 1. Major lakes and rivers in Uganda (source: Ref. [16]).

Table 3. Major lakes in Uganda and their associated characteristics.

Lakes	Surface area (km^2)	Area in Uganda (km^2)	Mean elevation above sea level (m)	Maximum depth (m)	Volume in Uganda (km^3)	Mean depth (m)
Victoria	68,457	28,665	1,134	82	1237	40
Albert	5,335	2,913	621	51	80	25
Edward	2,203	645	913	117	16.8	34
Kyoga	2,047	2,047	1,033	7	7.9	3
George	246	246	914	3	0.8	2.4

*Note: Source: [19].

3.2.1. Large-scale hydropower (LHP)

In Uganda, large hydropower (LHP) is defined as hydropower plants with installed capacity of over 20 MW [14,17]. As at the end of December 2020, large-scale hydropower plants contributed 67.4% (855 MW) of 1268.8 MW installed power capacity in the country, and 84.6% of the total hydropower installations in Uganda [18]. Table 4 presents information about operational, under construction and proposed large hydropower plants in Uganda. Therefore, if the proposed and under construction large-scale hydropower (LHP) plants are completed as indicated, the installed LHP would be 2460 MW by end of 2025.

Table 4. Status of large hydropower (LHP) projects (>20 MW) in Uganda.

Power stations	Community (district)	River	Capacity (MW)	Year completed
Operational				
Bujagali	Buikwe	Nile	250	2012
Kiira	Jinja	Nile	200	2000
Nalubaale	Buikwe	Nile	180	1954
Isimba	Kamuli	Nile	183	2019
Achwa 1	Gulu	Achwa	42	2021
Achwa 2	Gulu	Achwa	41	2019
Under construction				
Karuma	Kiryandongo	Nile	600	2023
Proposed				
Ayago	Nwoya	Nile	880	2025
Kiiba	Kiryandogo and Nwoya	Nile	400	WIP
Oriang	Kiryandogo and Nwoya	Nile	392	WIP
Muzizi	Kibaale	Muzizi	48	WIP
Achwa 3	Pader	Achwa	135	2022

*Note: source: [20]; WIP—Work in progress.

3.2.2. Small-scale hydro power (SHP) plants

In Uganda, small hydropower (SHP) is generally defined as hydropower plants with installed capacity of up to 20 MW [14,17]. Unlike large-scale hydropower, the small and medium hydro sites are not located on the Nile, they are mainly located in the Western and the Eastern regions of the country, which are hilly and mountainous. About 64 potential small hydropower sites have been identified on the rivers in these regions. Thirty (30) of these sites have been developed (see Table 5). At the end of 2020, small-scale hydropower contributed 155.7 MW to overall installed power in Uganda.

Table 5. Status of SHP projects (<20 MW) in Uganda (including micro and pico hydropower plants).

Power stations	Community (district)	River	Capacity (MW)	Year completed
Operational				
Bugoye	Kasese	Mubuku	13.0	2009
Kabalega	Hoima	Wambabya	9.0	2013
Kisiizi	Rukungiri	Kisiizi	0.4	2009
Kakaka	Kasese	Rwimi	4.6	2021
Nyamagasani I	Kasese	Nyamagasani	15.0	2021

Continued on next page

Power stations	Community (district)	River	Capacity (MW)	Year completed
Operational				
Kikagati	Isingiro	Kagera	14.0	2021
Timex Bukinda	Kibale/Hoima	Nkusi	6.5	2020
Bwindi Community	Kanungu		0.1	2014
Hydromax-Buseruka	Hoima	Buseruka	9.0	2012
Waki	Hoima	Waki	4.8	2018
Eco Power- Ishasha	Kanungu	Ishasha	6.6	2011
Africa EMS-Mpanga	Kamwenge	Mpanga	18.0	2011
Mubuku 3	Kasese	Mubuku	10.0	2009
Mubuku 1	Kasese	Mubuku	5.0	1956
Nyagak 1	Zombo	Nyangak	3.5	2012
Siti 1	Bukwo	Siti	6.1	2017
Muvumbe	Kabale	Maziba	6.5	2017
Rwimi	Bunyangabu	Rwimi	5.6	2017
Siti 2	Bukwo	Siti	16.5	2017
Mahoma	Kabarole	Mahoma	30.0	2018
Nyamwamba 1	Kasese	Nyamwamba	9.2	2018
Nkusi	Hoima	Nkusi	9.6	2018
Lubilia	Kasese	Lubilia	5.4	2018
Achwa 2	Gulu	Achwa River	42	2019
Nyamagasani II	Kasese	Nyamasagani	6.0	2019
Kyambura	Rubirizi	Kyambura	7.6	2019
Ndugutu	Bundibugyo	Ndugutu	5.9	2019
Sindila (Butama)	Bundibugyo	Sindila	5.3	2019
Gwera- Luzira	Moyo	Amoa	6.1	2017
Under construction				
Nengo Bridge	Rukungiri	Mirera	6.7	2022
Nyangak 2	Zombo	Nyagak	5.0	2023
Nyagak 3	Zombo	Nyagak	5.6	2022
Nyamwabwa 2	Kasese	Nyamwabwa	7.8	2022
Muyembe	Kapchorwa		6.9	2022
Projects at Feasibility Study				
Agbinika	Yumbe	Kochi River	20.0	2025
Nsongi	Bunyangabu	Nsongya	7.0	WIP
Kiraboha	Kasese	Rwimi	5.0	WIP
Latoro	Nwoya	Aswa	4.2	WIP
Buwangani	Manafwa	Manafwa	7.0	WIP

Continued on next page

Power stations	Community (district)	River	Capacity (MW)	Year completed
Projects at Feasibility Study				
Nyakinengo	Kanungu	Nchwera	5.2	WIP
Lower Achwa	Lamwo and Amuru	Achwa	17.4	WIP
Awera	Pader	Achwa	18.0	WIP
Okollo	Arua	Ora	5.0	WIP
Rwembya	Kasese	Rwembya	0.4	WIP
Lwakhakha	Namisidwa	Lwakhakha	6.7	WIP
Licensed but have not yet begun construction				
Senok Atari I	Kapchorwa	Atari	3.3	WIP
Kabeywa 1	Bulambuli	Mbigi	6.5	WIP
Kabeywa 2	Kapchorwa	Sirimityo	2.0	WIP
Sironko	Sironko	Sironko	7.0	WIP
Nyamabuye	Kisiro	Kaku	7.0	WIP
Nyabuhuka-Mujunju	Bunyangabu	Nsongya	3.2	WIP
Simu	Bulambuli	Simu	9.5	WIP
Sisi	Bulambuli	Sisi	7.0	WIP
Nshungyezi	Isingiro	R. Kagera	39.0	2025
Kigwabya	Kagadi	Nkusi	4.2	WIP
Warugo	Bushenyi	Warugo	0.5	WIP
Igassa	Bunyangabu	Igassa	0.3	WIP
Tokwe	Bundibugyo	Tokwe	0.3	WIP
Nyahuka	Bundibugyo	Nyahuka	0.7	WIP
Nsongya	Bunyangabu	Nsogya	0.7	WIP
Katooke	Kasese	Nyabyayi	0.3	WIP
Nchwera	Mitooma	Nchwera	0.5	WIP
Hoima	Hoima	Hoimo	3.3	WIP
Kabasanja	Kabarole	Wamikia	0.4	WIP

*Note: source: Ref. [20].

3.2.3. Performance of hydropower plants in Uganda

In general, electricity generation is traditionally and still dominated by hydropower in Uganda. It is evidenced in Figure 2, which presents a recent trend in total electricity generated by power plants. It can be deduced from Figure 2 that total electricity generated by all the power plants increased from about 3534.7 GWh in 2016 to 4411.6 GWh in 2020, which is mainly due to increase in installed power capacity from 905 MW in 2016 to 1268.9 MW in 2020. The additional capacities are mainly from Isimba and Achwa 2 hydropower plants (total installed capacity of 225 MW) and commissioning of 4 solar Photovoltaic power plants (with total capacity of 50.8 MW). Over these five years, on average, hydropower plants contributed about 90.6% electricity to the national utility grid, which is shared among the large hydropower plants (80.7%) and small hydropower plants (9.9%).

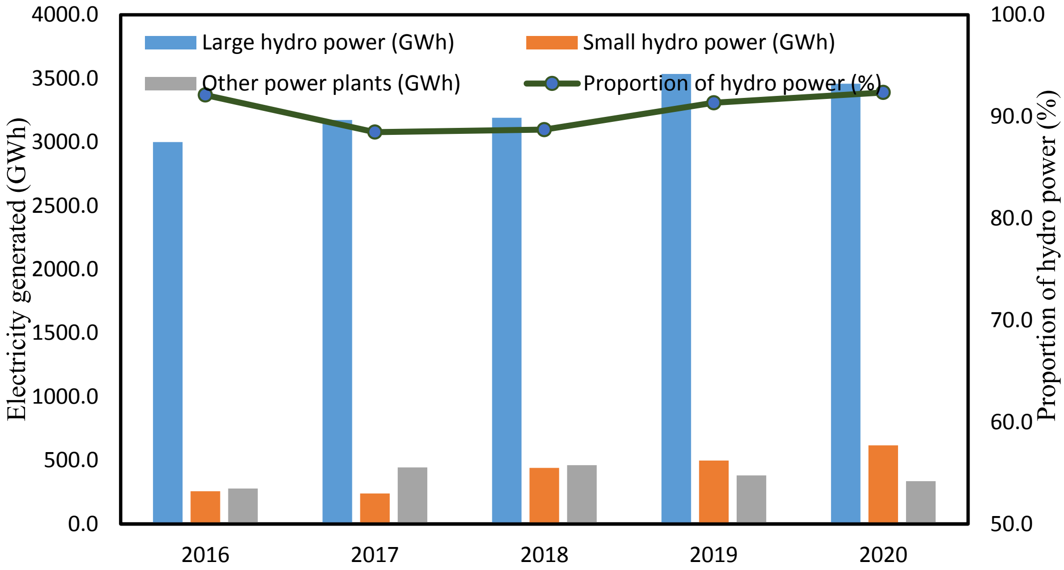

Figure 2. Recent trends in electricity generated by power plants in Uganda (Data for this figure are extracted from ERA database).

However, despite this increment in hydropower plants (both in terms of cumulative installed capacity and total electricity produced), the capacity factor ($C_f = \frac{E_a}{E_m}$, where E_a (kWh) is the actual annual electricity generated and E_m (installed capacity (kWh) * 8760 h) is the maximum possible electricity that could have been generated if the power plant was operated at full capacity for entire period (say, 1 year [21]) for these hydropower plants increased from 54.3% in 2016 to about 57.8% in 2018 and thereafter decreased to 46.2% by 2020 (see Figure 3), with an average value capacity factor of 53.1% over the last 5 years. This value is comparable with global weighted-average of capacity factors for large hydropower, which ranges between 33% (in Europe) and 60% (in South America, excluding Brazil) [9]. This shows that hydropower plants in Uganda are operating efficiently relative to global large hydro power installations. However, considering the level of available water and river resources in Uganda, it could be possible to improve the performance of the hydro power installations in Uganda through proper management which could be due to many factors, such as poor design, lack of or insufficient transmission network, uncoordinated maintenance operation and water resource management, inadequate skilled workforce, and economic and financial related factors.

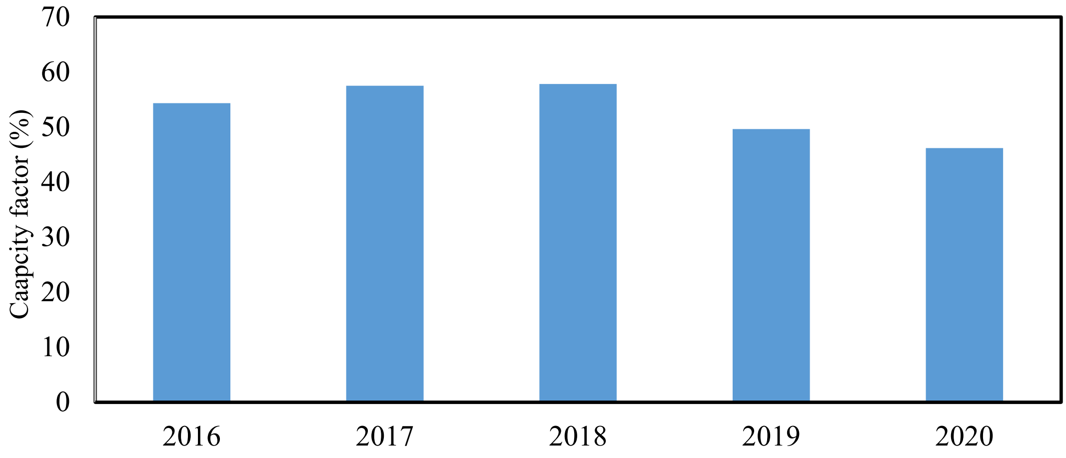

Figure 3. Recent trends in capacity factors for hydropower plants in Uganda (Data extracted from ERA website).

4. Hydropower Technology

Hydropower is the electrical power generated from falling or running water. Mathematically, the power output of any hydropower is given as:

$$P_H = 9810 * \eta_t * \dot{Q} * H \tag{1}$$

where P_H is power output (W), η_t is the hydropower efficiency (%), $\dot{Q}$ is the volume flow rate (m^3/s), H is the hydraulic head (m) and the value 9810 is a product of density of water (1000 kg/m^3) and acceleration due to gravity (9.81 m/s^2). Eq 1 shows that, even though the density of water varies slightly with ambient temperature, the performance of a hydropower plant is primarily a function of water volume flow rate and hydraulic head of the water resource. Furthermore, using these two parameters, the appropriate hydro turbines can be selected for specific hydropower projects. The hydro turbine is a mechanical device that converts energy contained in flowing water into rotational energy, which can be used to drive a generator and produce electricity. The maximum efficiency of most turbines, especially large turbines is of order 90% and this efficiency will be reduced if the flow is reduced. For the turbine to operate, there must be a minimum amount of water [22].

Based on the mechanism of power extraction from water resources, hydro turbines can be classified into impulse and reaction turbines [23]. Impulse turbines are driven by jets of water issuing from one or more nozzles distributed tangentially around the periphery of the wheel [24]. These turbines are generally used where a high head of water is available, and the flow rate is relatively low. On the other hand, reaction turbines use the water flow to generate hydrodynamic lift forces that propel the runner blades [22]. These turbines are completely submerged in the water flow, and more suitable for low hydraulic head and high flow rate. The common examples of impulse turbines are Pelton and Turgo turbines while those of reaction turbines are Kaplan and Francis turbines.

In addition to impulse and reaction turbines, hydrokinetic turbine [25,26], and gravity turbines [27] (such as waterwheel [28,29] and Archimedes screw [30]) are other hydropower technologies that can be viable for low head and low flow rate rivers and could represent an attractive solution for micro power generation, especially in rural areas with low electrical energy demand.

Gravity turbines are driven by the weight of water entering the top of the turbine and falling to the bottom, and thereby turning the turbine [27]. Hydrokinetic turbines on the other hand generate power by extracting kinetic energy from flowing water rather than potential energy from waterfall [25,31] with a zero head requirement. Hydrokinetic technology is more economical compared to solar power systems [31].

Table 6 shows some of the technical characteristics of the hydropower resource in Uganda. As shown in this table most sites with suitable resources for hydropower in the country have low hydraulic head and relatively high flow rate, and hence, reaction turbines (Kaplan and Francis turbines) are generally employed for hydropower projects in this country. However, some dams in this country use impulse turbines, which are appropriate for sites with a high head and low flow rate. For example, the Pelton turbine is proposed to be used at Muzizi hydropower plant (44.7 MW) due its high head (465 m) [32].

Table 6. Dams in Uganda and their technological characteristics (LHP > 20 MW).

Items	Unit	Nalubale	Kiira	Bujagali	Isimba	Karuma	Oriang	Ayago	Kiba
Maximum discharge	m^3/s	1,170	1,150	1,375	1500	1218.18	840	840	840
Effective head	M	19.5	21	21.9	14	60.0	52.8	87.0	40.4
Type of turbine	-	Kaplan	Kaplan	Kaplan	Kaplan	Francis	Francis	Francis	Francis
Number of units	No.	10	5	5	4	6	8	12	6
Maximum discharge per unit	m^3/s	117	230	275	375	203.0	105.0	70.0	140.0
Capacity per unit	MW	18	40	50	23	100	49	51.4	48.7
Installed capacity	MW	180	200	250	182.2	600	392	616.8	292
Size	MW	180	200	250	183.2	600	400	880	295
Type of plant		Run of River	Run of River	Dam	Run of River	Run of river	Run of river	Run of River	Run of river
Cost of construction	US$ (Million)	3.3*	97.3	860	567.7	1,653	1,754	1,618	2,667
Cost of generation	Cents/kWh	1.6	1.6	10.9	4.2	5.3	7.0	4.1	5.5
Flow rate, Q	m^3/s	1500	-	1200	1375	1092.06	840	840	840

* Note: source: Ref. [33–35]. *Only repaired and renovated the cost of the facility after damage was found.

Uganda has several small rivers and streams, in which micro and pico-hydropower technologies such as the hydro kinetic and gravity wheels could be employed to solve most of the country power generation problems and narrow the electricity access gap as well. Micro hydropower plants are small hydropower plants of size 100 kW and discharges of a few cubic meters per second or less while pico plants are less than 5 kW. Sites suitable for micro hydro exist in almost all countries [28,36], besides they are very attractive because of their eco-sustainability and wide applicability, especially for rural areas [37] for countries like Uganda which are largely rural. However, no information about current use of these micro- and pico- hydropower plants in Uganda are found in open literature.

5. Challenges facing hydropower development in Uganda

Hydropower plants in many developing countries are underdeveloped despite having a high potential to generate electricity [38]. This is attributed to low technological developments, inadequate finances, and remoteness in many such countries [38,39]. In general, under-development of Uganda's power sector and specifically hydropower generation subsector could be attributed to many factors which are environmental, economic, social, and technical [40]. These challenges have limited the amount of power generated from hydropower resources and have limited energy access from hydropower resources. They are briefly highlighted in the following subsections.

5.1. High investment cost

Hydropower projects require huge investment costs because of civil engineering work (which depends on the individual site's conditions) cost, equipment cost, land compensations costs and transmission system cost. Well-developed and planned transmission and distribution system is also essential for an economically viable and efficient power sector system. Furthermore, the land tenure in Uganda is largely freehold that requires both the government and hydropower developers to compensate landowners leading to further increase the investment cost of hydropower plants in Uganda [1]. In addition, development of power plants and high voltage transmission systems, concurrently, contributed to the high cost of power plants in Uganda. According to Sustainable Energy for All (SE4ALL) Action Agenda (AA) for Uganda, Uganda requires an investment of US$95.2 billion to allow power generation capacity to reach over 2400 MW by 2030 [14,41].

Table 7. Hydropower investment costs in Uganda compared with neighboring countries.

Uganda			DRC			Tanzania		
Hydropower plant	Installed capacity (MW)	Cost/kW (US$)	Hydropower plant	Installed capacity (MW)	Cost/kW (US$)	Hydropower plant	Installed capacity (MW)	Cost/kW (US$)
Karuma	600	2722.0	Kiyimbi/ Bendera II	43	1211.0	Ruhudji	358	1360.0
Bujagali 1–5	250	2103.0	Budana	13	97.09	Masigira	118	1612.0
Isimba	183.2	3098.8	Piana Mwanga	38	1065.0	Mpanga	144	1614.0
Mahoma	3	2666.7	Bangamisa	48	2572.0	Rumakali	222	2030.0
Nkusi	9.6	2395.8	Mugomba	40	2191.0			
Lubilia	5.4	1611.1	Muhuma	25	2868.0			

*Note: sources: Ref. [42–44].

Table 7 shows the hydropower investment costs in Uganda compared with other neighboring countries. Table 7 clearly indicates that the cost/kW of hydropower plants in Uganda (US$2433/kW), on average, is higher than hydropower plants in Tanzania (US$1654/kW) and Democratic Republic of

Congo (DRC) (US$1814/kW). When compared with the global average of US$1254/kW to 1824/kW between 2010 and 2019, while hydropower plants costs are within these averages for Tanzania and DRC, however, that of Uganda is outside this range. In addition, Table 6 shows that construction cost of large hydropower dams in Uganda is quite high, despite the fact these are run-of-river hydropower. For instance, 600 MW Karuma hydropower currently costs US$1653 million.

5.2. High operation and maintenance costs

The operation and maintenance expenses (OPEX) include salaries, administrative costs, repairs, and maintenance. These costs are relatively higher in Uganda when compared to some East African countries (as shown in Table 8). This can be attributed to employment of foreign expatriates to run and manage these plants due to low skilled and low experienced personnel in the country [1]. Among these countries only Rwanda has higher operation and maintenance costs of hydropower plants per kW billed than Uganda [44].

Table 8. Cash collected and OPEX per kWh billed in some East African countries.

Country	Cash collected (US$/kWh)	OPEX (US$/kWh)
Uganda	0.17	0.13
Sudan	0.05	0.06
Burundi	0.07	0.10
Ethiopia	0.04	0.02
Kenya	0.15	0.12
Rwanda	0.23	0.31
Tanzania	0.14	0.12

*Note: sources: Ref. [44].

5.3. Inadequate infrastructure

In addition to hydropower plants specific equipment and facilities such as transmission lines, road network as well as resources assessment facility and readily available land, are some of the issues that can contribute to economic viability of hydropower plants. The high costs of land acquisition, land encroachment, weak local construction industry in terms of technical and financial capacity are some of the challenges facing transmission lines and road network development in Uganda [46], and hence, are challenges facing power projects in this country. Furthermore, transmission lines are restricted to some selected areas due to limited resources and, additionally the costs of providing transmission lines to rural areas are too high due to remoteness of the areas, dispersed populations, and difficulty of the terrain [47]. Similarly, delay in implementation of various transmission projects, such as Tororo-Lira transmission line, Bujagali-Tororo-Lessos and Kurama-Kawanda transmission projects [3] across the country, which is due to financial inadequacy, also have significant effect on hydropower power development in the country. Similarly, the highly centralized nature of the country's electricity related infrastructure development is a challenge to hydropower resource development through bureaucratic formalities that delay developments [48].

5.4. Low human and institutional capacity

Low human and institutional capacities to manage design, construction and management of hydropower plants are another barrier to hydropower plant development in Uganda. This is attributed to low-training, lack of workforce and skilled labor that possess strong knowledge in hydropower related activities (such as resource assessment, engineering work, and project management) in the country. Therefore, Uganda mainly depends on international expertise, to evaluate and manage hydropower plants in the country [1]. For instance, the concession for operation and maintenance of Kiira and Nalubaale hydropower stations is fully outsourced [44]. Therefore, most hydropower plants in Uganda are designed, constructed, and maintained by foreign expertise with minimal input from Ugandans, which leads to high life-cycle cost hydropower facilities. This situation is like in many countries in sub-Saharan Africa [49], where lack of local professionals is identified as a major impediment to implementation of hydropower technologies, especially those of small hydropower projects.

5.5. Community resistance to hydropower projects

Community resistance arises due to fear of displacement, loss of agricultural land, loss of vegetation and loss of social connections between people of the same community along the river basin, as well as clashes among different communities which hinders hydropower projects [49]. For instance, in Uganda, setting up a hydropower plant along River Achwa was estimated to cause vegetation clearance and loss of cultivation land with effects ranging from 'medium negative' to long term negative duration [50]. Also, the hydropower project along River Achwa claimed approximately 315 ha from Achwa Ranch, affecting livestock in the region [50]. Such negative consequences have provoked community resentments to hydropower projects. Some community members also fear losing the source of their livelihood, which is mainly fishing due to dam construction, restricted access to rivers and the commonly unfulfilled compensation promises by the hydropower plants developers. For instance, developers of Bujagali hydropower plant promised to establish a market for community members for livelihood sustenance due to loss of fishing sites and construction of a technical school for skills development for community members to access gainful employment. After over 10 years, these promises were never fulfilled [15]. Hence, community settlements around potential hydropower sites are now more resistant to hydropower plants establishment and their smooth operations.

5.6. Climate change and variation

Hydropower generation depends on the run-of river water, which has a direct relationship with the amount of water entering and leaving the rivers. Between 2005 and 2007, Uganda experienced a drought [51,52], which affected hydropower electricity generation. There was a clear sharp decline in power generation from the large hydropower plants, mainly Nalubaale hydropower plant between 2006 to 2008, due to the decrease in water levels of Lake Victoria and high evaporation from the lake due to high temperature [52,53]. This affected power generation from the power plants that depend on White Nile River, whose source is Lake Victoria. There is a fear that hydropower potential will face a projected 26% decline due to an estimated reduction in precipitation in the country by 2050 [54]. Climate change also has an impact on the electricity infrastructure in the country. This is created by weather extremes like floods that damage hydropower spillways and damage the electricity transmission infrastructure. An example was observed in May 2020, when the Nyamwamba small hydro project camp (in Uganda) was washed away by heavy flood, which was attributed to climate change, leaving the region in a total black out [55].

6. Suggested policy solutions

The government of Uganda has come up with various policies to solve the challenges to hydropower production. It has among other factors liberalized hydropower generation by encouraging Independent Power Plants (IPPs) and Public Private Partnerships (PPPs) for hydropower generation power plants (Ministry of Energy and Mineral Development, 2019) to solve financing problems. The Energy and Mineral Development Sector Development Plan (EMDSDP) 2015/16–2019/20, was also set up to raise short- and long-term measures to eliminate hindrances to power generation in Uganda and set up policies to enhance power generation [6]. However, various challenges to power generation have persisted in the country, hydropower inclusive [56]. Thus, much more is required to tackle some impediments to hydropower production in the country.

6.1. Reducing investment and operation and maintenance costs

To minimize investment costs, the engineering hydropower policy in Uganda should, among other factors, consider large dam projects with a smaller reserve surface area in comparison with power generated [44]. This would reduce expenditure on land compensations and curtail the bureaucracies in land negotiation procedures. In addition, the government of Uganda should enact laws restricting human settlement upstream and downstream of river basins. This shall gazette areas for establishment of dams and other infrastructures for hydropower generation plants, hence minimizing expenses on land compensation which exaggerate investment bills.

Furthermore, Uganda should endeavor to increase access to electricity and distribute the unit costs of production/kWh to a wider sample of consumers. Access to electricity in Uganda is rated at 28% [1], which puts a big burden on electricity consumers, to recover the costs of generation, transmission, and distribution, and widens the recovery period of funds invested to produce and supply electricity. Increase in electricity access rate can therefore neutralize the costs/kWh consumed.

To reduce the operation and maintenance costs, Uganda needs to benchmark cost efficiency of hydropower generation within plants in the country [57–59] and across plants with the neighboring countries, using benchmarking models [59,60]. Such a policy can expose inefficiencies among hydropower generation plants arising from the different parameters that influence hydropower generation [61,62]. Cost inefficient plants can be penalized by setting high targets for them, as cost-efficient plants are incentivized. Incentive regulation shall then force inefficient cost firms to move to the frontier hence minimizing operation and maintenance expenses [62].

6.2. Developing local capacity

Furthermore, to minimize dependency on foreign expatriates, who are costly, conditions should be set in the agreements with hydropower developers to train local manpower to manage the hydropower plants, and clear deadlines established to when the local manpower should take over from the foreign expatriates. However, caution should be taken to ascertain the nature of skills equipped to the local personnel which can be augmented by further research and training workshops [44]. Furthermore, specialized curriculums in collaboration with industrial partners should be developed by Uganda's Universities in energy technologies with focus on hydropower and other energy resources in the country.

6.3. Reducing impact of climate change

To minimize the effects of climate change and variation, the government may consider investing more in small scale and medium scale hydropower generating plants instead of large-scale hydropower generating plants. Small hydropower generating plants depend on less water levels to run turbines and hence are less affected by reduced water levels [63,64]. Furthermore, structural policies on Integrated and Sustainable Water Management in Uganda should be done in consideration of the Dynamic Adaptive Policy Pathways (DAPP) to attain robust water management plans. With DAPP, the design posts to the impact of changes in climate to the water systems is catered for by estimating different scenarios and mitigation measures predicted ahead of time [65]. In scenario analysis, inter-annual water flow variability and intra-annual water flow variability should be scrutinized to predetermine the increases in water flows that cause floods and the decline in water flows that reduce water flow levels [66,67]. This should be done in addition to systematic reservoir operation management to heighten power production [67].

6.4. Reducing community resistance

To solve the problem of community resistance to hydropower projects, the government of Uganda needs to establish a clear and well-defined resettlement plan for natives that are to be displaced by the establishment of hydropower generation plants. The resettlement plan should be discussed by the affected populace and the project development partners to come up with a win-win resolution [68]. The plan implementation should be carefully supervised by the government officials and communities' leaders not to divert from the intended objectives. Furthermore, nearby communities should be given access priority to the electricity generated from these water resources and subsidized their connection and access fee to the electricity distribution network.

7. Discussion and conclusions

Uganda's electricity generation sector is dominated by hydropower. The country has a big potential for hydropower generation and is highly preferred due to its renewable nature. Hydropower has a total installed capacity of 1011.3 MW by 2020 and there is a future prospect of over 4,000 MW of hydropower yet to be developed. Both large hydropower projects and small hydropower projects have been established with small hydropower projects dominating. Considering its friendliness to nature and environment, hydropower has attracted financing from both the government and private sector.

Public Private Partnerships for investment in large hydropower plants have been undertaken, while Independent hydropower plants are mainly operating on a small-scale, with capacity not more than 20 MW. Small hydropower plants have dominated the hydropower generation industry, due to many rural and remote areas in the country, and a low industrial base whose energy consumption rate is low. Besides, small hydropower plants are relatively cheaper in terms of construction and reclaim less land for plant construction compared to large hydropower plants. However, Uganda still lags in terms of total populace with access to electricity making the country one of the countries with the lowest electricity consumption in the world and sub-Saharan Africa. This could be attributed to the challenges faced by the hydropower developments within the country which are categorized as financial, economic, social, and environmental challenges.

To address the challenges facing hydropower developments in Uganda, it is imperative to invest in human capital, establish measures to increase access to electricity to reduce the average costs/kWh generated and distributed, and invest in large dam projects with a small reserve surface area in comparison with power generated, especially for the urban dwellers and for the industrial parks. We recommend a scientific study to be done, assessing the cost efficiency of electricity generation by hydropower plants within plants in Uganda and across plants in neighbouring countries using benchmarking models. This could scientifically explain why hydropower plants development in Uganda is relatively more expensive than hydropower plants development in other East African countries.

Conflict of interest

The authors declare no conflict of interest.

References

1. National Planning Authority (NPA) (2020) Third national development plan (NDPIII) 2020/21–2024/25. *Kampala, Uganda: Government of Uganda.* Available from: http://www.npa.go.ug/wp-content/uploads/2020/08/NDPIII-Finale_Compressed.pdf.
2. International hydropower association, Country profile: Uganda, 2018. Available from: https://www.hydropower.org/country-profiles/uganda.
3. BMAU briefing paper. (2019) *Ministry of Finance Planning and Economic Development*, Kampala. Available from: https://www.finance.go.ug/publication/policy-briefing-papers-2019.

4. Government of Uganda-National Development Plan II (2015/16-2019/20). Available from: http://npa.go.ug/wp-content/uploads/NDPII-Final.pdf.
5. Aarakit SM, Ssennono VF, Adaramola MS (2021) Estimating market potential for solar photovoltaic systems in Uganda. *Front Energy Res* 9: 602468.
6. Ministry of Energy and Mineral Development, Draft national energy policy, 2019. Available from: https://www.energyandminerals.go.ug/site/assets/files/1081/draft_revised_energy_policy_-_11_10_2019-1_1.pdf .
7. International Renewable Energy Agency (IRENA), Renewable capacity statistics 2021. Available from: https://www.irena.org/publications/2021/March/Renewable-Capacity-Statistics-2021.
8. UBOS, 2021—Population Projections By District, 2015 to 2021. Available from: Explore Statistics – https://www.ubos.org/explore-statistics/20/.
9. Electricity Regulatory Authority, Electricity generation statistics, 2020. Available from: https://www.era.go.ug/index.php/stats/generation-statistics/energy-generated.
10. Fashina A, Mundu M, Akiyode O, et al. (2019) The drivers and barriers of renewable energy applications and development in Uganda: a review. *Clean Technol* 1: 9–39.
11. Wabukala BM, Otim J, Mubiinzi G, et al. (2021) Assessing wind energy development in Uganda: Opportunities and challenges. *Wind Eng* 45: 1714–1732.
12. International Hydropower Association, Hydropower status report, 2021. Available from: https://www.hydropower.org/publications/2021-hydropower-status-report.
13. National Planning Authority (NPA), Uganda Vision 2040, Kampala: Uganda, 2013. Available from: http://www.npa.go.ug/uganda-vision-2040/.
14. Nabutsabi DM (2020) Hydropower solutions for developing and emerging countries: Framework analysis and research needs in Uganda. Available from: https://www.hyposo.eu/pdf/HYPOSO_Framework_Conditions_Uganda.pdf.
15. Kimbowa G, Mourad KA (2019) Assessing the Bujagali hydropower project in Uganda. *Mod Approaches Oceanogr Petrochem Sci* 2: 162–173.
16. UBOS, Uganda boundaries shape files, 2019. Available from http://geoportal.icpac.net/documents/644.
17. Van der Ven MJ (2020) An overview of recent developments and the current state of the Ugandan energy sector. Working Paper: *International Growth Centre*. reference number: E-20046-UGA-1.
18. Electricity Regulatory Authority (ERA), Installed capacity, 2021. Available from: https://www.era.go.ug/index.php/stats/generation-statistics/installed-capacity.
19. Nsubuga FN, Namutebi EN, Nsubuga-Ssenfuma M (2014) Water resources of Uganda: An assessment and review. *J Water Resource Prot* 6: 1297.
20. Electricity Regulatory Authority (ERA), 2021. Available from: https://www.era.go.ug/index.php.
21. Oloya IT, Gutu TJL, Adaramola MS (2021) Techno-economic assessment of 10 MW centralized grid-tied solar photovoltaic system in Uganda. *Case Stud Therm Eng* 25: 100928.
22. Wagner HJ, Mathur J (2011) Introduction to Hydro Energy Systems. Springer, Berlin, ISBN 978-3-642-20708-2.
23. Okot DK (2013) Review of small hydropower technology. *Renewable Sustainable Energy Rev* 26: 515–520.

24. Chitrakar S, Solemslie BW, Neopane HP, et al. (2020) Review on numerical techniques applied in impulse hydro turbines. *Renewable Energy* 159: 843–859.
25. Yagmur S, Kose F (2021) Numerical evolution of unsteady wake characteristics of H-type Darrieus Hydrokinetic Turbine for a hydro farm arrangement. *Appl Ocean Res* 110: 102582.
26. Brian K (2020) Hydrokinetic turbines for moderate sized rivers. *Energy Sustain Dev* 58: 182–195.
27. Cora E, Fry JJ, Bachhiesl M, et al. (2020) Hydropower technologies—The state of the art. Hydropower Europe. WP4-DIRp-02.
28. Quaranta E, Revelli R (2018) Gravity water wheels as a micro hydropower energy source: A review based on historic data, design methods, efficiencies and modern optimizations. *Renewable Sustainable Energy Rev* 97: 414–427.
29. Muller G, Kauppert K (2010) Performance characteristics of water wheels. *J Hydraul Res* 42: 451–460.
30. Bouvant M, Betancour J, Velásquez L, et al. (2021) Design optimization of an Archimedes screw turbine for hydrokinetic applications using the response surface methodology. *Renewable Energy* 172: 941–954.
31. Kusakana K, Vermaak HJ (2013) Hydrokinetic power generation for rural electricity supply: Case of South Africa. *Renewable Energy* 55: 467–473.
32. Bahati HK, Ogenrwoth A, Sempewo JI (2021) Quantifying the potential impacts of land-use and climate change on hydropower reliability of Muzizi hydropower plant, Uganda. *J Water Clim Change* 12: 2526–2554.
33. Electricity Regulatory Authority, ERA. (2018) Renewable energy opportunities.
34. Japan International Cooperation Agency (JICA), Electric Power Development Co. Ltd., Nippon Koei Co. Ltd., (2011) Project for master plan study on hydropower development in the Republic of Uganda. Final report.
35. UETCL (2018) Grid Development Plan 2018–2040. Kampala: Uganda Electricity Transmission Company Ltd.
36. Laghari JA, Mokhlis H, Bakar AHA, et al. (2013) A comprehensive overview of new designs in the hydraulic, electrical equipment and controllers of mini hydro power plants making it cost effective technology. *Renewable Sustainable Energy Rev* 20: 279–293.
37. Bódis K, Monforti F, Szabó S (2014) Could Europe have more mini hydro sites? A suitability analysis based on continentally harmonized geographical and hydrological data. *Renewable Sustainable Energy Rev* 37: 794–808.
38. Mdee OJ, Nielsen TK, Kimambo CZ, et al. (2018) Assessment of hydropower resources in Tanzania. A review article. *Renewable Energy Environ Sustainability* 3: 12 pages.
39. Hossain M, Huda ASN, Mekhilef S, et al. (2018) A state-of-the-art review of hydropower in Malaysia as renewable energy: Current status and future prospects. *Energy Strategy Rev* 22: 426–437.
40. Twaha S, Ramli MAM, Murphy PM, et al. (2016) Renewable based distributed generation in Uganda: Resource potential and status of exploitation. *Renewable Sustainable Energy Rev 57:* 786–798.
41. Ministry of Energy and Mineral Development. (2015) *Sustainable Energy for All (SE4ALL) Action Agenda.* Kampala: MEMD.
42. Nile basin initiative. (2007) Strategic Social and Environmental Assessment of Power Development Options in the Nile Equatorial Lakes Region. *SNC Lavalin International*.

43. IRENA. (2017) Renewable Readiness Assessment: United Republic of Tanzania. *Abu Dhabi: International Renewable Energy Agency*.
44. World Bank. (2020) Increasing access to electricity in the Democratic Republic of Congo. *Washington DC: The World Bank*.
45. World Bank Group. (2016) Financial Viability of Electricity Sectors in Sub-Saharan Africa; Quasi-Fiscal Deficits and Hidden Costs. *World Bank Group*.
46. Ministry of Transport and Works. (2017) Works and Transport Sector Development Plan *2015/2016 to 2019/2020.* Kampala: ROU.
47. Energypedia, Uganda Energy Situation, 2020. Available from: https://energypedia.info/wiki/Uganda_Energy_Situation.
48. Ministry of Foreign Affairs. (2018) Final Energy Report. Kampala: ROU
49. Kaunda, CS, Kimambo CZ, Nielsen TK (2012) Potential of small-scale hydropower for electricity generation in sub-Saharan Africa. ISRN *Renewable Energy* Article ID 132606.
50. African Development Bank. (2015) Achwa II Hydro Electric Power Project. *African Development Bank.*
51. Baastel consortium (2014) Economic assessment of the impact of climate change in Uganda*:* Data water sector report. Available from: https://www.futurewater.eu/wp-content/uploads/2015/03/Impacts-of-CC-in-Uganda-Water_v3-clean-final.pdf.
52. Godinho C, Eberhard AA (2019) Learning from power sector reform the case of Uganda (Issue April).
53. UNDP. (2009) Enhancing the contribution of weather, climate and climate change to growth, employment and as prosperity. Kampala: UNDP/NEMA/UNEP Poverty Environment Initiative, Uganda.
54. NEMA. (2020) *National Environmental Management Authority*.
55. Ministry of Water and Environment. (2015) Economic assessment of the impacts of climate change in Uganda. Kampala: Republic of Uganda.
56. Probst B, Westermann L, Anadón LD, et al. (2021). Leveraging private investment to expand renewable power generation: Evidence on financial additionality and productivity gains from Uganda. *World Dev* 140: 105347.
57. Kilinc C (2012) Efficiency assessment of the hydropower plants in Turkey by using data envelopment analysis. *Renewable Energy* 46: 192–202.
58. Calabria FA, Camanho AS, Zanella A (2018) The use of composite indicators to evaluate the performance of Brazilian hydropower plants. *Intl Trans Op Res* 25:1323–1343.
59. Meinecke S, Sarajli D, Drauz SR, et al. (2020) SimBench—A benchmark dataset of electric power flow analysis. *Energies* 13: 3290.
60. Jamasb T, Pollitt M (2001) Benchmarking and regulation: International electricity experience. *Util Policy* 9: 107–130.
61. Jain S, Jain B (2015) A cost frontier model for Indian electricity generating utilities: A stochastic approach. *Int J Eng Tech Res* 3: 47–53.
62. Du Y, Liao H, Wei Y (2020) Integrating cost information in energy efficiency measurement: An empirical study on thermal power companies. *Energy Effic* 4: 697–709.

63. Kichonge B (2018) The status and future prospects of hydropower for sustainable water and energy development in Tanzania. *J Renewable Energy* 2018: 1–12.
64. Zhou Y, Chang LC, Uen TS, et al. (2019). Prospect for small hydropower installation settled upon optimal water allocation: An action to stimulate synergies of water-food-energy nexus. *Appl Energy* 238: 668–682.
65. Nicholas RE (2018) Exploring how changing monsoonal dynamics and human pressures challenge multi-reservoir management for flood protection, hydropower production, and agricultural water supply. *Water Resour Res* 54: 4638–4662.
66. Ehteram M, Koting SB, Afan HA, et al. (2019). New evolutionary algorithm for optimizing hydropower generation considering multireservoir systems. *Appl Sci* 9: 2280.
67. Samad A, Rahaman SA, Watada J, et al. (2020). Optimization of the hydropower energy generation using Meta-Heuristic approaches: A review. *Energy Rep* 6: 2230–2248.
68. Li X, Chen Z, Fan X, et al. (2018). Hydropower development situation and prospects in China. *Renewable Sustainable Energy Rev* 82: 232–239.