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Performance Analysis of a Hybrid of Solar Photovoltaic, Genset, and Hydro of a Rural-Based Power Mini-Grid: Case Study of Kisiizi Hydro Power Mini-Grid, Uganda

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Abstract: The power sector in Uganda has increased steadily, focusing majorly on rural electrification to increase the proportion of the rural population accessing electricity using grid extension and isolated mini-grid approaches. Hydropower mini-grids implemented in rural communities have issues regarding system failures leading to shutdowns and load shedding. A study on an existing isolated hydropower mini-grid was made to find the possible causes. A review of published articles and reports, and an analysis of enrollment patterns, energy sales, and load demand was carried out. A field survey with a guided questionnaire to collect information about real energy demand data was carried out. The performance of the system was accomplished through simulation using HOMER pro × 64 software. The findings from the study show a reduction in customer enrollment, a reduction in energy sales, and a reasonable number of system shutdowns. Hybridization of the existing hydropower was modeled with different options. The hybrid system proposed indicates that, when implemented, it would reduce fuel consumption from 222 to 23.2 L/day and emissions from 82.5 to 8.3 kg/year on average and increases system reliability. Simulated values of NPC, LCOE, and operating costs are appreciable. Despite mini-grid shortfalls, there is notably improved livelihood due to improved social and economic services.

Keywords: rural electrification; mini-grid; hydropower; hybrid system; HOMER pro × 64; livelihood

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1. Introduction

The Power sector development in Uganda has been on a steady increase since the year 2000, with major emphasis put on rural electrification to increase the percentage of the population accessing electricity using various approaches, including grid extension and isolated mini-grids [1]. Energy use is very critical to the welfare of households and economic development [2]. It is obvious that in all developing countries like Uganda, access to modern energy services contributes positively to household welfare and has a relationship with population growth [3,4].

In terms of hydro resources, Uganda covers an area of 241,038 km^2; a third of this is freshwater bodies and wetlands, which are sufficient enough to act as sources of energy in the form of Hydropower [1].

Regarding challenges faced with urbanization, such as inadequate housing, poor air pollution, and limited access to basic services and infrastructure, paves the way for a shift to rural communities to minimize rural-urban migration (RUB) by extending similar services of the urban setting to rural communities [5–7].

Rural community (RC) is defined based on social and economic aspects the world over. In Canada, RC is defined as sparsely populated lands outside urban areas [8]. In

Japan, RC is defined based on population density [8]. In Uganda, a rural community is defined as an area with an open swath of land with few homes located very far from their businesses. It can also be an area with small population density figures whose major activity is Agriculture. The population shows homogeneity of language, culture, and customs; people live in close contact with nature, have slower means of communication, population less qualified with a few technical skills, homesteads characterized by poor planning and maintenance practices, and are largely dependent on vegetation cover for house construction and source of energy [9–12].

The use of hybrid systems increases the reliability of the optimal utilization of resources. Hybrid installation centered on the use of gensets and Renewable Energy generations common in various countries such as Pakistan, Fiji, Morocco, Oman, Malaysia, and Nigeria [13–19] have proved to be efficient, reliable, and sustainable [20]. There are various isolated mini-grids in Uganda, namely Kisiizi hydropower station, Kanyegaramire, and Kyamugarura solar PV stations, Kasese Cobalt, WENRECO, Kitobo Island, Buggala Island, to mention but a few. Most of them use renewable resources like solar PV and hydropower [19,20]. These systems have performance challenges such as system breakdown, load shedding, and insufficient power supply. Records have scanty information about their performance in terms of economic and technical issues and hence need to be investigated. This research explores the cause of mini-grid system failures, mini-grid performance challenges alongside customer energy demands, cause of continuous load shedding, cause of discomfort among mini-grid power users, and the possibility of hybridizing a mini-grid for better performance options [21].

Using a hybrid system (HS) and conventional Diesel Generator minimizes fuel consumption, reduces gas emissions, and later alone improves the standard of living of the rural communities served by the mini-grid [22]. Joseph et al. suggested that it is very hard to satisfy human power demands throughout the year using hydropower sources alone. It needs a backup of additional renewable sources to form an HS to remedy rural electrification problems [19].

1.1. Literature Review

Many scholars have attempted to look at Hydropower development in rural areas of African countries and beyond. The study made by researchers in Uganda [23] found that hydropower is dominant and the rate of development is low. They used a systematic review approach and concluded that Uganda lacks the human ability that possesses satisfactory skills to handle hydropower projects. However, they never went into detail to relate human needs with hydropower development. Moreover, Ref. [24] indicates that Uganda is endowed with scattered energy-generating sources that make the generation of power expensive and looks at the possibility of reducing cost by increasing substations and never considered the possibility of hybridization.

A study made by Kimera et al. on Wanale village in Eastern Uganda [25] shows that villages need mini-grid electricity to get out of poverty. They used a combination of Renewable energy technologies and conventional energy Generators to achieve synergies in operation hence providing reliable services in remote areas. They considered component sizing but did not carry out the real energy demand of the village. The study made on Kalangala Island on Lake Victoria in Uganda analyzed energy cost and cost comparison of a thermal generator and proposed a hybrid system of solar and wind. They used daily load profile data given by a power analyzer and did not look at the growing energy demand of the island [26]. The study made by Shaffic et al. proposed a design of a hybrid of solar and wind systems to irrigate an acre of a banana plantation in Kalangala District and minded much on wind and solar parameters for irrigation only [27]. The study made by [28] in Uganda examines the variability of peak electricity demand before and after the application of power factor improvement schemes. They found that there is a visible decrease in electricity at the times of use and progress in consumption of electricity during the non-peak time. They did not look at the effect of the incentive regulation on electricity peak demand and the extent of policy implications as a result of implementing power factor correction schemes.

A study made in Ntoroko village, Uganda, emphasizes that the use of a hybrid storage system is economical in remote areas where electrical demand is low and uses a method of varying PV sizes, batteries, inverters, and batteries to come up with different designs of hybrid systems [29].

In Uganda, electricity suffers from long-standing supply-side constraints that result in suppressed demand and outages. The researchers compared peak demand with the recent trends in hydropower development. They used descriptive data analysis and polynomial functions to come up with the conclusion that peak demand does not stagnate but only shifts to the nonpeak time-of-use zone. The study did not use rural-based methods to analyze the peak demand of a rural community [30].

A study on mini-grids in India shows that despite the allocation of substantial funds to rural electrification, rural electrification still lags behind other services in India [31]. Moreover, energy demand is on the increase in an effort to accelerate industrial activities to boost economies [32].

The study made by [33] puts more emphasis on having related energy models to enhance rural electrification in developing countries and mind much on the benefits brought about by having renewable energies as a means of lowering carbon emissions and having low-carbon societies. At the same time, a study made by [34] proposes a shift to hydrogen technologies that contribute to the economy's significant energy needs and also reduce urban pollution emissions.

The study [35] also shows that mini-grid development is a better way to increase rural electrification. They compare Load following and cycle charging strategies with predictive strategies based on Linear programming to come up with mini-grid operating strategies.

A study made on Indonesia's rural electrification strategies shows that isolated grids powered by independent renewable sources are considered paramount and sustainable solutions for rural electrification. The other non-renewable are characterized by high costs and high percentages of carbon gas emissions [36].

The study made on need assessment found that inputs and assumptions are required in business modeling and mini-grid design. The study goes ahead to realize that for energy need assessment of a rural community is by obtaining reliable input data for the mini-grid development [37] and that energy access and security are crucial factors for any country's economic growth [38]. Relatedly, the study suggests that electricity usage plays a vital role in raising overall growth in the economy coupled with industrial sector attention initiatives [39]

The study made by [40] suggests that there are difficulties in the attempt to provide sustainable cellular mobile services in rural areas where there is no power supply.

Antonanzas et al., in their study, found out that solar PV mini-grids have lower carbon emissions than national grids in Sub-Saharan Africa and diesel Generators [41] and, therefore, needed to be given attention. However, the study made by Niwagira et al. stresses that small modular reactors are better than other competing energy sources because of their higher percentage contribution to Uganda's future energy mix and, therefore, a remedy for environmental degradation [42].

There is also a relationship between livestock production and emissions. The study made by Macleod et al. found that a reduction in Green House Gas emissions increases livestock production [43]. Therefore, Uganda should adopt Renewable energy mini-grids because of sustainability, climate change mitigation, and a quick means of achieving Sustainable Development Goals by 2030 and realizing vision 2040 [25,44].

Uganda's generation capacity has grown from 60 MW in 1954 to 400 MW in 2000 then to approximately 1237.49 MW as of October 2020 and rose to 1837.49 MW by mid-2021 [23].

A study which was conducted on hydropower development in Uganda from November 2009 to March 2011 agreed that;

- There was a power shortage in Uganda;
- There was a lack of power generation infrastructure of installed capacity;
- There was a need to raise the hydropower supply capacity;
- There was a need to export power as a result of implemented hydropower projects.

At the end of the study, the Government of Uganda realized an urgent need to develop more power plants and expansion of power grids as a prerequisite for continued economic growth and development [45], of which one of them is our case study.

1.2. Kisiizi Hydropower Mini-Grid (KHPMG) as a Case Study

KHPMG is located along River Rushoma on Kisiizi waterfalls in Kisiizi trading center, Nyarushaje Sub County, Rubabo County, Rukungiri District in the western province of Uganda. Its location coordinates are 00°59′44″ S 29°57′45″ E. Its generation capacity is 0.3 MW. KHPMG is owned and managed by a private missionary Hospital administered by the church of Uganda and majorly supported by a Non-Governmental Organization (NGO) in the United Kingdom called Friends of Kisiizi.

The 300 kW power plant was commissioned in 2008 to replace an old power plant that had a maximum capacity of 60 kW. It has a normal elevation of 1640 m, and its construction cost amounted to $700,000. It started as a hospital property to help in hospital operations, mainly lighting and in the theater. Later alone, after upgrading to 300 kW, they started serving the communities outside the hospital. Currently, it serves more than 600 external customers. It is mandated and licensed by the Government of Uganda to carry out Generation, Transmission, and Distribution activities. The power from the station is used for Domestic and Commercial activities of the Kisiizi hospital, and the surplus is sold to customers of the 33 villages of the Kisiizi sub-county, as shown in Table 1.

Table 1. A list of villages supplied by KHPMG.

S/N	Village Name	S/N	Village Name
1	Kisiizi (Kisiizi Lower)	18	Stage Nyarushanje
2	Binyena	19	Ibanda
3	Kisiizi Upper Trading Centre	20	Ngarama
4	Kamobwe	21	Ruyonza
5	Nshugyezi	22	Gomborora Headquaters
6	Omukikona	23	Ahamuginda
7	Kasikizi	24	Nyakaginga
8	Omukatooma	25	Rwentare
9	Kahanga	26	Nyakasa
10	Mucondo	27	Kicubanyungu
11	Rubirizi	28	Kahumiro
12	Rwere	29	Kanyinya
13	Nyarutuntu	30	Kyakabarisinga
14	Kasoni	31	Omukishanda
15	Mushunga	32	Kamira
16	Rutooma. A	33	Katobotobo
17	Rutooma. B		

In these villages in Table 1, there are two categories of customers, namely;

- Domestic customers. These are customers that use electricity for lighting, charging, ironing, playing music, and watching television;
- Commercial customers. These are customers who use electricity for business purposes, and these include Institutions such as schools, churches, and health centers. Small businesses, which include welding, Bakery, Wood workshop, Grain millers, Coffee hullers, Fuel stations, and Saloons.

These categories of customers outside Kisiizi Hospital are generally termed "Outside customers".

KHPMG has a turbine, a generator, a load tank, and a powerhouse. The turbine changes the kinetic energy of falling water pushing against turbine blades into Mechanical Energy. The Generator connected to the turbine by shafts and gears converts Mechanical Energy produced by the turbine into Electrical Energy. The load tank contains immersion elements. As the generator produces more than what is being used at the time, the excess goes to the load tank. When a sudden load is added on line, the excess power in the load tank immediately compensates for the sudden load as the generator prepares to open the gate valve to allow in more water hence maintaining the frequency. If the sudden load is put in the absence of a load tank, the generator over speeds and causes a change in frequency that results in a possible shutdown of the facility.

2. Materials and Methods

The research methodology of this manuscript is divided into sections as discussed below:

2.1. Introduction and Literature Review

The study involved desk study methods which included a review of written literature and authentic published articles.

2.2. Case Study Area

The study involved community member interaction methods and a prepared questionnaire to guide the flow of interviews in determining the number and rating of appliances used by customers to help in the sizing process. The site data was obtained from station officers, operators, and concerned record attendants.

The study concerns of the case study area and their corresponding methodologies are shown in Table 2 below.

Table 2. Research concerns and methodology used.

Analysis	Concern	Methodology
Performance analysis	Cause of system failure Mini-grid power output visa vie customer demands Cause of continuous load shedding Cause of fluctuations in customer enrollment Emission levels	Load demand analysis (Enrollment trend, Energy sales, and average peak demand) Field survey Data collection System sizing HOMER pro × 64 software Excel analysis
Systems Analysis	Initial cost Replacement cost Salvage value Operation and maintenance cost Fuel consumption Emissions Economic parameters (NPV, LCOE, and OC)	HOMER pro × 64 software

Key: NPV Net Present Value, LCOE Levelised Cost of Energy, OC Operating Cost.

The researchers explored the possibility of hybridizing the existing system and proposed a solar Photo Voltaic (PV) system with storage to supplement the existing diesel generator and hydropower and named it option 1 (solar PV +Genset + hydropower). Solar PV storage includes solar batteries, solar panels, inverters, and controllers. Using the data collected, the sizing process was made. Moreover, the research carried out by Mateusz Andrychowicz about optimization of distribution systems by using Renewable Energy Sources (RES), which included Wind, Photovoltaic, and Biomass, found that the combination of allocation and sizing RES, energy storage, and grid development using mixed integer linear programming, reduce power losses in a distribution system was analyzed to help in further methodology of this research [46].

2.3. Design of a Hybrid of Solar PV, Diesel Generator, and Hydropower

A global horizontal solar irradiance of the area (Figure 1) was obtained from HOMER pro × 64, and the average daily energy demand was obtained from sized data and fed into HOMER pro × 64 software.

Figure 1. Monthly average solar global irradiance of Kisiizi area.

2.4. Software Used: The Software Used Is HOMER pro × 64

The HOMER pro × 64 Micropower Optimization Model is a computer model created by the U.S. National Renewable Energy Laboratory (NREL) to make it easier to compare power generation technologies for a wide range of applications and design micropower systems [47]. HOMER pro × 64 helps the modeler comprehend and quantify the effects of uncertainty or changes in the inputs and allows them to compare various design options based on their technical and economic advantages [48].

HOMER Technical modeling

PV array: HOMER pro × 64 calculates the output of the array and Renewable fraction as follows [49,50]:

$$\mathrm{P_{pv}} = Fpv \times Ypv\frac{It}{Is} \tag{1}$$

$$\mathrm{RF_{pv}} = \frac{Epv}{Ean.t} \tag{2}$$

Hydro: HOMER pro × 64 calculates the output of a hydro turbine and net head as follows:

$$\mathrm{P_{hd}} = \eta t \times \rho w \times hnet \times \varphi t\frac{1}{1000} \tag{3}$$

$$\mathrm{h_{net}} = h(1 - fh) \tag{4}$$

Generator: HOMER pro × 64 calculates the fuel consumption as follows:

$$\mathrm{Fc} = Fo \times Yg + Pg \times F1 \tag{5}$$

Battery Bank: HOMER pro × 64 calculates the life of a battery bank as follows:

$$\mathrm{L_b} = Min(\frac{Nb \times \phi lt \times Lbf}{\varphi thr}) \tag{6}$$

2.5. Homer Economic Modeling

HOMER pro × 64 assumes that all prices escalate at the same rate over the project lifetime and tries in its simulations to minimize the Net Present Cost (NPC) to represent the life cycle cost of a project [30,43,44]. In economic analysis, HOMER pro × 64 calculates NPC, Salvage value, Capital Recovery Factor (CRF), and Levelized Cost of Energy (LCOE) using the following formulae [51]:

$$\mathrm{NPC} = \frac{Can.t}{CRF(i, Rproj)} \tag{7}$$

$$\mathrm{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{8}$$

$$\mathrm{Sv} = Crep\,\frac{Rrem}{Rcomp} \tag{9}$$

$$\mathrm{LCOE} = \frac{Can.t}{Eprim} \tag{10}$$

3. Results

3.1. Customer Enrollment

Figure 2 below shows customer enrollment from the time of commissioning to December 2021.

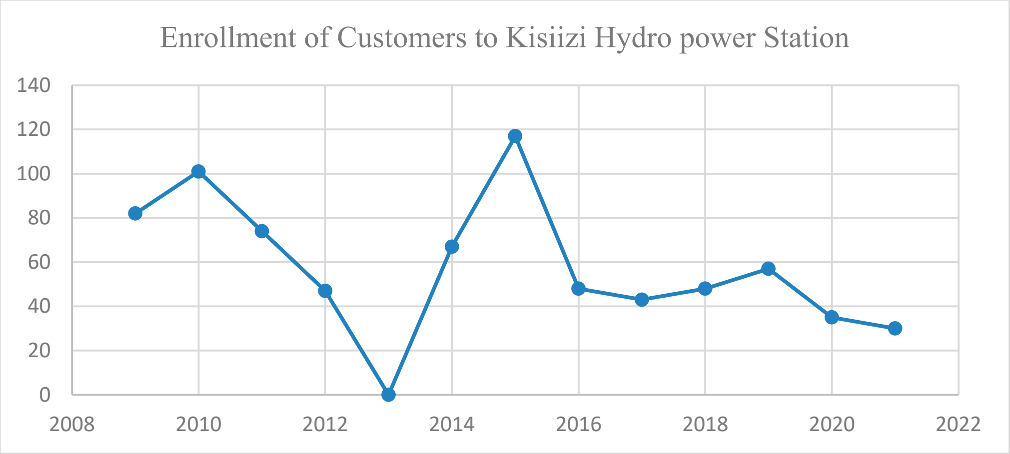

Figure 2. Enrollment of outside customers to KHMG.

In 2009, 82 customers were enrolled; in 2010, people were excited, and 101 customers were recruited. In 2011, enrollment declined to 74 and to 47 customers due to system failures. In 2013, the plant was out of function for a whole year due to a complex technical problem that was costly to rectify, hence no enrollment. The power station was invaded by floods and destroyed the civil works, short-circuiting alternators and turbine, which needed an assessment of the destruction situation and made a requisition to a German company for a replacement. This took time to replace civil works and equipment. A big basement wall has been built to prevent further invasion of floods. In 2015, the company registered the highest number of 117 customers due to the steady supply that was registered due to system repairs and maintenance. Declined again in 2016 due to technical faults. Enrollment has persistently reduced since 2019, and overall, as of December 2021, 749 customers were already enrolled and using the services of KHPS.

3.2. Energy Sale Analysis

A three-year energy sale analysis was performed in Figures 3–5.

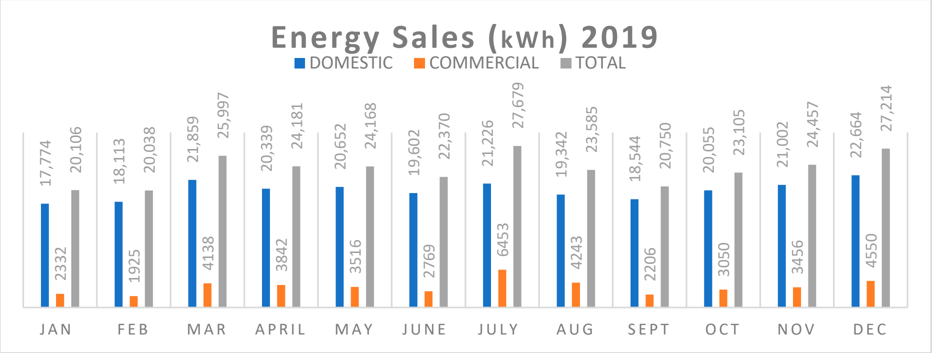

Figure 3. Energy Sales January–December 2019.

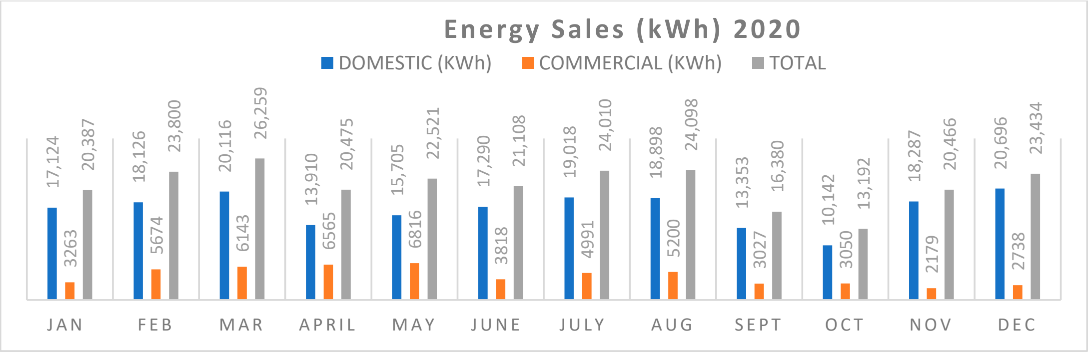

Figure 4. Energy Sales January–December 2020.

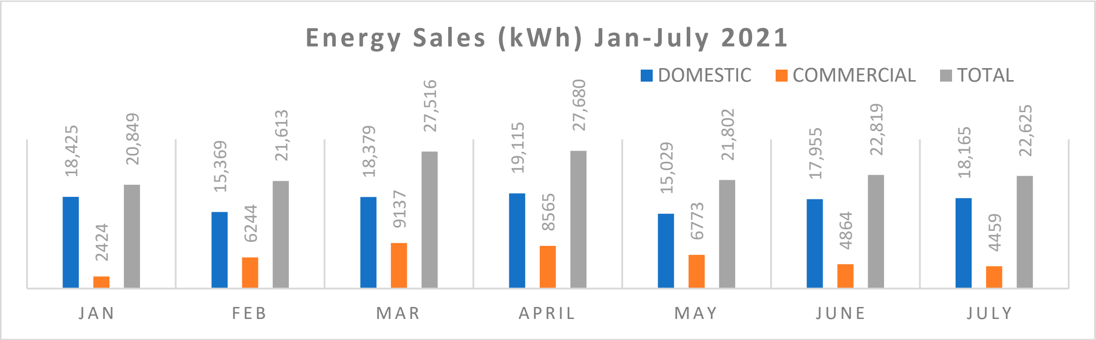

Figure 5. Energy Sales January–July 2021.

Figure 3 shows the sales made by KHMG to customers outside Kisiizi hospital, making a total of 241,170 kWh of domestic sales and 42,480 kWh of Commercial sales. The highest sales were in March, April, May, July, November, and December. This is due to school holidays when children are at home and spend time on television watching, charging, and making revisions. The Commercial sales were high in March, July, August, and December. This was due to the increased market brought by the students in school holidays.

In Figure 4, the domestic sales reduced by 38,506 kWh and Commercial sales increased by 10,984 kWh in 2020. This was due to the COVID-19 total lockdown in March 2020, where only small businesses were allowed to operate in Uganda. The sales dropped from 20,116 in March to 13,910 kWh in April of the same year. In Figure 5, the Domestic Sales further decreased by 80,227 kWh, and commercial sales also reduced by 10,998 kWh from 2019 to 2020. This was due to persistent infections of COVID-19. People had lost hope, some had to lose jobs, and some industries closed operations. Generally, there were overall reductions in total sales, as indicated in Figure 6.

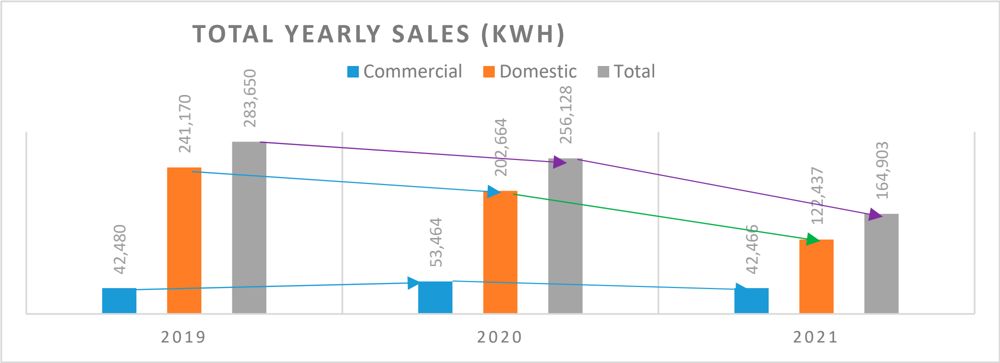

Figure 6. Total yearly sales showing declines in energy sales.

3.3. Peak Demand Analysis

This is the highest electrical power demand that occurs over a specified period, and it is characterized as annual, daily, or seasonal and has a unit of power. A three-and-a-half-year peak demand analysis was performed in Figures 7–10.

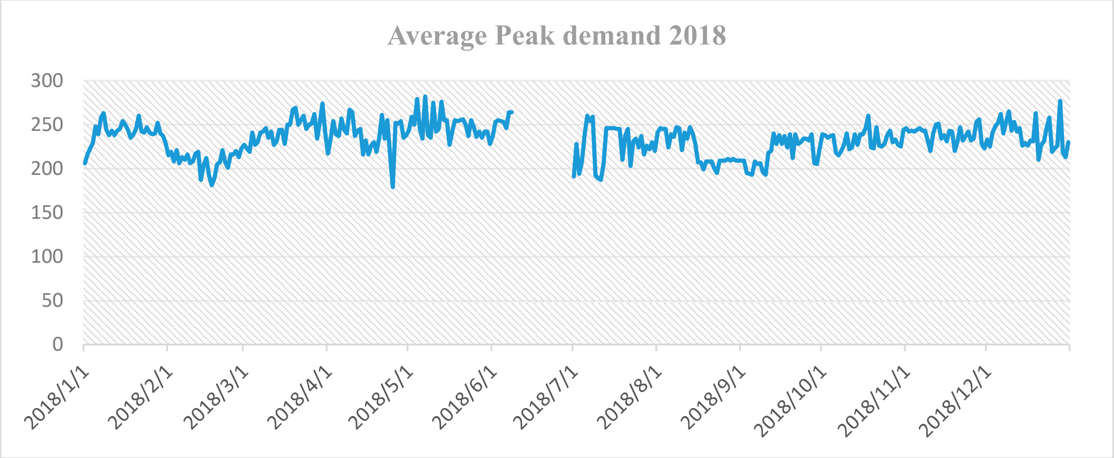

Figure 7. Simulated average peak demand for the year 2018.

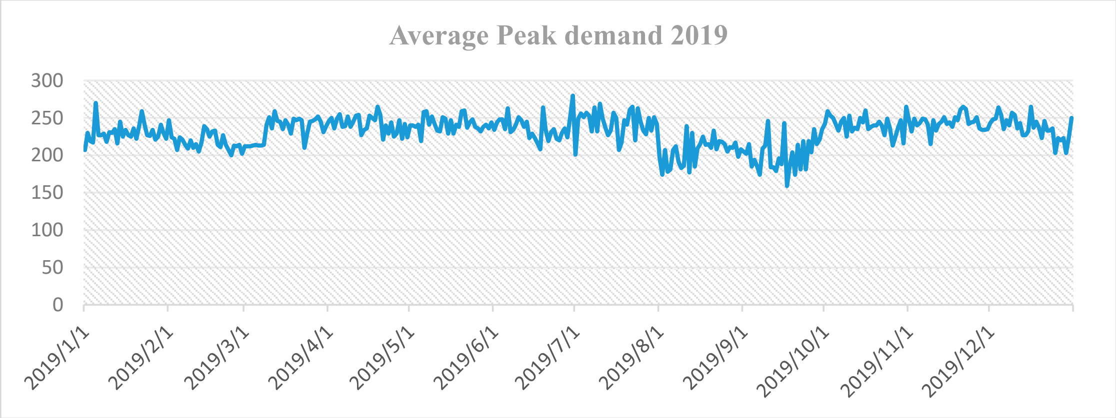

Figure 8. Simulated average peak demand for the year 2019.

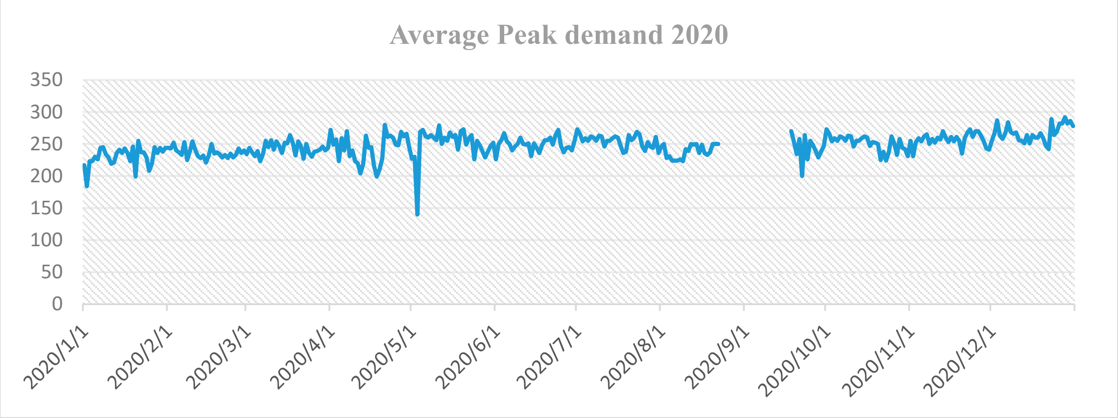

Figure 9. Simulated average peak demand for the year 2020.

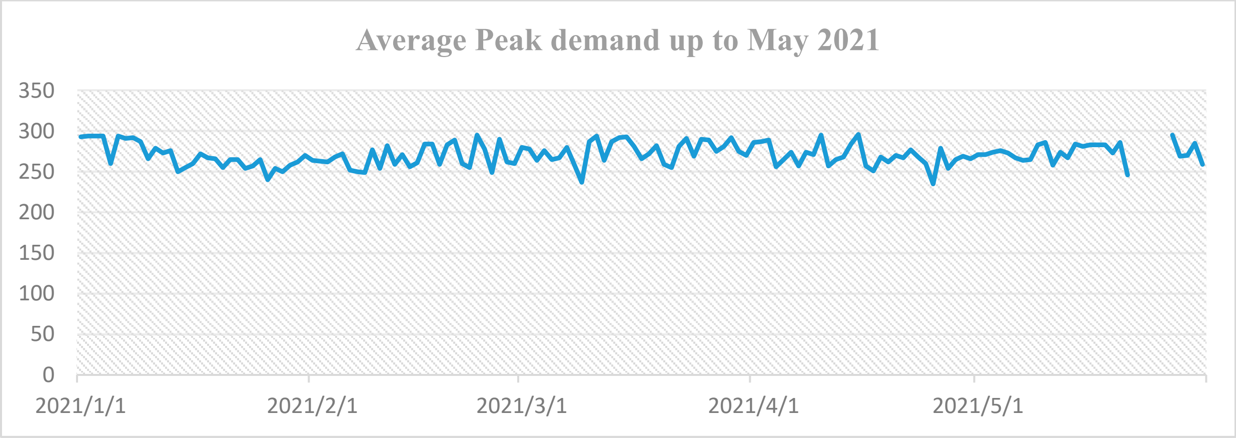

Figure 10. Simulated average peak demand for the year 2021.

The highest average peak demand was registered in the months of May, October, November, and December, and the lowest was in February, April, July, and August. From 9–30 June 2018, there was no generation due to the burnt alternator that needed replacement as shown in Figure 7.

In 2019, the highest average peak demand was recorded in January, June, October, and December, and the lowest in February, August, and September as indicated in Figure 8.

In 2020, the highest average peak demand was recorded in May, October, and December, and the lowest in January and May. However, there was no generation from 23 September to 18 October 2020 due to floods that eroded the power station and destroyed some plant components as shown in Figure 9.

In 2021, only five months were considered. The results of the other months were still sketchy at the time of compiling this manuscript. There was no power generation from 22 to 26 May 2021 because of general repairs that involved fixing gearbox bearings. May recorded the highest average peak demand, and April registered the least as indicated in Figure 10.

It was found that there were several shutdowns in 2019, as shown in Figure 11.

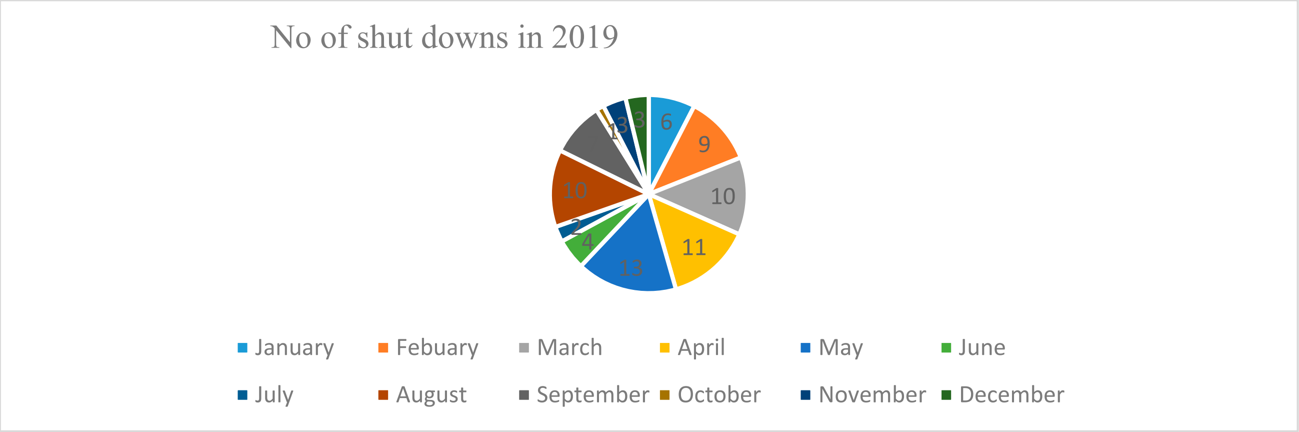

Figure 11. Number of system shutdowns in 2019.

April, May, and August registered the highest number of shutdowns.

Notable gaps: The reduction in enrollment, reduction in energy sales, and the high number of system shutdowns due to system failure brought about by repairs and maintenance, component replacement, and seasonal variations like floods and drought.

When the number of customers enrolling in the grid declines, this increases the excess electricity, reduces mini-grid revenue, and impacts employees' payments negatively. When energy sales reduce, it means that the demand for electricity is low. This could be because of unreliability or the high cost of units of electricity. In due course, the mini-grid cannot meet its investment, operation, and maintenance costs and is, therefore, liable to fail.

When there are uncontrollable numbers of system shutdowns due to system faults and system maintenance, customers lose confidence and begin opting for other sources, hindering mini-grid growth and revenue collection.

When a Generator or hydropower turbine fails, the system shuts down for some time. When there is routine maintenance on the system, the whole system is switched off. The authors, therefore, proposed a design of a hybrid system of Solar PV with storage, diesel generator (Genset), and hydropower turbine, earlier termed "Design option 1".

When the hydropower turbine has a mechanical problem or during months of low flow rate Figure 12, then a design of a hybrid system of Solar PV storage and a diesel generator is proposed, termed "Design option 2".

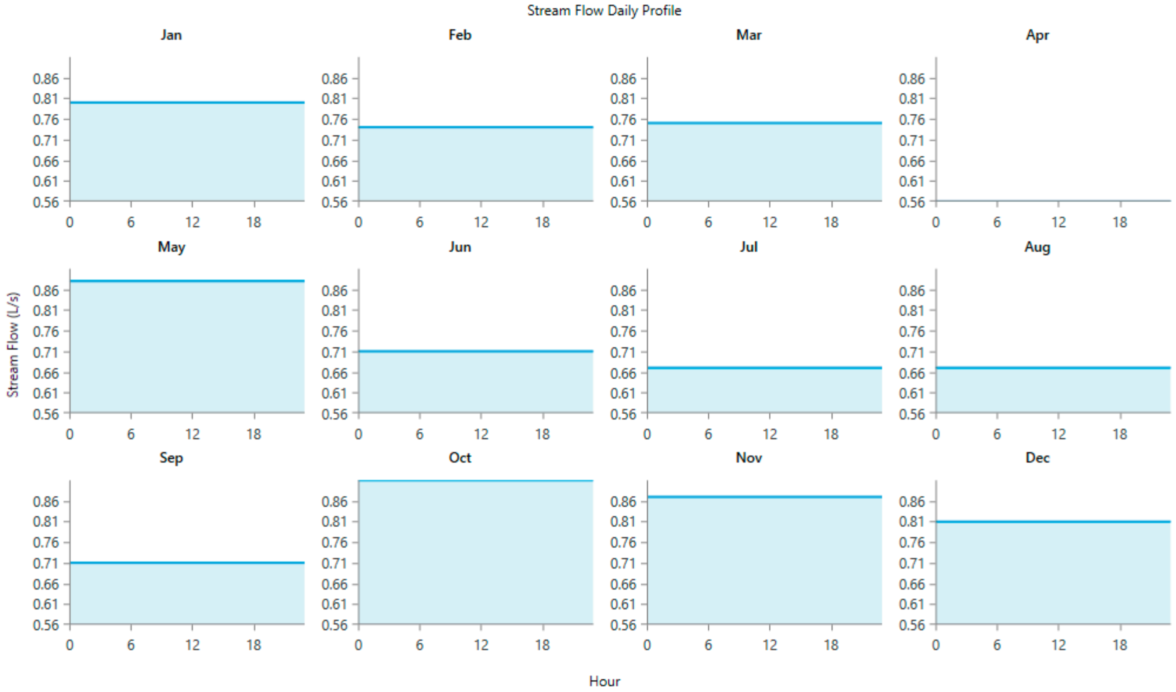

Figure 12. Average monthly stream flow rate for river Rushoma that supplies KHMG.

When the generator is faulty, then a hybrid of Solar PV storage and hydropower turbine is proposed, termed "Design option 3".

Using the data obtained from the field, the procedure of determining energy use per day, as described in Table 3 below, was followed.

Table 3. Determining total daily energy demand of KHMG users.

1			**Grain Millers and Coffee Hullers (12)** **CFLs = Compact Fluorescent Lamps**			
Appliance	**Power Rating (W)**	**Quantity**	**Hours Used (h)**	**Energy Use (Wh)**	**Total in Number**	**Total Energy Use a Day (Wh/d)**
CFLs	10	4	10	400		
Electric motor	4000	1	2	8000		
				8400	12	100,800
2			Fuel stations (06)			
Fuel pump motor	1000	1	12	12,000		
CFLs	25	4	6	600		
Decoder	60	1	6	360		
				12,960	6	77,760

Table 3. *Cont.*

1	**Grain Millers and Coffee Hullers (12)** **CFLs = Compact Fluorescent Lamps**					
Appliance	**Power Rating (W)**	**Quantity**	**Hours Used (h)**	**Energy Use (Wh)**	**Total in Number**	**Total Energy Use a Day (Wh/d)**
3	Uganda Martyrs Polytechnic Institute (01)					
CFLs	5	40	6	1200		
Printer	60	1	1	60		
Desktop computer	80	2	6	960		
Television	40	1	2	80		
Photocopier	80	1	1	80		
Workshop motor	4000	1	1	4000		
				6380	1	6380
4	Schools (12)					
CFLs	5	30	6	900		
Printer	60	1	1	60		
Desktop computer	80	1	6	480		
Television	40	1	1	40		
Photocopier	80	1	1	80		
				1560	12	18,720
5	Churches (07)					
CFLs	5	20	4	400		
Address system	1000	1	1	1000		
				1400	7	9800
6	Health centers (02)					
Fridge	400	1	6	2400		
CFLs	3	30	9	810		
Computer	80	1	2	160		
Television	40	1	8	320		
Printer	60	1	1	60		
				3750	2	7500
7	Small and Medium Enterprises (12)					
Electric motor	1000	1	1	1000		
Fridge	400	1	2	800		
Decoder	60	1	6	360		
Television	40	1	5	200		
CFLs	5	6	5	150		
				2510	12	30,120
8	Barber shops (saloons) (03)					
CFLs	7	4	10	280		
Electric clipper	15	1	6	90		
Hair drier	1500	1	2	3000		
Decoder	60	1	10	600		
Television	40	1	10	400		
				4370	3	13,110
9	Domestic customers (649)					
CFLs	5	5	4	100		
Television	40	1	2	80		
Radio	30	1	2	60		
				240	649	155,760
10	Kisiizi Hospital Domestic customers (133)					
CFLs	5	5	5	125		
Television	40	1	3	120		
Decoder	60	1	1	60		
Laptop	65	1	1	65		
				370	133	49,210
11	Kisiizi Hospital commercial customers (07)					
CFLs	5	6	6	240		
Television	40	1	6	240		
Fridge	400	1	2	800		
Decoder	60	1	1	60		
				1340	7	9380
				Total energy demand per day		478,540 kWh/day

HOMER pro × 64 software input data

Considered inflation rate at 3.2% as of 28 February 2022, according to the Uganda Bureau of Statistics.

Discount rate at 6.5% as of 12 April 2020 Bank of Uganda.

Project lifetime 25 years.

Table 4 below shows hydro and Generator parameters together with daily peak demand values and monthly average flow data of Rushoma river where the kisiizi hydropower station is located. These values were fed into HOMER pro × 64 for analysis.

Table 4. HOMER input values.

Hydro			**Generator**		
Item	**Amount**	**Unit**	**Item**	**Amount**	**Unit**
Capital cost	700,000	$	Initial cost	50,000	$
Replacement cost	350,000	$	Replacement	50,000	$
O&M cost	150,000	$	O&M cost	2	$/op h
Lifetime	25	Years	Fuel price	1.2	$
Available head	29.8	M	Min Load ratio	25	%
Design flow rate	500	L/s	Lifetime	15,000	h
Minimum flow ratio	50	%			
Maximum flow ratio	150	%			
Efficiency	80	%			
Pipe head loss	15	%			
Daily Peak Demand Averages		Monthly Average stream flow data			
Time	Peak Demand(kW)	Month		Stream flow(L/s)	
0:00	250	JAN		0.8	
1:00	240	FEB		0.74	
2:00	235	MAR		0.75	
3:00	230	APR		0.56	
4:00	250	MAY		0.88	
5:00	275	JUN		0.71	
6:00	270	JUL		0.67	
7:00	249	AUG		0.67	
8:00	230	SEP		0.71	
9:00	220	OCT		0.91	
10:00	220	NOV		0.87	
11:00	200	DEC		0.81	
12:00	231				
13:00	274		Annual average 0.76 L/s		
14:00	268		Residual flow rate 0.26 L/s		
15:00	261				
16:00	214				
17:00	202				
18:00	226				
19:00	227				
20:00	217				
21:00	219				
22:00	258				
23:00	270				

Figure 12 below shows a graphical representation of the stream flow rate of the river at the study site. The flow rates are lowest in the months of April (0.56), June (0.71), July (0.67), August (0.67), and September (0.71). Therefore, Hydropower production is lower to meet the growing peak demand

The graphical representation of the solar energy load profiles for the site study area is shown in Figure 13 below.

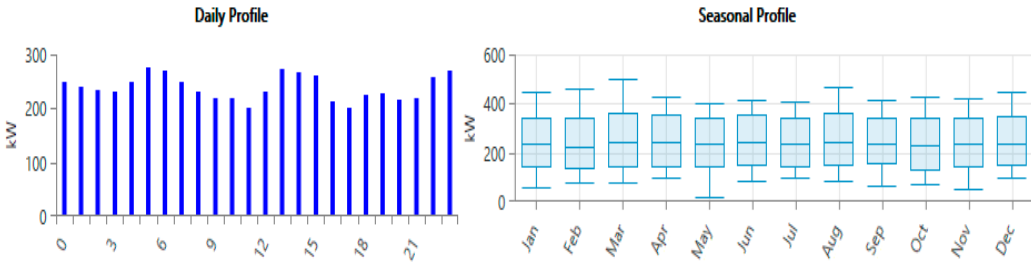

Figure 13. Daily and seasonal profiles for solar Energy at KHMG.

Figure 14 shows HOMER system architecture with energy sources, loads, storage and conversion components

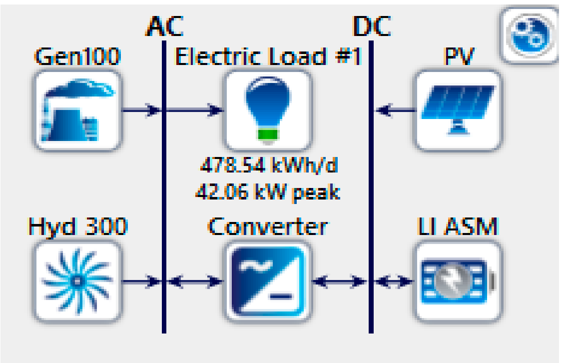

Figure 14. HOMER system architecture showing the interconnections of the loads, components, and resources.

Figure 15 shows HOMER result table with base system (BS) and design options 1, 2 and 3 indicating technical and economic parameters of the simulated data.

	Architecture						Cost			
	PV (kW)	Gen100 (kW)	LI ASM	Hyd 300 (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
2	159	100	449		39.3	LF	$1.11M	$0.372	$24,298	$691,590
	370		807		56.3	LF	$1.72M	$0.577	$21,061	$1.36M
1	152	100	445	117	40.6	LF	$2.06M	$0.693	$40,435	$1.37M
		100	69		20.6	LF	$2.10M	$0.705	$117,682	$91,791
		100				LF	$2.47M	$0.830	$142,085	$50,000
	2.49	100			0.333	LF	$2.48M	$0.832	$142,043	$56,337
3	352		854	117	46.4	LF	$2.67M	$0.897	$37,241	$2.03M
		100	73	117	20.7	LF	$3.05M	$1.03	$132,558	$793,868
BS		100		117		LF	$3.43M	$1.15	$157,085	$750,000
	2.49	100		117	0.333	LF	$3.43M	$1.15	$157,043	$756,337

Figure 15. The result table showing the architectural design and cost comparison of simulated system, highlighting the base system (BS) and design options 1, 2, and 3.

4. Discussion

4.1. Technical Analysis

This looks at the system design, the components' operation, power production, emissions, and maintenance. The discussion is made based on a comparison of the existing base system that includes a Generator and hydropower turbine and the proposed hybrid system.

Table 5a: the generator operates at 10% and a high renewable fraction of 86.2% from 100% operation with the existing system. Excess electricity is low with Genset systems due to controllable measures of switching on and off during peak and off-peak periods.

Table 5b: the battery bank is expected to work for 16 h a day and last for 15 years. The efficiency of the batteries considering Energy output and Energy input is 92%.

Table 5c: the generator with the existing system has a high time of operation, a very low lifetime, and a very high fuel consumption of 90.2%. This results in high operating costs.

High fuel consumption leads to high fuel costs and carbon emissions, which is a reason why it should be avoided.

Table 5d: the figure shows the rated capacity of PV and mean output is low and with very low LCOE at 0.103$/kWh. Hours of operation indicate the hours of half a year. Therefore the operation is for 12 h a day.

Table 5e: the inversion value is higher than the rectification value because solar PV generates DC, which has to be changed to AC. The efficiency of the inverter and rectifier stands at 95%, considering the energy it receives and what it gives out. The losses are also minimal.

Table 5f, Emissions are very high with the existing base system at 90.2% and very low with the proposed hybrid system at 9.8%.

Table 5. (**a**–**f**): Design option 1 comparing technical parameters of the base system and proposed hybrid system of simulated values.

(**a**) Electricity Production (%)

	Generator (%)	PV	AC Primary Load (kWh/yr)	Excess Electricity (%)	Unmet Load (%)	Renewable Fraction (%)
Existing Base system	100	0	174,667	21.5	0	0
Design option 1	10	90	174,667	20.7	0	86.2

(**b**) Generic Battery

	Batteries No	Autonomy (h)	Lifetime throughput (kWh)	Expected life (yrs)	Energy in (kWh)	Energy out (kWh/y)	Losses (kWh/yr)
Existing system	0	0	0	0	0	0	0
Design option 1	445	16	1,393,862	15	96,840	89,010	8174

(**c**) Generic 100 kW Fixed Generator

	Operation (h/yr)	Operation life (yr)	Capacity factor (&)	Electricity production (kWh/y)	Fuel consumption (L)	SFC L/kWh	MEE (%)
Existing system	8760	1.71	25.4	222,617	80,850 (90.2%)	0.363	28
Design option 1	965	15.5	2.76	24,191	8822 (9.8%)	0.365	27.9

(**d**) PV System Generic Flat Plate

	Rated capacity (KW)	Mean output (kW)	Capacity factor (%)	Hrs of Operation (h/yr)	Levelised cost ($/kWh)
Existing Base system	0	0	0	0	0
Design option 1	152	24.7	16.2	4380	0.103

(**e**) System Converter Inverter/Rectifier

	Rated capacity I/R(kW)	Capacity factor I/R (%)	operation I/R (h/yr)	Energy out I/R (kWh/y)	Energy in I/R (kWh/y)	Losses I/R (kWh/y)
Existing Base system	0	0	0	0	0	0
Design option 1	40.6/40.6	43.4/1.02	8036/723	154,299/3632	162,420/3823	8121/191

(**f**) Systems' Emissions

	Carbon dioxide (kg/y)	Carbon monoxide (kg/y)	Unburnt carbons (kg/y)	Particulate matter (kg/y)	Sulpher dioxide (kg/y)	Nitrogen oxides (kg/y)
Existing Base system	211,470	1439	58.2	5.76	518	115
Design option 1	23,076	157	6.35	0.628	56.6	12.6

MEE Mean Electrical Efficiency SFC Specific fuel consumption.

4.2. Economic Analysis

This deals with the calculation of NPC, COE, IRR, Payback period, and discounted payback period using the formulae described under methodology Section 2.5.

Table 6 is a summary of economic parameters for the hybrid system components. It shows individual's component capital cost, replacement cost, operation and maintenance cost, salvage value and total cost.

Table 6. System architectural costs for proposed hybrid system option 1.

Component	**Capital ($)**	**Replacement ($)**	**O&M ($)**	**Fuel ($)**	**Salvage ($)**	**Total ($)**
Hydro 300kW	700,000	0	255,536	0	0	955,536
Genset 100kW	50,000	30,654	32,879	180,356	8915	284,974
Battery(1kWh) Li-Ion	229,620	143,206	87,472	0	34,845	425,453
Flat plate PV	380,572	0	171	0	0	380,742
System converter	12,189	6495	0	0	4162	14,522
System	1,372,387	180,355	376,058	180,356	47,922	2,061,228

Table 7 shows the comparison between technical parameters of the base system and proposed hybrid of the design option 2.

Table 7. (**a**–**f**): Design option 2 comparing technical parameters of the base system and proposed hybrid system of simulated values.

(**a**) Electricity Production (%)

	Generator (%)	PV	AC Primary Load (kWh/yr)	Excess Electricity (%)	Unmet Load (%)	Renewable Fraction (%)
Existing Base system	100	0	174,667	21.5	0	0
Design option 2	8.9	91.1	174,667	23.3	0	87.3

(**b**) Generic battery

	Batteries No	Autonomy (h)	Lifetime throughput (kWh)	Expected life (yrs)	Energy in (kWh)	Energy out (kWh/y)	Losses (kWh/yr)
Existing system	0	0	0	0	0	0	0
Design option 2	449	16.1	1,405,991	15	97,701	89,785	8254

(**c**) Generic 100 kW fixed generator

	Operation (h/yr)	Operation life (yr)	Capacity factor (&)	Electricity production (kWh/y)	Fuel consumption (L)	SFC L/kWh	MEE (%)
Existing system	8760	1.71	25.4	222,617	80,850 (90.2%)	0.363	28
Design option 2	889	16.9	2.54	22,259	8121	0.365	27.9

(**d**) PV system Generic flat plate

	Rated capacity (KW)	Mean output (kW)	Capacity factor (%)	Hrs of Operation (h/yr)	Levelised cost ($/kWh)
Existing Base system	0	0	0	0	0
Design option 2	159	25.9	16.2	4380	0.103

(**e**) System converter Inverter/Rectifier

	Rated capacity I/R(kW)	Capacity factor I/R (%)	operation I/R (h/yr)	Energy out I/R (kWh/y)	Energy in I/R (kWh/y)	Losses I/R (kWh/y)
Existing Base system	0	0	0	0	0	0
Design option 2	39.3/39.3	45.3/0.961	8094/666	155,888/3306	164,093/3480	8205/174

(**f**) Systems' Emissions

	Carbon dioxide (kg/y)	Carbon monoxide (kg/y)	Unburnt carbons (kg/y)	Particulate matter (kg/y)	Sulpher dioxide (kg/y)	Nitrogen oxides (kg/y)
Existing Base system	211,470	1439	58.2	5.76	518	115
Design option 2	21,241	145	5.85	0.578	52.1	11.6

MEE Mean Electrical Efficiency SFC Specific fuel consumption.

When the flow rate of the river is low or when the power house is affected by floods and other seasonal variations, as found out in Figure 13, the hydropower turbine can be neglected and operate a hybrid of Solar PV storage system and diesel generator system termed as option 2 (no hydro) in this text. The following HOMER pro × 64 results were obtained.

Table 8 shows individual component cost i.e capital, replacement, operation and maitainance, fuel, salvage and total of the proposed hybrid system of design option 2.

Table 8. System architectural costs for proposed hybrid system for option 2.

Component	**Capital ($)**	**Replacement ($)**	**O&M ($)**	**Fuel ($)**	**Salvage ($)**	**Total ($)**
Genset 100 kW	50,000	29,398	30,290	166,013	11,799	263,901
Battery (1 kWh) Li-Ion	231,684	144,493	88,258	0	35,158	429,277
Flat plate PV	398,126	0	178	0	0	398,305
System converter	11,780	6277	0	0	4022	14,035
System	691,590	180,168	118,726	166,013	50,979	1,105,518

When the generator or generator parts develop a mechanical problem and goes off, as found out in Figures 7–11, then the system can run as a hybrid of Solar PV storage and hydropower, termed Scenario 3 (no Genset), and this avoids system shutdown.

Table 9 shows the comparison of technical parameters of the base system and proposed hybrid system of the design option 3.

Table 9. (**a**–**d**): Design option 3 comparing technical parameters of the base system and proposed hybrid system of simulated values.

(**a**) Electricity Production (%)

	Generator (%)	PV	AC Primary Load (kWh/yr)	Excess Electricity (%)	Unmet Load (%)	Renewable Fraction (%)
Existing Base system	100	0	174,667	21.5	0	0
Design option 3	0	500,478	174,554	61.5	0.0648	100

(**b**) Generic battery

	Batteries No	Autonomy (h)	Lifetime throughput (kWh)	Expected life (yrs)	Energy in (kWh)	Energy out (kWh/y)	Losses (kWh/yr)
Existing system	0	0	0	0	0	0	0
Design option 3	854	30.6	1,544,386	15	107,519	98,683	8970

(**c**) PV system Generic flat plate

	Rated capacity (KW)	Mean output (kW)	Capacity factor (%)	Hrs of Operation (h/yr)	Levelised cost ($/kWh)
Existing Base system	0	0	0	0	0
Design option 3	352	57.1	16.2	4380	0.103

(**d**) System converter Inverter/Rectifier

	Rated capacity I/R (kW)	Capacity factor I/R (%)	operation I/R (h/yr)	Energy out I/R (kWh/y)	Energy in I/R (kWh/y)	Losses I/R (kWh/y)
Existing Base system	0	0	0	0	0	0
Design option 3	46.4/0	42.9/0	8760/0	174,554/0	183,741/0	9187/0

MEE Mean Electrical Efficiency SFC Specific fuel consumption.

The economic cost results of the system components i.e., capital, replacement, operation and maintenance, fuel, salvage and total of the proposed hybrid system of design option 3 are summarized in Table 10 below.

Table 10. System architectural costs for proposed hybrid option 3.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Hydro 300 kW	700,000	0	255,536	0	0	955,536
Battery (1 kWh) Li-Ion	440,664	74,827	167,868	0	66,871	816,487
Flat plate PV	879,450	0	394	0	0	879,844
System converter	13,933	7424	0	0	4757	16,599
System	2,034,047	282,251	423,798	0	71,628	266,8467

Table 11 shows cost comparisons of the base system and proposed hybrid systems of design options 1, 2 and 3.

Table 11. Comparison of NPC, LCOE, and Operating Cost (OC).

	Base System	Design Option 1	Design Option 2 (No Hydro)	Design Option 3 (No Genset)
Total NPC ($)	3,426,054.0	2,061,228.0	1,105,518.0	2,668,467.0
LCOE ($)	1.15	0.6927	0.3715	0.8974
OC ($)	157,084.7	40,435.36	24,297.62	37,240.55

The proposed system Design option 1 has moderate NPC, LCOE, and operating costs because Genset operations are controllable during on-peak and off-peak periods.

Since a hydro turbine cannot operate without a generator, the system without hydro indicates less NPC and low COE but a very high operating cost due to high fuel consumption. option 3 has high NPC and LCOE, and low OC (no cost of fuel required)

The economic parameters of Table 12 show that Design option 1 is more feasible with a simple payback period of 5.26 years. Option 2 would lead to the overuse of Genset, which results in high carbon emissions and high fuel prices, making it expensive to operate. Option 3 appears cheap due to the elimination of fuel costs and O&M costs, but it will result in an increase in PV capacity, the number of storage batteries, and inverters, as in Table 7.

Table 12. Comparison of economic parameters.

Economic Parameter	Design Option 1	Design Option 2 (No Hydro)	Design Option 3 (No Genset)
Present worth ($)	1,364,826	2,320,536	757,587
Annual worth ($/yr)	80,115	136,216	44,470
Return on Investment (%)	14.7	0.0	5.3
Internal Rate of Return (%)	18.8	N/A	8.0
Simple Pay Back (yr)	5.26	N/A	9.88
Discounted Pay Back (yr)	5.72	N/A	11.72

Figure 16 shows the overall cost comparison of the base system, design Options 1, 2, and 3 for capital, replacement, operation and maintenance, fuel, salvage and totals.

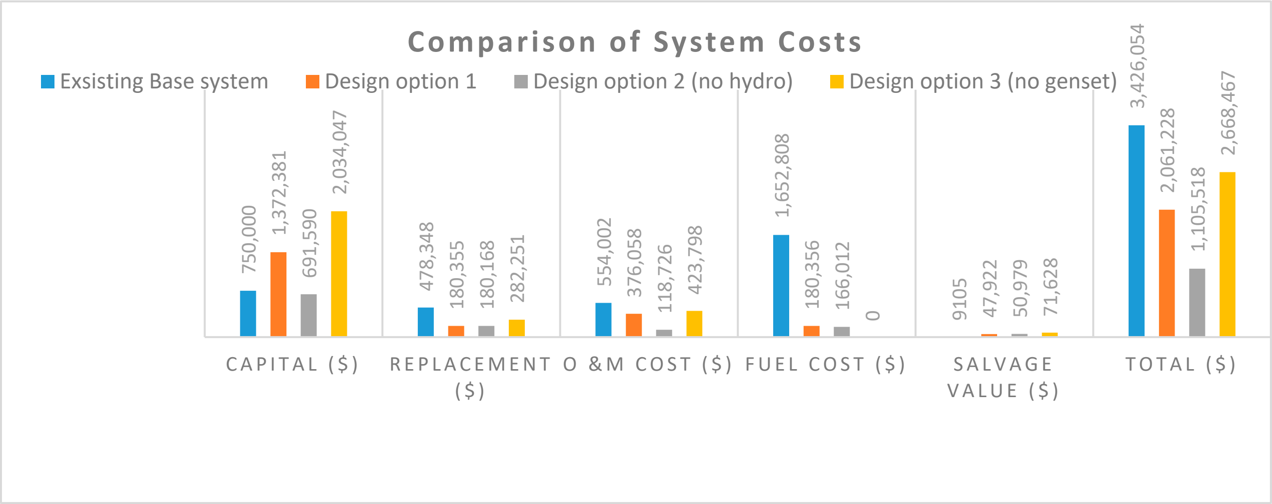

Figure 16. Comparison costs of base and proposed systems.

Figure 16 shows the summary of all costs involved in the four systems. The totals also indicate the total NPC of the base and proposed systems.

Figure 17 shows comparisions of systems average fuel consumption per hour and per day.

The base system consumes more fuel, about 90.2%, and increases emissions and operation and maintenance costs. Considering carbon dioxide and carbon-monoxide emissions and neglecting other small emissions, the graphical representation is shown in Figure 18 below;

Indeed several studies have also found that there is a need to reduce carbon emissions by reducing and minimizing non-renewable sources; for example, a study made by Yimen et al. agrees that using hybrid systems reduces carbon emission and stresses that solar PV-based mini-grids provide sustainable electricity in rural areas [52]. Moreover, the research made on one village, Ntoroko in Uganda, shows that using solar PV/Diesel mini-grids reduce fuel consumption and minimize carbon emissions [29].

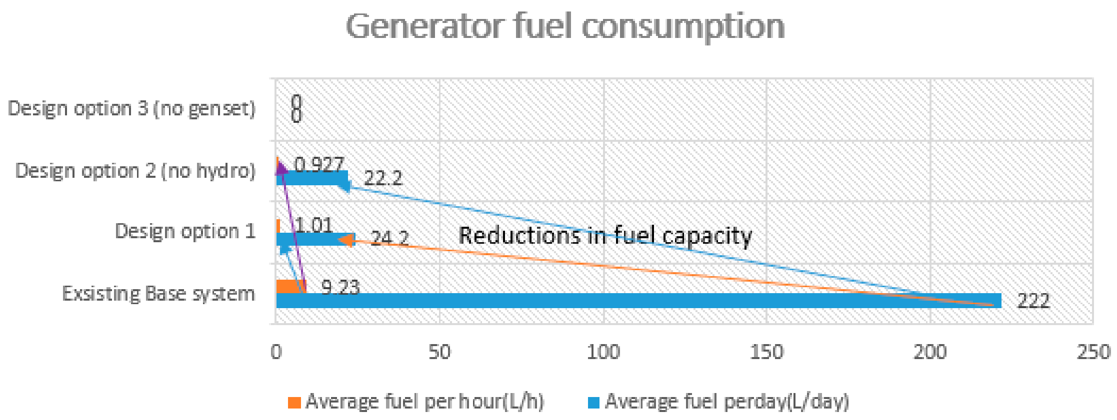

Figure 17. Comparison of systems' average fuel consumption per day and per hour.

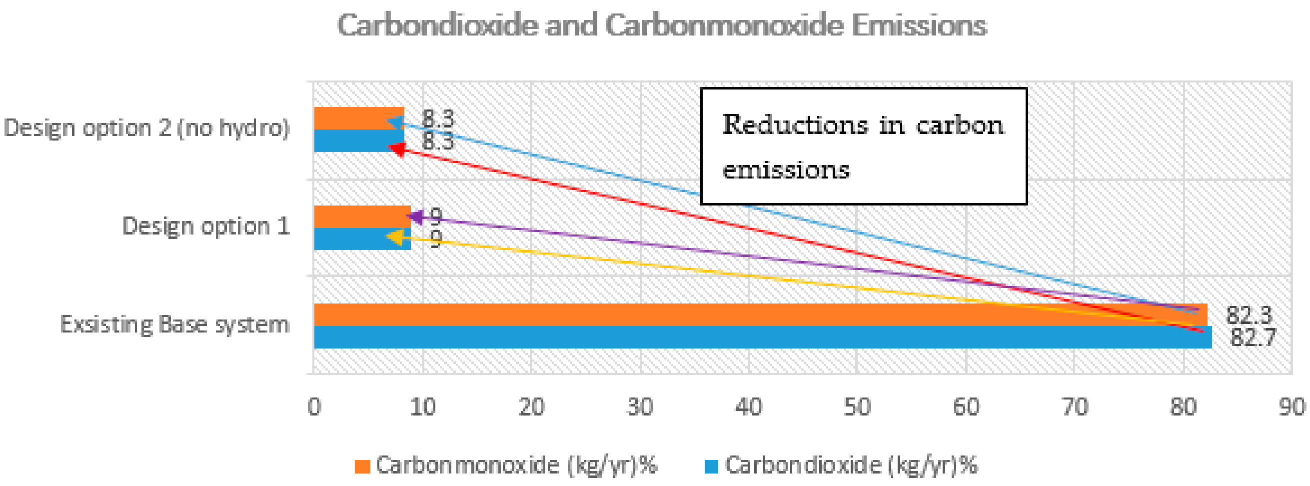

Figure 18. Carbon dioxide and Carbon monoxide emissions.

Although the study made by Murphy et al. stressed that Diesel is the most economical energy source in rural areas where the grid is not reliable, the research further agrees that solar PV/Diesel mini-grids are better in cost reductions and carbon emissions [51]. Moreover, in agreement with the study made in refugee camps in Uganda about pumped water provision using electricity, it was found that solar PV systems are better options to replace non-renewables such as Diesel that emits carbon [53].

For a long time, Uganda has depended on Hydropower for electricity provision and has Diesel as the second option, which is associated with increasing fuel prices and, ultimately, high energy payments and high impacts on the environment in return. So the study made by Twaha et al. also confirms that using solar PV systems is a better option to supplement the existing power sources [54].

5. Conclusions

It has been noted that the power sector in Uganda has been on steady growth since early 2000. The use of various approaches to rural electrification and increase in electricity access has been focusing on grid extension, standalone solar PV systems, and isolated mini-grids. In this research, a rural-based Kisiizi hydropower mini-grid has been used as a case study to assess the techno-economic viability of the isolated mini-grids in Uganda. The findings indicate that the fluctuations in enrollment to KHPMG are due to unpredictable system failures that make customers uncomfortable while using the mini-grid power. The stagnant and declining energy sales were a result of system shutdowns, less power supply, and partly COVID-19 effects, especially during the years 2020 and 2021. The variations in peak demand were due to the increasing economic status of connected customers, weather conditions, seasonal variations, and planned routine maintenance. During the months of the low flow rate of the river, Figure 12 (April, July, August, and September), causes low power production, and this matches with the peak demand analysis of Figures 7–10. During the low flow rate months, the generator is overused, which in turn increases the cost of fuel, maintenance, and environmental pollution. When the generator encounters a mechanical problem, the system stops operations leading to customer discomfort. The suggested hybrid system of solar PV with storage (Design option 1) to supplement the existing system of hydropower and generator would offer solutions to the existing gaps. The results show moderate values of NPC, LCOE, operating costs, fuel consumption, and emissions for option 1. When a hydropower turbine encounters a mechanical problem, Option 2 is proposed. When the generator encounters a mechanical problem or fault or needs general or part repairs, Option 3 is proposed. The proposed systems give battery operation efficiency of 92% and 95% for converters. The capacity factor, operation hours per year, and losses are minimal with option 1. The proposed systems reduce emissions from 83% to approximately 8% due to a reduction in fossil fuel use. The generator produces electricity at close to 10% of the maximum use of the base system, with a high percentage generated by solar PV at 90%. This makes a renewable fraction contribution of 87.3%. The proposed mini-grids are supposed to be beneficial as follows: increase savings, increase the lifespan of a system component, reduce load shedding, and attract more connections to utilize excess load

The findings show that there has been a notable increase in livelihoods as a result of the extension of energy services in the area. This research is beneficial to other rural communities using power from hydropower mini-grid by adopting hybrid options suggested in this research.

Rural electrification in Uganda has enabled the rural population seeking urban relocation to reduce. This is because affordable clean energy supports other intentions of development as a means to achieve SDGs by 2030.

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Abbreviations

Ppv	Output of PV array	Yg	Rated capacity of Generator	Crep	Replacement cost
Fpv	Pv derating factor	Nb	Number of batteries in a bank	Pg	Generator electrical output
Ypv	Rated capacity of PV array	i	Annual interest rate	F1	Fuel curve slope
It	Global solar radiation	hnet	Net head of hydro	Lbf	Maximum life of a battery
Is	1 kW/m^2 standard	ρw	Density of water	φlt	Lifetime of a single battery
RFpv	Renewable fraction	h	Available head	thr	Annual throughput Energy of battery
Epv	Energy output of PV	φt	Turbine flow rate	Can.t	Total annualized cost
Ean.t	Total annual energy	fh	Pipe head loss	Rcomp	Lifetime of the component
ᾐt	Turbine efficiency	Rproj	The project lifetime	Rrem	Remaining life of a component
Fo	Fuel curve intercept coefficient	N	Number of years taken		

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