Original Research Article

Design of Stand-Alone Solar-Wind-hydro based Hybrid Power System: Case of rural village in Malawi.

Abstract

Malawi has current electrification rate of less than 10% for a population of 18 million connected to the grid. The electricity generation company in Malawi (EGENCO) is greatly affected by low water levels making it difficult to satisfy the existing demand of electricity. This makes it difficult for Malawi to extend its National electricity grid. Thus, the aim of the study is to design stand-alone hybrid renewable energy system which is economically and technically feasible with focus on hydropower, wind, solar and battery bank within Dwangwa area. The study area is estimated to have 420 households, commercial and public service load with primary load demand of 5,556.31 kWh/day and peak load of 302.93 kW. River discharge data were collected from ministry of irrigation and water development while solar and wind data were collected from NASA. HOMER modeling tool was used to design a stand-alone system. From simulation results, the best design flow for Dwangwa river is 159 L/s at elevation of 100 metres and the best hybrid system combination was hydropower-wind-solar-battery and converter. The whole hybrid system initial capital cost was $2,662,638 while Net present cost (NPC) and levelized cost of energy (LCOE) were $3,597,197 and $0.134/kWh respectively. However, the cost of electricity in Malawi on the grid is K88.02/kWh ($0.11/kWh) which makes the system expensive. Therefore, the study has shown that the hybrid system is not economically viable. However, Government intervention can help to make the system monetarily acceptable and viable.

Introduction

The road map for Africa encourages rural electrification because Africa is home to the largest unelectrified population in the world, with about 600 million people lacking access, expected to reach 700 million by 2030. Off-grid solutions, including mini-grids and stand-alone solutions, are necessary to complement centralised grid [1]. Remote communities are commonly assessed based on the existent physical infrastructure. Thus, remote communities are those communities that are not connected to the electrical grid, not connected to the piped natural gas network, considered permanent or long-term settlements (e.g., 5 years or more), and have at least 10 inhabitants [2].

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Electricity demand is increasing and cannot be fulfilled by non-renewable energy sources alone. Renewable energy sources such as micro hydro, solar and wind are environmental friendly. Currently, renewable energy sources are emerging options to fulfill the energy demand, but unreliable due to the stochastic nature of their occurrence. Hybrid renewable energy system (HRES) combines two or more renewable energy sources like small hydro, wind turbine and solar system [3]. Technological advancements in renewable energy sources, and increasing prices of petroleum products, has made hybrid renewable energy systems more promising for remote areas [4].

Rural areas are usually difficult to access and it is therefore important to design a renewable energy system that is reliable and requires little maintenance. The main challenge with one energy source such as solar photovoltaics is during the night and when there is no sun. This also applies to wind turbine technology which does not generate electricity when there is no wind. Therefore, if more than one independent source is employed for energy generation, for example a combination PV panels and wind turbines, the energy demand generation can be split between these two sources and therefore the system depends less on one intermittent energy source. This improves energy supply security [5].

Electricity in Malawi is largely dominated by hydroelectric power which is mainly located in Shire River. However, the Shire River is experiencing low water levels due to climate change hence frequent power outages. Currently, less than 10% of the population of 18 million is connected to the electricity grid [6]. Only 1% of the rural households are electrified while around 25% of the urban households have access to electricity. A plan to extend the Grid to the rural areas is constrained due to low generation capacity and high cost of transmission and distribution infrastructure. The majority of Malawians lives in the rural areas where the main sources of light for the non-electrified households are battery-powered torches, candles and paraffin. For cooking, most of the households are depending on firewood and charcoal. Without such access to electricity, it is virtually impossible to carry out productive economic activities or to achieve environmental sustainability [7].

The absence of power in different rural areas has affected the rural livelihood in general. Electricity providers have for many years depended on producing electricity at a centrally located position and distribute it through extensive transmission and distribution networks. However, as the demand increases the capacity to generate, transmit and distribute the energy is always constrained. The most obvious direction to take is to build new plants to meet the increasing demand. The fact that renewable energy sources are also distributed sources offers an opportunity to save on the capital investment for the transmission and distribution of electricity. The current international trend in rural electrification is to ~~utilize~~ develop renewable energy resources such as solar, wind, biomass, and micro hydro power systems.

Many studies have shown that different combinations of renewable energy systems are possible and are economically viable. Since most common hybrid systems are associated with two systems then combining all the three systems (wind, hydro and solar) the output is expected to be much greater than the two stage hybrid systems [8]. Therefore, this proposed hybrid system is aimed at sizing a hybrid renewable energy system (HRES) to design a system that minimises ~~the necessary~~ cost ~~as much as possible to~~ and ensure its affordability for rural settlers ~~electrification~~.

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Solar energy in Malawi: According to Taulo et al., (2015), the country receives about 2138 to 3087 hours of sunshine and $2133\, KWh/m^2/year$. The global solar radiation on a horizontal surface has a minimum value of $4.3\, KWh/m^2/day$ and maximum of $7\, KWh/m^2/day$. In Malawi, maximum irradiation of $6.5\ to\ 7.0\, KWh/m^2/day$ are received in September to October whereas the minimum irradiation of $4.3\ to\ 4.6\, KWh/m^2/day$ are received in January to February or June to July depending on the location. This solar energy is high enough for the development of solar thermal and photovoltaic energy projects

Solar energy deploying in Malawi is growing in small scales particularly for household application. Solar water heaters have been locally ~~manufactured~~ developed for domestic purposes. The total amount of installed solar water heaters in the country is estimated to have reached approximately 4,855 square meters. On the other hand, photovoltaic is also increasing in the day to day application such as lighting, water pumping, telecommunication, refrigeration and other home use application. ~~More~~ Recently, 870 kWp solar photovoltaic plant has been commissioned at Lilongwe International Airport which is the biggest solar power plant in Malawi today [9].

Wind energy in Malawi: Malawi has quite a good number of areas with mean speeds above 5 m/s throughout the year [10]. Wind energy has been applied on a small scale ~~is~~ in Malawi such as to supply water for both livestock and irrigation. Although it seems like the wind speeds are moderate to low, ~~a~~ typically in the range of 2.0 – 7.0 m/s [9]. However, wind speeds also increase with height of the hub, ~~then~~ though most areas of Malawi have data for wind speeds at lower hub height. For instance, Dedza has some areas of reasonable wind resource of 4 m/s at 18m hub height. Therefore, individual site assessment for each proposed site would be required to determine the actual wind data [11].

Hydropower in Malawi: Malawi has abundant water resources in form of lakes, rivers and aquifers which can fully be utilized for electricity generation. The trends of annual mean flows in most rivers has generally remained constant for past years excluding random fluctuations which is due to annual rainfall variations [12]. The northern region of Malawi has more perennial rivers than other parts of the country as shown in the figure. This can make the hydropower plant sustainable and reliable as water can be available in the river throughout the year.

The most important rivers in Malawi include: Shire, Bua, Dwangwa, North Rukuru, South Rukuru, Rumphi, Songwe, Wovwe, Lufira, Dwambazi, Luweya and Ruo. These rivers show that Malawi can generate electricity from these rivers in order to satisfy the current electricity demand. For small hydropower plant installations, small streams can technically be diverted from the main river for such purpose with respect to the topography of the site [12].

An estimation of 95% of Malawi's electricity generation is mainly from hydro with Shire River as the main source of the hydro-electricity [13]. According to ESCOM (2015), the maximum generated capacity for hydro-electricity is 351 MW. Estimates indicate that shortage of capacity frequently exceeds 60 MW or over 17% of peak demand in Malawi. There are no reserve margin and a stressed system, the reliability and quality of electricity supply is poor [6]. Thus, a considerable investment in electricity generation is necessary to improve security and regularity in supply and meet a growing demand.

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However, the hydropower generation is facing so many challenges in Malawi which include old machinery and ~~reduced~~ low water levels. During summer season, electricity generation maybe reduced by up to 40% due to declining water levels. Therefore, ESCOM generate an average of 200 MW out 351 MW hence, increased load shedding periods [13].

Hybrid energy system: A combination may include solar, wind, hydropower and biomass with other technologies like batteries and diesel generator. The renewable energy hybrid system offers clean, efficient and sustainable power for off-grid rural electrification [14]. Agarkar & Barve (2011) found out that combination of solar-wind, wind- hydro and solar-hydro yields more power. Hence combination of the three systems should yield more power too.

Wind and solar resources are highly variable and they vary in time intervals from seasons to minutes and even seconds. These resources are very difficult to predict for the near future hence a hybrid system can be more advantageous due to combined energy systems. This enables production of an amount of energy in accordance with the consumption [15]. Another great advantage of hybrid systems is that some of the different energy sources can complement each other such as solar and wind [16].

The combination of hydropower system to other renewable energy system such as wind and solar can be more advantageous even during peak load hours. For instance, if pumped hydro is incorporated to the system, wind and solar can be used in water pumping during off peak hours. This can help to satisfy the energy need during peak hours [16].

Hybrid system in Malawi: As the world is researching and trying to install hybrid renewable energy systems, Malawi has not been left behind as it has already installed solar-wind hybrid systems. Malawi has installed six solar-wind hybrid systems. This project which was funded by the Government of Malawi in 2007 and it covered the following districts: Nkhata Bay, Mzimba, Nkhotakota, Ntcheu, Chiradzulu and thyolo [12], [17].

Energy storage: Renewable energy resources do not provide constant supply of energy, for instance, solar and wind power are available when sun and wind are available. However, constant supply of energy is needed for steady function of our equipment hence energy storage mechanism must be used in our hybrid system [18].

Materials and Methods

Load estimation

In this paper, a community of 420 households were considered and the selected appliances were considered based on low energy saving technologies. Dwangwa is close to Lake Malawi and is a place for tourists, thus, business activities considered for the community include: small hotel, restaurants and local bars. Other load considered include, maize mill, bakery, butchery, welding, grocery, saloon, barber shop. Water pumping and irrigation load, administration and tourist office, police unit, church, mosque, schools and hospital (Health centre) were also considered.

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In summary, the proposed study site has a total daily consumption of 5,556.31kWh with an exception of rainy season (December, January, February and March) where there is no irrigation. Thus, the annual energy consumption for the community is 2,028.05 MWh. The study site has a peak load of 302.93 kW which occurs in the evening. Thus, solar PV alone cannot satisfy the load during the peak hour hence hybrid system can be the solution. Residential load has the highest energy demand of 75% of the total daily load. The figure 1 gives the power curve for community in a day.

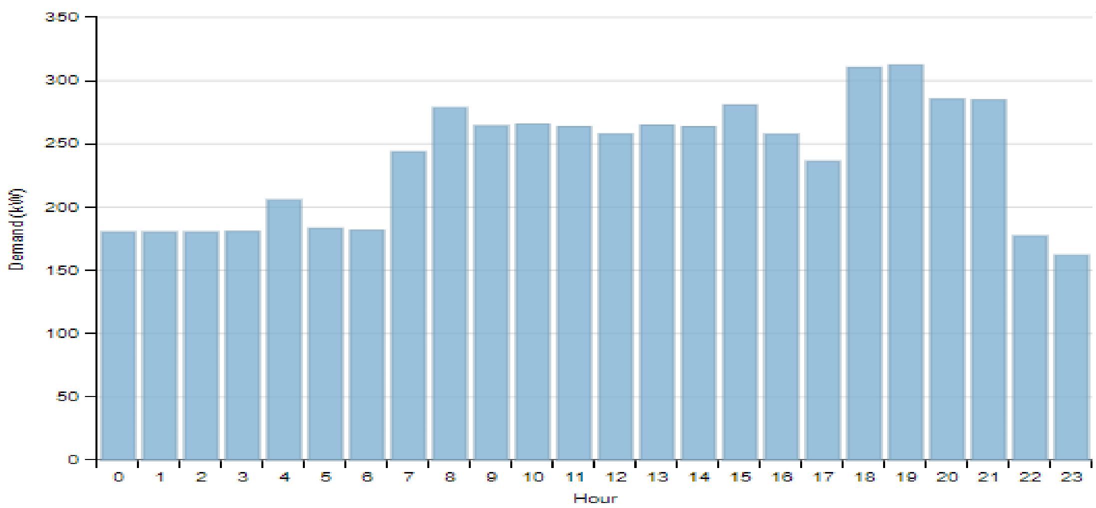

Figure 1: The daily load profile for the study site

Hybrid energy system configuration

HOMER is a user friendly software developed by Mistaya Engineering, Canada, for the National Renewable Energy Laboratory (NREL) USA. It simplifies the evaluation task for design of both off-grid and grid-connected power systems for various applications [19]. The proposed system design shows the arrangement of components for optimization and modeling of the system. Figure 2 display the schematic representation of HOMER simulation model of the proposed hybrid system architecture considered.

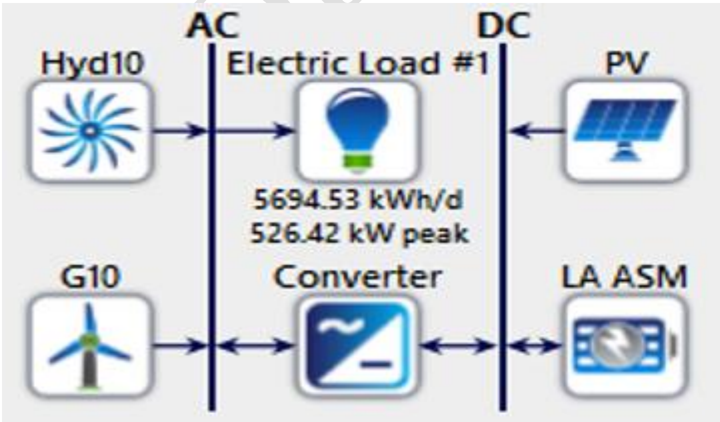

Figure 2: Configuration of the system in HOMER

Input data for solar PV power system: The solar resource data for the study site was obtained from NASA Surface meteorology and solar energy database. The approximate location to the study site used is 12°31.1′S and 34°7.8′E The monthly averaged value for Global horizontal radiation were obtained for a period of 22 years from July, 1983 to June, 2005. Figure 3 shows Dwangwa's daily radiation in kWh/m^2/day and their clearness index which ranges from 0 to 1 for the whole year.

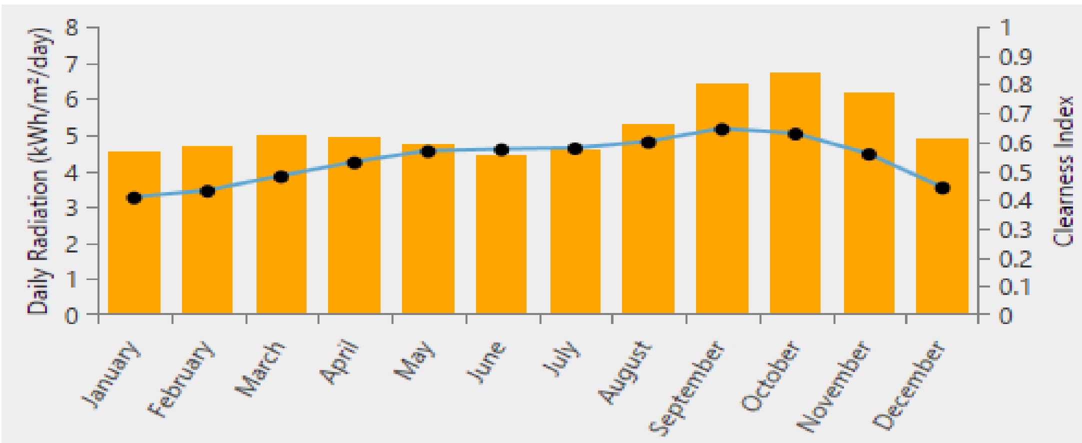

Figure 3: Solar Radiation and Clearness Index for Dwangwa

The PV system for the proposed site has no tracking system due to financial burden and complexity of the system. The solar panel considered was a 1kW, which is 2 solar panels of 500W from Bluesun (Jiangsu, China). The selected panel was Monocrystalline Silicon made with model number of BSM500M-96. The price for the product was at $0.31/watt ($155 per 500W panel). The efficiency of the module is 19.51% [20].

In this research paper, the initial cost of 1kW solar panel was considered as $2,822 while the replacement cost is the same as capital cost [21]. The operation and maintenance of the solar PV is estimated as 1% of the capital cost which is about $ 28.22 per year per kW [22]. The PV module rated power is 1 kW with lifetime of 25 years. The derating factor for the solar module was considered as 95% and the ground reflection of 20%. The solar module slope for the study site is 12.518° and Azimuth angle is 180°. However, Zalengera (2015) proposed initial cost of 1, 175 per kW for Likoma Island in Malawi hence 0.5 multiplier on cost initial cost was considered for sensitivity analysis.

Input data for wind power system: Malawi in general has poor wind speed and few areas have been identified to have some potential for wind energy generation. The wind speed data for Dwangwa were obtained from NASA Surface meteorology and solar energy database. The wind speeds were measured at anemometer height of 50 metres for a period of 10 years from July, 1983 to June, 1993 which is also similar to airport data. The figure 4 shows the average wind speeds in m/s for Dwangwa.

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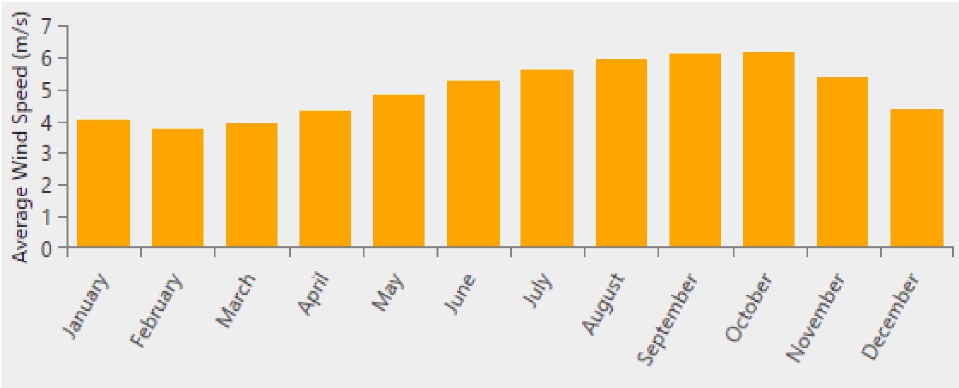

Figure 4: Monthly average wind speed in Dwangwa

Figure 5 also shows that wind speeds start increasing from April reaching maximum wind speed in September and October with a value as high as 6.15 m/s. The annual average wind speed for Dwangwa is 4.98 m/s. The wind power curve for Generic 10 kW wind turbine is shown in figure 5 below.

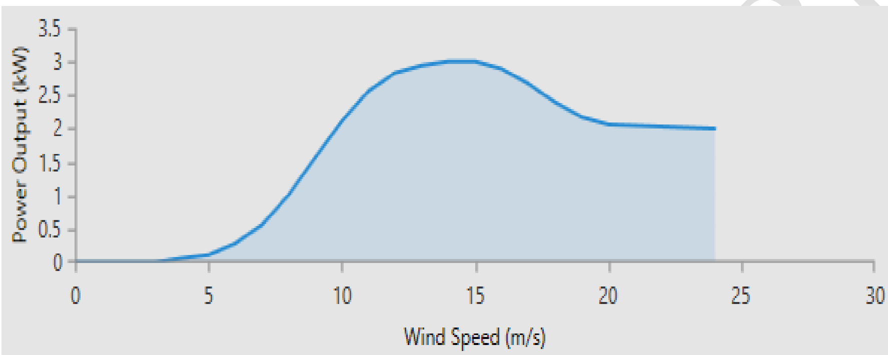

Figure 5: Wind power curve of Generic 10 kW wind turbine

The wind turbine selected has 10 kW power rating of model number NE-10k and brand name of Naier (Jiangsu, China). This 10kW wind turbine cost ranges from $5,500 to 7,100$ [24]. In this research paper, the initial capital cost of a wind power was considered as $2,120 per kW. Hence the estimated cost of 10 kW wind turbine is $21,200. The cost reduction for a wind turbine is around 12% between 2015 and 2025, hence, the replacement cost for a 10 kW wind turbine was estimated to be 80% of the capital cost which is $16,960. The operation and maintenance cost is assumed to be 2% of capital cost which is about $42.4 per year per turbine [16], [21], [22]. The hub height for the wind turbine was considered to be 40m. However, according to Zalengera (2015), the proposed initial cost of $5,765 per kW for Likoma Island in Malawi hence multiplier of 2 on initial cost was considered for sensitivity analysis.

Input data hydropower system: Dwangwa river receives more waters during rainy season and nearly dry during dry season. Thus, in January the average flow rate is 112,025.33 L/s while in September the value is 168.351 L/s. The average river discharge for Dwangwa were obtained from the Ministry of irrigation and water development, Malawi Government. The river discharge was measured at a period of 24 years from January, 1986 to January, 2010. However, due to

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some missing data the most recent dataset ~~without missing~~ with complete data for the year 2005 was chosen. The figure 6 shows average river discharge for the year 2005.

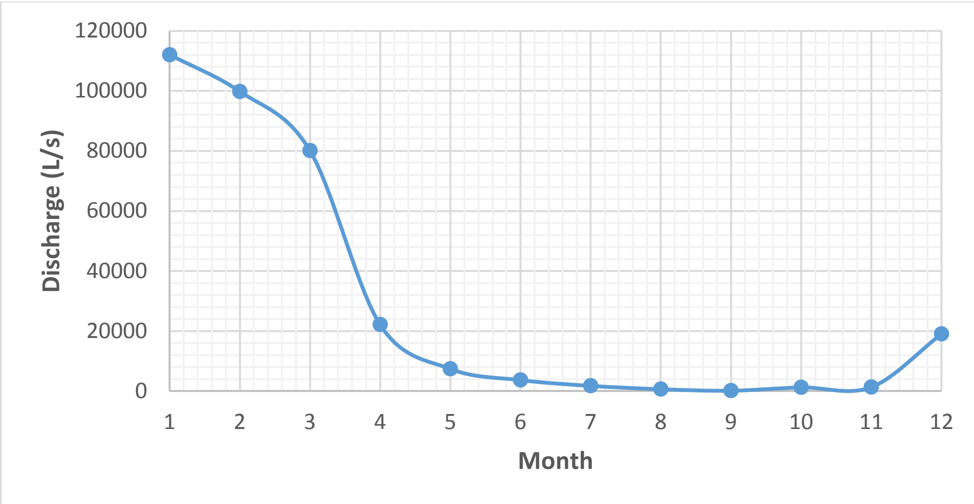

Figure 6: Mean monthly discharge for Dwangwa river for 2005

The scaled annual average flow for Dwangwa river is 29,129.47 L/s which is huge amount of discharge for energy generation. However, this discharge cannot be realized in run-off-river since the water levels decreases during dry season. Thus, for design purpose, three design flow were considered.

Scenario 1: The design flow was considered to be available throughout the year. Thus, the design flow of 159 L/s was chosen to ensure that the hydropower plant is in operation at 100% time of the year.

Scenario 2: The design flow was considered to be available at about 95% of the time of the year. Thus, a 95% design flow for Dwangwa river is 400 L/s.

Scenario 3: The design flow was considered to be available at about 91% of the time of the year. Thus, a 91% design flow for Dwangwa river is 637 L/s.

In each case, the available head for Dwangwa river is 100 m. The pipe head loss was estimated to be 5% while residual flow was assumed to be 2% of the design flow for environmental reasons thereby saving life of aquatic plants and animals. The estimated total lifetime of the system was set at 30 years. The efficiency for the turbine was assumed to be 90%. The figure 7 below shows how the design flow was determined for both 91% and 95% design flow.

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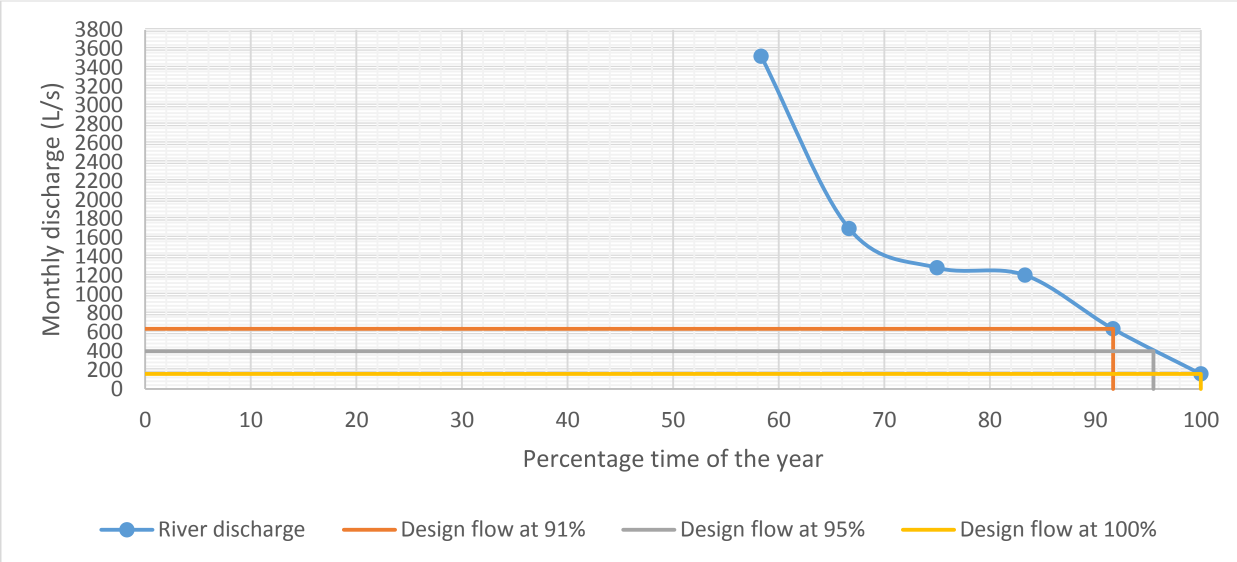

Figure 7: Determination of design flow for Dwangwa river.

The hydro system was considered to have capital cost of $ 1,790 per kW and the replacement cost was assumed to be 50% of the capital cost which is $ 895 per kW. The operation and maintenance of the hydropower plant was assumed to be 2% of the capital cost which is $ 35.8 per kW [21]. Acording to Lako (2010), the capital cost of small hydropower plant ranges from $ 2,500 to $ 10,000 per kW which is relatively higher than our proposed capital cost. Thus, a multiplier of 1.5 for capital cost was considered for sensitivity analysis.

Input data for Battery system: The Lead acid battery was considered for the design because they are relatively cheap, simple and affordable. The selected Generic 1kWh Lead Acid battery has rated capacity of 513 Ah with nominal voltage of 2V. The battery stores total amount of energy equal to 1 kWh. According to Alibaba.com (2019), the cost of 1 kWh battery was $ 217.5 while Wiemann et al. (2014) estimated it as $ 225. Thus, this thesis paper considered $ 225 as capital cost for battery. The replacement cost was assumed to be 70% of the capital cost which is about $ 157.5 per battery. The operation and maintenance cost were estimated to be 1% of the capital cost which is about $2.25 per battery per year.

Zalengera (2015) considered capital cost of $ 806 for 1,150 Ah battery which is relatively higher as compared to the cost of this thesis paper, hence, a multiplier of 2 was considered on capital cost for sensitivity analysis.

Input data for power converter: A converter needs to maintain flow of whether AC or DC electric energy into power system components. The rated power of the inverter should be equal to or larger than the peak load. In this thesis paper, a 1 kW converter was considered for AC/DC or DC/AC conversion with efficiency of 95%. The converter's initial cost of 1 kW capacity was considered to be $ 1,445 and the replacement cost is estimated to be 80% of the capital cost which is $ 1,156. The operation and maintenance cost is assumed to be 1.2% of the capital cost which is $ 17.34 per year. The lifetime of a converter was 15 years [21], [22].

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Zalengera (2015) considered capital cost of $ 26,067 per 100 kW converter which is relatively cheaper as compared to the proposed capital cost in this paper. Thus, a multiplier of 0.5 was considered on capital cost for sensitivity analysis.

Summary of components costs: The table 1 gives the summary of the input costs of all the components and their lifetime for the optimal system design.

Table 1: Summary of components costs

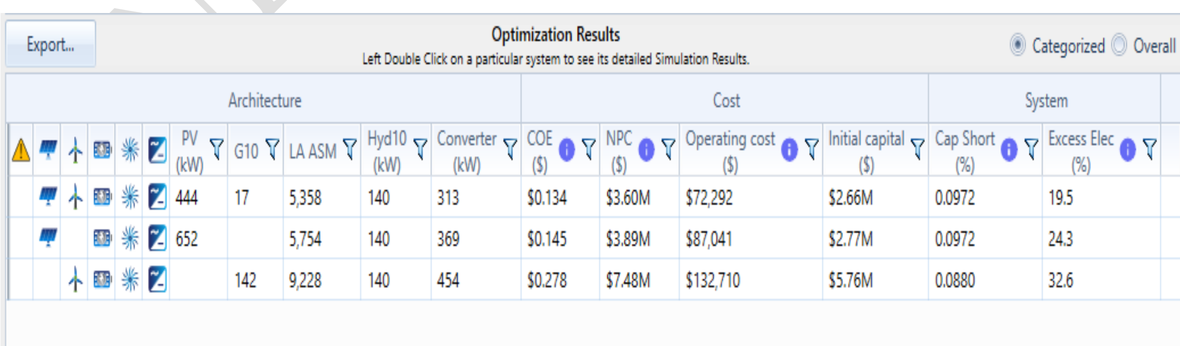
Component type	Capital cost ($)	Replacement cost ($)	O&M cost ($)	Lifetime (Years)
Solar PV (per kW)	2822	2822	28.22	15
Wind turbine (per kW)	2120	1696	42.4	25
Hydro (per kW)	1790	895	35.8	30
Battery (LA ASM) (per 1 battery)	225	157.5	2.25	5
Converter (per kW)	1445	1156	17.34	15

Results and Discussion

Systems Optimization and Selection of Scenarios

HOMER simulated different configurations of energy system components and displays the feasible hybrid combination. There are 3 different scenarios being proposed in this paper for further analysis in order to increase the chances of finding most optimized system. The result from all the scenarios has the optimal system combination which encompasses wind-solar-hydro-battery and converter. The best combination will be selected based on less COE, less NPC, smaller excess electricity and less initial capital cost. The suggested scenarios based on the most optimal system design with different hydro input data will be compared in terms of techno-economic aspects.

Scenario 1 simulation results: The HOMER window displays the optimal system design with design flow of 159 L/s which is based on hydropower plant operating at 100% time of the year (precedence). The figure 8 shows the most optimal system combination with the selected parameters.


Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

PV (kW)	G10	LA ASM	Hyd10 (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Cap Short (%)	Excess Elec (%)
444	17	5,358	140	313	$0.134	$3.60M	$72,292	$2.66M	0.0972	19.5
652		5,754	140	369	$0.145	$3.89M	$87,041	$2.77M	0.0972	24.3
	142	9,228	140	454	$0.278	$7.48M	$132,710	$5.76M	0.0880	32.6

Figure 8: Optimization results at 159 L/s design flow

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Scenario 2 simulation results: Scenario 2 has design flow of 400 L/s which is based on 95% of hydropower plant availability throughout the year. The HOMER window in figure 9 displays the most optimal system combination with selected parameters.

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Categorized / Overall

Architecture					Cost				System	
PV (kW)	G10	LA ASM	Hyd10 (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Cap Short (%)	Excess Elec (%)
1,286	9	9,198	353	403	$0.227	$6.10M	$110,020	$4.68M	0.0983	67.4
1,436		9,312	353	431	$0.231	$6.21M	$112,374	$4.76M	0.0938	68.2
1,548	34	10,422		496	$0.339	$9.10M	$242,697	$5.97M	0.0983	24.6
1,889		11,334		503	$0.357	$9.60M	$282,718	$5.94M	0.0872	28.4
	186	17,718	353	642	$0.430	$11.5M	$206,742	$8.88M	0.0990	64.9
	1,028	38,910		1,375	$1.56	$41.8M	$714,249	$32.5M	0.0958	78.3

Figure 9: Optimization results at 400 L/s design flow

Scenario 3 simulation results: Scenario 3 has design flow of 637 L/s which is based on 91% of hydropower plant availability throughout the year. The HOMER window in figure 10 displays the most optimal system combination with selected parameters.

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Categorized / Overall

Architecture					Cost				System		
PV (kW)	G10	LA ASM	Hyd10 (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)	Cap Short (%)	Excess Elec (%)
1,286	9	9,198	562	403	$0.227	$6.10M	$110,020	$4.68M	100	0.0983	75.7
1,436		9,312	562	431	$0.231	$6.21M	$112,374	$4.76M	100	0.0938	76.2
	186	17,718	562	642	$0.430	$11.5M	$206,742	$8.88M	100	0.0990	74.4

Figure 10: Optimization results at 637 L/s design flow

Comparison of Scenarios for Economic Power Systems

The most optimal system designs are displayed in the figures 8-10 above. The comparison of scenarios was done by keeping all the constraint values constant to all system configurations. The comparison of scenarios was done based on the following:

Based on net present cost (NPC): The three scenarios presented in this paper indicate that scenario 1 has the lowest NPC while scenario 2 and 3 have the same NPC which are higher. With reference from the figures 8-10, the NPC for scenario 1 is $ 3,600,000 while NPC for scenario 2 and 3 is $ 6,100,000.

Based on cost of energy (COE): The detailed information about COE for each power system configuration is displayed in figures 8-10. Scenario 1 has COE of $0.134/kWh while scenario 2 and 3 have the same COE of $0.227/kWh. This shows that scenario 1 has the smallest value of COE as compared to scenario 2 and 3. Thus, the scenario 1 is better because the cost of energy is cheaper than the other scenarios.

Based on Excess Electricity Production: Excess of electricity production is another comparison parameter which was adopted. The lowest excess electricity production is the optimal system design. Scenario 1 has the lowest excess electricity production of 19.5% as compared to scenario 2 and 3 which have excess electricity production of 67.4% and 75.7% respectively. Thus, scenario 1 is the best option here. However, excess electricity production can be good for the expansion of the load demand but it attracts extra cost.

Based on initial capital cost: The initial capital cost is one of the determinants in making a decision to start the investment. Thus, the system which has less initial capital cost while serving the same purpose is the optimal system. With reference from the figures 8-10, scenario 1 has lowest initial capital cost of $2,660,000 as compared to scenario 2 and 3 which have the same initial capital cost of $4,680,000. This shows that the optimal system design in terms of initial capital cost is scenario1.

The figures 11 gives the summary of all the scenarios compared based initial capital cost, NPC, excess electricity production and COE per kWh.

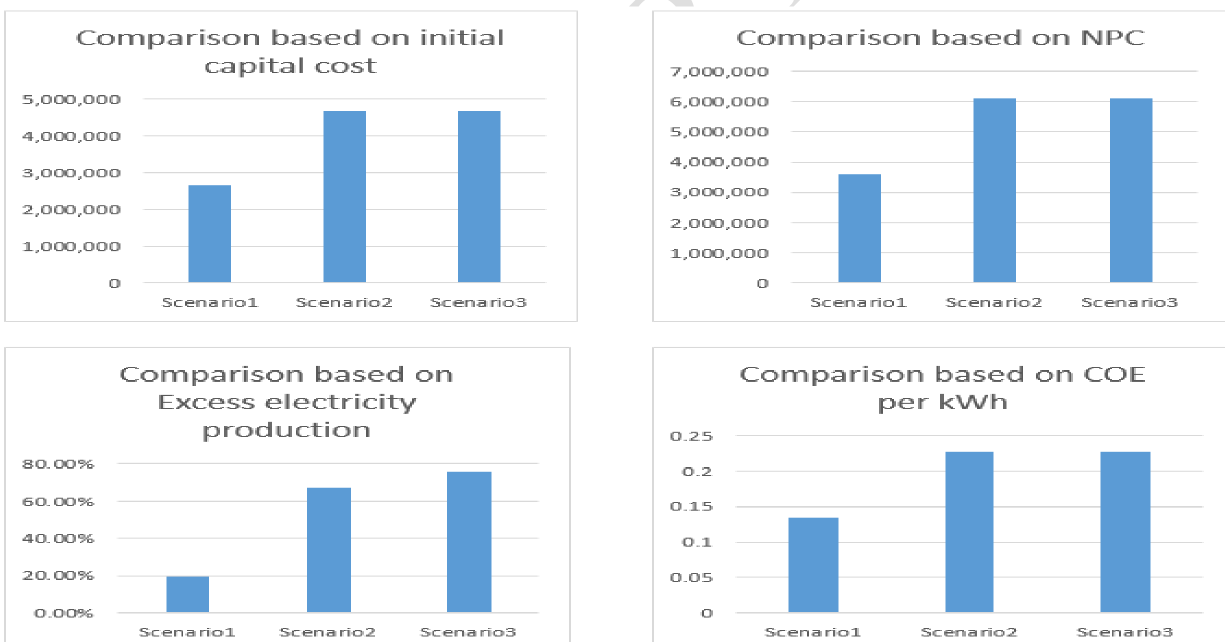
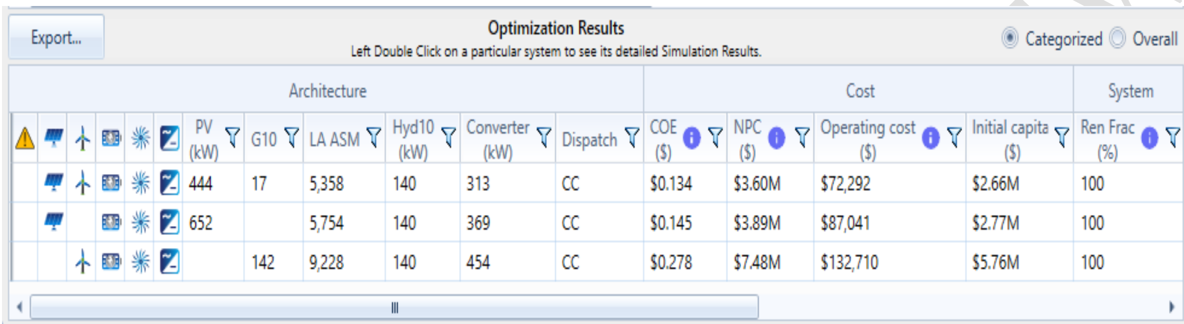


Figure 11: Comparing results of different scenario

From the comparison, it clearly shows that scenario 1 has the system architecture with less initial capital cost, low cost of energy, less NPC and less excess of electricity production. The optimization analysis of the selected (scenario 1) which comprises of the design flow of 159 L/s which will be available throughout the year.

Optimization Analysis of the Selected Scenario

After the simulation of three scenarios, scenario 1 was the winner of the three scenarios. The categorized results of simulation were shown in the HOMER window on figure 12. The most optimal system design is comprised of wind-solar-hydro-battery and converter. The system set up in the first row of figure 13 is the cost efficient system composed of 17 units of wind turbine with rated capacity of 10 kW each, 444 kW of solar photovoltaic capacity, 140 kW of hydro turbine with rated capacity of 10 kW each, 5358 units of batteries while the converter capacity is 313 kW.


Export...
Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.
Categorized Overall

PV (kW)	G10	LA ASM	Hyd10 (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capita ($)	Ren Frac (%)
444	17	5,358	140	313	CC	$0.134	$3.60M	$72,292	$2.66M	100
652		5,754	140	369	CC	$0.145	$3.89M	$87,041	$2.77M	100
	142	9,228	140	454	CC	$0.278	$7.48M	$132,710	$5.76M	100

Figure 12: HOMER window of selected scenario

The monthly power generation for all the three technologies were obtained after simulation as shown in figure 13. The wind speed potential is comparatively small throughout the year, however, the wind speed potential is fairly high from month of June to November. The lowest electricity production occurs in September due to declining water levels while production from wind is the increases.

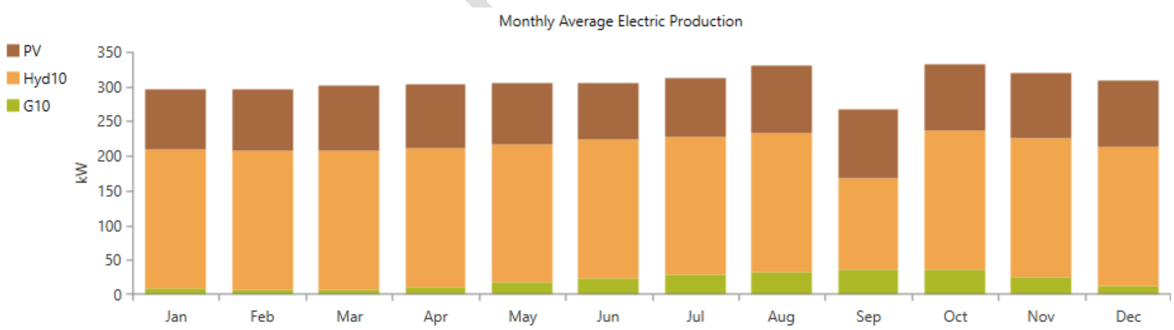


Figure 13: Monthly average electricity production.

The results show that the annual AC primary load consumption 2,077,528 kWh which is supplied by all the three power units of the hybrid system. The electricity generation by each power unit of the hybrid system is given in figure 14. Hydro is the highest power producer which contribute 63.4% (1,703,110 kWh/year) seconded by PV which contributes 29.9% (802,761 kWh/year). The smallest electricity producer is wind which contributes 6.67% (179,113 kWh/year). Thus, the total electricity production for the system is 2,684,984 kWh/year.

Figure 14: Electricity Production Share for Hybrid System

Looking at the power production of this hybrid system and total electric power consumption of the load, the surplus of 19.5% (522,715 kWh/year) was realized from the simulation results. Although 19.5% excess of electricity was produced but there was a capacity shortage of 2,020 kWh/year (0.0972%) in the course of the year. However, this power system design has shown that it would be able to accommodate ~~for~~ the growing demand of the community in future. The figure 15 shows the comparison of electricity production, electricity consumption and excess electricity.

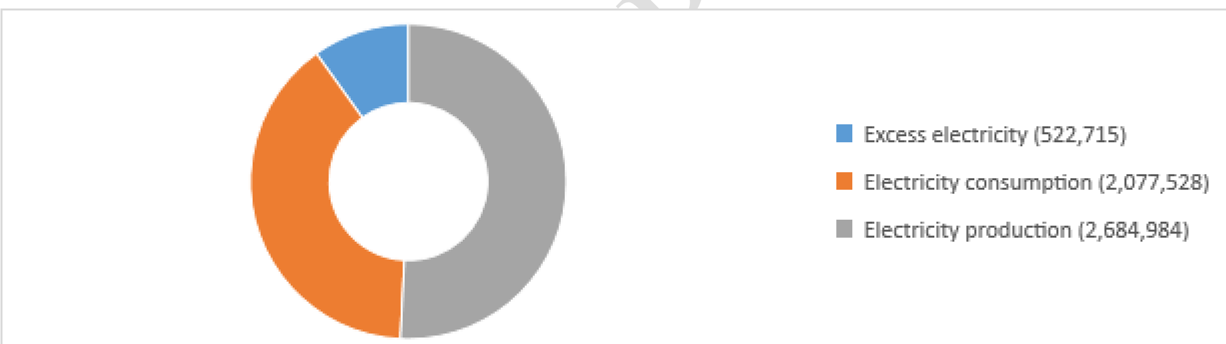


Figure 15: Electricity production versus consumed and excess electricity

Electricity production by wind turbines: The results in figure 16 clearly show that energy production by wind turbine is comparatively higher in July, August, September and October. The total rated capacity of wind turbines is 170 kW and the maximum output power is also 170 kW. The mean power output for wind system is 20.4 kW. The levelized cost of energy for wind is $0.196/kWh.

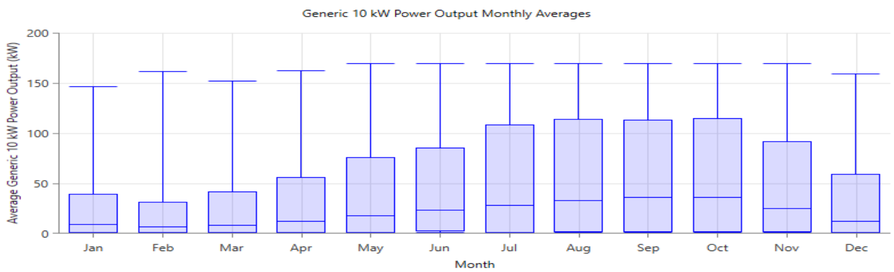


Figure 16: Wind turbine (Generic 10kW) monthly avearge power output

Electricity production by solar PV: The rated power capacity is 444 kW and the average power output is 91.6 kW with 0 kW during no sun. Solar PV only operate when the sun is available hence no production at night hence total hours of operation is 4,332 hours per annum. The levelized cost of energy for solar PV is $0.076/kWh.

Electricity production by hydropower: The hydropower plant has nominal capacity of 140kW with total production of 1,703,110 kWh/yr. The results in figure 17 show that the electricity production by hydro turbine is nearly constant throughout the day. Maximum production of 200 kW is experienced throughout the year except the month of September which has the minimum production of 132 kW. Hydropower system has operation hours of 8,760 hours per year (whole year). The levelized cost of energy for hydropower is $0.00101/kWh.

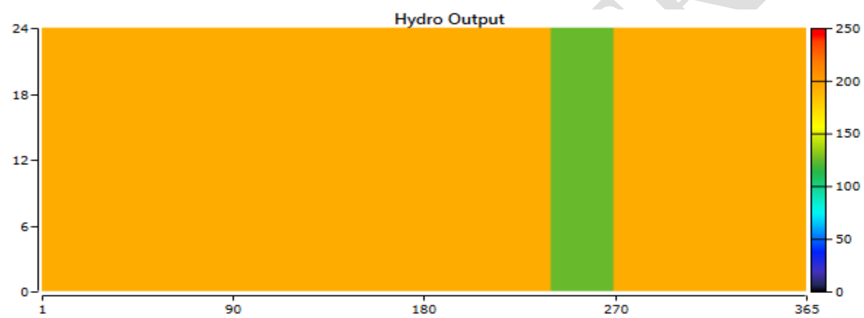


Figure 177: Hydropower hourly production in a year

Battery simulation results: The simulation results show that the whole hybrid system needs 5358 batteries of 5,496 kWh total capacity with autonomy of 18.5 hours. Since the battery storage has minimum state of charge of 40% then usable nominal capacity is 3,298 kWh. The expected lifetime of the battery system is 14.2 years. The battery state of charge in figure 18 indicate that the month of September, storage was heavily used by the load which is evidenced by low hydropower capacity due to low water levels.

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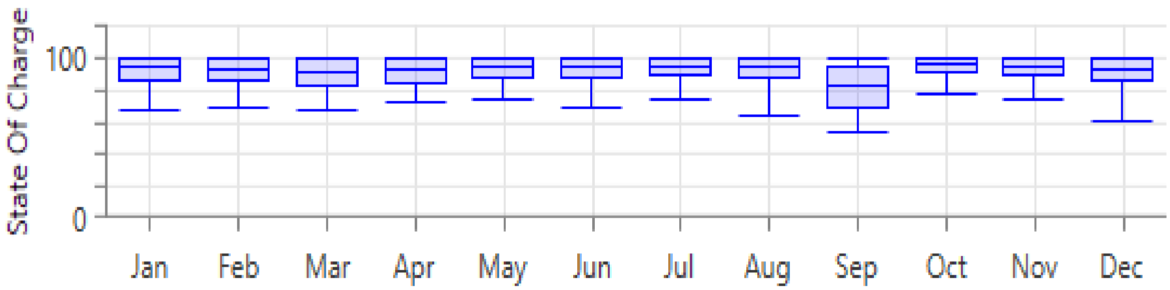

Figure 18: Monthly Battery state of charge

System converter simulation results: The converter capacity for the optimal system is 313 kW and inverter is expected to operate at about 5,139 hours in a year while rectifier is 1,937 hours.

Cost summary of the system: Table 2 clearly indicate that battery (Generic 1kWh Lead Acid) is the largest contributor of capital followed by solar panels (Generic flat plate PV). However, hydro turbine (10 kW Generic) is smallest contributor of capital cost.

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Table 2: Cost summary of the system from simulation results

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
10kW Generic	$17,900.00	$0.00	$4,628.05	$0.00	($357.34)	$22,170.71
Generic 10 kW	$360,400.00	$0.00	$93,181.54	$0.00	$0.00	$453,581.54
Generic 1kWh Lead Acid [ASM]	$1,205,550.00	$373,927.20	$155,847.68	$0.00	($49,412.50)	$1,685,912.37
Generic flat plate PV	$626,628.54	$0.00	$162,015.02	$0.00	$0.00	$788,643.56
System Converter	$452,158.97	$153,471.37	$70,143.51	$0.00	($28,884.86)	$646,888.99
System	$2,662,637.51	$527,398.57	$485,815.79	$0.00	($78,654.70)	$3,597,197.17

The whole hybrid system capital cost $2,662,638 and battery had highest contribution. Figure 19 gives the percentage share of capital cost for the individual component.

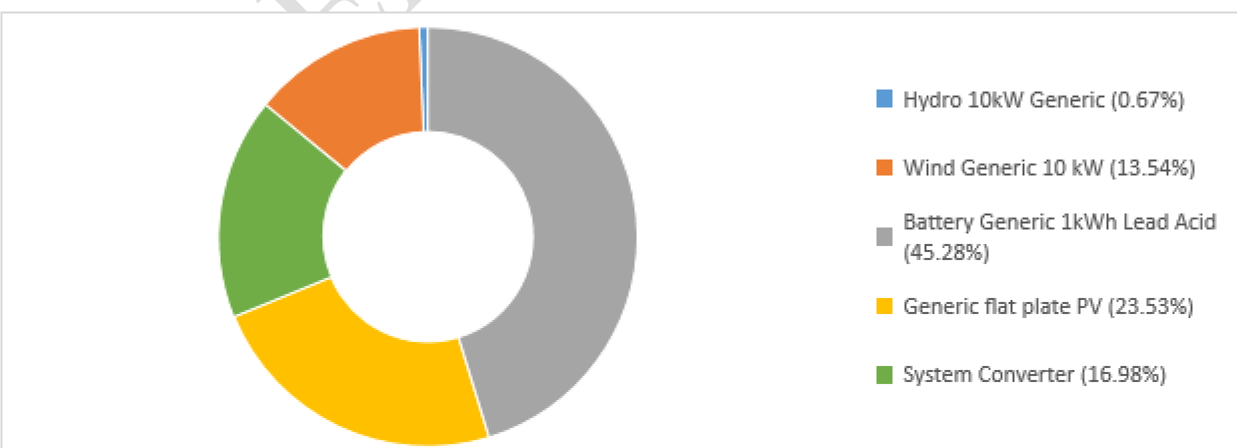

Figure 19: Percentage share of capital cost by component.

Sensitivity analysis

Sensitivity analysis is done in order to determine the effects of varying some parameters in the proposed system design. The first sensitivity analysis was done to determine the best design flow for the hydropower plant. This was done to determine the effect of changing the design flow for the river where the system was simulated at 159 L/s, 400 L/s and 637 L/s. The results, which are already presented, showed that increase in flow rate result in increase in capital cost, levelised cost of energy and also increase excess production of electricity. Therefore, this sensitivity analysis was used to choose the best scenario which showed that the best design flow was 159 L/s which will be available throughout the year.

Other sensitivity variable considered include; the wind capital cost multiplier of 2, solar capital cost multiplier of 0.5, hydro capital cost multiplier of 1.5 which yielded $26,850, converter capital cost multiplier of 0.5 and finally battery capital cost multiplier of 2. The spider plot of capital cost of hydro, wind, solar PV and lead acid battery show the effect of changing the capital cost with respect to cost energy as shown in figure 20. This plot shows how each of the components responds to change in terms of cost energy for the whole system. The results show that if capital cost increases for lead acid battery (LA ASM), it has greater impact on the cost of energy followed by solar PV and wind turbine (G10). However, hydropower (Hyd10) has relatively little impact on the cost of energy.

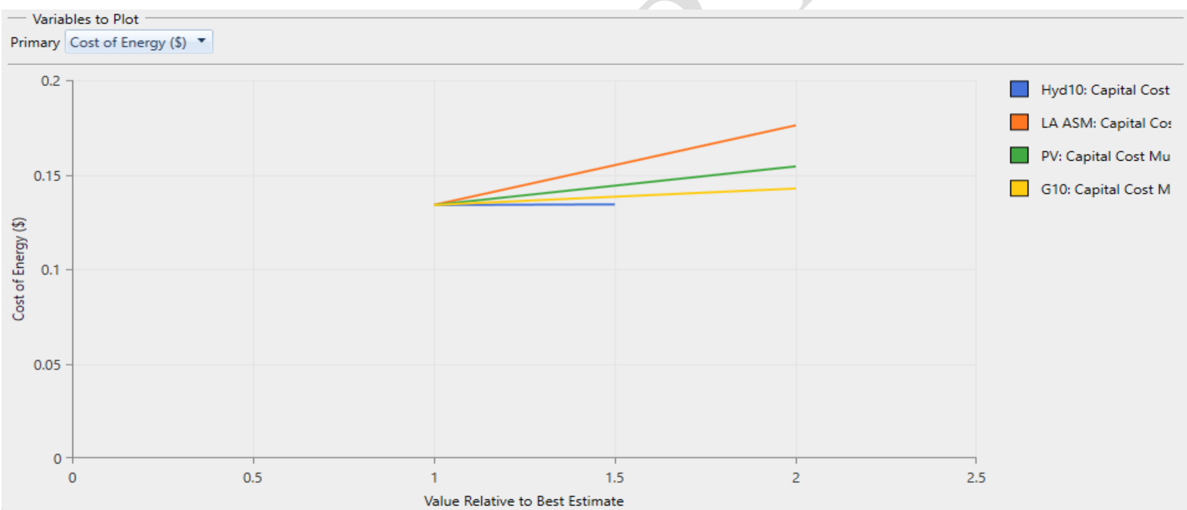

Figure 20: The spider plot of capital cost of hydro, wind, solar PV and lead acid battery on value relative to best estimate against cost of energy.

Conclusion

The optimal system design for the site is comprised of hydro-wind-solar and battery with design flow for hydropower of 159 L/s. The proposed hybrid system had proven to be feasible on technical grounds in this particular area with initial capital cost of $2,662,638. ~~According to MERA (2019), the cost of electricity in Malawi on the grid is K88.02/kWh ($0.11/kWh).~~ This shows that the cost of energy for the proposed hybrid system which is $0.134/kWh is relatively higher. This makes it difficult for people in the rural areas to pay for the electricity. However, Malawi heavily depend on hydropower and looking at the challenges faced by hydropower plants such as low water level and old machines, rural communities might remain without electricity. Therefore, with collective effort from Government and other organisation, this kind of energy system would improve living standards of the rural community.

Data Availability

The wind and solar data used to support the findings of this study can be accessed from NASA database using HOMER software on coordinates $12^{\circ}31.1'S$ and $34^{\circ}7.8'E$. The river discharge data used to support the findings of this study were supplied by Ministry of irrigation and water development, Malawi Government. Requests for access to these data should be made directly to Ministry.

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