

Effects of Global Horizontal Irradiance on Power Output of Hybrid Solar PV/Mini-hydro Renewable Energy System

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Conflicts of Interest

There are no conflicts to declare.

ABSTRACT

The initial capital and cost per kilowatt-hour (cost/kWh) for the PV subsystem with storage is high even with the cost reduction of PV products in recent times. The availability of solar resources determines the economics of solar PV systems. Hybridization of solar PV with a mini-hydropower subsystem reduces the cost per kilowatt-hour and improves the system's performance. The paper presents a comparative analysis of technical and economic aspects of the hybrid solar PV/mini-hydropower scheme focusing on the effects of differences in global horizontal irradiance (GHI). The regions of Bamenda and Buea (Cameroon) were chosen for the study. The resource availability for PV and mini-hydropower in the two locations selected for the study are reasonable. Storage options are needed, in particular, for seasonal power storage. The solar resource was obtained from the National Renewable Energy Laboratory database and the site temperature profile from NASA surface meteorology and solar energy database. The maximum demand considered for the analysis is 3MW, and the hydro system is designed to supply 2MW in the rainy season and 1.2MW in the dry season. Homer Pro software was used for the simulation. Homer-Pro's one-hour time step is sufficiently small to capture the most important statistical aspects of the load and the intermittent renewable sources. The battery considered for the project is a lithium-ion 1MWh capacity battery with supplier integration into HOMER-Pro software. A generic large free converter was selected from the Homer database to allow battery sizing without having to size the converter for different energy storage systems and charging configurations. The results show that for the same load demand, the zone with higher global horizontal irradiance (GHI) has a higher PV penetration, consumes more energy from the system, has a higher excess generation, and lower unmet load and capacity shortage than the zone with lower global horizontal irradiance. The cost difference for the two areas is quite significant. The site with higher global horizontal irradiance has 0.267 USD per kWh compared to 0.308 USD per kWh for the location with lower global horizontal irradiance.

Keywords: HYBRIDIZATION, GLOBAL HORIZONTAL IRRADIANCE, SOLAR PV, MINI-HYDROPOWER, HOMER PRO, CONVERTER.

Introduction

Cameroon is the most populated country in the CEMAC region, with an estimated population of 26.028 million (1) and covering a surface area of 475,440km² (1) (2). The total installed electricity capacity is 1,600 MW (3). The electricity consumption per capita (2016) stood at 281 kWh with a renewable energy mix of less than 1% (3). It also has a fast-growing population with an annual population growth rate of 2.8%, with 48% of the people living in rural areas (4). Cameroon has the second largest hydropower potential in Africa, and its location near the equator provides high solar irradiation. Solar and hydropower energy are auspicious, as the cost of fabrication of photovoltaic (PV) devices and hydropower components becomes less as the technologies improve. The use of hybrid systems can be more reliable and equally sustainable. Hybrid systems provide a high level of energy security, flexibility, cost-effectiveness and reliability through the integrated mix of complementary generation methods.

Solar Energy in Cameroon: Like many countries close to the equator, Cameroon has good potential for solar energy exploitation but hasn't been developed certainly because of the government's insufficient commitment and dedication in taking significant actions to boost the sector. In the Northern parts of the country, the average solar irradiance is estimated at 5.8kWh/m²/day, while other parts of the country have about 4.5kWh/m²/day (5) (6) (7). However, parts of the South West, Littoral and South Regions have a much lower average irradiance of about 3.5kW/m²/day as seen in the solar map of Cameroon. The solar map of Cameroon is shown in figure 1 (6).

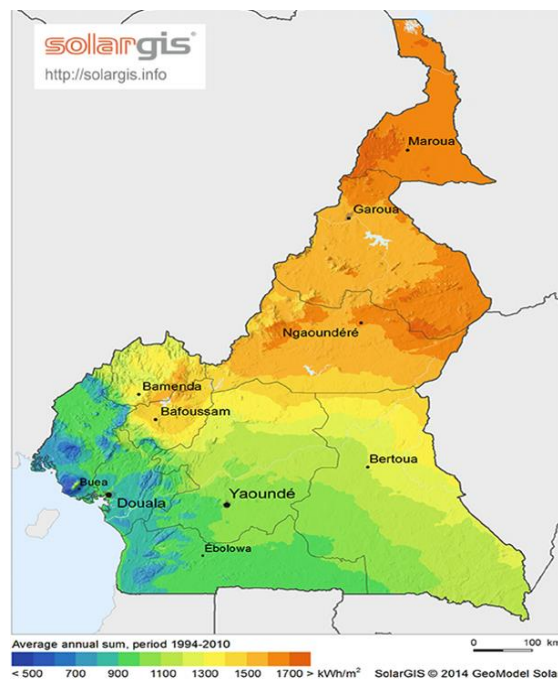


Figure 1: Map of Cameroon showing solar irradiance

Hydropower in Cameroon: Cameroon has the second-largest hydroelectric potential in Sub-Saharan Africa. The country's hydropower development potential is estimated at over 12 GW across the country, with half of this potential concentrated in the Sanaga River Basin. In the CEMAC region, Cameroon's electrical system is the largest, with an installed generation capacity of 1600 MW. There is a high concentration of small hydropower resources in the west of Cameroon, as shown in figure 2. However, this potential is yet to be adequately exploited (8).

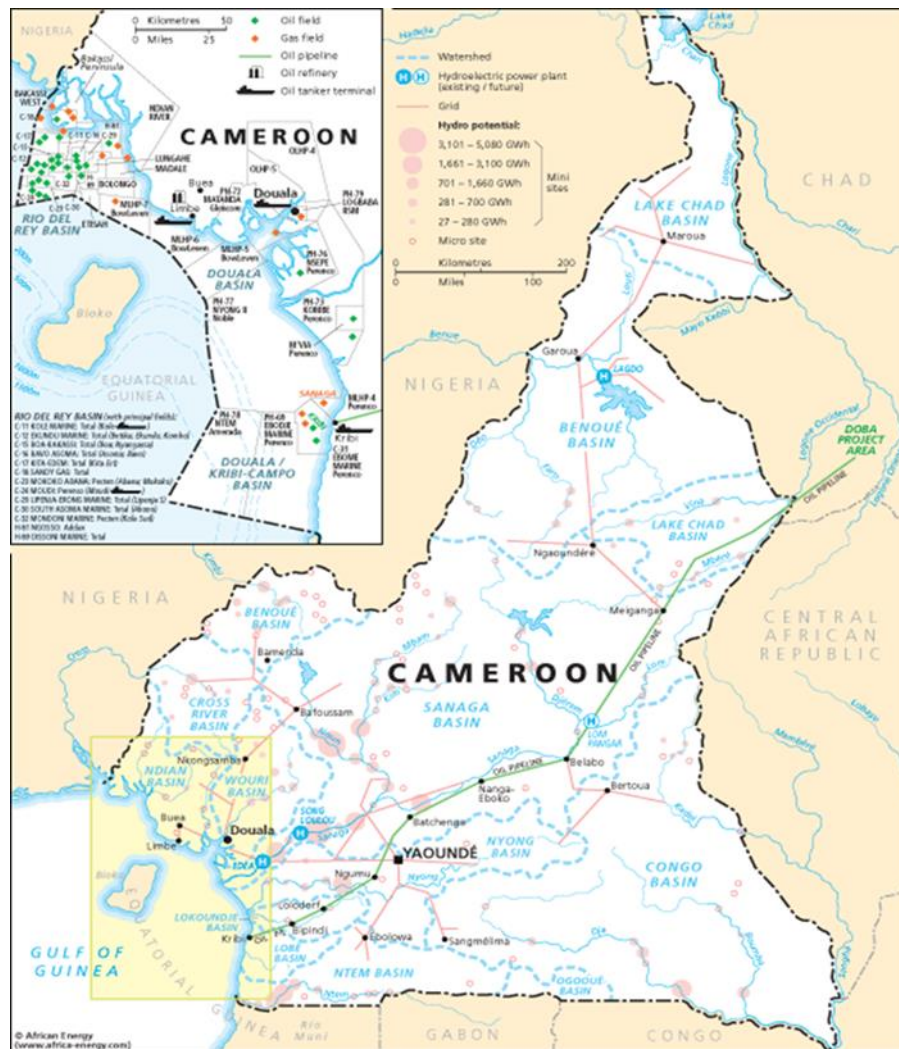


Figure 2: Map showing the hydro resources in Cameroon

Types of small hydropower plants: In hydropower systems, running water is used to produce mechanical energy which is later converted to electrical energy using electrical generators (9). Small hydropower plants do not require reservoirs or dams. The plant is established on a run-of-river, where water is diverted from the mainstream to create a head that is then passed through the penstock with high energy. The pressurised water in the penstock rotates the turbine that spins the shaft coupled to the generator (10) (11) (12). Most small hydropower plants are run-of-river schemes; hence, the hydro-turbine generates electric power when the water is available. When the flow falls below some predetermined amount, as may be the case in the dry season, the generation ceases (13). Therefore, small independent schemes may not always supply electrical energy unless

there is always enough flow. Distributed energy resources can be used to overcome this problem. Medium and high head schemes use weirs to divert water to the intake, from where it is conveyed to the turbines through the penstock (14) (15) (16). This configuration is not economical because of the high cost of the penstock (13). An alternative method is to convey the flow by a low slop canal running alongside the river to the forebay and then to use a short penstock to convey the flow to the turbine. In situations where the topology and morphology of the landscape do not permit the easy layout of the canal, a low-pressure pipe with more considerable latitude in slope can be an economical option (13). Low head schemes are most appropriate in river valleys where a small dam creates a head, or the power is diverted to the intake with a short penstock. The turbine outlet is discharged into the river via the tailrace canal. Figure 3 illustrates different types of run-of-river hydropower schemes (17). In this paper, the comparative study is limited to the barrage system.

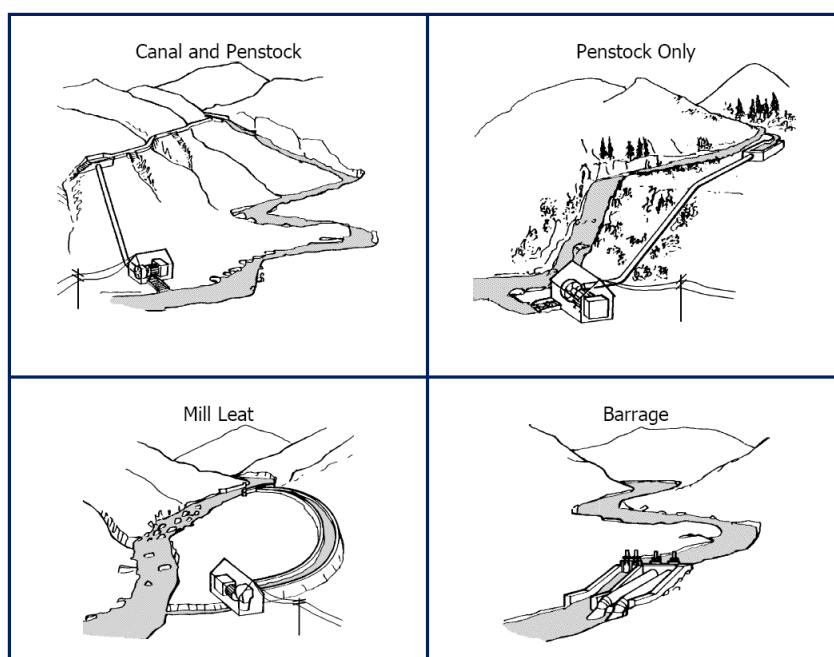


Figure 3: Illustrating different types of run-of-river hydropower schemes

Materials and methods

Load profile

The maximum demand considered for the analysis is 3MW. The hydro system is expected to supply 2MW in the rainy season and 1.2MW in the dry season. The daily load profile, seasonal load profile and yearly profile for the analysis are shown in figure 2. The load profile for the project has a peak load of 3MW, including a random variability of 10% daily and 20% timestep.

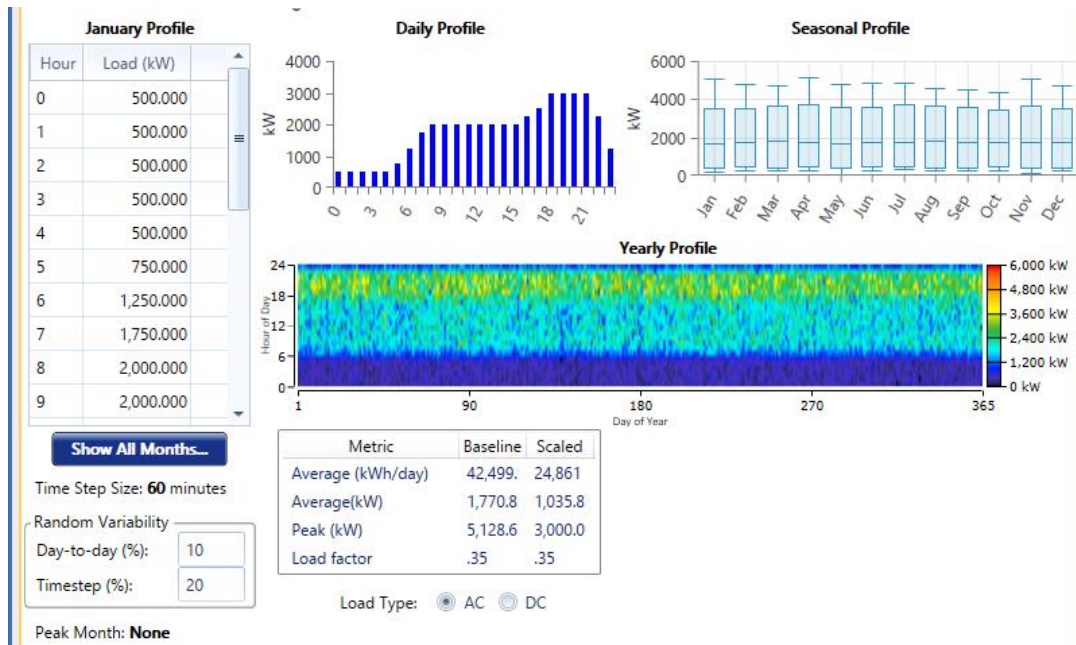


Figure 4: Illustrating load data

Solar resources

The solar resource is obtained from the National Renewable Energy Laboratory database. The site temperature profile is obtained from NASA surface meteorology and solar energy database.

Solar resource for Bamenda zone: The location for Bamenda zone is: N6, 5° 55.9'N, 10° 8.7'E, Bamenda, Cameroon. As shown in fig. 5, the average solar radiation for the Bamenda area is 5.02kW/m²/d, and the average clearness index is 0.55. Figure 6 shows the site temperature profile.

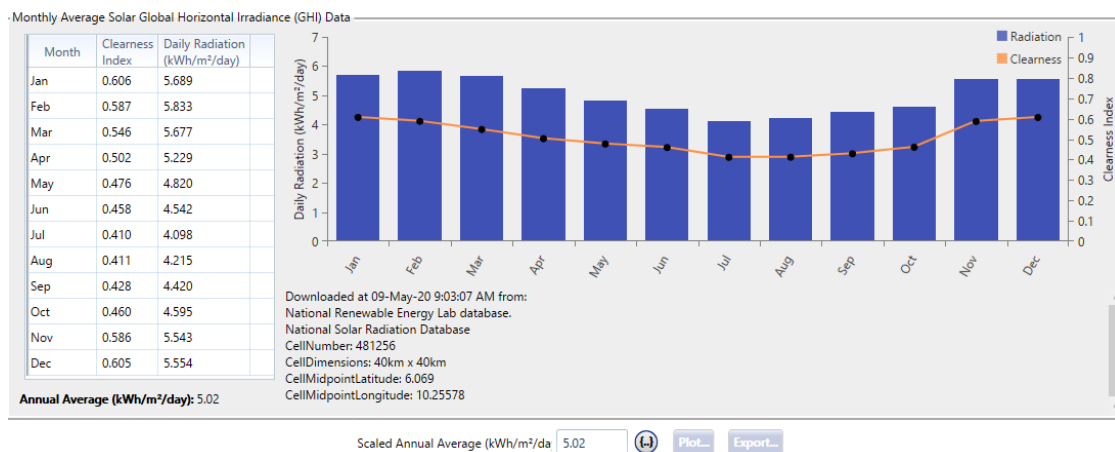


Figure 5: Solar resource input for Bamenda zone

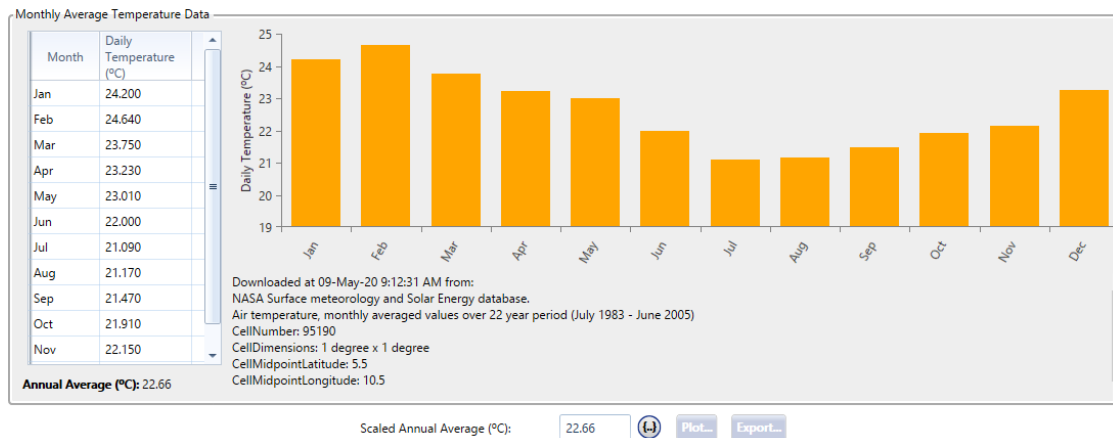


Figure 6: Site temperature profile for Bamenda zone

Solar resource for Buea zone: The location for the Buea zone is: D61, 4° 9.4'N, 9° 15.8'E, Buea, Cameroon. As shown in figure 7, the average solar radiation is for the Buea area is 4.37kW/m²/d, and the average clearness index is 0.51. Figure 8 shows the site temperature profile.

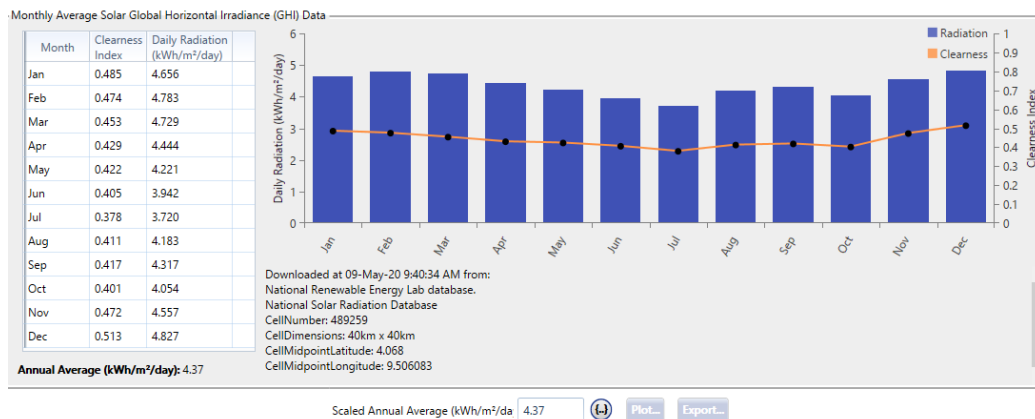


Figure 7: Solar resource input for Buea zone

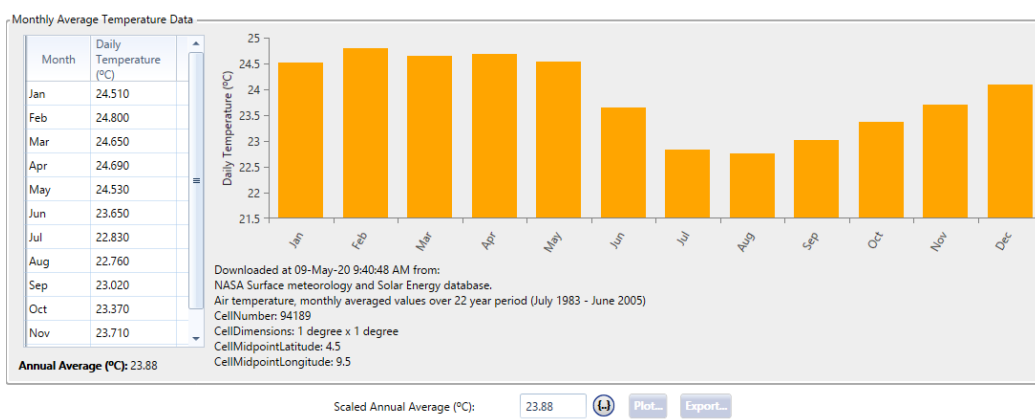


Figure 8: Site temperature profile for Buea zone

Hydro resources

The hydro scaled annual average flowrate is $22.17\text{m}^3/\text{s}$, and the minimum residual flow is $1\text{m}^3/\text{s}$. Fig. 9 shows the hydro resource input.

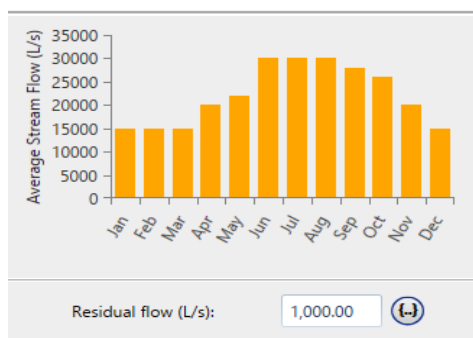


Figure 9: Hydro resource input

Equipment selection and project optimisation

Photovoltaic Array: The PV module used is generic. The PV array size is estimated from the load demand. The considered PV system rating is 1800kW, but the sizes considered for the simulation are 1500kW and 1800kW. The initial cost, replacement cost, operation and maintenance cost are adjusted to cover the balance of system cost and others. The solar module parameters are shown in table 1.

Table 1: The solar module parameters

Module parameter	Value
Type	Generic flat-plate PV
Rated capacities considered	1500kW and 1800kW
Panel type	Flat plate
Output current	DC
Lifetime considered	25 and 30 years
PV derating factor	90%
Tracking system	No Tracking
Azimuth	0 deg
Ground reflectance	20%
Capital Cost per kW	1250USD
Replacement cost	1250USD
Operation and maintenance cost	300USD

Batteries: Batteries are an integral part of hybrid renewable energy systems. The battery backup adds stability to the network by storing energy during peak generation and releasing the energy for peak consumption when there is insufficient generation from renewable sources. The battery considered for the project is a lithium-ion 1MWh capacity battery with supplier integration into HOMER-Pro software. The specifications and price are provided in the software. The battery model parameters are shown in Table 2

Table 2: The battery model parameters

Module parameter	Value
Type	Idealised battery model
Quantities considered	4, 6, 8
String size	2
Expected lifetime	25 years
Nominal voltage	600 V
Nominal capacity in MWh	1.0 MWh
Nominal capacity in Ah	1,670 Ah
Roundtrip efficiency	90%
Maximum charging current	1.67 kA
Maximum discharge current	5 kA
Annual throughput	3,000,000 kWh
Initial state of charge	100%
Minimum state of charge	40%
Capital Cost per unit	700,000 USD
Replacement cost	700,000 USD
Operation and maintenance cost	10,000 USD

Converter: The bidirectional converter is used to interface between the DC bus connected to the PV system and the AC bus powered from the hydro system. A generic large free converter was selected from the HOMER database to allow battery sizing without having to size the converter for different energy storage systems and charging configurations such as load following (LF) and cycle charging (CC). The inverter and rectifier efficiencies of the converter were taken as 95% each. Table 3 shows the converter model parameters.

Table 3: The converter model parameters

Module parameter	Value
Type	Generic large free converter
Lifetime	15 years
Inverter can parallel with AC generator?	Yes
Rectifier relative capacity	100%
Rectifier/Inverter efficiency	95%
Capital Cost per unit	750 USD
Replacement cost	750 USD

Hydro Turbine: The hydro system includes hydraulic equipment, including the intake gates and trash screens, the electromechanical equipment, which consists of the turbine, generator, transformer and controls. Table 4 shows the parameters of the hydro turbine.

Table 4: The hydro turbine parameters

Module parameter	Value
Type	2MW Generic
Lifetime	25 years
Available head	10 m
Design flowrate	22,000 L/s
Minimum flow ratio	50%
Maximum flow ratio	110%
efficiency	85%
Pipe head loss	10%
Output current	AC
Capital Cost	3,000,000 USD
(including generator, controls, transformers and transmission system)	
Replacement cost	1,000,000 USD
Operation and maintenance cost	100,000 USD

Operating strategies

There are two types of dispatch strategies in HOMER Pro software: the load following (LF) dispatch and cycle charging (CC) dispatch (18). In the load following dispatch strategy, renewable power sources charge the battery, but the generators produce just enough power to meet the load demand. In the cycle charging dispatch strategy, whenever the generators operate, they produce more energy than required to serve the load with the surplus electricity going to charge the battery bank. With a set-point state of charge chosen, the generators charge the batteries to a set point of about 80%, and the load following dispatch strategy is used to top up the batteries (18). Table 5 shows the system control inputs for the simulation.

Table 5: The system control inputs

Simulation	Value
Simulation time step (hours)	1
Include hydro turbine in all simulations	Yes
Generator control: Load following	Yes
Generator control: Cycle charging	Yes
Set-point state of charge	80%

Cost

Figures 10 and 11 from (19) shows the total installation cost range for PV and hydropower renewable energy installations. The figures are used as a guide in choosing the cost range for the PV and hydropower renewable energy installations.

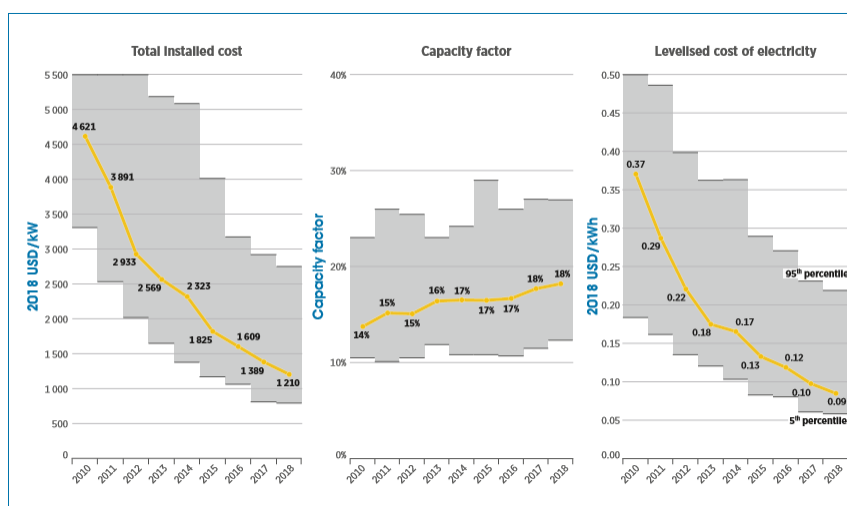


Fig. 10: Global weighted average of total installed costs, capacity factors and LCOE for solar PV, 2010-2018

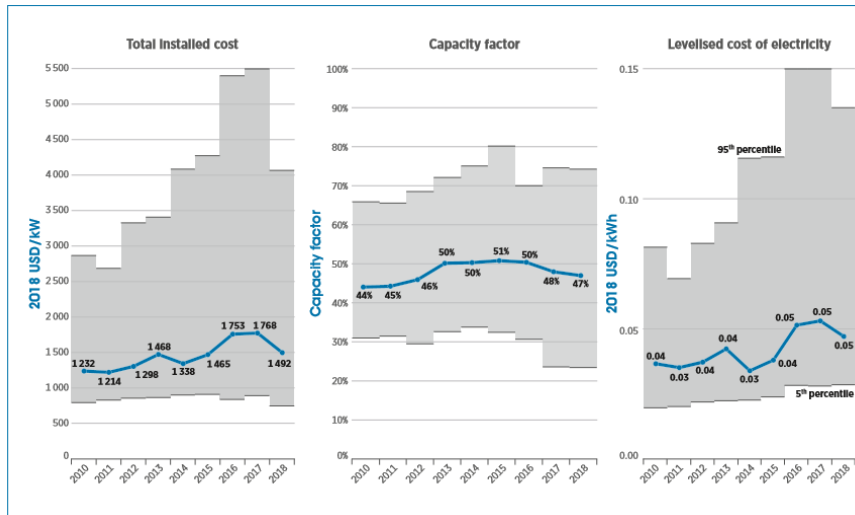


Figure 11: Global weighted average of total installed costs, capacity factors and LCOE for hydropower, 2010–2018

System architecture

Fig. 8 shows the system architecture. Microgrids are, by their nature, very dynamic systems in which several variables can be changing simultaneously and continuously. The solar resource has a very erratic behaviour following local meteorology, and loads can change rapidly and subject the system to peaks and transients. Batteries and electronic devices have their logic and response to changes in electric parameters. The interaction of all these variables and behaviours can result in a very complex system to analyse. The simulation serves two purposes: it determines firstly whether the system is feasible, that is, being able to serve the electric load, and secondly, it estimates the lifecycle cost of the system. The lifecycle cost is represented by the total net present cost, which includes all expenses and revenues within the project lifetime with future cash flows discounted to the present. HOMER-Pro's one-hour time step is sufficiently small to capture the most important statistical aspects of the load and the intermittent renewable sources and equally appropriate to allow computation to the extent that optimisation and sensitivity analysis can be handled (18). The solar PV system is used to balance the supply. At peak load periods, the storage system comes in to support generation. During periods of low demand, excess generation from the hydropower is used to charge the storage systems. The stored energy can then be used to provide power during periods of high demand.

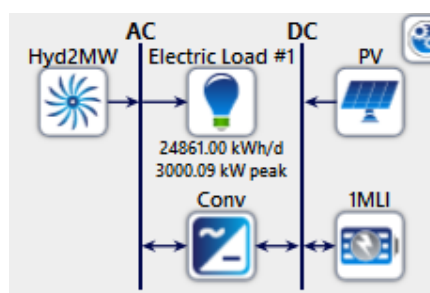


Fig. 12: Schematic of system components and configuration

Results and analysis

The proposed system involves mini-hydro, solar PV, batteries and a converter. The energy sources are mini-hydro and solar power sources. The supportive component used to improve stability and reliability is the battery bank. An inverter is included for power conditioning. The mini-hydropower interconnects with the PV solar system. In the simulation, the mini-hydropower resources and load demand are constant. As shown in figures 5 and 7, the solar resources are different for the two locations. The Bamenda zone has an irradiance of 5.02 kW/m²/day with an average temperature of 22.8°C, as shown in figures 5 and 6. The Buea zone has an irradiance of 4.37 kW/m²/day with an average temperature of 23.88°C, as shown in figures 7 and 8. The results point out the differences in the systems performance and cost due to differences in solar radiation of the two locations. Figure 13 shows the electrical summary for the Buea zone.



Figure 13: Electrical Summary, Buea zone

Electrical summary

The generation summary shown in table 6 shows that the solar PV generation for Bamenda is higher than that of Buea. For the same load demand, the results show that the Bamenda system consumes more energy from the system than the Buea area. The excess generation for the Bamenda zone is also higher than that of Buea, as shown in table 8. The unmet load and capacity shortage is lower for the Bamenda zone. Table 8 shows that the PV penetration for Bamenda is higher but with lower hours of operation and lower Levelized cost of energy. The cost difference is quite significant as the Bamenda zone has 0.267 USD per kWh, and the Buea zone has 0.308USD per kWh. The difference is 0.041USD, which is equivalent to about 24Fr CFA in the local currency. This shows a better return on investment in solar projects in Bamenda than in Buea.

Table 6: Generation summary

Quantity	Bamenda		Buea	
	kWh/yr	%	kWh/yr	%
Solar PV	2,492,395 kWh/yr	14.1%	2,158,175 kWh/yr	12.5%
Hydro	15,145,285 kWh/yr	85.9%	15,145,285 kWh/yr	87.5%
Total	17,635,680 kWh/yr	100%	17,303,460 kWh/yr	100%

Table 7: Consumption summary

Quantity	Bamenda		Buea	
	kWh/yr	%	kWh/yr	%
Solar PV	2,492,395 kWh/yr	14.1%	2,158,175 kWh/yr	12.5%
Hydro	15,145,285 kWh/yr	85.9%	15,145,285 kWh/yr	87.5%
Total	17,635,680 kWh/yr	100%	17,303,460 kWh/yr	100%

Table 8: Excess generation and unmet load

Quantity	Bamenda		Buea	
	kWh/yr	%	kWh/yr	%
Excess electricity	8,448,594 kWh/yr	47.906%	8,113,016 kWh/yr	46.9%
Unmet electrical load	2,321 kWh/yr	0.0256%	2,791 kWh/yr	0.0308%
Capacity shortage	8,537 kWh/yr	0.0941%	9,019 kWh/yr	0.0994%

Solar PV performance

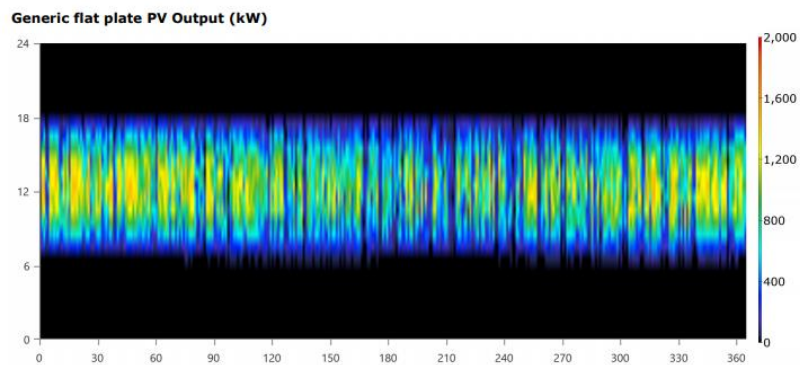


Figure 14 : Solar PV output, Bamenda zone

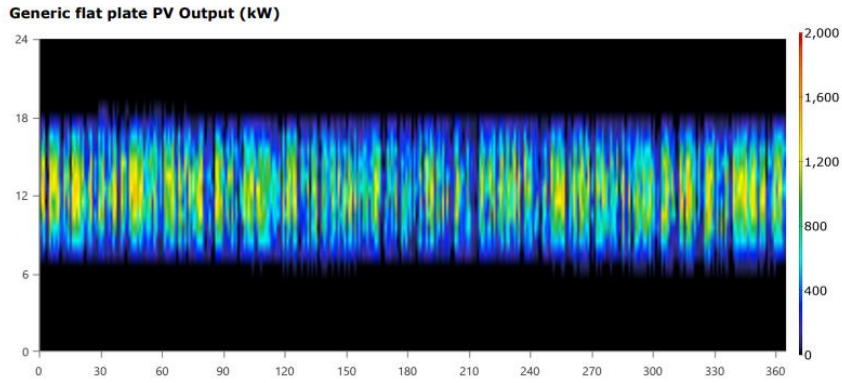


Figure 15: Solar PV output, Buea zone

Table 9: Solar PV summary

Quantity	Bamenda	Buea
Minimum output (kW)	0	0
Maximum output (kW)	1,643	1,630
PV penetration (%)	27.5	23.8
Hours of operation hrs/yr	4,361	4,415
Levelized cost (\$/kWh)	0.267	0.308

Storage system performance

The storage system in the Buea zone received more input energy and equally supplied more to compensate for the solar PV deficiency. This is illustrated in table 10, the storage system summary table. The Buea zone also has higher losses, lower annual throughput for the same storage depletion and autonomy as the Bamenda zone. The lifetime throughput for the Buea zone is much higher. The differences in the performance of the converter are slight, as shown in table 11.

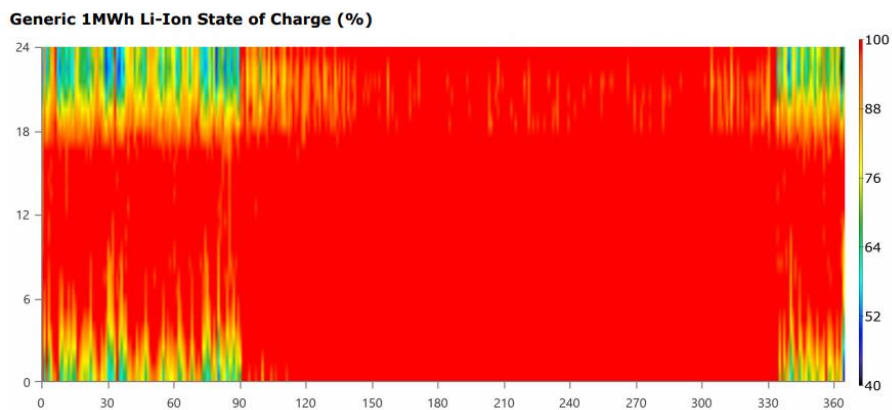


Figure 15: Storage system output, Bamenda zone

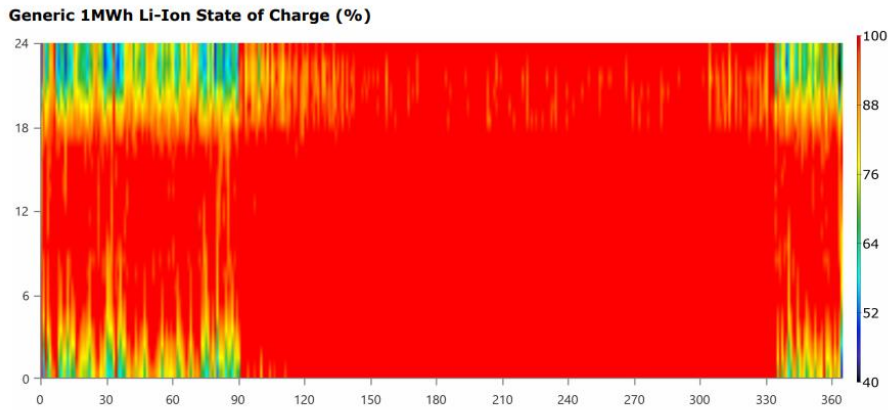


Figure 17: Storage system output, Buea zone

Table 10: Storage system summary

Quantity	Bamenda	Buea
Batteries -1MWh Li-Ion (qty)	12	12
String size (batteries)	2	2
Strings in parallel (strings)	6	6
Bus voltage (V)	1,200	1,200
Energy In (kWh/yr)	563,046	577,459
Energy Out (kWh/yr)	510,3.7	523,306
Storage depletion (kWh/yr)	3,758	3,786
Losses (kWh/yr)	56,497	57,940
Annual throughput (kWh/yr)	537,910	551,612
Autonomy (hr)	6.95	6.95
Storage wear cost (\$/kWh)	0.246	0.246
Nominal capacity (kWh)	12,000	12,000
Usable nominal capacity (kWh)	7,200	7,200
Lifetime throughput (kWh)	16,137,314	16,548,375

Converter performance

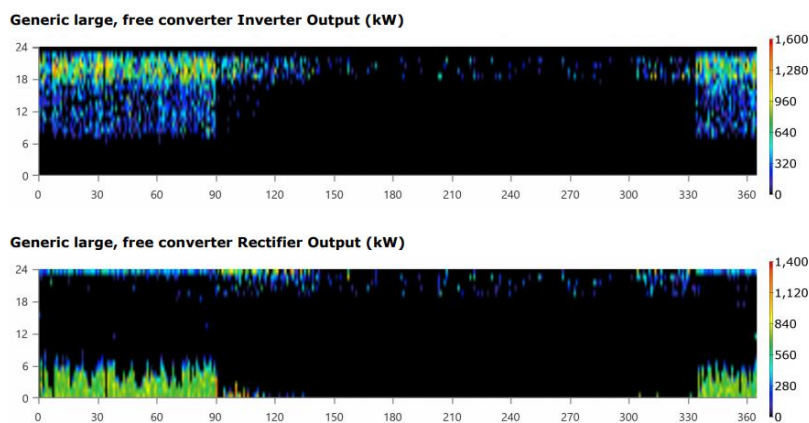


Figure 18: Converter output, Bamenda zone

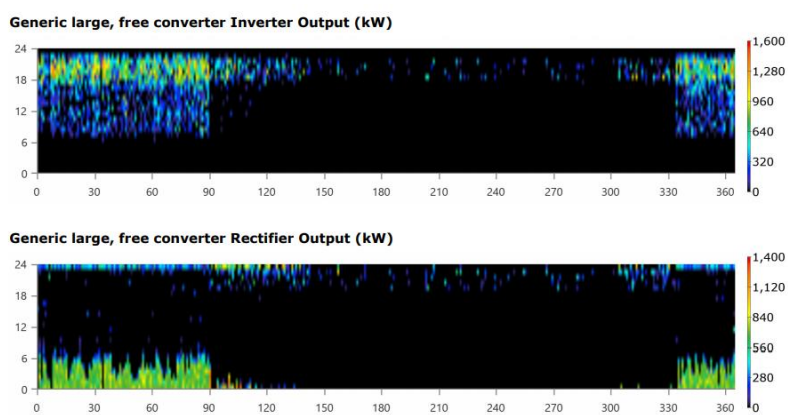


Figure 19: Converter output, Buea zone

Table 11: Converter summary

Quantity	Bamenda	Buea
Hours of operation (hrs/yr)	1,714	1,713
Energy Out (kWh/yr)	686,559	668,089
Energy In (kWh/yr)	722,693	722,199
Losses (kwh/yr)	35,135	36,110
Capacity (kW)	1,430	1,430
Mean output (kW)	78.4	78.3
Minimum output (kW)	0	0
Maximum output (kW)	1,430	1,430
Capacity factor (%)	5.48	5.48

Hydropower performance

Table 12 shows the simulation results for the mini-hydropower system. The parameters of the mini-hydropower system were the same for the simulation; hence no differences were recorded in the simulated results.

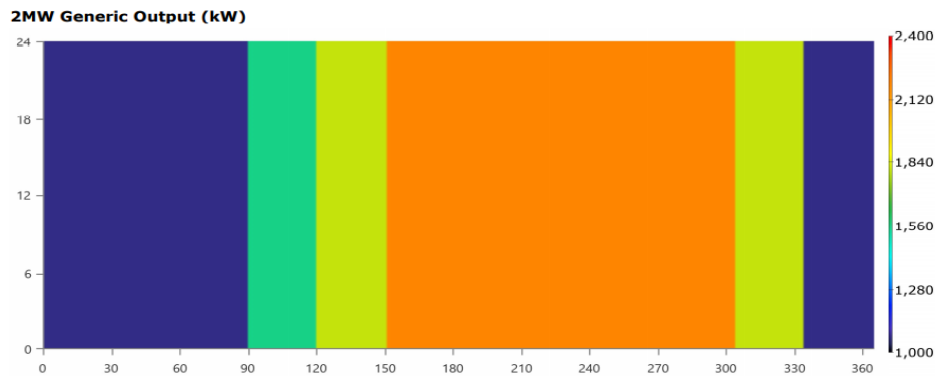


Figure 20: Hydropower output, Bamenda zone

Table 12: Hydropower summary

Quantity	Bamenda	Buea
Nominal capacity (kW)	2,251	2,251
Mean output (kW)	1,729	1,729
Capacity factor	76.8	76.8
Total production	15,145,285	15,145,285
Minimum output (kW)	1,075	1,075
Maximum production (kW)	2,229	2,229
Hydro penetration (%)	167	167
Hours of operation (hrs/yr)	8,8760	8,8760
Levelized cost (\$/kWh)	0.0198	0.0198

Cost

For the optimal results selected by the researchers, the total net present cost of the system is 28,575,300 USD, and the Levelized Cost of energy is 0.180 USD in both cases. Despite the differences in solar PV and mini-hydropower system costs, the final energy cost is the same. This is because the hydropower was included in all the simulations and projected to supply the baseload.

Cost Summary

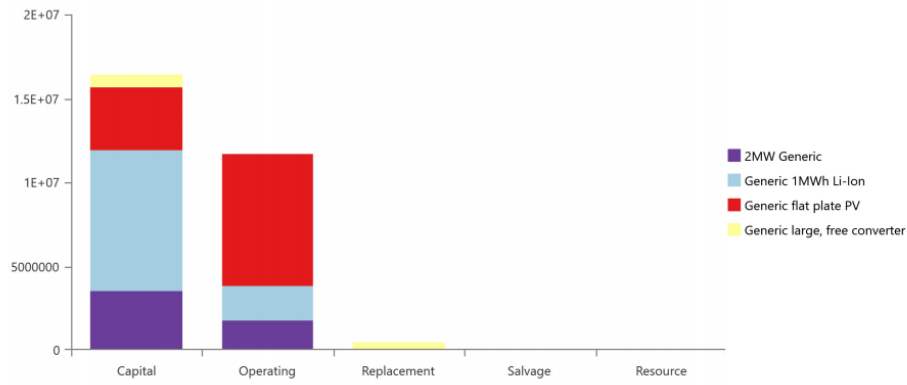


Figure 21: Cost summary

Cash Flow

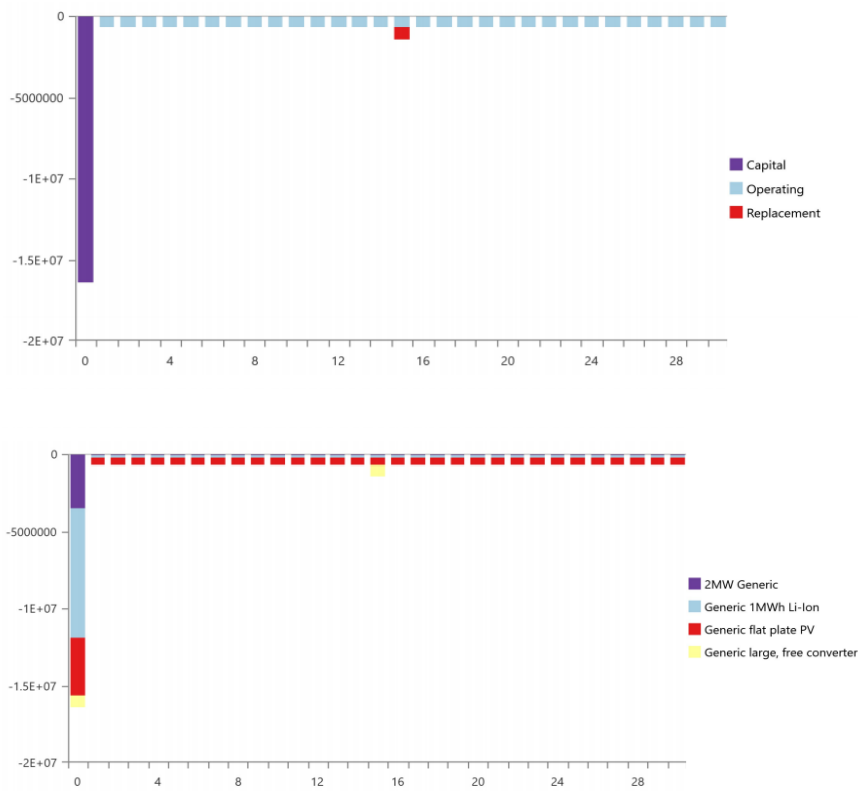


Figure 22: Cash Flow

Table 13: Net Present Costs

Name	Capital	Operating	Replacement	Total
Mini-hydro system (USD)	3.50M	1.75M	0.00	5.25M
1MWh LI-Ion storage system (USD)	8.40M	2.09M	0.00	10.5M
Solar PV system (USD)	3.75M	7.86M	0.00	11.6M

Converter (USD)	786,703	0.00	441,800	1.23M
System total (USD)	16.4M	11.7M	441,800	28.6M

Table 14: Annualized Costs

Name	Capital	Operating	Replacement	Total
Mini-hydro system (USD)	200,486	100,000	0.00	300,482
1MWh LI-Ion storage system (USD)	481,157	120,000	0.00	601,157
Solar PV system (USD)	214,802	450,000	0.00	664,802
Converter (USD)	45,063	0.00	25,307	70,369
System total (USD)	941,505	670,000	25,307	1.64M

Conclusion

The study covers the effects of Differences in GHI in the performance and costs analyses of hybrid solar/mini-hydropower Schemes. The main objective of the research is to evaluate the performance of a hybrid solar PV/mini-hydropower system in different regions of Cameroon. Sources considered were mini-hydro and solar PV systems since the selected areas have an abundance of these resources. The zones considered were Bamenda; the headquarter of the North West Region, and Buea, the headquarter of the South West Region. The results show that hybrid renewable energy systems, though small-scaled, are endowed with high operational and constitutive sophistication. The system was simulated with Homer Pro software, and the simulated result illustrates the system's performance.

In this research, special attention was given to the system performance and cost. The results show that the mini-hydro system could be given priority in rural electrification projects due to its low capital cost, low Levelized cost of energy and better power quality. The solar PV system could be used to top up generation when the hydro resources are insufficient, as is the case during the dry seasons. However, the capital cost and the Levelized Cost of energy are relatively high with the solar PV system. As shown in the cost analysis plots of figures 22 and 23, the storage system amounts to about half of the capital investment. This is also illustrated in the cost summary of table 13. In the study, the 1MW Li-Ion storage system is assumed to cover the project lifetime. If the storage system were to be replaced within the project lifetime, the cost of energy would be much higher; hence may not be feasible for rural electrification projects in sub-Saharan Africa country where the income levels are very low.

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