TECHNICAL, ECONOMIC AND SUSTAINABILITY CONSIDERATIONS OF A SOLAR PV MINI GRID AS A TOOL FOR RURAL ELECTRIFICATION IN UGANDA

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***Abstract* –** The challenges facing rural electrification in Uganda are diverse with less than 3% of the rural population having access to electricity. The establishment of mini-grids powered by renewable energy sources makes it possible to electrify remote areas at affordable rates. In this study, an assessment of a solar PV mini-grid system to provide electricity to forty households in rural Uganda was carried out. The considered system comprised six solar modules each rated 175 Wp, a controller, off-grid inverter and batteries with a capacity of 600 Ah. Manufactured by SMA, the Sunny Island inverter proposed for the mini-grid would ensure provision of grid-quality electricity. The study aimed to investigate the mini-grid's technical design with focus on optimal distribution against constraints of voltage drops, electrical losses and increasing load. Customised load limiters shared between households using thermistors were included to reduce costs and limit consumption. The incomes of rural households are often seasonal and thus issues pertaining to affordability and sustainability were also considered. Results of the economic analysis showed a payback period of less than 5 years given an affordable fixed monthly tariff for the case study area.

***Keywords* –** Mini-grid, Photovoltaics (PV), rural electrification

1. Introduction

Despite Uganda's national grid electrification rate being only 5% [1], the concept of renewable energy mini-grids is not widespread in the country. About 85% of the population relies on biomass and kerosene to meet their energy needs. These energy sources often pose hazards to domestic health through smoke-related illnesses and also to the environment through widespread deforestation and greenhouse gas emissions.

Mini grids powered from renewable energy sources can provide a cost-effective way to electrify remote sites while helping to mitigate the above challenges. The main objective of this study was to carry out an assessment of the technical, economic and sustainability aspects involved in establishing a solar photovoltaic (PV) mini-grid in a rural case study area in Uganda. Analysis was made on how the PV system could be used to provide electricity commercially to 40 households in Kabanga village.

2. The Kabanga Case Study

Kabanga is a trading centre located in the Ntenjeru sub-county, Kayunga district, Uganda. Field surveys in the area established that it consisted of 250 households, 20 retail shops, a farm (Miti farm), 3 schools, 2 dispensaries and a health centre. The area lacked grid electricity and remained largely unelectrified at the time of this study.

For this study, 40 households in Kabanga were considered for electrification using a solar PV system. The community chosen consisted of a group of residential houses close together with an average of 5 inhabitants per household. The area generally received sunshine evenly throughout the year with average insolation of 5.5 peak-sunshine hours (PSH) [2]. The majority of the households depended on farming and the average household monthly income in Ugandan shillings (UGS) was UGS 150,000[1].

3. Technical Analysis

3.1 The electrical energy demand of the community

The demand in the case study area was estimated from the energy consumption from prevailing alternative energy sources. Using focus group discussions with the household residents, information on the different energy sources, consumption and expenditure was obtained. This included usage of kerosene for lighting, dry cells, wet batteries, mobile phone charging, and the average daily number of hours spent using each. The alternative energy expenditure ranged from UGS 15,000 to UGS 50,000.

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[1] Exchange rate: US$ 1 = UGS 2,000 (December 2009)

The electrical load pattern showed a high concentration of the load at night, most of the population being subsistence farmers working during the day. The most common loads established during the demand survey included lighting, radio, and cell-phone charging. The area considered is very small comprising only residential houses. The community was divided into two consumer categories as summarised in table I.

Table I: The electrical energy consumption of households

Consumer category	**Appliances per household**	**Daily energy demand**	
		Average peak demand (kW)	**Average daily energy (kWh/day)**
Low consumer households (30)	2 ights; 1 radio; 1 cell-phone charger	0.87	2.76
Medium consumer households (10)	3 lights; 1 radio; 1 cell-phone charger; 1 TV	0.69	1.93
	Total	**1.56**	**4.69**

3.2 Sizing the PV Generator

Only the energy consumption at the time of this study is considered here. Given the energy demand in table I, the peak power rating (W_P) of the solar PV generator (solar modules) to be used was obtained using (1) [2].

$$W_P = \frac{E_{load}}{PSH} S.F \qquad (1)$$

where E_{load} is the daily energy consumption (4.69 kWh/day), S.F is the safety factor to cater for losses, inefficiencies of the system components and PV module temperature compensation (S.F = 1.25). From (1), the estimated size of the PV generator required was 1,066 W_P. The modules selected were of mono-crystalline silicon type with ratings (P_{MAX} = 175 W_P, V_{MAX} = 36.5 and I_{MAX} = 4.8 A). Equation (2) gave the estimated number of solar modules (N_{PV}) required as 6 with 2 modules connected in series and in turn connected in parallel to develop 3 parallel strings.

$$N_{PV} = \frac{W_P}{P_{MAX}} \qquad (2)$$

3.3 Sizing Storage

Since solar radiation is available during the day yet most of the energy is required at night, electric energy storage was necessary. Considering the load size and energy demand, the required storage capacity was quite large. Thus, special deep cycle lead-acid batteries with long life time and high cyclic stability rate were selected. To ensure supply reliability even during days with low solar insolation, 3 days of autonomy were assumed for the storage. The battery capacity, C_{AH} (Ah), was obtained from (3).

$$C_{AH} = \frac{E_{load} \times S}{V_{SYS} \times DoD \times \eta_{Sys}} \quad (3)$$

Where S = 3 days (reserve days); V_{SYS} = 48 V (system voltage or nominal voltage for the DC side or battery); η_{sys} = 0.8 (the system efficiency); DoD = 0.6 (depth of discharge). Hence, the required battery capacity was estimated at 611 Ah. The storage to be installed consisted of deep cycle long-life lead-acid batteries with a total of 48 V and 600 Ah (28,800 Wh). This could be accomplished using twelve 12 V, 200 Ah batteries with 3 batteries connected in parallel and four of the parallel strings connected in series.

3.4 Charge Regulation and Power Inverter

In order to protect the batteries against deep discharge and over-charging, charge regulation was needed. This would be provided by the inverter’s inbuilt charge regulator. To build up and control the AC-grid (240 V, 50Hz), an off-grid/master inverter (SMA Sunny Island 2224) was used. A 1 kW solar inverter (Sunny Boy SB1100) was included mainly to stabilise the input of the off-grid inverter. The off-grid inverter considered was 2 kW to ensure that the capacity of the loads was met for all scenarios as shown in fig. 1.

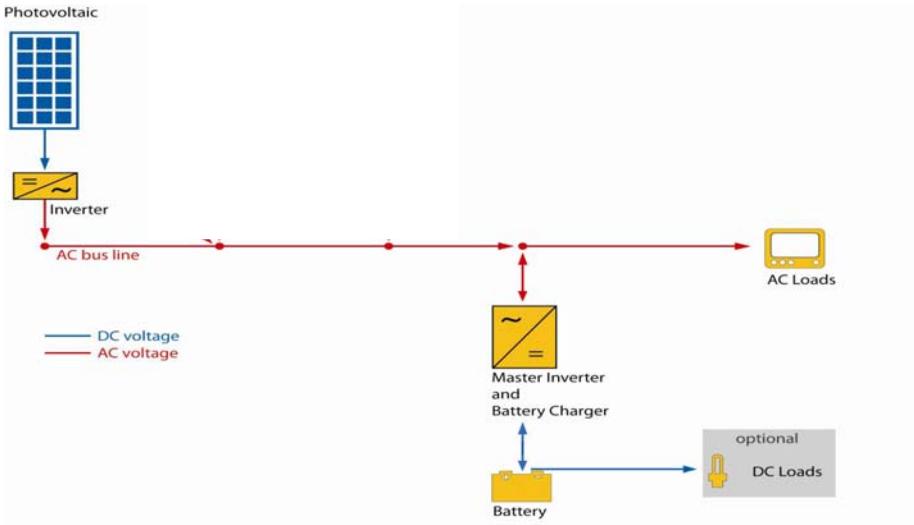

Fig. 1. Proposed topology of AC coupled PV mini-grid system (source: Phaesun)

3.5 Distribution Network

The major considerations for the design of the PV mini-grid's distribution network in addition to optimised cost are that it be safe, adequate, efficient and expandable [3]. It was required to identify available conductors optimised for size to meet the mini-grid's load requirements. The objective was to minimise the life cycle cost (LCC) of the distribution network while ensuring sustainable and adequate power delivery. The solar PV system would be centrally located for optimal interconnection with the possibility of stringing more than one conductor in different directions [3].

The interconnection of the households was optimised for shortest total network line length by using the Minimum Spanning Tree (MST) algorithm [4]. The MST was determined after estimating the distances between households. The closeness of the households in the rural community allowed four conductors supplying 10 households each to be strung from the central PV supply location. This also ensured that there would be no requirement for poles and their associated costs since the conductor could be strung from house to house given sufficient ground clearance. The total line length was then estimated as 210 m using the above-mentioned network optimisation method.

Using single-phase two-wire line configuration, a cable size that would minimise voltage drop to within 6% was considered. Conductors considered were 13, 21 and 25 mm^2 ACSR (Aluminium Conductor Steel Reinforced). The voltage drops (V_D) of the lines were estimated from (4) using the proposed network's weighted loading, i.e. the product of the power drawn at each node and its distance from the beginning of the line [3]. The total weighted loading (*PxL*) of the households was obtained as 0.00873 kW·km. A power factor (p.f) of 0.9 and nominal a.c voltage (V) of 240 V were assumed.

$$\%V_D = 2(R_L \times p.f + R_{Lx} \times 0.44)\frac{(P \times L)}{V^2 \times p.f}.10^5 \qquad (4)$$

where R_L is the line resistance (ohm/km) and R_{Lx} the line reactance (ohm/km). The 25 mm^2 IEC standard ACSR cable with resistance 1.1 ohm/km and reactance 0.32 ohm/km was chosen for this case study in order to allow future load growth and minimise costs. Its voltage drop and line power losses for the 210 m line length were estimated as 3.8% and 0.0115 kW respectively as obtained from (4) and (5) respectively. Assumptions made were a conductor spacing (l_s) of 0.30 m with maximum load of 1.56 kW [3].

$$P_l = \frac{2}{3}(l_s \times R_L)(\frac{P}{V \times p.f})^2.10^3 \qquad (5)$$

3.6 Load Control

Load limiters would be installed in the households to limit consumption. The load limiters chosen were of type PowerProvider. The PowerProvider allows customers to draw supply current up to a specified maximum for which they are charged a fixed monthly fee. Once 1.1 times the maximum current is exceeded, the PowerProvider will automatically disconnect the supply and reconnect it after 15 seconds [5]. The PowerProvider is cheaper than the conventional meter and is easier to install hence reduced overall costs of electrification and billing [6].

The current ratings of the chosen load limiters were 0.25 A and 0.5 A which at 240 V give 60 VA and 120 VA respectively. For the 30 households with a maximum load of 29 W per household, two households could be connected to one 0.25 A rated load limiter using simple thermistors. For the 10 higher consumption households with maximum load 69 W, each household would be installed with a 0.5 A rated load limiter. The excess capacity would cater for future load growth.

4. Sustainability

In order to sustain the mini-grid, it was important to identify a responsible individual or organisation in the case study area to coordinate the operation and maintenance of its activities [3]. This was simplified by the fact that interest in Kabanga as a case study area had been initiated by the requests of a well established and relatively wealthy resident for electricity from the Rural Electrification Agency (REA). He demonstrated an ability and willingness to play a pivotal role in such a mini-grid project in this village. The issue of theft of solar equipment is a very important consideration in Uganda. Therefore, the ownership of the mini-grid by the community is key to ensuring that the equipment is adequately protected from theft and vandalism.

The Ugandan government's policy on rural electrification is highly favourable. The Ministry of Energy and Minerals together with the Private Sector Foundation of Uganda (PSFU) offers annual training on PV system operation and maintenance to rural area technicians and inhabitants. The installation of the above system in Kabanga would benefit from this initiative to ensure that qualified residents would be available to provide technical expertise in case of failures or routine maintenance.

5. Economic Analysis

The economic analysis was based on the financial evaluation of the investment for the entire system. Comparison was made between the PV system and a diesel generator supply. In order to establish the absolute or relative acceptability of the investment, dynamic methods proposed in [2] were applied on the two supply options.

Table II: Costs of the solar PV system (2009)

Component or activity/work	Quantity	Unit cost, UGS	Total cost, UGS	Life time, years
PV modules	6 modules each 175W_P	1,600,000	9,600,000	26
Support structure	6	350,000	2,100,000	26
Battery	12	850,000	10,200,000	10
Solar inverter	1	2,500,000	2,500,000	20
Off-grid inverter	1	5,000,000	5,000,000	20
Circuit breakers and switches			750,000	26
Installation material		1,500,000	1,500,000	26
Civil works			1,000,000	26
Installation cost			2,500,000	
	Total		36,100,000	

Table III: Costs of a diesel generator system

Components or items	Unit	Life time, years/hours	Unit price, UGS
Diesel generator, 5 kW	1	16	11,000,000
Fuel (diesel)	Litres	2.2 Litres/hour	2,050
Engine oil	Litres	3 litres/120 hours	8,500
Diesel filter	1	600 hours	45,000
Air filter	1	2,700 hours	120,000
Overhaul	1	25,000 hours	2,200,00

5.1. Results from Economic Evaluation

The inputs to the developed computer algorithm were variables such as costs, salvage values, life time of system components, etc. An interest rate of 8% was considered with consumers paying flat rates of UGS 16,000 and UGS 25,000 per month for low and medium demand consumers respectively. The economic evaluation results are illustrated in table IV. For simplicity the unit (kWh) cost presented is that when the generated electricity is sold to consumers at its production cost.

Table IV: Economic indicators for the two systems

Economic indicator	Solar PV System	Diesel generator system
Net Present Value (NPV), (UGS)	52,198,295	17,723,466
Internal rate of return (IRR), (%)	22	12
Annuity (UGS)	3,968,207	5,273,985
Cost of a kWh (UGS)	2,318	3,081
Payback period (years)	4.9	5.8

6. Conclusion

Proper load sizing and choice of system components for the solar PV mini-grid would ensure grid-quality electric supply to consumers. The long-term economic comparison with a diesel generator supply indicated more favourable results for a solar PV system. The annuity and unit energy production cost of a PV system are less than the costs related to the diesel generator systems. The NPV of the PV system is more than 2.5 times the NPV of the diesel generator system. However, the pay-back period of the PV system is less than that of the diesel generator system. Moreover, whereas the IRR for the two systems is greater than the interest rate, the PV system provides a higher IRR. On the long term basis, a PV system is more economically feasible for electrification of Uganda's remote communities with similar geographic, climatic, load and socio-economic conditions as those of the case study area. Besides the economic benefits, the PV system also presents greater environmental benefits.

7. References

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