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Research Article

Techno-Economic Assessment of a Hybrid Solar Photovoltaic – Diesel Genset for Rural Electrification, Case study of Namabasa Village – Uganda

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Abstract

In recent time, hybrid renewable energy systems are increasing being utilized to provide electricity in remote areas especially where the grid extension is considered very expensive. This study presents a techno –economic analysis of a Mini grid solar photovoltaic system for five (5) typical Zonal Communities in Namabasa ward Mbale District while promoting renewable energy system adaption and rural electrification. The assessment technique includes the establishment of the socio-economic state of the rural community through a field survey. The cost of system development ,electricity tariffs and sizing of energy production are realized via the Levelized Cost of Electricity (LCOE) technique Sensitivity analysis was carried out to identity the parameters that affect the evolution of the (LCOE) during the life of the project, the results have shown that the annual energy production at a rate of 12,693.2 Mwh/year and capacity of 1449kW, while the lowest is predict at Namabasa Zone II at the rate of 2847MWh/year a capacity of 325KW where business consumers. The standard (LCOE) for system during the 15-year lifespan in the five (5) zones is estimated 350/= per KWh except at Doko II, this cost per Kilowatt Hour is more attractive and competitive compared with the current rate charged by the National electricity company.

Nomenclature and units

kW	Kilowatt
kWh	Kilowatt hour

1.0 Introduction

The demand for modern energy services among the under privileged rural communities of developing countries has shown a considerable growth. Reliability, sustainability and affordability are key issues which must be considered when providing electricity to these communities. For example, Uganda (the country considered in this research) is among the few nations in the world endowed with a significant potential of renewable energy resources. However, only about 20% of the country's population has access to electricity and most of them found in urban settings. The low electrification rate in the country is among the major barriers for economic development and poverty reduction. The government of Uganda is committed to use modern energy services to contribute to the development goal of reducing poverty by self-determination, improving health and education. Indirectly this will also alleviate the pressure on over-crowded cities by minimizing rural-urban migration. Unfortunately, the demography of most rural communities is characterized by low population density and/or scattered population with low electricity demand. The kind of rural arrangement makes it financially challenging to attract national grid extension.

Various approaches have been deployed to extend electricity to these communities. Complementary off grid solutions using renewable energy applications have proven possible to bring the benefits of electricity services to many more low-income rural households. The fastest way to achieve the targets of universal electrification, the reliance on grid extension alone will not be sufficient but off-grid electrification through both, product delivery and local grid-based supply, will have to play an important role (Bhattacharyya, et al, 2016). The two options are considered to be potentially complimentary approaches (Bahaj et al, 2019). According to Pedersen (2016), mini-grid solutions are emerging as a third alternative to rural electrification, coming between the option of large-scale grid extension and pico-scale stand-alone solutions like solar home systems (SHS) or solar lanterns. The adoption of mini-grids in African countries is becoming popular to address electrification problems emerging among off grid populations in the rural communities. The mini-grids considered in this approach are utilizing clean and sustainable energy resources, using proven and low-cost technologies attracting business approach. The mini-grid option helps to address the reliability problem by extending longer hours of operation as reliable mixed generation can operate sustainably in a manner similar to the large grid networks. This is realized as a significant benefit for the off-grid consumers, with limited hours for electricity access rarely experience positive impacts to their socioeconomic development while the opposite is true for counterparts with longer access (Lozano et al, 2021).

The research study focused on the assessment of the feasibility of using a mini-grid with a hybrid power generation to electrify a community in Eastern Uganda. The community is remote from the national grid and characterized as a small trading center with significant population to attract the development of a local distribution network. The economic activities in the community indicate the demand for productive use of electricity for economic development. The research set to develop the technical design of the power system including the generation capacity and the layout of the distribution network, and economic analysis based on the anticipated periodical energy generation from the system. Provision of power to the community depends on the viable demand, thus the load or demand is assessed considering the various groups of consumers. In the selected community the consumers are categorized as: households, business and institutions.

2.0 Materials and Methods

2.1 Load Profile as Input for Sizing and Operation

Load profile was categorized as daily, weekend, monthly and annual load profile. There are several references concerning how load curves are developed to design mini-grids. Using information about the energy demand and usage patterns in households in several areas nearby for already electrified communities was adopted. This information is availed by the local utility. By acquiring demographic data and daily activities patterns of the communities then the hourly demand profile of basic electricity demand (named "basic" demand) and a forecast demand profile (named "aspirational" demand), by combining the basic loads with aspirational loads, to be formed of desirable devices, assuming their usage in line with known population and literature. Then to hypothesize different service levels for the households as well as consumption for public services such as lightning or water pumping. The resulting load profile for the village is presented along with a design proposal.

2.2 Developing Demand and Load Characteristics

This includes the assessment of the users or application subsystem or demand subsystem. This subsystem includes all the equipment on the end-user side of the system, such as meters, internal wiring, grounding, and the devices which use the electricity generated by the hybrid power plant. But the research is aiming at assessing and characterizing demand. The development of the proposed mini-grid system in Namabasa community will depend on the viability of demand for economic sustainability of the system. Estimation of demand and supplies for electricity resources has become important when clarifying the issues involved in bringing supply and demand into equilibrium.

The load depends on the uses of electricity which include household or domestic uses and productive use. The productive use of electricity is considering the three categories:
Livelihoods focus - agricultural, commercial and industrial activities that generate income through consumption of electricity
Energy focus - income generating activities that increase consumption of electricity
Socio-economic focus - livelihood activities plus other activities related to health, education, connectivity, e-mobility etc.

Prospectus small scale industrial owners in the area are among those that jointly look forward for electrification. Key among them include maize and rice mills that highly demand for electricity to be distributed. Apparently, some maize mills in the area use generators run by the diesel. This means that there is high demand for electrification for small scale industrial purposes in Namabasa ward for the three-phase. The other grouping is the domestic consumers. Their demand for power is high but meant for domestic use like lighting among other purposes. Apparently, homes use solar power panels, kerosene (paraffin) as the sources of light. Electrification is therefore necessary to improve the lighting system in the residential areas of Namabasa ward.

2.3 Load Model

Load modelling is an integral part of many studies in power engineering. Load models are among some of the most challenging models to develop. This is due to the ever-changing nature and unpredictability in end-use behavior. To develop accurate demand curves, load forecasts employing decades of data as well as economic and sociological trends have to be undertaken. Statistical methods may then be employed to probabilistically predict variations in demand curves.
However, for the purpose of this research a simplistic approach is used to model the nature of the load. A typical relative demand profile is used (typical for developing in countries). The relative load, defined as a percentage of the peak load, is then multiplied by the peak load of the day to produce the daily load curve.

The variation in daily peak demand is assumed to follow a Gaussian (normal) distribution. A new normal random variable representing the peak load is therefore generated for each day in the simulation timeline.

$$P_{peak} = \mu + Z\sigma \tag{1}$$

where:
μ is the mean peak demand.
σ is the standard deviation
Z is the randomly generated z-score of the normal distribution.

The mean peak demand, μ, is provided by the user and it represents the assumed long-term average peak demand of the given system. This method requires the standard deviation has to be known. The value of standard is rarely known, however. In this case, it is determined by defining the Gaussian distribution, whose mean is the average peak demand, using the total installed capacity of the system P_{inst}. The total installed capacity, P_{inst} is assumed to be 3 standard deviations away from the mean. Furthermore, P_{inst} is determined using typical a typical demand factor value for the given location.

$$P_{inst} = \frac{average\ peak\ demand}{demand\ factor} \tag{2}$$

$$3\sigma = P_{inst} - \mu \tag{3}$$

The typical load profiles for rural communities in the area are based on the previous research done in the country (Sendegeya, 2010). The relative load curves for the weekdays and weekends are given in figures 3.1. The curves are giving an average load factor of about 55%. These are the load profile curves that are used in the research. The relative load is based on the peak demand; therefore, the load characteristics of the community have been presented in terms of the possible peak demand by different categories of consumers (domestic, business and social consumers).

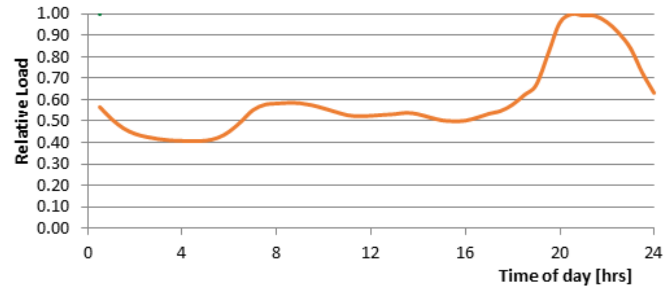

Figure 1: Weekend load profile.

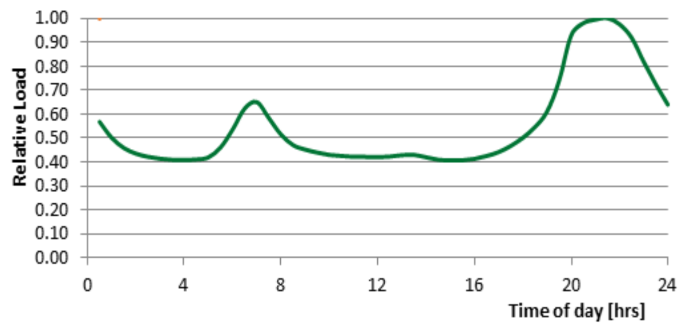

Figure 2: Weekdays load profile.

2.4 Modelling Generation

This subsystem includes the generation (solar PV System and genset), storage (batteries), converters (convertors, rectifiers, and inverters to convert DC power to AC), and management (energy management systems) components. The production subsystem determines the capacity of the hybrid system to provide electricity, and connects all the components through the bus bar (i.e., the electrical wiring connecting the different components together) at the required voltage (AC/DC) for the distribution subsystem.

The size of each generation technology (Solar PV and Genset) will depend on the available demand and the demand characteristics as to be developed in the load assessment. Using the meteorological data about solar energy resource together with the demand, the components of a solar PV system and layout will be developed. The strategy will be using the static and/or dynamic solar sizing system. The capacity of the genset will depend on the contribution from solar generation to the load, the operational requirement of the genset and the reliability requirement.

2.5 Modelling Diesel Genset

Diesel gensets are referred to as thermal power plants and also referred to as dispatchable plants, whereby the generation can easily be controlled provided the fuel supply is assured. The thermal power plants under consideration are those powered directly by regular fossil fuel (diesel) engines. Diesel generators dominate remote power applications compared to gasoline generators. Its common practice in theory to model thermal power plants using a quadratic function. The model is based on the fuel consumption relationship between fuel consumption and power output. The fuel consumption functions of the fossil-fueled thermal generating unit in the form:

$$F = aP^2 + bP + c \tag{4}$$

where P is power output of the unit (in kW), F is the amount of fuel consumption (in liters of fuel per hour) and a, b and c are constants.

Power system comprises of more than one gensets, the sets are modelled as (for the k[th] genset):

$$F(P_k) = aP_k^2 + bP_k + c \tag{5}$$

and the generation limits are: $P_{MIN,k} \le P_k \le P_{MAX,k}$.
If the cost of the fuel used is known then the fuel consumption function is converted into a cost function, thus, for each plant the cost functions, $F(P_k)$ *given in [¤/hour], where the symbol "¤" represents a fictitious currency e.g., it can represent US$ or UGX.* The information used to develop this kind of model is obtained from the manufacturer's data sheets. The data includes the power output rated capacity, fuel consumption rates related to percentage power generation from genset.

2.6 Modelling Generation from Renewable energy

The renewable energy systems considered are the as non-dispatchable supply options, examples include solar, wind and small hydropower (run-of-the-river type). The systems are non-dispatchable because the flow of the resources is beyond the users' control. Generation from these sources normally follows the statistical nature of weather conditions, thus a random variable which requires probability modelling methods. The non-dispatchable supply option used in the model is generation from solar resource utilizing direct conversion technology using photovoltaic technology. The modelling of generation from the solar resource begins with the assessment of the resource.

PV array sizing: A round trip efficiency of 85% was assumed and the design month of the lowest solar insolation considered.

$$\text{Required array output per day } (A_{od}) = \frac{Dt}{Be} \tag{6}$$

$$\text{Design operating voltage for each module } (V_{op}) = V_{ms} \times B \tag{7}$$

$$\text{Amount of Energy produced by array per day during worst month } (E_{om}) = P_{rated} \times H_p \tag{8}$$

$$\text{Module Energy output at operating temperature } (E_{ot}) = D_F \times E_{om} \tag{9}$$

$$\text{Number of modules to meet energy requirement } (M_{Np}) = \frac{Aod}{Eom} \tag{10}$$

$$\text{Number of modules required per string } (M_{NS}) = \frac{Vbs}{Vms} \tag{11}$$

$$\text{Total number of modules to be purchased } (M_{Nt}) = M_{NP} \times M_{NS} \tag{12}$$

$$\text{Nominal rated array output } (A_N) = M_{NP} \times M_{ON} \tag{13}$$

Inverter sizing: Assumption made are that inverter value shouldn't be lower than the total wattage and that 20% should be allowed to cater for system losses

$$\text{Inverter size } I_S = W_t \times 120\% \tag{14}$$

Sizing the MPPT inverters: This was done by comparing the peak power output of the SPV array, maximum voltage and current input. Redundancy is always required; however, the systems are designed with two or more inverters, to allow for convenience in future expansion.

2.7 Modelling of battery storage

Battery bank was designed for power storage. For battery storage, provides enough capacity with autonomy for the purpose of supplying the load when the sun goes (sunset, night time and early morning hours). At any hour the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from t-1 to t. During the charging process, when the total output of PV is greater than the load demand, the available battery bank capacity at hour t can be described as:

$$C_{bat}(t) = C_{bat}(t-1).(1-\sigma) + \left(E_{PV}(t) + E_{WG}(t) - \frac{E_L(t)}{\eta_{inv}} \right) \eta_{bat} \tag{15}$$

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at hour t can be expressed as:

$$C_{bat}(t) = C_{bat}(t-1).(1-\sigma) - \left(\frac{E_L(t)}{\eta_{inv}} - \left(E_{PV}(t) + E_{WG}(t)\right) \right) \tag{16}$$

where $C_{bat}(t)$ and $C_{bat}(t-1)$ are the available battery bank capacity (Wh) at hour t and t-1, respectively; η_{bat} is the battery efficiency (during discharging process, the battery discharging efficiency was set equal to 1 and during charging, the efficiency is 0.65 to 0.85 depending on the charging current).
σ is self-discharge rate of the battery bank. $E_{PV}(t)$ and $E_{WG}(t)$ are the energy generated by PV and wind generators,

respectively; $E_L(t)$ is the load demand at hour t and η_{inv} is the inverter efficiency (in this study it is considered as constant, 92%).

At any hour, the storage capacity is subject to the following constraints:

$$C_{bat\,min} \leq C_{bat}(t) \leq C_{bat\,max} \quad (17)$$

where $C_{bat\,max}$ and $C_{bat\,min}$ are the maximum and minimum allowable storage capacity.

Using for $C_{bat\,max}$ the storage nominal capacity C_{batn}, then

$$C_{bat\,min} = DOD.C_{batn} \quad (18)$$

where DOD (%) represents the maximum permissible depth of battery discharge.

2.8 Modelling Generation from Solar Photovoltaics

The modelling of expected generation from the PV module is not established using the traditional solar PV sizing methodologies. The assessment is based on the expected energy supply from the PV arrays and the available solar radiation. To have the relationship between the supply from the PV with the genset, also a cost function is developed. The cost of PV module is dominated by the initial cost and limited or almost zero variable operation costs. However, to cater for the other costs related to cleaning, maintaining and replacement of some system components, a cost component which varies with power supply is also considered.

In this case a linear model for the cost function is assumed: $F = \alpha P_k + \beta$ (19)

where P is power output of the unit (in kW), F is the operation cost (in liters of fuel per hour) and α and β are constants. The generation limits are: $P_{MIN} \leq P_k \leq P_{MAX}$ depend on the specifications of the inverter system used. Similarly, the cost function is *given in [¤/hour], where the symbol "¤" represents a fictitious currency e.g., it can represent US$ or UGX.*

The cost function constants are obtained from the annuity of the components replaced during the life time of the system and the fixed component of the investment cost. As follows:

$$\alpha = \frac{C_{01} \times CRF\left[\frac{¤}{year}\right]}{\frac{kWh}{year}} \quad (20)$$

where C_{O1} is the initial capital cost of the equipment replaced during the operational or life time of the system, CRF is the capital recovery factor obtained for the operational years of the components to be replaced. The main component replaced in a solar system during its operational life time is mainly the battery and inverter. Assumed to be replaced every after 10 years, kWh/year are the annual units of energy supplied by the renewable energy system.

$$\beta = \frac{C_{02} \times CRF\left[\frac{¤}{year}\right]}{\left(\frac{24hrs}{day} \times 365\frac{days}{year}\right)} \quad (21)$$

where C_{02} is the initial capital cost of the main solar PV equipment which operated through the life time of the system, CRF is the capital recovery factor obtained for the same period.

The panel costs were taken as Fijian 32,000,000/= per kWh. The life time was taken as 25 years.

2.9 Schematic configuration of the Proposed Solar PV System

The system shall consist of solar modules, inverters, Batteries, MPPT charge controller and accessories for measuring and communication. The schematic diagram in figures below illustrates the system configuration and lay-out.

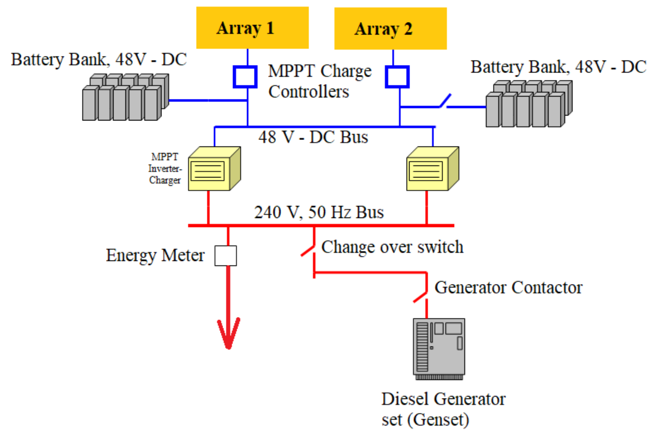

Figure 3: Schematic diagram of SPV system configuration.

2.10 System Investigation

Appropriate tools for investigation were used to size all the components of the solar PV system. The assumptions used during design include:

The plant capacity was to be agreed upon basing on demand forecast to be satisfied versus resource envelope for implementation of works;

Modules were to be mounted on existing roofs or independent power houses/ containers for energy systems for education, health and local government offices. Modules for water pumping systems will be ground mounted;

Mono or poly-crystalline modules was used;

Deep cycle batteries, MPPT charge controllers and Inverter-chargers was used for energy systems for education, health and local offices;

Solar water pumping inverters with MPPT capabilities was used;

2.11 Distribution Network

This subsystem includes the distribution equipment. This subsystem is in charge of distributing the produced electricity to the users by means of the mini-grid. The primary issues to assess are whether to make use of a distribution mini-grid based on DC or AC, and whether to build a single phase or three-phase grid. The decision depended on the impact on the cost of the project and mainly determinate the devices which were used.

The distribution of electric power includes that part of an electric power system below the sub-transmission level, that is, the distribution substation, primary distribution lines or feeders, distribution transformers, secondary distribution circuits, and customers' connections and meters among others. There are several components that were considered for use in the network in case study community. Pole-mounted distribution transformer with center-tapped secondary winding used to provide "split-phase" power for residential and light commercial service, were be used accordingly. A transformer is a passive component that transfers electrical energy from one electrical circuit. Aluminum cables and surge arrestors are also among the components used. They are used around transformers such that they are earthed. The method of earthling was Protective Multiple Earthing (PME). Wooden poles were used accordingly as part of the components in the distribution network. On the poles are cups that are called pole cups placed on the top of every pole. However, another pole cup is placed at the bottom of the pole before it is planted or mounted in the ground.

2.12 Modelling losses

The distribution network assumed to be using insulated Areal Bundled Conductors (ABC). These conductors are having various advantages despite the challenges related to initial costs. Therefore, the power loss in the distribution network is modelled as follows:

$$P_{loss} = I^2 R \tag{22}$$

where the current depends on the distribution voltage of V_P, power factor (cosφ) and power delivered to the load, P_L. At the distribution resistance R, thus, the loss model simplified as

$$P_{loss} = \left(\frac{P_L}{V_P cos\phi}\right)^2 R = \frac{R}{(V_P cos\phi)^2} {P_L}^2 \tag{23}$$

The typical values of the distribution network considered are: V_P = 240 V, cosφ = 0.8 and R = 0.62 Ω/km, then the loss function is modeled as:

$$P_{loss} = \frac{0.62\frac{\Omega}{k}\times 26\ km}{(240\ V\times 0.8)^2} {P_L}^2 = 0.00043728{P_L}^2 \tag{24}$$

2.13 Design of Hybrid Power Supply Systems

The type of mini-grid considered in the design consist of specialized components for the generation, distribution, metering, and consumption of electricity. A typical mini-grid used in the research consists of a solar-hybrid generation system that includes solar panels, batteries, charge controllers, inverters, and diesel backup generators. The distribution network consists of poles and low-voltage wires; larger mini grids sometimes also have medium-voltage systems. The system considered the use of smart meters that provide both prepaid payment options for consumers and real-time, granular information about energy consumption patterns and system performance. For modernity the use remote monitoring systems was considered, which allows operators to identify technical issues before they affect energy services and rectify problems quickly and inexpensively, thus improving the quality of customer service. The research proposed to encourage and incentivize customers to use efficient appliances for household uses as well as efficient machines and equipment for income-generating activities, and proposed ways to provide or facilitate access to financing options to help customers overcome any barriers presented by upfront costs.

A hybrid mini-grid proposed composed of three subsystems: the production, the distribution, and demand subsystems. Each subsystem varies greatly in its components and architecture according to the availability of resources, desired services to provide, and user characteristics.

2.14 Technical Analysis

The technical analysis was done using RET Screen software, sizing, simulation, and data analysis of complete hybrid system. The software has an extensive database of meteorological data for different locations, system components, and their specifications from manufacturers and simulates the performance of the PV system and other generation options (hybrid generation), taking into consideration the various possible losses. The total energy yield of the system is the total amount of energy generated by the system against the case study system, the total amount of electricity that is supplied into the load. The annual energy yield and the share of the generation systems with the load to be presented based on different scenarios through a sensitivity analysis. The capacity factor of a power plant at the ratio of the actual output of a power plant over some time and its potential output if it had operated at full nameplate capacity the entire time was assessed under different scenarios. The initial costs for the proposed system to include both equipment and installation costs.

2.15 Power Balance

It should be noted that the energy requirements on any power network varies periodically, i.e., hourly daily, weekly, monthly, annually and seasonally. For example, following the daily load curve, generally the energy demand is higher during the daytime and during early evenings when business loads are high, lights in the residential and commercial establishments consume large amount of electrical energy. However, during late in the evenings and early mornings when most of the establishments are closed the energy requirement is low. Similarly, the energy requirement during week days is higher as compared to weekend days.

One option would be to connect all the available generating units on to the bus bar all the time so that any amount of energy requirement can be met. But this is highly uneconomical as during off-peak periods some of the units may not be contributing much, yet we are spending lot of fuel to keep them synchronized with the grid. A lot of saving in fuel cost can be made by switching off some of the units (generators) when these are not required. Unit commitment is, therefore, one way to suggest just sufficient number of generating units with sufficient generating capacity to meet a given load economically with sufficient reserve capacity to meet any abnormal, operating condition *e.g.,* failure of one of the generators *i.e.,* to commit generating capacity to obtain reliable and economical supply for a given load. The study considered the unit commitment problem purely from economic point of view.

2.16 Economic Analysis

Since more concerns are given to the lowest energy cost in such projects, the economical approach can be the best benchmark of cost analysis. Several methods are used to evaluate different options for energy system; the levelized cost of energy is often the preferred indicator (Nelson et al., 2005; Ramakumar et al., 1993). In this section, an economic sizing model is developed for the HPWS according to the LCE concept.

The economic analysis of the entire system will be carried out to assess the cost and intended benefits of the project. This was carried out using RETScreen software. The software is easy to use and has the capability of simulating the net present value and simple payback period as well as estimating the greenhouse gas saving potential of renewable energy projects over their entire operational life. The costs of the various solar PV components used for this study were international and local estimates taken from the online and Directory of local Solar Companies, this will be the same for other equipment. The cost of developing a distribution network to be obtained from the utility and Rural Electrification Agency (REA).

The economic analysis was accomplished by first developing a base case scenario consisting of the current electricity cost and other financial parameters. Then subsequent scenarios developed from the base case to help analyze the implications of the various financing options on the project. The scenario to include different discount rates and inflations, different levels of subsidies, various load growth levels and generation mixes. The economic parameters to be considered at different scenarios including generation mixes, levels of subsides and discount rates are: internal rate of return, levelized cost of energy (LCOE) and marginal cost of energy, pay back etc.

2.17 Pay back

Payback is a quick method for comparing different alternative energy projects. Simple Payback Method Payback considers the initial investment costs and the resulting annual cash flow. The payback period is the amount of time (usually measured in years) to recover the initial investment in an investment or energy project as considered in this project. Unfortunately, the payback method doesn't account for savings that may continue from a project after the initial investment is paid back from the profits of the project, but this method is used for a quick assessment or analysis of a project.

Payback with Equal Annual Savings: If annual cash flows are equal, the payback period is found by dividing the initial investment by the annual savings. Payback Period (in years) = Initial Investment Cost divide by the Annual Operating Savings.

Payback with Unequal Annual Savings: In reality, there are significant costs such as depreciation and taxes that will cause cash flows to vary each year. If the annual cash flow differs from year to year, the payback period is determined when the accrued cash savings equal the initial investment costs (i.e., when the cumulative cash flow balance equals zero).

2.18 Methodology for NPV and IRR

A number of tools are available for financial analysis of projects including the time for recovery of investment, internal rate of return (IRR), and the Net present value (NPV). The following parameters are essential inputs to a financial analysis formula: Initial Investment costs, Gross benefits obtained from energy sales, Operation and maintenance costs; and Prevailing interest rates (Central Bank & Commercial rates) and Operational period. Calculation of NPV and IRR gives a fairly precise idea of the economic performance of project. The former value (NPV) provides the amount of savings obtained and the latter (IRR) the rate of interest that would make the reference and proposed project economically equivalent. Consequently, the information obtained may be considered complementary. The formula and methods used for financial and economic analysis are listed below:

Net Benefits (NB): These are sales as the outcome of the energy delivered by the plant to the load centers.

PV costs: The Present Value [PV] of costs was calculated as the sum of the investment costs and the discounted value of the operation and maintenance costs as follows.

$$PV_{costs} = Investment_{cost} \times PV_{O\&M\ costs} \quad (25)$$

Gross benefits: The Present Value of discounted annual benefits (energy sales) is calculated for the project. This includes discounted benefits during each year of the useful life of the power plant.

$$PV_{benefits} = \frac{[(1+i)^n - 1]NB}{[i(1+i)^n]} \quad (26)$$

where i is the initial discount rate; n is the number of years; and NB is the Net Benefits

Net Present Value

One of the advantages of the Net Present Value (NPV) method is that is accounts for the time value of money (i.e., the value of a shilling tomorrow is not the same as a dollar today). The NPV method determines the worth of a project over time, in today's money. Unlike the payback method, NPV also accounts for the savings that occur after the payback period. The greater the NPV value of a project, the more profitable it is. This method will be used to rate and compare the profitability of several competing options. The Net Present Value is calculated as the difference between the Present Value of benefits and costs (including operation and maintenance costs).

$$NPV = PV_{benefits} - PV_{costs} - PV_{O\&M\ costs} \quad (27)$$

Internal Rate of Return

An economic index called the Internal Rate of Return (IRR). This index is, by definition, the rate of interest that reduces NPV to zero. The internal rate of return (IRR) is defined as the discount rate that makes the net present value (NPV) of all cash flows (both positive and negative) from an investment or project equal zero.

It is the expected compound annual rate of return that is earned on an investment (Maginm 2010). In the research the formula was be used and the simulation was based on any of these two ways of calculation: using Excel and/or using an iterative process where the analysis tries different discount rates until the NPV equals zero. Since the IRR is obtained in the same line with the NPV, then is offers the advantage of accounting for the time-value of money. IRR is ideal for analyzing capital budgeting projects to understand and compare potential rates of annual return over time. The IRR is an indicator to measure the return on investment of an energy project as an income generation project and is used to make the investment decision. A project is feasible if the calculated interest rate (IRR) is far higher than the prevailing bank interest rate.

$$IRR = r_a + \frac{NPV_a}{NPV_a - NPV_b}(r_b - r_a) \qquad (28)$$

where,
r_a = the lower discount rate used in the calculation
r_b = the higher discount rate used in the calculation
NPV_a = NPV at lower discount rate
NPV_b = NPV at higher discount rate

Generally, the Internal Rate of Return is the **interest rate that makes the Net Present Value zero**

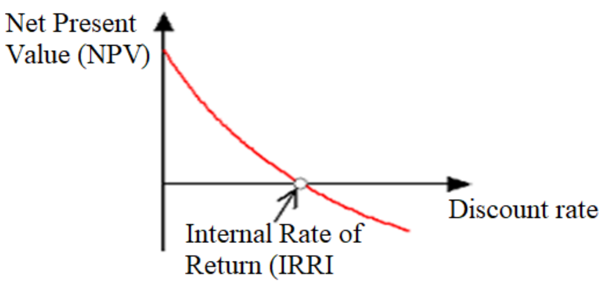

Figure 3: Plot of NPV versus discount rate, showing the point for IRR.

It is also common practice to consider another concept of performance known as the Return on Investment (ROI). It is an indicator that can be used in the analysis of investment energy projects. ROI is a concept of performance in any form of investment (Zamfir et al, 2016). The indicator is obtained as the ratio between the operating profit obtained after the action of investment and the total amount invested (or the total investment costs).

2.19 Cash-Flow Statement of Project

After the NPV and IRR analysis of the project option were computed, the cash-flow statement of the project was carried to assess the real project cash benefits, expenses and savings. This is essential to determine the periods when operation and maintenance funds are needed from outside sources, and the periods when the project will break-even to its positive savings and sustainability, amidst any requirements from re-investments.
Factors considered for perfect project cash flow included the following: Capital investment costs, Regular operation and maintenance costs, Repairs and replacement of parts due to aging, Amount of energy sold to customers, Energy end-user sales tariff and Central bank-Inflation and interest rates.

2.20 Levelized Cost of Energy (LCE)

For the purpose of this research, the levelized cost of electricity/energy (LCE) represents the energy-normalized cost of generating and distribution assets by considering all associated costs (investment and operation). The total energy generated and supplied over the life cycle of the system. Since the LCE is a levelized value, it provides a quick and easy measure to compare different energy resource technologies with different characteristics. There are various models to determine LCE, presented by different researchers and organizations (Lotflet al, 2016). All methods are basically based on dividing the sum of the net present costs of capital, fuel, and O&M costs associated with producing energy, by the sum of total energy produced in the asset lifetime (Lotfl et al, 2016; Ragnarsson et al, 2015). The research will make use of this quantitative definition to determine the cost of supplying energy which will be the basis to estimate the possible tariff. The parameter will be obtained at different economic variables and different operational scenarios. The levelized cost of energy is defined mathematically as

$$LCE = \frac{TPV \times CRF}{E_{annual}} \qquad (29)$$

where, E_{annual} is the yearly output in kWh, TPV and CRF are the total present value of actual cost of all system components and the capital recovery factor, respectively, which can be expressed as follows:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (30)$$

$$TPV = \sum_{i=1}^{N} C_{System,i} \qquad (31)$$

where, *i* is the annual discount rate, *n* is the system life in years, $C_{system,k}$ is the sum of present value of capital and maintenance costs of the power generation plant or system "k" in system life. The systems include the power generation systems, storage and distribution network. For the battery storage the costs include the sum of present value of capital and replacement costs of battery bank in system life.
In this research, it is assumed that that the system life is the life of the PV arrays corresponding to 25 years and the storage system life is 7 years. Therefore, the battery storage will need to be replaced several times along the system lifetime, while the rest of the components can last the entire system life. Additionally, the balance of system (BOS) costs, referred to support structure, power conditioning and interface units, installation and safety and control components, is taken as 50 % of the cost of PV module. The annual maintenance cost has been set at 5% of capital cost for the PV generator and 0.5 % for the storage batteries. The annual discount rate is considered as 10%. For the purpose of sensitivity analysis, the annual discount rate if investigated in the range between 6% and 18%. However, in practice the loaning financial

institution rates are used. For large capital projects the discount rates considered are as given by the IMF and world bank. At local level the discount rate used is as provided by the central bank.

2.21 Assumption for the Financial Analysis

For the financial analysis it is assumed that the projects under consideration can be funded through public means, where funds are secured from financial institutions with commercial interest rates. The costs will include the entire project cost of installation and/or construction. The cost estimates comprise, operation and maintenance and financial analysis:

Table 1: Cost estimates

S/N	***ITEM/DESCRIPTION***	**QUANTITY**	**UNIT COST**	**AMOUNT**
1	Generators	2pcs	5,000,000	10,000,000
2	Solar panels	10 pcs	300,000	3,000,000
3	Batteries	6 pc	600,000	3,600,000
4	Inverter	1 pc	500,000	500,000
5	Frames for stand alone	6pcs	150,0000	900,000
6	Fuel tank	1 pc	2,000,000	2,000,000
7	Fuel	60 liters	6000	360,000
8	Cables A.C	5Rolls	300,000	1,500,000
	D.C	5 Rolls	400,000	2,000,000
9	Poles metallic	20 pcs	50,000	1,000,000
10	Protective devices (Fuses)	5 pcs	50,000	250,000
11	Switches	5pcs	20,000	100,000
12	Socket outlets	10 pcs	20,000	100,000
13	Metering	1pc	100,000	100,000
14	Loads A.C	10pcs	30,000	300,000
	D.C	10pcs	30,000	300,000
15	Earthing systems	1pc	2,000,000	2,000,000
16	Lightening Arrester	2pcs	2,000,000	2,000,000
17	Battery Banks	1pc	1,000,000	1,000,000
	GRAND TOTAL			**31,010,000**

Cost estimate: The cost estimates include cost estimates for entire plant and installation services, including operation & maintenance aspects for two options to be discussed. The costs have been made in United States Dollars (USD) and including the cost of engineering and supervision, as well as environmental and social impact mitigation based on the results of the situational assessment study.

The costs are categorized as Capital investment costs and Operation and maintenance costs for the purpose of facilitating the foregoing financial and economic analysis for each respective power generation/supply option.

Operation and Maintenance (O&M) costs estimation: To ensure sustainability of the power plant, the costs for O&M take into account the following cost factors: General maintenance and repairs for power plant, Office running costs, Wages/salaries plus allowances for O&M staff & management committee and Pool funds towards the replacement of battery bank, inverters and major repairs of equipment within the planning horizon of 10-years.

Financial analysis: For each of the technically evaluated alternative in the sensitivity analysis, the net present value and internal rate of return are computed using the considered discount rates.

3.0 Results and Discussion

3.1 Case Study Community

The case study community was Namabasa village located in Mbale City District eastern Uganda. The place is in Namabasa Parish, Nakaloke Sub County, Bungokho county, at, Latitude: 1;1131^{0}N, Longitude: 34.14993^{0}E (map in figure 1). The place is about 35 km from the main grid. The village is made up of proposed seven (7) load centers meant to distribute power to the targeted consumers. The load centers are apparently being installed with distribution transformers. A distribution transformer or service transformer is a transformer that provides the final voltage transformation in the electric power distribution system, stepping down the voltage used in the distribution lines to the level used by the customer. The invention of a practical efficient transformer made AC power distribution. It is anticipated that installation of the load centers is still on-going and could take a relatively long time. This is because the Namabasa ward is relatively big area of 23.6km squared and with a population density of 3.3% annually as per the population change of between 2015-2020. The population is estimated to be 8090. However, it is hoped that real time for installation is one year and the process is still ongoing.

3.2 Site Conditions and Meteorological Data

All proposed systems and components should be designed, manufactured, engineered and installed in a manner that in their proper functioning is observed. They should withstand the average climatic conditions and environment within Uganda during their normal lifetime.

Table 2: Average Climatic Conditions of Uganda (Source: NASA)

Altitude of project area above Sea Level (m):	1,041
Ambient Temps:	Max. 29.2ºC and min. 22.5ºC
Relative Humidity:	Max. 73.2%, Min 38.8%
Rainfall Average annual (mm):	1000
Maximum wind load (outdoor wind gusts):	20 m/s at 10m above the ground
Air Mass:	AM1.5
Atmospheric pressure:	89.6 kPa

3.3 Solar Resource Assessment

Data obtained from SolarGis has been used to assess the solar resource of Uganda. From this map the average annual irradiation for Uganda can be estimated at 1,770kWh/m^2 per year.

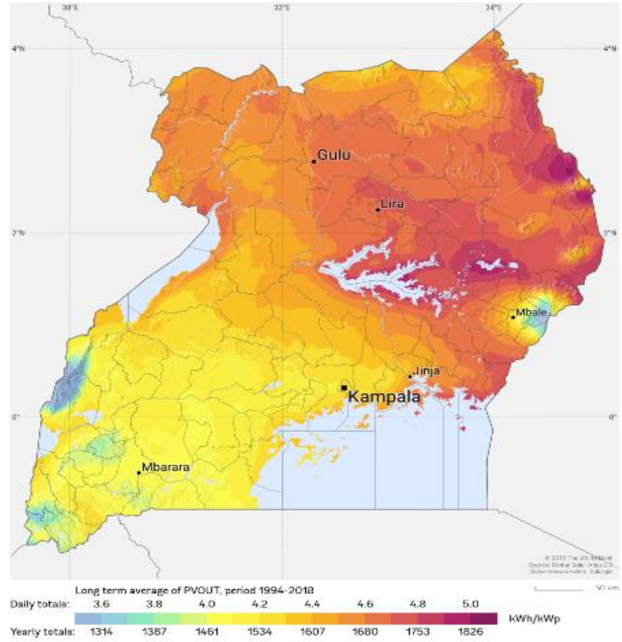

Figure 5: Solar Resource Map (Source: https://solargis.com/maps-and-gis-data/download/uganda)

Sizing of the solar-photovoltaic (SPV) array uses the solar radiation (W/m^2) and insolation (kWh/m^2/day) of the area, given its geographical location (latitude and longitude). Once the location is known, solar meteorological data can be got from online weather resources such as the NASA website and RETScreen. Table 3 shows the solar radiation data of the project areas used in sizing the system. It can be seen that, in this area of Kololo, the average solar radiation is about 5.28kWh/m^2/day; while the equivalent number of no-sun or dark days is 3.28 (79hours) per month. This means that, the battery storage autonomy needs to take care of this shortfall, to ensure that the required energy within the estimated dark days is provided for 100% system reliability.

Table 3: Daily insolation data for Project site (source NASA) includes latitude 1.1049 degrees and Longitude 29degrees

Monthly Average Radiation Incident on An Equator-facing Tilted Surface (kWh/m^2/day) – 15^0 max tilt													
Calendar Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average Annual
Monthly Average daily Insolation (kWh/m^2/day)	5.76	6.05	6.16	5.72	5.47	5.12	5.14	5.39	5.88	5.56	5.40	5.54	5.60
Equivalent "No of Sun" days	7.4	7.0	7.9	7.1	7.0	6.4	6.5	6.8	7.3	7.1	6.8	7.1	7.03

3.4 Assessing Demand for the Community

In this section a qualitative description of demand or categorization of consumers is presented. The potential electricity consumers are categorized as domestic consumers, business consumers, social services.

3.4.1 Domestic Consumers

The village comprises of about 2000 households (HHs) with an estimated population of 8200 persons expected to have a growth of 3.3% per annum. This gives an average household to have about 4.2 persons. The average energy consumption in a standard household in Uganda is about 0.886 kWh per month. The peak load requirement for an average household is about 0.385 kW, this gives approximately a peak demand of domestic users to be 0.770 kW. The use of electricity in most of the households is mainly for lighting, radio, phone charging etc. The use of electricity for cooking is not yet popular in most parts of the country.

3.4.2 Business Consumers

These include: shops, kiosks, markets, guest houses, welding machines and milling machines. The established numbers and estimated load requirements are summarized as in the table 4. The village is located at the outskirts of Mbale City whereby the place is busy with various business places including retail and wholesale shops. The place is located along the high way to the eastern part of the country, therefore there a number of guest houses and resting places developing in the area. Considering the increasing population in area with the development of residential houses there is increasing need for carpentry and welding workshops. The place is well known for nature of agricultural practices where the growing of crops like beans, sorghum and maize are common. The staple food of the region is mainly these cereal foods. Therefore, there is an increased number of milling facilities in the area.

Table 4. Business Loads at Namabasa ward Mbale District

Type of Business	Quantity	Daily Estimated peak, kW	
		Unit	Total
Shops	60	2.5	150
Guest Houses and Restaurants	30	3.5	105
Grinding machines	3	10	30
Welding machines	5	8	40
Total			**325**

The energy estimations are based on the peak demand and load factor. The peak demand is obtained from information availed by the utility company in the area. The daily energy demand is estimated basing on the load factor of 0.42 a typical value for such facilities as there are operated for few hours on a day.

3.4.3 Social Services

The social services include: schools, health centers and worshiping places. There are 3 government health centers, 5 private clinics and seven drug shops. There are nine (9) schools which comprise of 6 primary schools and three secondary schools. The worshiping centers are twenty-five (25) in total including Catholics, Anglicans, Pentecostal, mosques and orthodox churches. The daily load factor for the health facilities is slightly higher than those of other social facilities. The value for health facilities is estimated to be 72% and the other facilities is considered to be 2 8%.

Table 5: Social services at Namabasa ward Mbale District

Type of Business	**Quantity**	**Daily Estimated peak, kW**	
		kW	**Total**
Health Centers	3	3	9
Private Clinics	5	2.7	13.5
Drug shops	7	1.2	8.4

Primary Schools	6	2.5	15
Secondary Schools	35	6.8	238
Worshiping places	25	2.8	70
Total			**353.9**

The total peak load assuming it takes place at the same time will be 1,449 kW. This gives an average load of 797 kW basing on the load factor of 55%. The daily energy demand direct to the load estimated to be 19,125 kWh. The annual energy production becomes 14498x365x24 =12,693,240 KWh which is 12,693.2 MWh/year with the lowest being for business consumers 325x365x24=2,847,000kwh (2,847Mwh).

The load is sectionalized into hourly average values using the relative load curve for the weekly characteristics. The plot given in Figure 4.4 shows the load curve for the community based on the aggregated peak demand of about 1.5 MW.

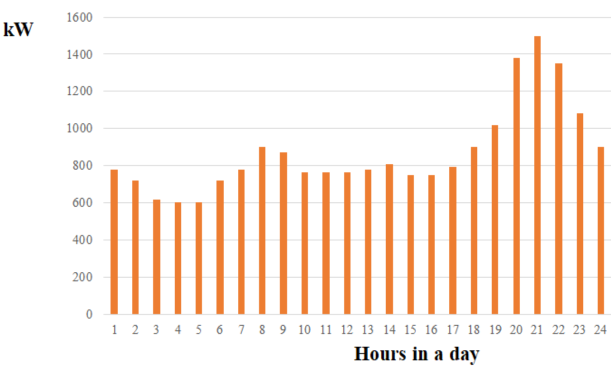

Figure 6: The estimated Load Profile the given Community.

3.5 Generation Systems

Considering the load characteristic and capacity to ensure autonomous supply three diesel generator sets (gensets) are suggested to be used in hybrid with a solar PV system. The standalone PV system will be using two parallel inverters each rated 500 kVA operating at power factor of 0.8.

3.5.1 Gensets Model

The capacity of genset used was 1000kVA operated at 0.8 power factor. The generators are operated for 8 hours each daily. This ensured reliability of supply when the gensets are not over-stressed. The generator fuel cost function is derived basing on the information provided by the manufacturer as shown in table 6.

Table 6: Specifications of the Diesel Genset (as operated power factor of 0.8)

Power, Kw	*Fuel Consumption, liters/hour*
250	65
500	130
750	194

Fitting the given data onto the quadratic function of the cost function (as given in chapter 3). The procedure is done by applying different power output and develop three simultaneous equations as follows:

$$60 = 40000a + 200b + c, \tag{32}$$

$$110 = 160000a + 400b + c, \tag{33}$$

$$170 = 360000a + 600b + c, \tag{34}$$

The equations are solved simultaneously to obtain the cost function as:

$$\mathrm{F} = 0.000125\mathrm{P}^2 + 0.175 - 113.5 \tag{35}$$

where P is the power delivered by the generator.

3.5.2 Initial Cost of the generator set

The initial investment cost of the genset is USD 8,500 (Ush 332,300,000) and the total installation cost is 10% (Ush 3,230,000) of the cost of the generation then the overall initial investment cost is USD 9,350 (Ush 35,530,000).
Considering the life time of 15 years and discount rate of 9%

3.6 Solar PV Model

The Photo Voltaic materials and devices convert sunlight into electrical energy, a single PV device is known as a cell .an individual PV cell is usually about 1 or 2 watts of power. These cells are made of different semiconductor materials and are often less than the thickness of four (4) human hairs.

3.7 Economic Analysis

The analysis is accomplished in two categories:
By considering fixed rate at the given operating conditions when the load is supplied by only by individual generation system, under various scenarios based on the share of the generation is done at different varying percentage shares.
By considering sensitivity analysis through varying discount rate under different scenarios which are based on the contribution of the generator systems to the load.

4.0 Conclusion

From the findings, it is noted that power blackout can be solved as light can be in abundance and regularly. With the establishment of milling machines, the problem of moving long distances would have been solved. The standards of living will be improved as a result of modernizing the existing social infrastructure in the case study area. Likely improved security due to power connectivity and hence reducing the theft rate. Happy and engaged employees in the study area. Improved employees and company's culture. More efficient work places and lower operational costs.

5.0 Recommendation

The following are the recommendations made from the study area of Namabasa ward Mbale District.

This study developed an environmentally friendly and cost-effective hybrid power system. This work analyses whether the viability of using renewable can be used to supplement. The model shows all the possible configurations of renewable energy sources. Keeping this initiative in mind this research aimed at optimizing several hybrid energy systems. The research conclusively investigated techno economic performance of hybrid power source. In recent times, hybrid renewable systems are increasingly being utilized to provide electricity in remote areas like the case study. Health and safety must be emphasized. Protective devices must be installed according to the agreed standards. Periodic maintenance schedule should be put in place and adhered to from time to time. Enhancement of more power connectivity across the case study area. Hybrid work policies are a long-term strategy that can help companies adopt to the changing needs of the modern work force, by creating a more flexible and inductive work environment, companies can attract and retain top talent, booger productivity, improve retention and align with Environmental Social Governance (ESG). Future work should be undertaken in other areas where there is no grid electricity.

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Declaration of Conflict of Interest

The authors of this paper declare no conflict of interest.

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