Economic Comparative Analysis between Grid Extension and Off- Grid Solar PV-Genset Hybrid System in Rural Communities

(A Case Study at Atwetwesu)

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Abstract:- The priority of most governments in the world today is to boost economic growth and drive development across all sectors of the economy, especially through industrialization. To do thissuccessfully, governments should not downplay the role of electricity in the growth process especially when it comes to the electrification of rural communities.

Over the past years, rural electrification has taken on different approaches such as grid extension, off-grid energy home systems and mini-grids harnessing one or more renewable resources to produce electricity. This project made an economic comparison between two different approaches of rural electrification – Grid extension and Off-grid Solar PV-genset hybrid mini-grid system. Using a rural community located in the Bekwai, district of the Ashanti Region in Ghana called Atwetwesuas, the economic comparison for the two alternatives was done using three economic analysis parameters – The net present cost (also called the life cycle cost), the levelized cost of energy and the break-even grid extension distance. The study employed the HOMER Pro in calculating most of these economic analysis parameters. In all the three parameters, it was found out that the off-grid solar PV-genset hybrid system is economically more viable than the grid extension approach giving reference to the site under study, Atwetesu.

***Keywords**:- EHS – Energy Home Systems, EDL – Economic Distance Limit , Genset – Generator Set, HOMER – Hybrid Optimization Model for Electric Renewables , IRR – Internal Rate of Return, LCC – Life Cycle Cost, LCOE – Levelized Cost of Electricity, SHS –Solar Home , SOC –State of Charge, WHS – Wind Home Systems*

CHAPTER 1: INTRODUCTION

BACKGROUND

The priority of most governments in the world today is to boost economic growth and drive development across all sectors of the economy, especially through industrialization. To do this successfully, the role of electricity cannot be downplayed since the demand of electricity is a variable in the function to access the growth of a country. Globally, electricity demand grows at 2.1% per year especially in developing economies where it holds 24% of total final energy consumption [1]. This demand is set to increase even further as a result of rising household incomes, the electrification of transport and heat and digitalization [1].

The rate of electrification has been relatively sluggish in rural communities as compared to that of urban centres in developing nations like Ghana. Presently, more than 1.5 billion people worldwide do not have access to electricity in their homes with an estimated 80% of them livingin rural areas [2]. In sub Saharan Africa, an estimated six hundred million people living in rural areas are excluded from grid supply [3]. The increased cost of generation of electricity, transmission and distribution losses and the high cost of centralized management system associated with small loads such as rural communities make supply of grid power unattractive for remote places, and in some cases impossible [4].

That notwithstanding, these rural areas form the linchpin of economic growth in the sub Saharanregion. In Ghana, the bulk of agricultural activities- which are the country's largest foreign exchange earner occur in these areas. The economy relies on these operations to remain sturdy and hence, the unavailability of electricity in most of these communities hampers productivity. Heavy machinery and other industrial tools cannot be employed. Small and medium scale enterprises rely on small-sized diesel generators for their daily activities, which threatens the survival of their businesses and even further investments. The socio-economic impact that this will have on the nation as a whole is profound.

As the primary energy demand increases, the diversification of the energy mix has also become prominent. The use of renewable energy technology to replace fossil fuels has become more widespread for many reasons, among them being the reduction in the high rate of greenhouse gasemissions, which cause climate change.

Examples of local electrification approaches to produce energy services with a quality that can rival that of grid electricity are diesel generator, photovoltaic system and photovoltaic diesel hybrid systems. Though renewable energy technologies such as solar PV systems offer flexible,small scale solutions that match the energy needs of rural populations, the scale of financial investment involved in their acquisition make them less attractive to rural dwellers.

The popular method of electrification by the use of diesel generators for rural dwellers not connected to grid supply has also become unattractive due escalated fuel prices and environmental policies against the greenhouse gas emissions.

Until 1998, the primary fuel for electricity generation in Ghana was hydropower, when the Aboadze thermal plant was established. Since then, electricity generation in the country has taken on different forms such as power barges, power ships and renewable energies. This diversity in electricity generation has also come up as a result of increased demand due to high population growth and increased economic activities over the years. A study made by the USAID showed that although the generation capacity of Ghana has increased to 4399 MW installed capacity with current access rate of 83%, the rural communities in the country still facelow connection rate of 50% as against 91% of urban centers [5] due to same reasons spelled out above in the first paragraph of this section of the report.

On the global front, energy home systems and renewable technologies mini-grids are the most popular off-grid rural electrification methods. However, the problems with renewable energy technologies is that they are often unpredictable and are also expensive as stated earlier. It is therefore economical and proactive to combine two or more of these energy generation systems into hybrids to improve the overall system reliability. Some other potential benefits of hybrid systems include a minimized mismatch between energy generation and usage, an optimized costof installation and reduced carbon emissions.

To make the choice between grid extension and off-grid electrification methods of rural areasusing hybrid systems, an economic feasibility needs to be first established.

To do this, a case-study was developed with Atwestwesu, a rural community in the Bekwai district of the Ashanti region in Ghana, where economic comparative analysis was made betweengrid extension and off-grid solar PV-Genset hybrid electrification.

The results that would be obtained from this analysis will go the long way to help public institutions like the Energy Commissions as well as private companies who are interested in investing in off-grid electrification projects to make sound decisions concerning rural electrification. This project upon completion would also serve as a guide to engineers and policy makers in deciding the best electrification option for rural communities in line with achieving theseventh sustainable development goal (SDG) which is making affordable and clean energy accessible to everyone, everywhere.

CHAPTER 2: AIMS AND OBJECTIVES

The aims and objectives of this project has been spelled out as follows;

1. Literature review of similar scholarly publications.
2. Carry out an economic analyses of power supply to a selected rural community using the gridand using a solar PV-Genset hybrid system.
3. Do a comparative analysis between the two options for rural electrification.

CHAPTER 3: THEORY AND DESIGN CONSIDERATION

Rural Electrification Methods

Rural electrification is defined as the supply of electricity to small towns and villages, and agro- based industries outside the regional capitals to bring about important social and economic benefits [6]. There are three general approaches for expanding the access to electricity in rural areas- energy home systems, mini-grids, and grid extension. While energy home systems usually offer limited energy service, grid extensions and mini-grids can provide users with a higher degree of power supply in terms of voltage and capacity [7]. More light is thrown on these threegeneral approaches of rural electrification in the subsections below;

Energy Home Systems as a means of rural electrification

Energy home systems (EHS) are designed for the standalone supply of typically singular loads, homes, or small buildings. They can provide relatively inexpensive electricity close to individual households or small buildings (thus negating transmission and distribution costs) and don't require extensive infrastructure often making them the most viable alternative for rural energy supply [8]. The examples of energy home systems include diesel energy systems and renewable energy systems (or technologies). Renewable energy technologies utilizes wind energy, solar, biomass, or hydro power to generate electricity for domestic use [8]. Depending on the energy being utilized, the name of the renewable energy system is derived. Example is solar home systems (SHS) and wind home systems (WHS) that utilizes solar energy and wind energy respectively.

The dispersed character of rural settlements is an ideal setting for these energy solutions, inparticular with renewable energies that are especially competitive in remote areas [9].

A typical solar home system, which is one of the most popular energy home system would have the following components; photovoltaic module, solar charge controller, inverter and batteries. The synergic impact made by these individual components in a typical solar home system is marvelous since it can supply both AC and DC loads. An image of a typical solar home system employed in a dispersed-kind-of rural community is shown in figure 1. It is advisable to employ the right energy home system for the right environment.

Citing an example, a typical wind home system would be employed in a windy environment where there is much wind to be converted into energy for the loads' consumption.

The initial cost for energy home systems can be relatively high. Moreover, the use of Energy home systems limits the consumer to certain kinds of loads. (i.e. lighting and entertainment loads) due to its sizes. This high initial cost coupled with the cultural belief that grid extension provides a higher reliability than energy home systems and poor maintenance culture (in developing countries) often than not suffocate rural electrification by this method. However, proper education and government's support to individuals or corporate bodies who are willing to venture into business that will harness the use of energy home systems to electrify rural communities can kindle the interest in such energy systems for rural electrification.

Figure 1: A rural Community that is employing SHS in providing electricity for its dwellers (Google images)

3.1.1 Grid Extension as a means of Rural Electrification

Extending the national grid is often the most obvious and desirable option for rural electrification. It involves extension of transmission lines from areas already covered by the national electricity grid into new areas. With such a solution, the high level of service delivered to rural areas can be equivalent to that received by urban areas. In some cases however, the difficult terrain (such as mountainous or forest areas) increases expansion costs significantly and therefore makes extension unfeasible [10]. Moreover, the dispersed character of rural settlementsalong with small energy demand increases the cost per kWh of grid extension and there is often aneed to cross subsidize between urban and rural networks.

Consequently, the public authorities and utilities responsible for rural electrification may see grid extension as an economic impossibility [8]. Furthermore, access to the national electricity grid in developing countries may not necessarily mean secure and reliable supply, as black outs and brown outs can be commonplace [8] .The initial capital cost of extending grid supply to a rural community is chiefly influenced by the distance of the rural community from the nearest grid supply tower and varies across different countries. Figure 2 shows the initial capital cost (in $/km) of extending grid supply to rural communities in 5 different countries that harness European configuration. It must be noted that the cost component combines the cost of materialsand as well as labour.

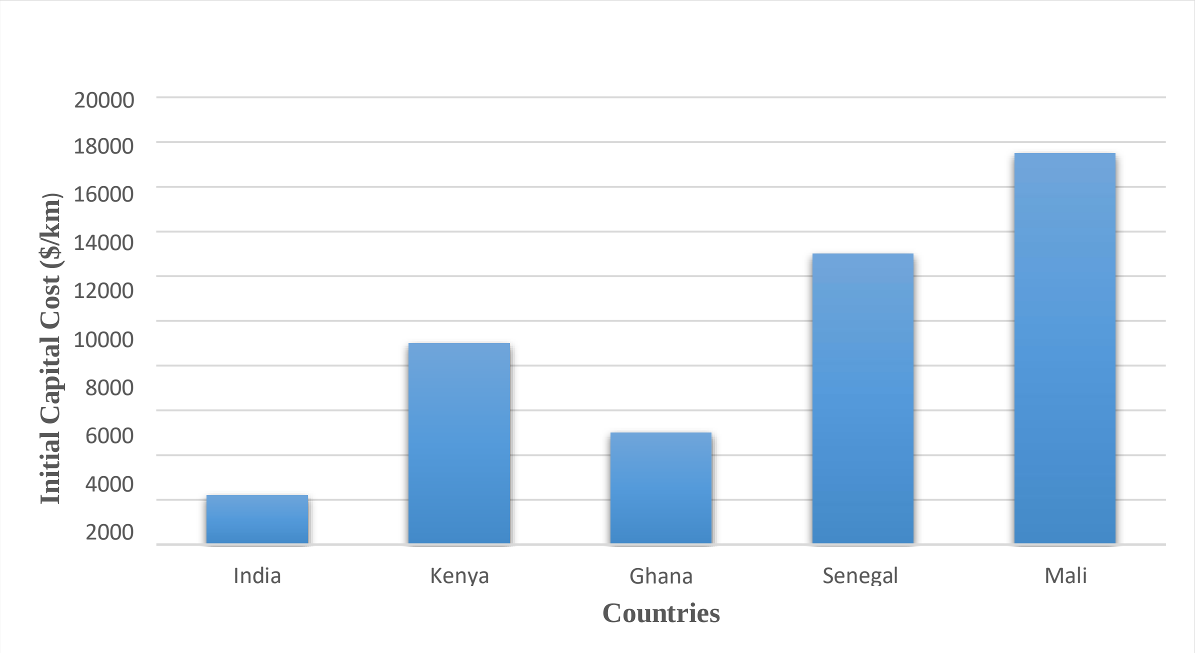


Figure 2: A bar chart portraying the initial capital cost ($/km) of extending grid supply to rural communities in 5different countries that uses European configuration

Despite the afore-mentioned impediments to employing this method for rural electrification, some of the advantages this method of electrification offer over the energy home system methodcan be outlined as followed [10];

- ✓ The grid provides enough electricity to permit broad economic development activities ratherthan simply lighting and entertainment.
- ✓ Extending the grid into often neglected rural areas is perceived by rural households as a permanent community investment and creates a national infrastructure on which to basefuture socio-economic development.
- ✓ When power lines are extended to a village, all rural households-even those who do not have the financial resources to afford electricity in their own homes-can enjoy the benefits, such aspumped or irrigation water, street lighting, improved educational and health services, agro- processing, and employment.

3.1.2 Mini-grids as a means for rural electrification

A mini-grid is a set of small-scale electricity generators and possibly energy storage systems interconnected to a distribution network that supplies the electricity demand of a limited number of customers [11]. Mini-grids provide capacity for both domestic appliances and local businesses, and have the potential to become the most powerful technological approach for accelerated rural electrification [2]. It also offer an optimal solution for utilizing localized renewable energy resources [2]. Many locations offer excellent natural conditions for the use of solar photovoltaic (PV), wind, or small hydro power [2]. Mini-grid systems can be divided into two categories: grid-connected and standalone [8]. While grid connected mini-grid be able to provide stability to weak grids and fringe of grid services, stand-alone mini-grids systems have the greatest potential for supplying load in remote and rural areas [8].

Today, most mini-grids take the form of combining two or more renewable energy technologies to produce electricity. These kinds of mini-grids are called hybrid mini-grids. Hybrid mini-grids offer greater reliability than mini-grid systems that employ only one renewable energy technologies. Conservative calculations of life-cycle cost show that hybrid mini-grids, powered chiefly by renewable energy with a genset – normally working on diesel fuel, are usually the most competitive technical solution [2]. The initial capital cost of mini-grids especially hybrid mini-grids can be very high. However, the operation and maintenance cost of this method of electrification is comparatively lower than the grid extension method. Figure 3 below shows a typical hybrid mini-grid system utilizing PV arrays and diesel generator for the production of electricity.

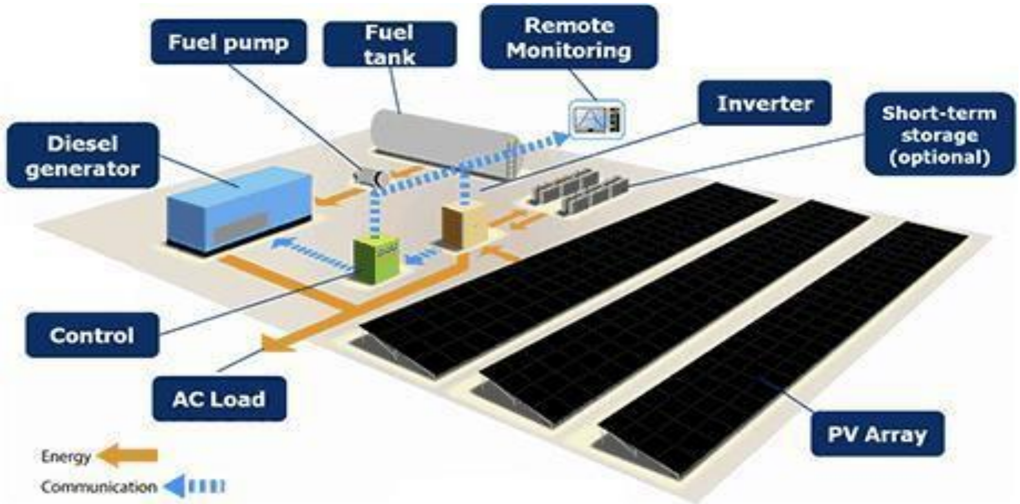


Figure 3: A typical layout of a Solar PV- genset hybrid mini-grid system

3.2 *Site Description and Load profiling*

The rural site under study is called Atwetwesu and it has the geographical coordinates **6º 27’ 0’’ North, 1º 35’ 0’’ West**. The site is a rural community located in the Bekwai district in the Ashanti Region of Ghana. The village is currently inhabited by a population of one hundred and eighty-nine (189) people segregated into twenty-one (21) households and have a total land area of 40,805.10 m^2. Most of the inhabitants of the community are engaged in farming activities. The village is currently not connected to the national grid and hence do not have access to electricity. The commercial loads in the community which are water pump machine and a corn-mill machine are powered with small-sized diesel generators. The distance from the village to the nearest grid transmission line (11 kV line) is approximately 36 km. The projected load demand was obtained to be 14.505 kW.

Figure 4: A picture of Atwetwesu taken during a visit to the community

3.3 Off-grid Solar PV-Genset Hybrid Generation System

3.3.1 Design Consideration

In the design of the off-grid PV-genset hybrid generation system for the site under consideration, a mini-grid configuration was chosen over other configurations like solar home system (SHS) and a genset (acting as a back-up source) for each household and commercial buildings. This choice was made because the houses in the village are clustered together and not dispersed making it easier and cheaper to supply all the households through an independent distribution network. Aside this advantage, the mini-grid can also easily be managed by a trained operator ascompared to the management of SHS for individual homes by household members who may have limited knowledge about such systems.

The main components that would be used to build the mini-grid solar PV-genset hybridgeneration system are as follows;

- **Solar photovoltaic (PV) system –** Solar photovoltaic (PV) generators convert the energy from the sun into electricity through their solar cells, which are semiconductor-based materials [2]. These solar cells are gathered together to form modules. And the modules arecombined together to form solar panels. The amount of solar energy received at a specific location is called insolation, and this factor determines the output of the PV generator [2].

Solar PV generators produce DC power and hence an inverter is also employed to convert theDC power to AC power since the loads would be supplied through an AC bus bar. Seasons have influence on PV generation. During the warmer months, the insolation is higher than cold months [2]. Similarly, insolation is higher during dry season than during the rainy season [2]. In this design, the lower production of PV during the rainy season would be offsetwith the genset and the battery storage system.

- **Diesel genset –** Diesel generators have commonly been used in rural electrification for years, though this technology is rarely the lowest-priced option, in the long run [2]. Within hybrid power systems, the advantage of diesel genset is their dispatchability [2]. Diesel genset was preferred to other genset (like ones that run on natural gas, oil or biofuels) in this design because they are more robust and reliable than the others. Also gas units burn hotter than diesel units, and hence diesel units have a significantly longer life than gas units. The probability of diesel units catching fires when working is also minimum. In this design, the genset would serve as a back-up generation system. The strategy is to use as little fuel as possible to reduce the expenses and maximize the lifespan of the generator. However, it mustbe noted that when gensets need to be used, they have to run on high capacities not to reducethe lifetime of the generator [2]. This means that even as a back-up generation, the genset must be made to run at a very high capacity when it is being called to supply the load and to charge the batteries.
- **Battery Storage System –** A battery is formed by series of electrochemical cells connected together to match the required voltage [2]. The battery is invariably one of the most important component of the whole hybrid generation system since it will store energy that may not be used by the load at a particular point in time. The most common type of battery used in a hybrid mini-grid is the lead-acid, deep cycle type, although many models like the Lithium Ion (Li-Ion) batteries and Nickel-Cadmium (Ni-Cd) batteries are available in the market. This type of lead-acid battery is preferred for PV systems due to the following points[21];

✓ Less costly and easy to transport
✓ It requires less maintenance so it can be used in remote application areas
✓ Addition of extra water not needed

- **Solar Charge Controller -** regulates the voltage and current coming from the PV panels going to battery and prevents battery overcharging and prolongs the battery life [13].
- **Inverter –** Converts DC output of the PV panels and the battery storage system intoclean AC current [13] for the AC bus bar.
- **Combiner Box –** Combines multiple wires from solar array to just a few number andmay contain breakers or fuses.
- **Inverter bypass Switch –** Selects output as either inverter or generator to supply the bus
- **Bus Bar –** AC bus bars were employed in this mini-grid configuration. This kind of bus was chosen over its DC counterpart because AC bus bars when employed would have higher efficiency and can be more flexible and expandable [2]. Regarding costs, the difference between both types of installation is negligible [2].
- **Protection equipment –** They include lightning arresters, fuses and circuit breakers which would be employed to protect the mini-grid against current fluctuations, voltagesurges and other faults that would occur in the system.

Fig. 4 below shows the proposed arrangement of the various components in the hybrid mini-gridsystem. The service box at the far right of the diagram would supply the bus bars.

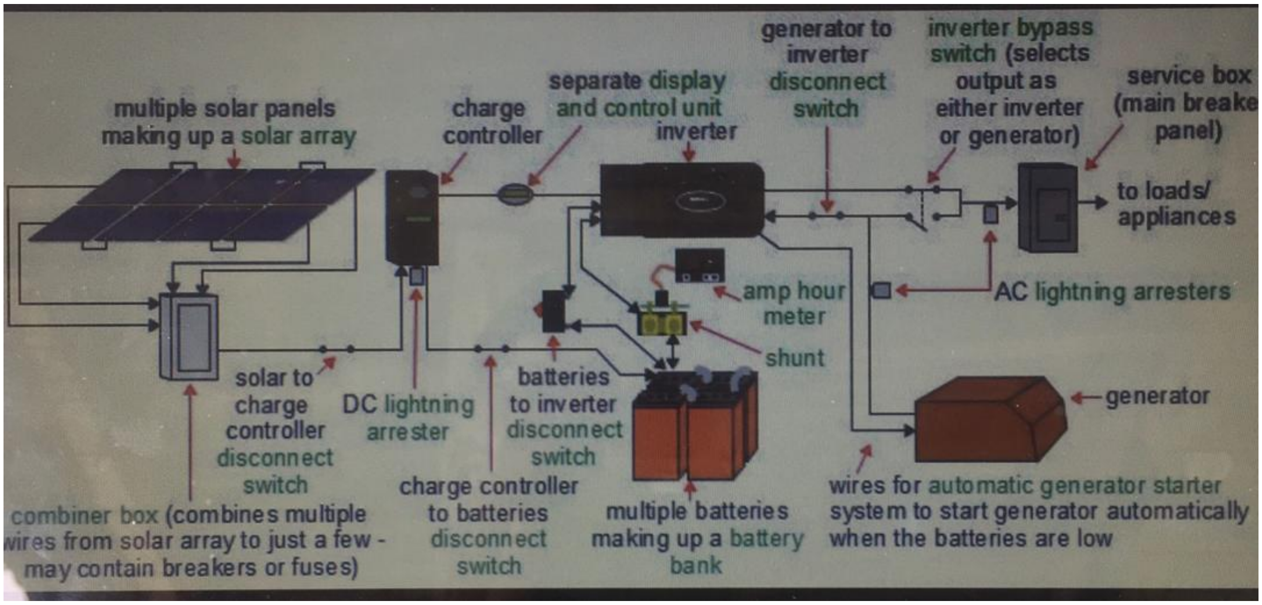


Figure 5: Proposed arrangement of the various components in the off-grid solar PV-genset hybrid mini-grid system(Google Images).

Off-grid Solar PV-genset hybrid Generation System- Proposed Operation

The proposed operation of the off-grid solar PV-genset hybrid system is presented briefly in thebullets below;

- The solar PV would generate energy to supply the loads and charge the battery storage from the hours of 09 00 hrs to 15 00 hrs of the day. The solar insolation between these hours has been examined to be great enough to fulfil this task giving reference to the siteunder study.
- The battery storage system would then supply the loads from the hours of 15 00hrs to 09 00hrs. This period is called the period of autonomy (sometimes called no-sun-periodsor dark periods), when the sun is not providing enough radiation for the production of energy.
- The system would be ran this way until the village enters into days of autonomy and thebattery system is below 50 or 45% State of Charge (SoC) thereby making it impossible for it to supply the loads. The genset would then be switched on to supply the loads andcharge the battery storage system at very high capacity.
- The switching process would also be automated to increase the speed by which thechange of supply from one component to the other would occur.

3.4 Introduction to Engineering Economy

Engineering economy involves formulating, estimating, and evaluating the expected economic outcomes of alternatives designed to accomplish a defined purpose [14]. Mathematical techniques simplify the economic evaluation of alternatives [14]. The basic concept in engineering economy would be employed in the economic analysis of the two alternatives (gridextension and off-grid PV-genset hybrid generation system) of rural electrification to the case study site, Atwetwesu.

An engineering economy study involves many elements: problem identification, definition of theobjective, cash flow estimation, financial analysis, and decision making [14]. Implementing a structured procedure is the best approach to select the best solution to the problem [14]. The steps in an engineering economy study are as follows [14];

1. Identify and understand the problem; identify the objective of the project.
2. Collect relevant, available data and define viable solution alternatives.
3. Make realistic cash flow estimates.
4. Identify an economic measure of worth for decision making.
5. Evaluate each alternative; consider noneconomic factors; use sensitivity analysis as needed.
6. Select the best alternative.
7. Implement the solution and monitor the results.

Applying the above steps of an engineering economy study to this project, the following can benoted;

1. Rural electrification is the broad problem; electrifying a case study site, Atwetwesu is theobjective.
2. The viable solution alternatives are grid extension and PV-genset generation system.
3. The cash flow estimates include the initial costs involved, the operation and maintenance(O&M) costs and other investments made in the two alternatives.
4. The economic measure of worth, as it will be explained in the next paragraph of this section is based on net present cost (NPC). This would be the primary means by which the two alternatives would be compared. The other means (which would be explained in the next section) - the levelized cost of electricity (LCOE) and grid extension break-even distance areall derived from the net present cost (NPC).
5. Each of the alternatives would be evaluated through sizing and optimization. And the least LCOE of each alternatives would be presented for the comparison.
6. The best alternative would then be the alternative with the least LCOE.

Before progress is made to talk about the levelized cost of energy, it is necessary to highlight some key terminologies, symbols and relations employed in engineering economy;

- P = value or amount of money at the time designated as the present or time 0. Also P is referred to as present worth (PW), present value (PV), net present value (NPV), discountedcash flow (DCF), and capitalized cost (CC); monetary units, such as dollars
- F = value or amount at some future time. Also F is called future worth (FW) and future value(FV); monetary units, such as dollars
- A = series of consecutive, equal, end-of-period amount of money. Also A is called annual worth (AW) and equivalent uniform annual worth (EUAW); dollars per year, euros per month etc.
- n = number of interest periods; years, month, days
- i = interest rate per time period; percent per month, percent per year
- t = time, stated in periods; years, months, days
- F = $P(1+i)^n$; where $(1+i)^n$ is called the single-payment compound factor (SPCAF)
- P = A*[$(1+i)^{n-1}$],i is not equal to zero; where the factor in the square bracket is referred to $i\,(1+i)^{n}$ as uniform series present worth factor (USPWF).
- $A = P*[\frac{i(1+i)^{n}}{(1+i)^{n}-1}$]; the term in the square bracket is called the capital recovery factor (CRF).

There are several of these equations that would not be applicable in this project. As progress is made in this report, some of these definitions and equations above would be referred to in ordermake elaborations.

3.4.1 The Total Net Present Cost (NPC / CNPC) as a means to evaluate the economic feasibility between grid extension and off-grid solar PV-genset hybrid generation system

The total net present cost (NPC), also called the life cycle cost (LCC) of a system is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime [15]. Costs include capital costs, replacement costs, operationsand maintenance costs, fuel costs, emissions penalties, and the cost of buying power from the grid [24]. Revenues include salvage value and grid sales revenue [15].

To be able to calculate the NPC of a component, system or project, cash flow diagrams are utilized. The cash flow diagram is a diagram depicting cash inflows and cash outflows during thelifetime of the project. The cash flow diagram would be utilized to make the NPC calculation forthe grid extension in chapter 4 of this report. The NPC for the solar PV-genset hybrid system canhowever be found using the HOMER Pro simulation software. The alternative with the least NPC would be judged as being economic feasible over the other. It is worthy to note that the total net present value (NPV) is the negated value of the net present cost (NPC).

3.4.2 The Levelized Cost of Energy (LCOE) as a means to evaluate the economic feasibility between grid extension and off-grid PV-genset hybrid generation system

The levelized cost of energy (LCOE) is defined as the net present cost (NPC) of the entire cost ofelectricity generated over the lifetime of a generation asset divided by the total generated energy [16]. In other words, the sum of investment costs, production cost, as well as the operation and maintenance (O&M) costs is calculated and divided by the total energy produced over the lifetime of the asset [16]. The LCOE can be used to efficiently determine if a generation unit is economically viable to be installed and to further investigate if the deployed technology cost can break-even over the lifetime of the project [16]. The LCOE also allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities [17]. Fig. 5 below is a diagram showing a simple way to find the LCOE of a typical energy system. The other remarkable benefit of the LCOE is that it enables cost comparison of the generation technology with the price of electricity grid at the point of connection to the grid [16]. The LCOE concept can be used to know the electricity tariffs to be chosen for the sales of electricity to the users. In this project however, the LCOE concept is used to compare the economic feasibility of the two alternatives and the alternative with the least LCOE is judged as been cost-effective over the other.

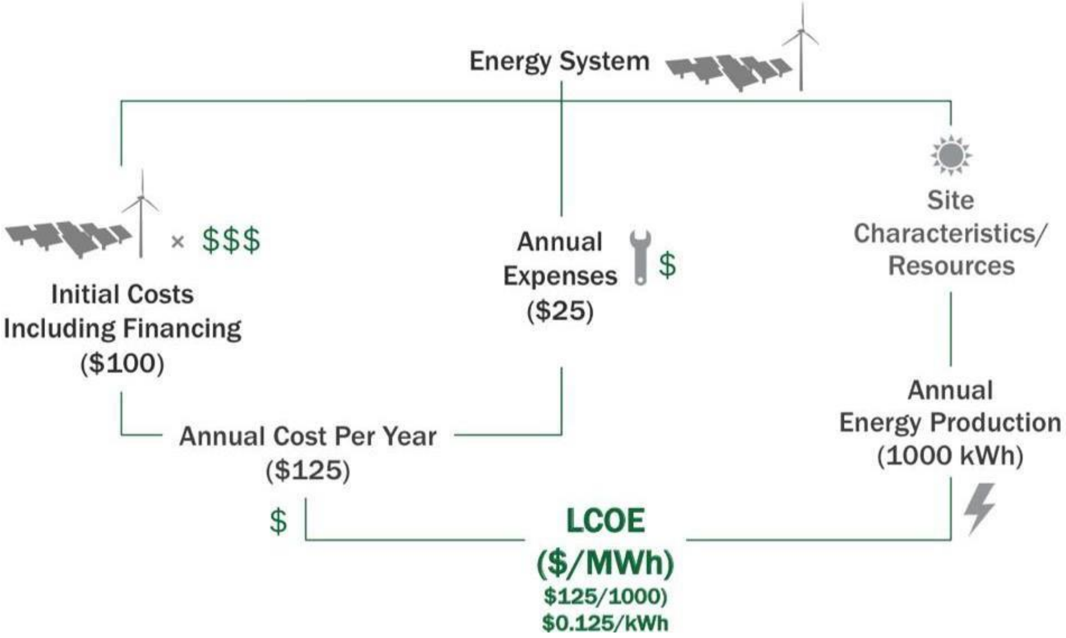


Figure 6: A diagram showing a simple way to calculate the LCOE of a typical energy system [26].

3.4.3 The Break-even grid extension distance, Dgrid as a means to evaluate the economic feasibility between grid extension and off-grid solar PV-genset hybridgeneration system

The break-even grid extension distance is the distance from the grid that makes the net present cost of extending the grid to the rural community equal to off-grid hybrid system [15]. If the Dgrid value is below the distance of the rural community to the nearest grid transmission line, the off-grid hybrid system is adjudged as the more cost-effective of the two alternatives and vice versa. The calculation of the Dgrid value can also be made with the HOMER simulation software which would be elaborated in chapter four of this report.

CHAPTER 4: MATERIALS AND METHODS

4.1 Methodology

The steps taken to complete this project are as followed;

- Review of past literature.
- Selection and description of site used as case-study.
- Collection of a model load profile information from the Electricity Company of Ghanafor the site under study.
- Measurement of the distance between the grid transmission line and the case-study site.
- Description and sizing of off-grid solar PV-genset hybrid generation system.
- Sizing of grid extension components.
- Collection of cost information of various components from the market.
- Collection of solar irradiation and the prices of diesel from the internet.
- Building optimization for off-grid solar PV-genset hybrid system using HOMERsimulation software.
- Calculating the net present cost (NPC), Levelized cost of energy (LCOE) and the grid extension break-even distance of the alternatives for the economic comparison.
- Evaluation and discussion of results.

4.2 Data Collection

4.2.1 Site Electric Load Data

Assessment of the village electric load data was done through the Electricity Company of Ghana. After choosing the rural community for the study, the description, the main activities and the number of households of the village were given to the Electricity Company Ghana, E.C.G. in order to obtain load information of such a typical village. This was done because the site under study currently have no access to electricity and getting the load data through interviews was not a good option due to the COVID-19 pandemic during this project.

The distance of the village from the nearest grid tower was however obtained through Districtassembly. Table 1 below shows the load data for the village. It must be noted that per demandside management (DSM) practices, most of the loads considered in this project are energy- efficient ones.

Since most of the inhabitants of the village are engaged in farming activities, two different demand profiles were speculated for the village - The first one, displayed on table 2 and fig. 5, shows the hourly power demand profile of the village for weekdays (and Saturdays); the secondone, displayed on table 3 and fig. 6 shows the hourly power demand of the village for Sundays.

Fig. 8 was obtained from HOMER Pro after importing the load data from table 2 and 3 unto thesoftware. Aside the diagram having the daily, seasonal and yearly load profiles, it also displaysimportant load parameters like average daily energy (in kWh), the average power demand (in kW), the peak power demand (in kW) and the load factor.

Load description	**Abb.**	**Power Rating (Watts)**	**Qty.**	**Total AC Power (Watts)**	***Use(h/d)**	***Use(d/w)**	**÷7**	**Energy(kWh)**
RESIDENTIAL								
Ceiling Fan	CF	70	21	1470	13	7	7	19.110
Iron	IR	1000	3	3000	0.5	1	7	0.215
Light bulbs	LBR	15	42	630	13	7	7	8.190
Mobile Phones	MP	10	21	210	2	7	7	0.420
Radio Set	RS	40	21	840	7	7	7	5.880
Refrigerator	RF	200	6	1200	13	7	7	15.600
Television Set	TV	80	21	1680	5	7	7	8.400
Corn Mill	CM	3700	1	3700	3	5	7	7.929
Light bulbs (at School)	LBC	15	5	75	13	7	7	0.975
Street Light	SL	25	8	200	13	7	7	1.600
Water Pump	WP	1500	1	1500	2	6	7	2.572

	AC Total connected Watts	**14505**	**Average daily energy demand = 70.891kWh**

Table 1: A table showing the load data of the site under study

Hours	**CF**	**IR**	**LBR**	**RF**	**MP**	**RS**	**TV**	**CM**	**LBC**	**SL**	**WP**	**Total (kW)**
0	19	0	32	6	0	5	0	0	5	8	0	3.485
1	19	0	32	6	0	5	0	0	5	8	0	3.485
2	19	0	32	6	0	5	0	0	5	8	0	3.485
3	19	0	32	6	0	5	0	0	5	8	0	3.485
4	19	0	32	6	0	5	0	0	5	8	0	3.485
5	19	0	32	6	0	5	0	0	5	8	0	3.485
6	19	0	32	6	0	18	3	0	5	8	0	4.245
7	2	0	3	0	0	3	2	0	0	0	0	0.465
8	2	0	3	0	0	2	1	0	0	0	1	1.845
9	2	0	3	0	0	2	1	0	0	0	0	0.345
10	2	0	3	0	3	2	0	1	0	0	0	3.995
11	2	0	3	0	3	2	0	1	0	0	0	3.995
12	2	0	3	0	0	2	0	1	0	0	0	3.965
13	2	0	3	0	0	2	0	0	0	0	0	0.265
14	2	0	3	0	0	2	0	0	0	0	0	0.265
15	1	0	3	0	0	2	0	0	0	0	0	0.195
16	1	0	3	0	0	2	0	0	0	0	0	0.195
17	1	0	8	0	0	3	0	0	0	0	1	1.810
18	21	0	42	6	10	18	20	0	5	8	0	5.995
19	21	0	42	6	10	20	21	0	5	8	0	6.155
20	20	0	42	6	8	20	21	0	5	8	0	6.055
21	20	0	42	6	8	20	21	0	5	8	0	6.055
22	20	0	42	6	0	10	10	0	5	8	0	4.695
23	19	0	32	6	0	5	5	0	5	8	0	3.885

Table 2: Tabulated daily load profile (Mondays – Saturdays)

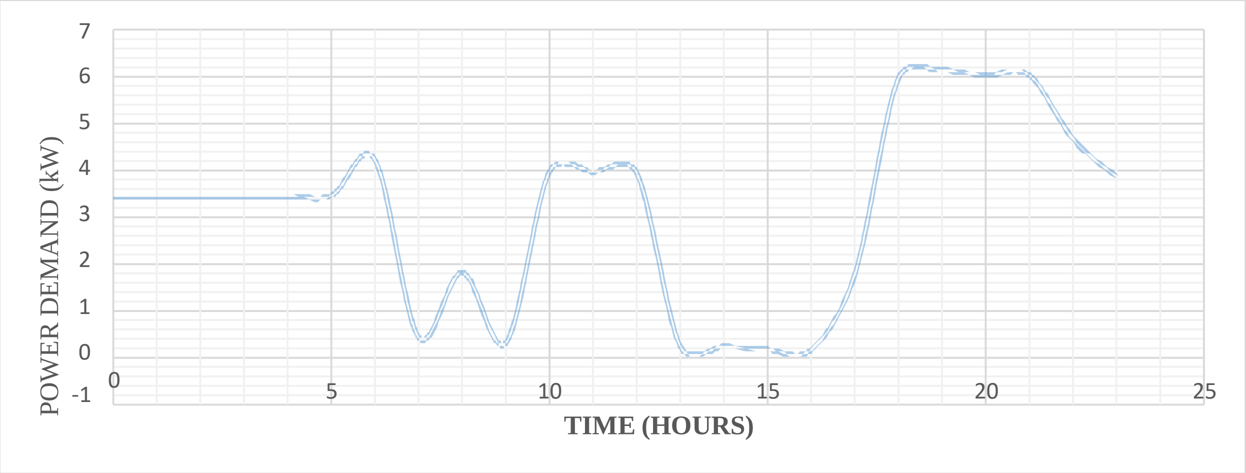


Figure 7: Graphical presentation of Table 2

Hours	**CF**	**IR**	**LBR**	**RF**	**MP**	**RS**	**TV**	**CM**	**LBC**	**SL**	**WP**	**Total (kW)**
0	15	0	32	6	0	5	0	0	5	8	0	3.205
1	15	0	32	6	0	5	0	0	5	8	0	3.205
2	15	0	32	6	0	5	0	0	5	8	0	3.205
3	15	0	32	6	0	5	0	0	5	8	0	3.205
4	15	0	32	6	0	5	0	0	5	8	0	3.205
5	15	0	32	6	0	5	0	0	5	8	0	3.205
6	10	1.5	32	6	5	18	10	0	5	8	0	5.725
7	10	1.5	10	3	5	10	10	0	0	0	0	4.200
8	10	0	10	3	3	10	8	0	0	0	1	4.020
9	10	0	10	3	3	10	8	0	0	0	0	2.520
10	10	0	10	3	3	10	8	0	0	0	0	2.520
11	8	0	8	3	3	10	8	0	0	0	0	2.420
12	8	0	8	3	2	15	10	0	0	0	0	2.770
13	8	0	8	3	2	8	10	0	0	0	0	2.490
14	7	0	8	3	0	8	10	0	0	0	0	2.410
15	10	0	10	3	0	7	10	0	0	0	0	2.610
16	12	0	12	3	0	10	12	0	0	0	0	3.020
17	12	0	13	3	0	10	12	0	0	0	1	4.535
18	19	1.5	40	6	10	18	15	0	5	8	0	6.925
19	19	1.5	42	6	10	15	18	0	5	8	0	7.075
20	18	0	42	6	8	15	20	0	5	8	0	5.485
21	18	0	42	6	8	15	20	0	5	8	0	5.485
22	16	0	42	6	0	15	15	0	5	8	0	4.945
23	15	0	32	6	0	5	5	0	5	8	0	3.605

Table 3: Tabulated daily load profile (Sundays)

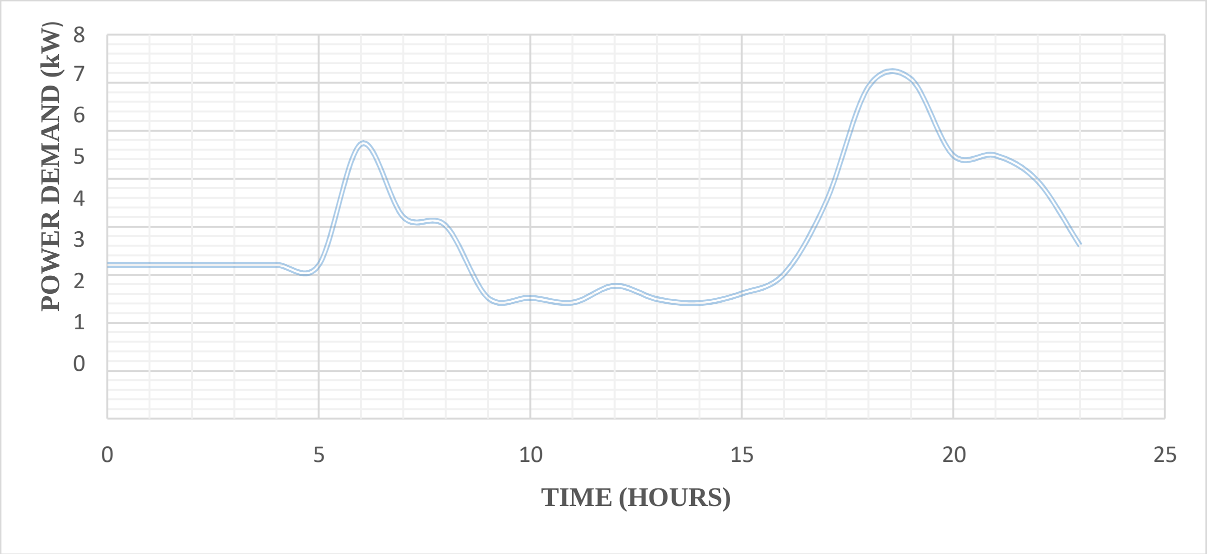


Figure 8: Graphical presentation of Table 3

Name: Electric Load #1

January Profile

Hour	Load (kW)
0	3.485
1	3.485
2	3.485
3	3.485
4	3.485
5	3.485
6	4.245
7	0.465
8	1.845
9	0.345
10	3.995

Time Step Size: **60** minutes

Random Variability
Day-to-day (%): 10
Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/day)	77.71	77.71
Average(kW)	3.24	3.24
Peak (kW)	10.96	10.96
Load factor	.3	.3

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)
Efficiency multiplier: 1
Capital cost ($): 0
Lifetime (yr): 10

Scaled Annual Average (kWh/day): 77.71

Figure 9: Daily, Yearly and Seasonal Load Profiles

4.2.2 Materials / Components Costs

To make an economic comparison between the two alternatives of electrification, it is vital to obtain the cost information for each component in each project. The cost information of the various components were obtained from the market after sizing the individual components of each alternative. The cost information for each component as it can be recalled from subsection of the report include capital costs, replacement costs, operations and maintenance costs etc.

Before progress is made to give tables showing the various components costs in each alternativeas obtained from the market, the following subsections shows the sizing and cost information ofthe each component of the two alternatives.

4.2.2.1 Sizing of off-grid Solar PV-Genset Hybrid Mini-Grid Generation System'scomponents

PV Array Sizing

- Average daily demand, $\mathbf{E^{I}}$ **= 70.891 kWh** (from Table 1)
- The number of user connections can be low in the beginning, especially in areas where no other projects have been installed previously; however, successful implementation and reliable service will increase the number of connections with time. Population dynamics alsochange once the village is electrified, and any growth in the local population will increase theconnection points. With this idea, it is inherently a good design practice to add a margin of safety to the current demand. This is the so called reserve margin. In this project, a calculation of 15% of the current daily demand to serve as reserve margin. Hence the total daily energy demand (including the reserve margin) is expressed below;

E = 1.15* 70.891 kWhE = 81.525 kWh

- All generation system is bound to face losses due to several factors including the individual system components losses. The mini-grid hybrid system considered in this project is not an exception and will inevitably encounter losses. It is therefore a must at the design stage to factor the overall efficiency of the system during the sizing of such a system component likethe PV arrays peak power rating. After consultation with an expert in PV array sizing, an overall efficiency of 0.71 was chosen based on factors such as PV soiling, converter, cable and battery losses and other miscellaneous losses not captured in the aforementioned losses. Hence the energy required from the system to supply our daily demand (including losses) will be;

$$\mathbf{E_r} = \frac{\mathbf{E}}{\eta(\boldsymbol{overall})} = \frac{\mathbf{81.525}\ \boldsymbol{kWh}}{\mathbf{0.71}}$$

Er = 114.824 kWh

- To get the peak power, P_p rating in kW of the PV array, the E_r calculated above is divided bythe minimum peak sun-hours per day, T_{min}. The T_{min} is calculated as;

T_{min} = hours in a day * Capacity factor of the country.
The capacity factor of Ghana was found to be 16%. Hence the minimum peak sun-hours perday and the Peak power of the PV array will be;

Tmin = 24 * 0.16 Tmin = 3.84 hours

$$PP = \frac{Er}{Tmin} = \frac{114.824\ kWh}{3.84\ hours}$$

PP = 29.902 kW ≈ 30 kW

- Total DC current required for the system is;

$$IDC = \frac{Pp}{VDC}$$

$$IDC = \frac{30\ kW}{48\ V}$$

IDC = 625 A

- The PV module used in this module has the following Voltage and current ratings.

VR = 48 V IR = 6.875 A

- Number of panels to be connected in series;
-

$$Nseries = \frac{(DC)}{V(R)}$$

$$Nseries = \frac{48\ V}{48\ V}$$

Nseries = 1 panel

- Number of panels to be connected in parallel;

$$Nparallel = \frac{(DC)}{I(R)}$$

$$Nparallel = \frac{625\ A}{6.875\ A}$$

Nparallel ≈ 90 panels.

- Total number of panels to be considered for the system is;

N = Nparallel * Nseries N = 90*1 = 90 panels

Battery Bank Sizing

- The amount of "rough" storage energy, **Erough** required is equal to the product of the total energy demanded, **E** (including the reserve margin) and the number of autonomy days, **D**(also known as the no-sun days).
- To throw more light on the autonomous days, they are the number of days the battery will supply the village without being charged. For the system proposed in this project, the battery should supply the village between the hours of 15 00 hrs and 09 00 hrs. This implies 18 hoursperiod of autonomy for the battery. This is equivalent to 0.75 days.
- This implies that the amount of "rough" storage energy required can be calculated below;

Erough = E*D
Erough = 81.525*0.75 = 61.144 kWh

- Consideration was given to two different batteries with two different maximum allowable depth of discharge, MDOD giving reference to the project at stake. These two batteries are theLithium ion battery (popularly known as the Li-Ion) and the lead Acid battery. The Li-Ion has its MDOD of 0.8 whilst the Lead Acid's is 0.5.

- This implies that the energy which will be required from the batteries will be;

$$E_{safe} = \frac{Erough}{\text{MDOD}}$$

- Calculations is done for the two types of batteries (i.e. Li-Ion and Lead Acid Battery).

Calculations for Li-Ion batteries

$$E_{safe} = \frac{61.144\ kWh}{0.8}$$

Esafe = 76.430 kWh

- The number of batteries for the system (based on only the Esafe value) can then be determinedby dividing the Esafe value of the battery with the respective kWh rating. The kWh rating of the Li-Ion batteries in the market is 10 kWh. Therefore the number of batteries is;
-

$$N_{\text{batteries (old)}} = \frac{76.430\text{ kWh}}{10\ kWh}$$

$N_{\text{batteries (old)}}$ ≈ **8 batteries**

- The number of batteries is also influenced by the system DC voltage, V_{DC}. The system's DC voltage was chosen to be 240 V (this is the approximate RMS voltage value used in the GRID distribution system) and this will be handled by the inverter, but on the battery side, the system's voltage will be 48 V.
- The number of batteries that will be connected in series to achieve this voltage value is expressed below. It can be seen that the voltage rating of the Li-Ion batteries used for thecalculation is 48V ;

$$N_{\text{batteries (series)}} = \frac{VDC}{Vb}$$

$$N_{\text{batteries (series)}} = \frac{48}{48}$$

$N_{\text{batteries (series)}}$ = **1 battery**

- The number of batteries also to be connected in parallel is also calculated as;

$$N_{\text{batteries (parallel)}} = \frac{N\ batteries}{N\ batteries\ (series)}$$

$$N_{\text{batteries (parallel)}} = \frac{N\ batteries}{N\ batteries\ (series)}$$

$$N_{\text{batteries (parallel)}} = \frac{8}{1}$$

$N_{\text{batteries (parallel)}}$ **= 8 batteries**

- Therefore the number of the batteries (based on both the **Esafe** and system's voltage, **VDC** values) can then be found by multiplying the number of batteries connected in series with thenumber of batteries connected in parallel.

$N_{\text{batteries (new)}} = N_{\text{batteries (parallel)}} * N_{\text{batteries (series)}}$

$N_{\text{batteries (new)}} = 1 * 8 =$ **8 batteries**

- The diagram below shows the skeletal arrangement of the batteries if the Li-Ion battery type is employed in the hybrid generation system. The terminals a-b would be connected to a transfer switch that switches between the supply to the batteries by the Solar PV modules andthe genset whilst terminals c-d will be connected to the inverter.

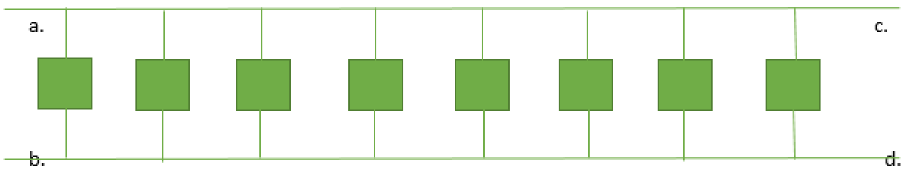


Figure 10: Skeletal Arrangement of Li-Ion battery storage

<u>Calculations for Lead Acid batteries</u>

$$E_{\text{safe}} = \frac{61.144\ kWh}{0.5}$$

Esafe = 122.288 kWh

- The number of batteries for the system (based on only the E_{safe} value). The kWh rating of theLead Acid batteries in the market is 24 kWh.

$$N_{\text{batteries (old)}} = \frac{122.288\ \text{kWh}}{24\ kWh}$$

$N_{\text{batteries (old)}} \approx$ **6 batteries**

- The number of batteries that will be connected in series to achieve this voltage value is expressed below. It can be seen that the voltage rating of the Li-Ion batteries used for thecalculation is 24V.

$$N_{\text{batteries (series)}} = \frac{VDC}{Vb}$$

Nbatteries (series) = $\frac{48}{24}$

Nbatteries (series) = **2 batteries**

- The number of batteries also to be connected in parallel is also calculated as;

Nbatteries (parallel) = $\frac{N\ batteries}{N\ batteries\ (series)}$

Nbatteries (parallel) = $\frac{N\ batteries}{N\ batteries\ (series)}$

Nbatteries (parallel) = $\frac{6}{2}$

Nbatteries (parallel) ≈ **3 batteries**

- Therefore the number of the batteries (based on both the **Esafe** and system's voltage, **VDC** values) can then be found by multiplying the number of batteries connected in series with thenumber of batteries connected in parallel.

Nbatteries (new) = Nbatteries (parallel) * Nbatteries (series)

Nbatteries (new) = 3 * 2 = **6 batteries**

- The diagram below shows the skeletal arrangement of the batteries if the Lead Acid battery type is employed in the hybrid generation system. The terminals a-b would be connected to atransfer switch that switches between the supply to the batteries by the Solar PV modules andthe genset whilst terminals c-d will be connected to the inverter.

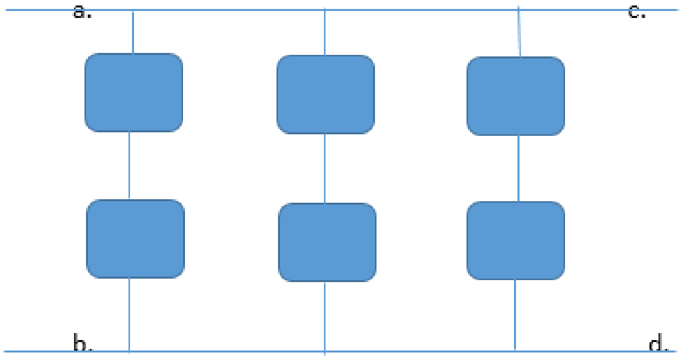


Figure 11: Skeletal arrangement of the Lead battery storage system

Sizing of Charge Controller

- According to its function it controls the flow of current. A good voltage regulator must be able to withstand the maximum current produced by the array as well as the maximum loadcurrent.
- Sizing of the voltage regulator can be obtained by multiplying the rated short circuit current of the modules connected in parallel by a safety factor Fsafe. The result gives the rated currentof the voltage regulator.

I = ISC * NP * Fsafe I = 9.11 * 90 * 1.25I = 1024.875 A

- With reference to the calculation made above, the rated short circuit current of the individual PV modules is found from the data sheet of the module chosen for this project. A snapshot ofthe data sheet that gives this parameter is shown below in fig.11. The number of the panels connected in parallel has however been calculated for earlier in this chapter. The Fsafe value isa 'standard' value chosen for such projects.

SPECIFICATIONS

Module Type	JKM330M-72		JKM335M-72		JKM340M-72		JKM345M-72		JKM350M-72	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	330Wp	246Wp	335Wp	250Wp	340Wp	254Wp	345Wp	258Wp	350Wp	262Wp
Maximum Power Voltage (Vmp)	38.2V	36.4V	38.4V	36.6V	38.7V	36.8V	38.9V	37.0V	39.1V	37.2V
Maximum Power Current (Imp)	8.64A	6.75A	8.72A	6.82A	8.79A	6.89A	8.87A	6.98A	8.94A	7.05A
Open-circuit Voltage (Voc)	46.7V	44.8V	46.9V	45.2V	47.1V	45.5V	47.3V	45.8V	47.5V	46.0V
Short-circuit Current (Isc)	9.11A	7.24A	9.18A	7.29A	9.24A	7.33A	9.31A	7.38A	9.38A	7.46A
Module Efficiency STC (%)	17.01%		17.26%		17.52%		17.78%		18.04%	
Operating Temperature(°C)	-40°C~+85°C									
Maximum system voltage	1000VDC (IEC)									
Maximum series fuse rating	20A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.40%/°C									
Temperature coefficients of Voc	-0.29%/°C									
Temperature coefficients of Isc	0.048%/°C									
Nominal operating cell temperature (NOCT)	45±2°C									

* STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

Figure 12: A screenshot of the data sheet for PV modules

- The factor of safety is employed to make sure that the regulator handles maximum current produced by the array that could exceed the tabulated value. And to handle a load current more than that planned due to addition of equipment, for instance. In other words, this safetyfactor allows the system to expand slightly.
- The number of controllers to be employed in the hybrid system can then be calculated for bydividing the current rating obtained above by the ampere rating of the controller to be used. The ampere rating of the controller to be used in this project is 100 A. Therefore the numberof controllers employed to be employed in the hybrid system is ;

$$\textbf{Ncontroller} = \frac{I}{\textit{Ampere Rating of each controller}}$$

$$\textbf{Ncontroller} = \frac{\mathbf{1024.875}\ A}{\mathbf{100}\ A} \approx \textbf{11 controllers}$$

- This means that 11 of the 100 A rated Voltage regulators would have to be paralleled to withstand the maximum current produced by the array as well as the maximum load current.

Sizing of Inverter

- During the sizing of the inverter, an array-to-inverter ratio of 1.25 was used based on market recommendation. The array-to-inverter ratio (also known as the DC/AC ratio) is the DC rating of the solar array divided by the maximum AC output of your inverter.
- Therefore to get the maximum AC output of the inverter, the peak DC rating of the solararray which has been calculated as 30 kW is divided by DC/AC ratio as shown in the following equations;

$$P_{inverter}\ (\text{kW rating of inverter}) = \frac{30\ kW}{1.25}$$

Pinverter (kW rating of inverter) = **24 kW**

- Most inverters used in such projects are rated in kVA, therefore to convert the kW ratings obtained above to an equivalent kVA, a power factor of 0.8 was chosen. This choice is alsobased on market recommendations.

$$S_{inverter}\ (\text{kVA rating of inverter}) = \frac{Pinverter}{\cos \varphi}$$

$$S_{inverter}\ (\text{kVA rating of inverter}) = \frac{24\ kW}{0.8}$$

Sinverter (kVA rating of inverter) = **30 kVA**

- Therefore the inverter that was chosen for this project had a rating of 30kVA, 48-Vdc, 240-Vac**.**

Sizing of Diesel Generator

- As mentioned earlier in the previous chapter, the diesel generator would be mainly used as aback-up in the hybrid system where it would be switched on to supply the load and charge the batteries when the batteries have a low state of charge and the PV system are not able toproduce energy at that moment in time.
- The size of the Genset to be used is calculated for by dividing the total power of the load bythe power factor (which is 0.8 as suggested by an expert in a genset distributing firm)
- The total power of the load is 14.505 kW. Adding a reserve margin of 15% gives a total of16.681 kW.

Size of genset = 16.681/0.8 = 20.85 kVA

The size chosen for this project is 30 kVA since available standard models are usually 15 kVA,20 kVA, 30 kVA, 40/45 kVA, 50 kVA, 60 kVA etc. Aside this reason, the size was also chosento give room for expansion in the future.

The table 4 below shows the various components of the solar PV-genset hybrid system and theirvarious cost components from retail outlets in the country.

The initial capital cost of the PV panels are slightly increased to cater for other ancillaries likethe combiner box, the cost of land, cost of installation and other related expenses.

Each major components' capital cost however include their installation and other miscellaneouscosts.

The components with a lifetime of 25 years did not have any replacement cost because they are supposed go through the project duration without being replaced. However, the components witha lifetime lower than that of the project itself had replacement cost components. Moreover, thesecomponents with a lifetime lower than that the project itself had no operation and maintenance (O&M) cost since they do not need any maintenance and need to be replace after their stipulatedlife span.

Component (Manufacturer)	**RequiredSize**	**Rating**	**Qty.**	**Total Capital Cost ($)**	**O&M Cost ($/year)**	**ReplacementCost ($)**	**Lifetime**
PV panels (Jinko)	30 kWp	335 Wp	90	42,800	54.00	-	25 years
Inverter (Victron multiplus)	30 kVA	5 kVA	6	13,800	-	5,520	10 years
Lead AcidBatteries (Hoppecke)	122.29 kWh	24 kWh	6	48,000	-	33,600	7 years
Charge Controller (Victron smartsolar mppt controller)	1024.875 A	100 A	11	12,100	-	6,050	10 years
Generator Set (Mann)	20.85 kVA	30 kVA	1	13,850.92	885.00	-	20,000 hours

Table 4: Costing of various components of off-grid solar PV-genset hybrid mini-grid system obtained from themarket

4.2.2.2 Grid Extension (Sizing and Costing Of Transmission Line and Substation)

Transmission Line Design and Costing

Considering a 3-phase short transmission line model. The distance of the village from the nearest11 kV tower is 36 km.

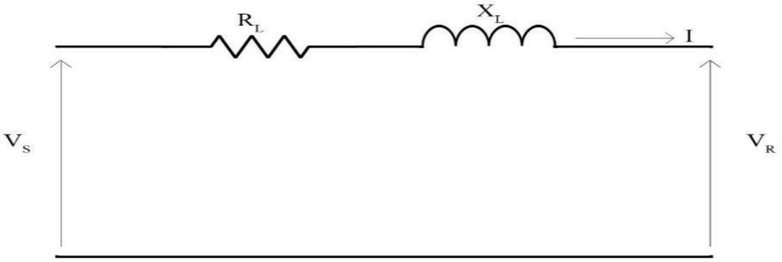


Figure 13: Circuit model of a 3-phase short transmission line

- The resistance (R_L) and inductive reactance (X_L) of the conductors is lumped into oneconductor as shown in the circuit above.

- From the circuit;
  The receiving end voltage per phase, $V_R = V_S - I^*(R_L + jX_L)$But $X_L = 2\pi f L$

- For a 3-phase laterally placed lines as shown below;

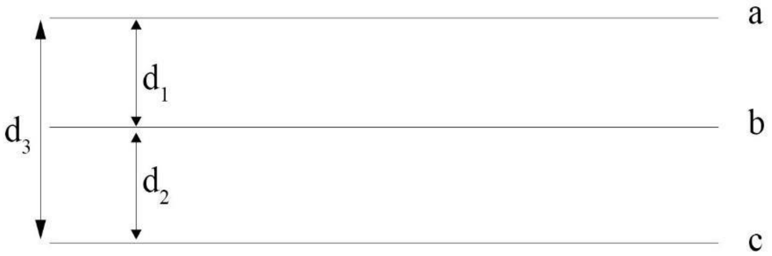


Figure 14: A diagram showing how the three conductors of a 3-phase transmission line are separated from eachother

$$\overline{L} = 2 \times 10^{-7} \ln \sqrt[3]{\frac{d_1 d_2 d_3}{r^I}}$$

Where $r^I = 0.7788^*r$
Using 50 mm^2 conductors gives r to be 3.99 mm (using $A = \pi r^2$)
The IEEE standard values for d_1, d_2 and d_3 are 0.9m, 0.9m and 1.8m respectively.Implies;

$$L = 2 \times 10^{-7} \ln \sqrt[3]{\frac{0.9*0.9*1.8}{0.7788\ (0.00399)}}$$

$L = 4.10 \times 10^{-7}$ H/m
$X_L = 2*\pi*50*(4.10\times 10^{-7}) = 0.1288\ \Omega/\text{km}$

- All Aluminum Conductor (AAC) selectedThe line resistance, $R_L = 0.54193\ \Omega/km$.
- $Z_L = (0.54193 + j0.1288)\ \Omega/km$
- The total demand in kW (plus reserve margin) is 16.69 kW and the power factor, cosφ istaken to be 0.8

- $I = \frac{P}{\sqrt{3}V\cos\phi} = \frac{16.69\times10^3}{\sqrt{3}\times11\times10^3\times0.8} = 1.095\ A$

$Z_L = (0.54193 + j0.1288)\ \Omega/km$ 8 *

Therefore, the receiving end voltage per phase would be; For a distance of 36 km, the line impedance would be;

- $(36\text{km}) = (19.510 + j4.637)\Omega$

$$V_R = \frac{11\times10^3}{\sqrt{3}} - (1.095 < -36.87^\circ)(19.510 + j4.637) = (6330.72 < 0.08^\circ)\ V$$

- To get the line voltage, the phase value is multiplied by √3, as shown below;

$V_{RL} = \sqrt{3} \times 6330.72 < 0.08^\circ = (10.97 < 0.08^\circ)V.$

Table 4 below shows the various components (with their respective quantity and their initial capital cost) for the transmission line design over the 36 km stretch between the nearest 11 kV and the site under study. Similarly, table 5 also shows the various components (with their respective quantity and their initial capital cost) of a typical pole mounted substation to serve theload at the site under study.

The total initial capital cost for the transmission line to the village as shown on table 4 is

GH¢ 994,609.93 (i.e. GH¢ 901,058.88 + GH¢ 93,551.05).

The total initial capital cost for the pole mounted substation that would serve the village asshown on table 5 is **GH¢ 24,175.47** (i.e. GH¢ 21,831.63 + GH¢ 2,343.84).

The grand total of the capital cost in extending the grid supply to the site under study is summation of the total initial capital cost of the transmission line and that of the pole mounted substation (i.e. GH¢ 994,609.93 + GH¢ 24,175.47). This value is **GH¢ 1,018,785.40.** Convertinginto USD gives **$ 175,652.66**.

Finding the capital cost in ($/km) yields **$ 4,879.24 per km** (i.e. $175,652.66/36 km).

The yearly operation and maintenance for both the transmission line and such substation considered in this study include bush clearance, conductor rejoining (after conductor breaks), re-installation of line insulator (after it has been destroyed by electrical faults), transformer oil replacement, replacement of aerial fuses, replacement of dropout fuses and replacement of lightning arresters. The estimated yearly O&M cost was then estimated to be **$75,234.24** given reference to the costs of these items on the table 4 and 5.

Finding the estimated O&M cost in ($/km) yields **$ 2,089.84 per km** (i.e. $75,234.24/36 km).

It must also be noted that the current price of electricity for majority of the loads underconsideration as given by the electricity company of Ghana (ECG) is approximately

$0.1 per kWh.

Description	Qty.	Unit Price(GH¢)	Total Cost(GH¢)	Unit Installation (GH¢)	Total Installation Cost (GH¢)
Wooden Pole (11 m)	362	884.19	320,076.78	130.07	47,085.34
Hard Drawn Aluminum. Bare Stranded Conductor(AAC) (m)	108000	2.54	274,320.00	0.20	21,600.00
11kV post/pin Type Silicon Base PolymerInsulator	1071	173.76	186,096.96	11.14	11,930.94
Fitting for strain insulators consistingof clevis, hook, section strap and anchor	18	43.00	774.00	3.30	59.40
11kV AluminumBinding stirrups	900	2.69	2,421.00	0.16	144.00
11kV Ancillary Channel Cross Arm(1.9 m)	363	220.18	79,925.34	31.39	11,394.57
Stay Equipment and Accessories (Rod, Bow, Plate, Bracket,Thimble etc.)	120	132.04	15,844.80	11.14	1,336.80
Bush Clearance (per km stretch)	27	800.00	21,600	-	-
SUB TOTAL			**879,458.88**		**93,551.05**

Table 5: Costing of transmission line materials required for the given 36 km stretch.

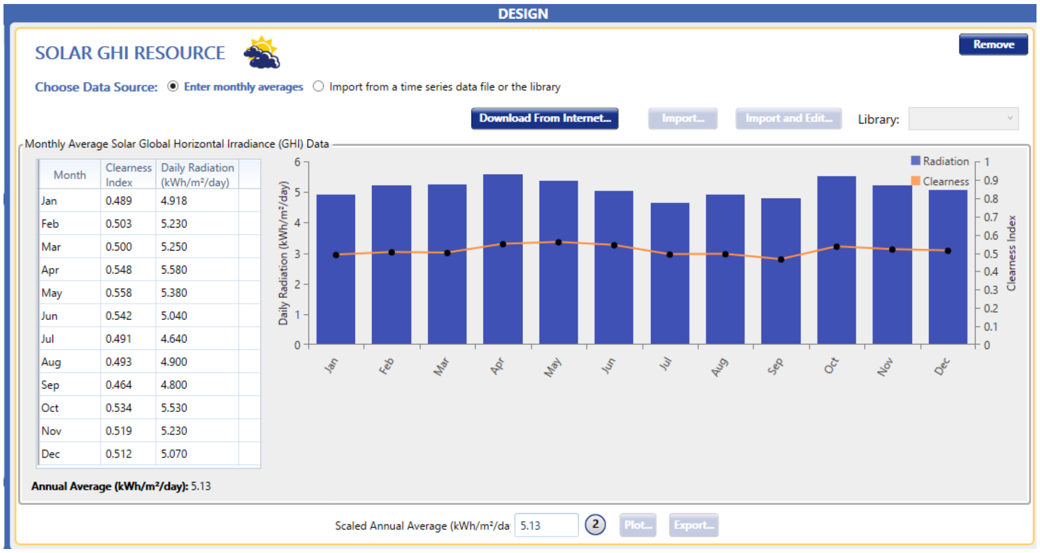
Description	Qty.	Unit Price(GH¢)	Total Cost(GH¢)	Unit Installation(GH¢)	Total InstallationCost (GH¢)
Wooden Pole (11 m)	2	884.19	1,768.38	130.07	260.14
50 kVA Transformer	1	14,039.00	14,039.00	1,334.10	1,334.10
Lightening Arrester	3	434.65	1,303.95	34.82	104.46
Dropout fuse	3	6.02	18.06	0.22	0.66
Copper Earth Rodand Clamp	18	63.52	1,143.36	7.85	141.30
35 mm^2 hard drawnbare stranded Copper Conductor (70m)	1	15.91	15.91	0.94	0.94
Angle ChannelCross-arm	5	220.18	1,100.90	31.39	156.95
LV fuse (3 set – 63A)	3	75.41	226.23	31.39	94.17
Miscellaneous	lot	-	2,215.84	-	251.12
SUB TOTAL			**21,831.63**		**2,343.84**

Table 6: Costing of Substation equipment and ancillaries needed to serve the load requirement for the site understudy

4.2.3 Solar and Diesel Price Information

Solar resource data point of the amount of global solar radiation in a typical year [18]. This amount includes beam radiation, which comes directly from the sun, plus diffusion radiation coming from all parts of the sky [18]. The quantity is presented as monthly average global solarradiation on the horizontal surface (kWh/m^2) [18]. The solar radiation directly affect the output power produced by the solar PV panel.

The solar information of the site under study was very difficult to obtain due to its remoteness and hence the solar information of the whole region, Ashanti Region was recommended. This information was obtained from the webpage of National Aeronautics and Space Administration(NASA).



Choose Data Source: ● Enter monthly averages ○ Import from a time series data file or the library

Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.489	4.918
Feb	0.503	5.230
Mar	0.500	5.250
Apr	0.548	5.580
May	0.558	5.380
Jun	0.542	5.040
Jul	0.491	4.640
Aug	0.493	4.900
Sep	0.464	4.800
Oct	0.534	5.530
Nov	0.519	5.230
Dec	0.512	5.070

Annual Average (kWh/m²/day): 5.13

Scaled Annual Average (kWh/m²/da 5.13 ②

Figure 15: Solar Energy Profile of Ashanti Region

The diesel fuel prices is also an input that is critical to the economics of the generator set and thesolar PV-genset hybrid system as a whole. The current as well as the past diesel prices of the country was also obtained from the webpage of GlobalPetrolPrices.com.

The solar and diesel price information varies without the influence of the system operator and they are often chosen as sensitivity variables in simulations. A sensitivity variable is an input variable for which multiple values can be specified [15]. HOMER, the software which was usedto build optimization for the solar PV-genset hybrid system and would be the focus in the next section, performs a separate optimization procedure for each specified value of the sensitivity variable.

4.3 Optimizing with the Homer Pro

HOMER (Hybrid Optimization Model for Electric Renewables) developed by NREL (National Renewable Energy Laboratory, USA) [19] is the simulation software which was employed in thisproject to design and evaluate the feasibility of the off-grid solar PV-genset hybrid system.

Cost, LCC), that you can use to compare system design options [20].
Since HOMER Pro would give the NPC and LCOE of the optimized hybrid system, there wouldn't be any need to do this calculation manually. The NPC and LCOE of the grid extensionwould however be calculated manually in the next section.

4.4 Manual NPC and LCOE Calculation for Grid Extension Alternative

The NPC and LCOE of the grid extension was calculated manually since this feature is payablein the HOMER Pro. Fig.16 below is the cash flow diagram of the grid extension alternative.

There are 26 demarcations representing year 0 to year 25;

- The first yellow arrow (pointing downwards) located at year 0 represent the initial capitalcost of the grid extension, **Ccap, grid** which was estimated in subsection 4.2.2.2 to be

$ 175,652.64.

- The 25 blue coloured arrows (pointing downwards) starting from year 1 through to year 25 represent the yearly maintenance cost, **CO&M, grid** which was also estimated to be **$ 75,234.24.**
- The 25 orange coloured arrows (pointing upwards) starting from year 1 through to year 25 represent the yearly revenues generated from the grid supply through the sale of electricity. From the fig. 85, HOMER Pro calculated the yearly consumption,

Eserved of the site under study to be **28,364 kWh**. The current price of electricity for majority of the loads under consideration as given by the electricity company of Ghana (ECG) is approximately **$0.1 perkWh.** Hence the yearly revenues generated from the sale of electricity, **Rgrid** would be $2,836.4

- The last green arrow (pointing upwards) located at year 25 represent the salvage value of the grid extension after the 25 year period. The life span of such a grid extension model is around45 years. This is given by;

Sgrid = Ccap, grid * ($\underline{rem}$)

N_{grid}

Where;
Ccap, grid is the initial capital cost of the grid extension
Nrem is the years remaining after the 25 years of the projectNgrid is the lifetime of the grid.
Hence the salvage value of the grid extension after 25 year period would be0

Sgrid = $ 175,652.64 * (^{20}) = **$ 78,067.84**
45

The net present cost, NPC of the grid extension is then given as;

(NPC) grid = Ccap, grid + CO&M, grid *[USPWF (i, n)] – (Rgrid*[USPWF (i, n)] +Sgrid*[SPPWF (i, n)])Where;
i is the annual real interest rate which was 14.5% at the time this report was written.n is the project period which is 25 years

USPWF (i, n) is called the uniform series present worth factor which is $^{(1+i)}$ $\underline{n_{-1}\quad}$

$(1+i)^n$

USPWF (i, n) = [$\underline{\quad {}^{(1+0.145)}}$ ^{2}] = 6.663; **CRF (i, n)** is the inverse of USPWF (i, n). Implies
5_{-1}

$0.145*(1+0.145)^{25}$

1/6.663 = 0.15

SPPWF (i, n) is called the single-payment present worth factor which I $\frac{1}{(1+i)^n}$

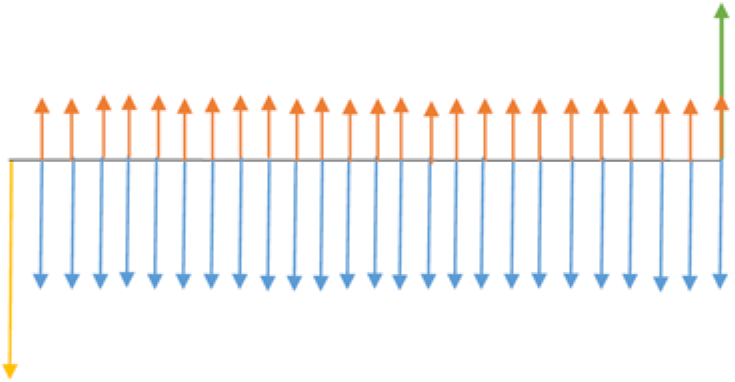


Figure 16: Cash flow diagram for grid extension alternative

SPPWF (i, n) = $\frac{1}{(1+0.145)^{25}} = 0.034$

(NPC) $_{grid}$ = \$ 175,652.64 + \$ 75,234.24 *[6.663] – (\$2,836.40*[6.663] +\$78,067*[0.034])

(NPC) grid = \$ 676,938.3811 – (\$ 21,553.21120) = **\$ 655,385.17**

The (LCOE) $_{grid}$ is also given by;

$$(LCOE)_{grid} = \frac{(NPC)_{grid} * [CRF\ (i,n)]}{E_{served}} = \frac{\$\ 655{,}385.17 * [0.15]}{28{,}364\ kWh} = \$\ \mathbf{3.47/kWh}$$

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Optimization Results

After simulating the solar PV-genset hybrid system using the HOMER Pro, an optimized system was obtained. The optimization result determines the best possible system configuration for a particular location [18]. The best system or optimum system is the one with the lowest total net present cost that can meet user requirement [18]. All possible hybrid system configuration are listed in ascending order of their total net present cost [19]. Figure 18 shows the optimal configuration obtained for each combination of sensitivity variables. The optimal combination of the hybrid system for the case study is a 30-kW PV Array, 25 kW diesel generator set, 25-KW converter and 124 1-kWh Li-Ion batteries. The total NPC, LCOE and the initial capital cost for such hybrid system (giving reference to the market price of diesel being $ 0.75 per litre and the solar irradiance of the area being 4.92 kWh/m^2/day) is $368,148, $ 235,810 and $1.95/kWh respectively.

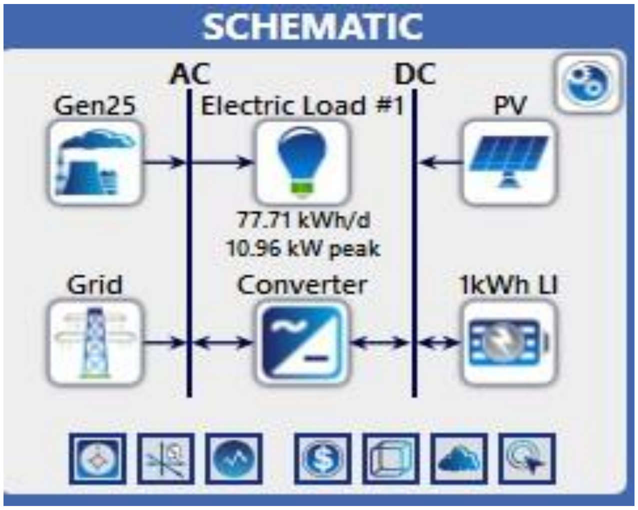
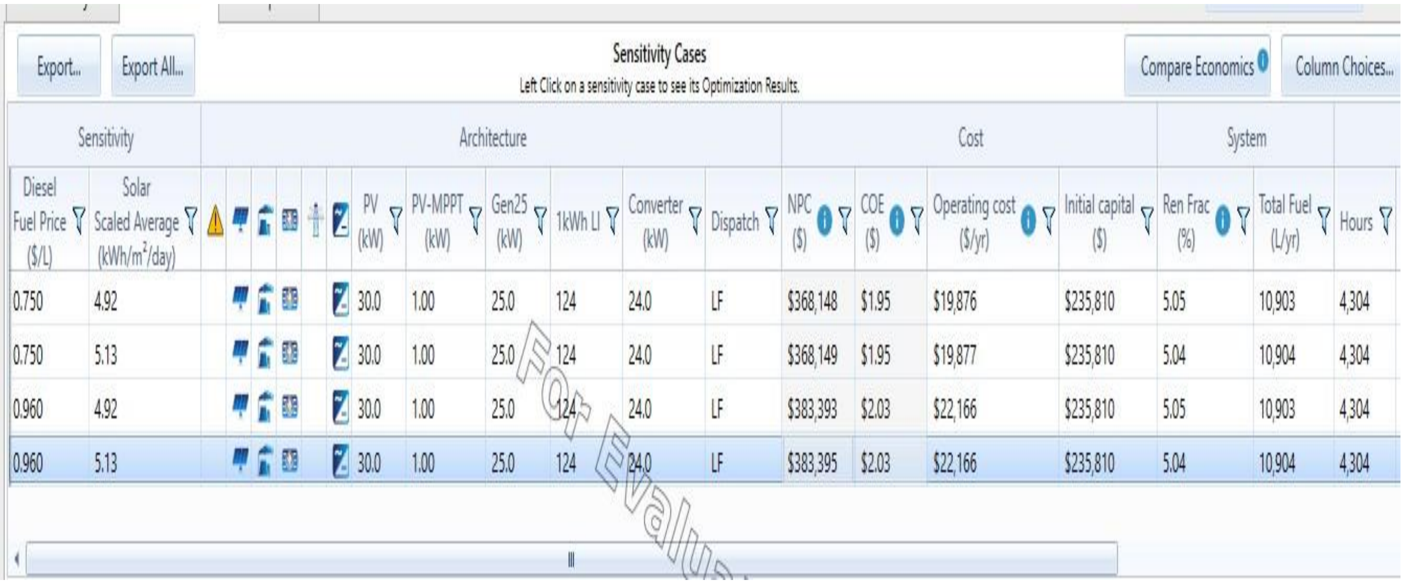


Figure 17: Solar PV-diesel genset hybrid model



Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Sensitivity		Architecture						Cost				System		
Diesel Fuel Price ($/L)	Solar Scaled Average (kWh/m^2/day)	PV (kW)	PV-MPPT (kW)	Gen25 (kW)	1kWh LI	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours
0.750	4.92	30.0	1.00	25.0	124	24.0	LF	$368,148	$1.95	$19,876	$235,810	5.05	10,903	4,304
0.750	5.13	30.0	1.00	25.0	124	24.0	LF	$368,149	$1.95	$19,877	$235,810	5.04	10,904	4,304
0.960	4.92	30.0	1.00	25.0	124	24.0	LF	$383,393	$2.03	$22,166	$235,810	5.05	10,903	4,304
0.960	5.13	30.0	1.00	25.0	124	24.0	LF	$383,395	$2.03	$22,166	$235,810	5.04	10,904	4,304

Figure 18: Optimization result obtained for each sensitivity variable combination

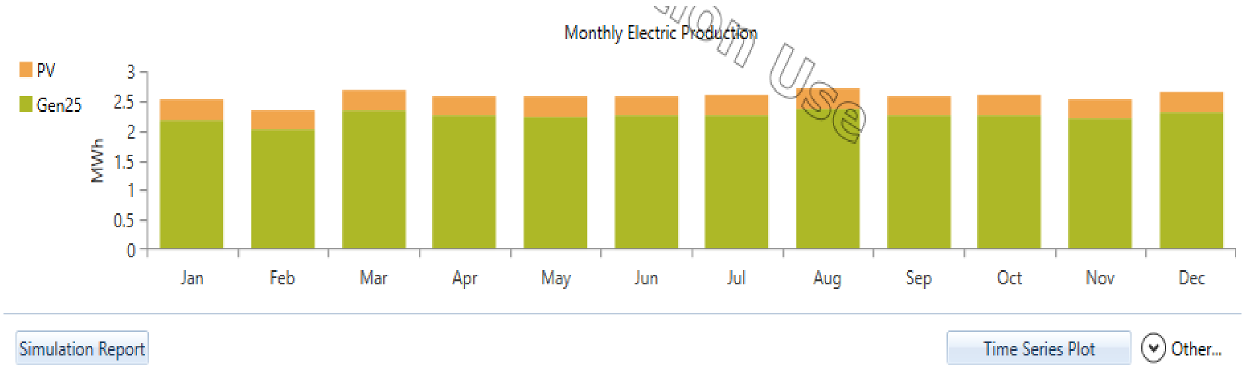
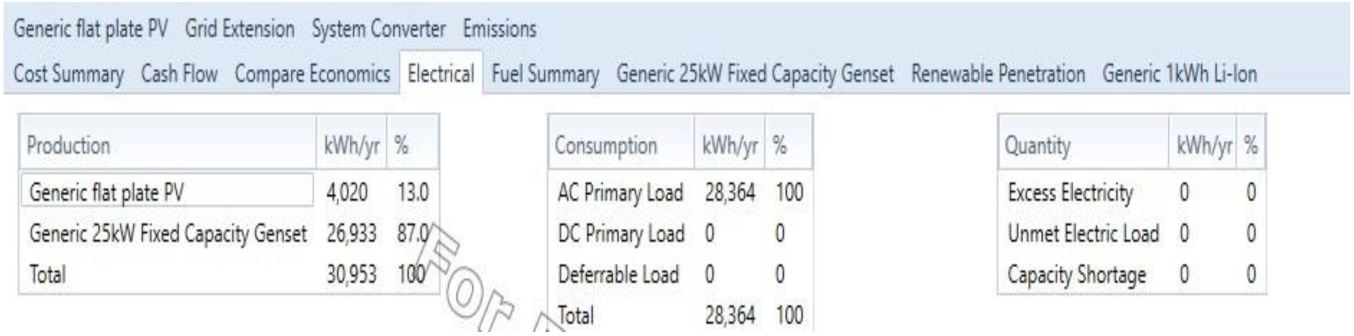


Figure 19: Average monthly electricity production

The monthly average power production is shown in fig. 19. Fig. 20 portrays that the PV panels generate 4,020 kWh per year representing 13% of the total energy produced in a year and the genset generate 26,933 kWh per year representing 87% of the total energy produced in a year. This ‘optimized’ system somehow goes against what was proposed in sub section 3.3.2 since it is technically desired to make the solar PV panels to generate more energy for the diesel genset to serve as a back-up. However, the values of the ‘optimized’ system would be adopted for the economic analysis with minimal errors (which would not change the comparison outcome with the grid extension) even if it is desired to use the proposed operation suggested in subsection 3.3.2 instead of HOMER’s ‘optimized’ system.



Production	kWh/yr	%
Generic flat plate PV	4,020	13.0
Generic 25kW Fixed Capacity Genset	26,933	87.0
Total	30,953	100

Consumption	kWh/yr	%
AC Primary Load	28,364	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	28,364	100

Quantity	kWh/yr	%
Excess Electricity	0	0
Unmet Electric Load	0	0
Capacity Shortage	0	0

Figure 20: Optimal least cost hybrid system for the rural load

5.2 Economic Analysis

As stated in section 3.4, the means by which the two alternatives would be compared in this study is by three main parameters – the total net present cost of the two alternatives (NPC), thelevelized cost of energy (LCOE) of the two alternatives and the breakeven grid extension distance.

5.2.1 Economic Analysis using Total net present cost (NPC)

The simulation results from the HOMER Pro gave the total net present cost of the optimizedsolar PV-genset hybrid system to be **$ 368,148**

In **section 4.4**, the manual calculation of the total net present cost of the grid extension yield
$ 655,385.17.

Therefore if the total net present cost is used as a means to compare the two alternatives, it can be seen that it would be more costly to extend grid electricity to the site under study than to builda solar PV-genset hybrid system to supply electricity for the same site.

5.2.2 Economic Analysis using Levelized Cost of Energy (LCOE)

The simulation results from the HOMER Pro gave the levelized cost of energy of the optimizedsolar PV-genset hybrid system to be **$ 1.95 per kWh**.

In **section 4.4**, the manual calculation of the total levelized cost of energy of the grid extensionyield **$ 3.47 per kWh.**

Juxtaposing the two LCOE results indicate that it will be more expensive to purchase power under the grid extension than under the hybrid system for same. This however not the ‘real’ casesince the electricity tariffs under the grid supply of a country is fixed and cannot be different for different communities in the country. This means that it wouldn’t be economically viable to extend grid electricity to this community from the point of view of utility companies.

In another view, if the community is to be very close to other communities, the extended grid transmission line can equally be used to serve the other communities which can therefore helpdecrease the LCOE for the grid extension alternative and make it even rival the LCOE of the solar PV-genset hybrid system.

5.2.3 Economic Analysis using the Break-even grid extension distance

The HOMER Pro was harnessed to make calculation for this parameter of comparison. Thiscomparison parameter was one of the several outputs the software gave after running the simulation; giving some form of means to compare between the optimized hybrid solar PV-genset system and the grid extension alternative.

As seen on fig. 21, this distance is the distance where the total net present cost of the twoalternatives intersect. The break-even grid extension distance was obtained to be 18.58 km. Which is less than the actual distance of the village from the nearest grid tower (i.e.36 km).

Giving reference to the break-even grid extension distance obtained for this study, it can be seenthat it is more cost-effective to employ the off-grid hybrid generation system than to extend gridsupply over the 36 km stretch to serve the load at the site of study. Had the actual distance between the village and the nearest grid tower been lesser than the break-even grid extension distance, the grid extension approach would have been more economically viable.

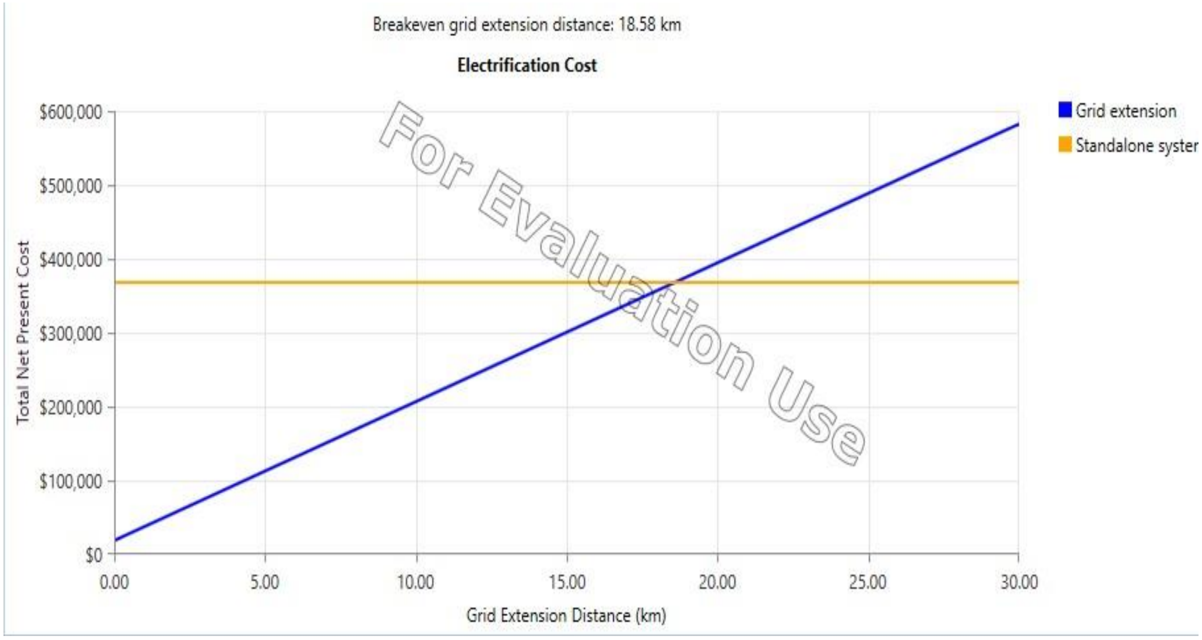


Figure 21: Break-even grid extension distance diagram

5.3 **Results Evaluation**

Evaluation of the results obtained above may seem impossible since there is no actual experiment to justify them. However, gleaning information from past literature on similar studiescan serve as a benchmark to validate the reliability of the results obtained in this work.

Rohit Sen and Subhes C. Bhattacharyya [19] researched on renewable energy-based mini-gridfor Rural Electrification using a village in India called Palari (as a case study) with an averageprimary load demand of 222 kWh/day and 51.2 kW peak load. The average daily demand is almost 3 times more than the electrical demand at site under consideration.

The average solar radiation at Palari was around 5.17 kWh/m^2/ day whiles that of the site considered in this studies is at 5.13 kWh/m^2/ day. The nearest distance to the grid tower from the village in the case of Palari is 60 km whiles it was 36 km in this study. The results obtained at thePalari villages reveals that the least LCOE for several renewable systems set up was $0.42\kWh which was lower than the grid extension’s alternative with an LCOE of $0.44\kWh. Comparing these results with the ones obtained in this study, ($1.95\kWh for hybrid generation system and $3.47\kWh for grid extension alternative) it can be seen that the off-grid renewable electrification method is more cost-effective than the grid extension alternative. The values in this case study are however higher than what was obtained in the Palari case study because thealternatives in this case study served a smaller load demand than in the Palari case study.

Mutasi Nour and Golbarg Rohani [18] researched on prospect of stand-alone PV-diesel hybrid power system for rural electrification using a village in UAE called Um Azimul as a case study. The number of households being 500 is way higher than the 21 households considered in this case study. The average solar radiation for Um Azimul is 5.94 kWh/m^2/day whiles that of the site considered in this studies is at 5.13 kWh/m^2/ day. The nearest distance to the grid tower from the village in the case of Um Azimul is 143 km whiles it was 36 km in this study. The results obtained from Um Azimul case-study showed that the break-even grid extension distance was

83 km. Comparing this value to what was obtained in this study validates that grid extension alternative is not a cost-effective approach for the rural electrification when it comes to juxtaposing this approach with off-grid solar PV-genset hybrid system.

These information and many others gleaned from literature reviews presented in chapter two can to be used to some extent validate the results obtained in this study.

CHAPTER 6: CONCLUSION

Ghana being a developing country has over the years been focusing on rural electrification using the grid extension approach. On the 13th day of February 2019, Ghana's Renewable Energy Master Plan was officially presented to the Ministry of Energy by the Energy Commission.

The Master Plan constitutes an investment-focused framework for the development and promotion of the country's rich renewable energy resources to propel economic growth, improve social life and reduce climate change effects [21].

The plan, when implemented, is expected to help the country achieve the following targets by 2030 [21]:

- Increase the penetration of renewable energy in the national energy generation mix from the 2015 baseline of 42.5 MW to 1363.63 MW (with grid connected systems totaling 1094.63 MW);
- Reduce the dependence on biomass as main fuel for thermal energy applications;
- Provide renewable energy-based decentralized electrification options in 1,000 off-grid communities; and
- Promote local content and local participation in the renewable energy industry.

According to the book, one of the several ways to achieve these targets is to increase the current number of hybrid mini-grids from thirteen (as at 2015) to three hundred by 2030 [21]. In view of this, it is believed that Ghana's Ministry of Energy would need a plethora of frameworks or studies that has already considered the economic viability of putting up such hybrid mini-grids in the various communities of the country.

The study presented in this report is therefore a very good reference to be used to look into the economic viability of putting up hybrid mini-grids in most rural communities of the country.

The study also made an economic comparison between the establishments of hybrid mini-grids and grid extension alternative when it comes to rural electrification. This means that institutions can use it as a reference for making a choice between the two alternatives.

The results obtained in here showed that the NPC of grid extension heavily depend on the distance of the community from the nearest 11 kV transmission lines. However, the distance would not be an issue to worry about if the load to be served is great since this will help reduce the LCOE of the grid extension approach.

In the case of the Solar PV-genset hybrid mini-grid system, the costs components as well as the lifetime of the system's individual components, the current fuel prices and the solar irradiance are the major factors that affect the system's NPC. To a lesser extent, the fraction of the solar energy to be produced by the system also affect the capital cost. The LCOE of the system would however depend on the load the system will serve.

Conflict of Interest

There is no conflict of interest in this work.

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