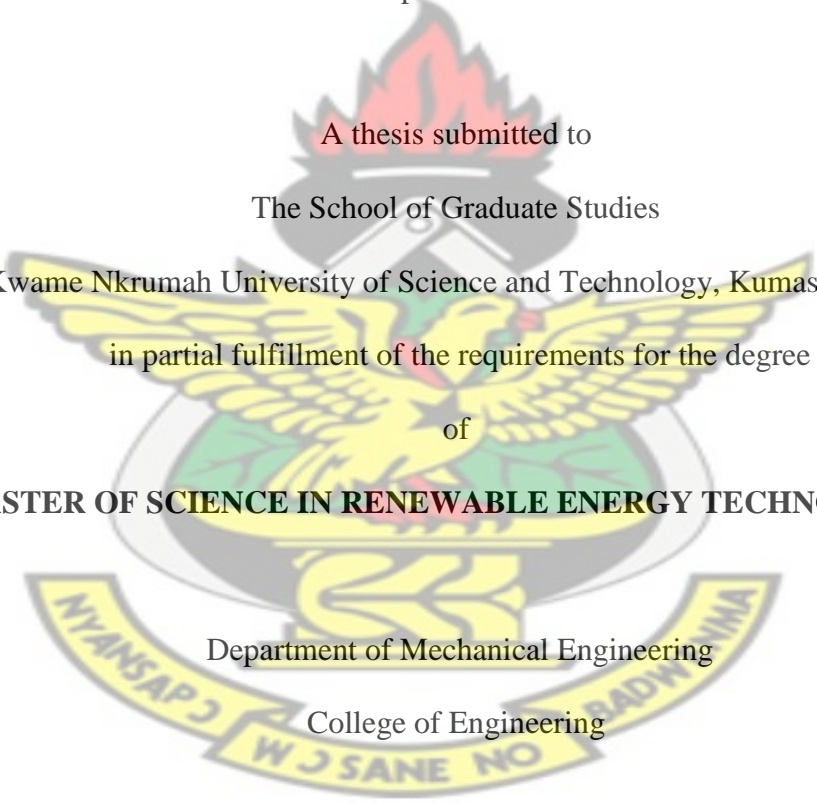


EXAMINING SOLAR PV MINI-GRID SYSTEM AS A COMPLEMENT TO GRID
EXTENSION FOR RURAL ELECTRIFICATION WITH REFERENCE TO YAMA
COMMUNITY, NORTHERN GHANA.

By
KNUST
Stephen Abaase

A thesis submitted to
The School of Graduate Studies
Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
in partial fulfillment of the requirements for the degree
of
MASTER OF SCIENCE IN RENEWABLE ENERGY TECHNOLOGIES
Department of Mechanical Engineering
College of Engineering



Supervisor: Dr George Yaw Obeng

July, 2013.

DECLARATION

I hereby declare that this submission is my own work towards the MSc and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

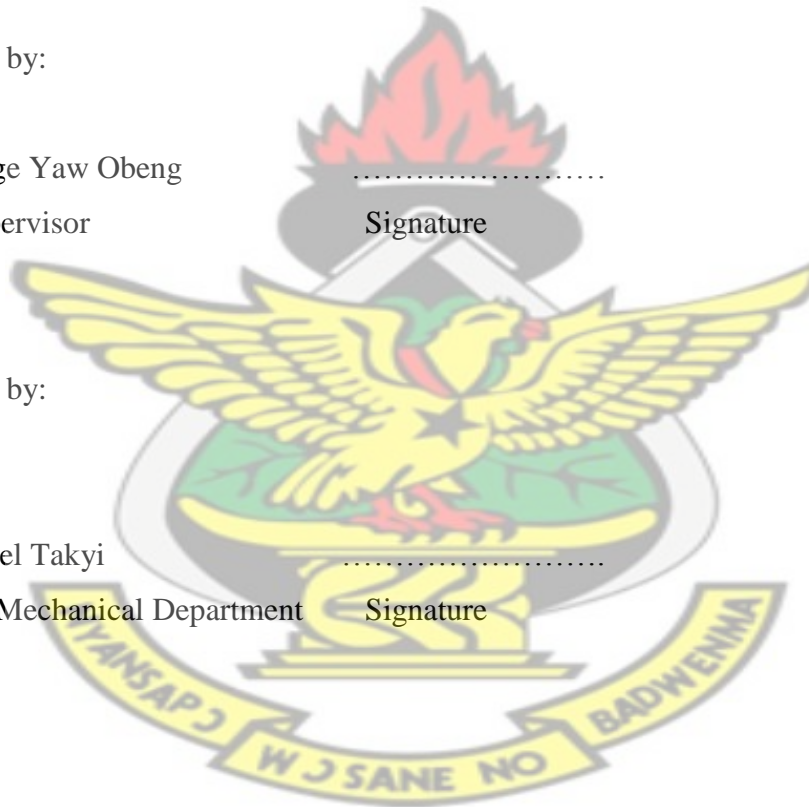
Stephen Abaase - 20256225
Student Name & ID Signature Date

Certified by:

Dr George Yaw Obeng
Lead supervisor Signature Date

Certified by:

Dr Gabriel Takyi
Head of Mechanical Department Signature Date



ABSTRACT

This research was undertaken to design, determine the cost and economic viability of solar PV Mini-grid System as an alternative to grid extension using Yama community as a case study. In this study energy demand survey was conducted in 300 households (3000 inhabitants) in YAMA. Average daily Energy demand considering 200 households (2000 inhabitants) and 50 households (500 inhabitants) was also determined. These sizes of PV mini grid systems obtained, 120kWp PV system for 300 households, 72.5kWp PV system for 200 households and 26kWp PV system for 50 households. The System wiring and system configuration procedures for the designed PV systems are outlined to show that it is theoretically possible to design a PV mini-grid system for unelectrified communities in Ghana. The 120kWp mini-grid photovoltaic system for Yama is estimated to cost US\$869,793 while the cost of extending the national grid of 34.5kV MV line over a distance of 18 km is estimated to cost US\$1, 091,145. The 26kWp PV mini-grid system for 50 households is estimated to cost US\$305,400. It also established that for the PV system to economically viable a feed-in-Tariff of between US35 Cents/kWh to US50 Cents/kWh giving a simple payback period of between 10 and 15 years was required. These results show that solar PV mini-grid connected system is economically viable for rural electrification for isolated, small and remote communities where the national grid has to be extended distances beyond 20km. Furthermore, PV mini-grid systems can be integrated into the national grid, when those communities are connected to the national grid in future. Solar PV mini-grid system can serve as a stop gap measure towards attainment of the universal access to electricity for communities with population above 500 inhabitants as in Ghana's electrification policy.

ACKNOWLEDGEMENT

Words cannot express my gratitude first and foremost to God Almighty for helping me throughout this research project. Without His grace and mercy this research work would not have been successful.

My greatest thanks go to my lead supervisor, the late Prof. Abeeku Brew-Hammond for his encouragement and support to pursue this particular topic even though; death did not allow him to witness its conclusion.

I am particularly grateful to Dr George Yaw Obeng who later accepted to take over after the untimely death of Professor Abeeku for his hard work, love and tolerance.

My appreciation also goes to Dr Gabriel Takyi and all MSc RETs lecturers for your time and patience.

Special thanks to all colleagues and friends especially Mr. Frank Yeboah Dadzie and all who made useful contributions to the success of this study

Finally, I would like to appreciate the prayers and moral support from my wife and children throughout my period of study. Thank you also for giving me the peace of mind to undertake this program successfully.

DEDICATION

THIS WORK IS DEDICATED TO THE LATE PROF. ABEEKU BREW-HAMMOND
(FORMER DIRECTOR, THE ENERGY CENTER, KNUST).
HE HAS BEEN AN ENCOURAGEMENT TO ME EVEN THOUGH DESTINY DID
NOT ALLOW HIM TO WITNESS THE CONCLUSION OF WHAT WE BEGUN,
MAY HIS GENTLE SOUL REST IN PEACE.

KNUST



TABLE OF CONTENT

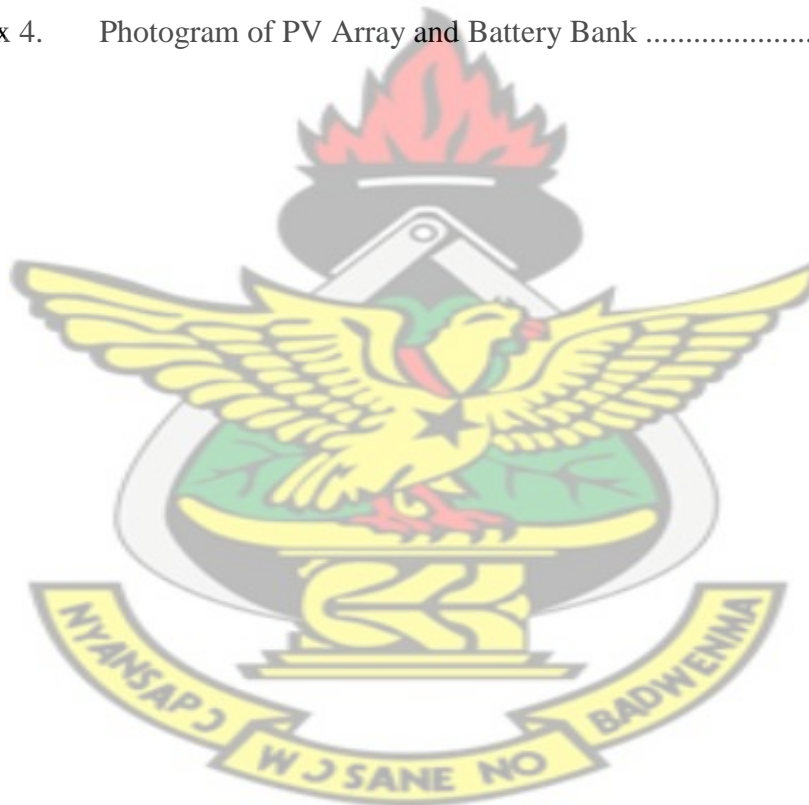
Contents

DECLARATION	ii
ABSTRACT	iii
DEDICATION	v
TABLE OF CONTENT	vi
LIST OF TABLES	x
LIST OF FIGURES	xi
MAJOR ABBREVIATIONS	xii
CHAPTER ONE	1
1.0 Introduction	1
1.1 Background	1
1.2 Problem statement and Justification	3
1.3 Research objectives	4
1.3.1 General objective	4
1.3.2 Specific objective	5
1.4 Scope	5
1.5 Chapter Outline	6
CHAPTER TWO	7
2.0 Literature Review	7
2.1 Ghana Renewable Energy Policy	7
2.1.1 Various Renewable Energy Technologies	7
2.2 Energy Needs and Statistics of Ghana	9
Source: VRA REDP, (2010)	10
2.3 Assessment of Ghana's available Solar Energy Resources and Systems	10
2.3.1 Solar Photo-Voltaic Energy System	11
2.4 Solar PV mini grid systems	12
2.4.1 Relevant experiences (International)	12
2.4.2 IEA-Photovoltaic Power System Programme: Stand Alone Photovoltaic Applications– Lessons Learned	14
2.4.2.1 Task 11 – PV hybrid systems within mini-grids	15
2.4.3 Recent mini-grid experiences	16

2.4.4 Case-studies involving mini-grids	17
2.4.4.1 Centralized power generation	17
2.4.4.2 Bulyansungwe mini-grid System- Uganda	17
2.4.4.3 Case study on the Benefits of interconnecting stand-alone PV into a mini-grid..	19
2.4.5 Approaches to mini-grid development.....	21
2.4.6 Opportunities of mini-grid implementation in developing countries	21
2.4.7 Challenges of mini-grid implementation in developing countries.....	22
2.4.8 Requirements for developing successful mini-grids.....	23
2.5 Relevant experiences - Ghana.....	25
2.5.1 KNUST Energy Center.....	25
2.5.2 Wechiau solar project.	26
2.6 Cost of Solar PV systems.....	26
2.7 Components of PV mini-grid system.....	27
2.7.1 PV array	27
2.7.1.1 Factors that affect the performance of a solar cell.....	28
2.7.1.2 Types of solar cells	29
Figure 2.5 Types of solar modules.....	29
2.7.2.1 Types of Batteries	30
2.7.2.1.1 Flooded batteries.....	30
2.7.2.1.2 Absorbed Glass Mat Sealed Lead Acid (AGM)	31
2.7.2.1.3 Deep Cycle Battery	31
2.7.2.2 Factors that affect the life of the battery bank	31
2.7.3 Inverter.....	32
2.7.4 The Power Distribution Network.....	34
CHAPTER THREE	36
3.0 Design Methodology.....	36
3.1 PV Mini-Grid Connected Photovoltaic System with Battery Backup Design ...	36
Figure 3.1 System design process flow chart.....	37
3.2 Selection of design configuration	37
3.3 Source of data and method of data collection for Load Assessment	38
3.4 Selection of system voltage	40
3.5 Determination of design daily load.....	41
3.6 Battery sizing and specifying.....	41
3.7 Sizing and specifying PV array.....	46

3.7.1 Selection of PV module to be used	46
3.7.1.1 Quality and safety	47
3.7.1.2 Typical electrical characteristics	47
3.7.2 Determining the size of array required	47
3.7.3 Sizing and specifying Inverter	50
3.8.6 Sizing of cables	55
3.8.6.1 Sizing cables between PV modules	56
3.8.6.2 Sizing of cable between inverter and battery bank	56
3.9 Mini-grid Distribution Network Mapping and Layout	57
3.9.1 Placing the lines	57
3.9.2 Locating poles	58
3.9.3 Line Configuration	58
3.9.4 System grounding	59
3.9.5 Conductor	59
3.9.6.1 Types of conductor	60
CHAPTER FOUR	61
4.0 Results and Discussion	61
4.1 Cost of Design	61
4.2 Sources of data for cost analysis	61
4.3 Estimation of project life	62
4.4 Difference between warranty period and expected life time	62
4.5 Estimated investment cost for 300 households	63
4.6 Estimated investment cost for 50 household	64
4.7 Material Estimate for MV/LV Construction	65
4.8 Cost Estimate MV/LV Construction	66
4.9 Economic viability of solar PV mini grid	67
4.9.1 Estimation of relevant financial rates	67
4.9.1.1 Interest rate	67
4.9.1.2 Inflation rate	67
4.9.1.3 Exchange rate	67
4.9.1.4 Selection of financing source	67
4.9.2 Life cycle cost of O&M of system	68
4.9.3 Lifecycle cost of Battery Replacement	68
4.9.4 Economic Viability using Simple Payback Analysis	68

CHAPTER FIVE	70
5.0 Conclusions and Recommendations	70
5.1 Conclusions.....	70
5.2 Recommendations.....	71
References.....	72
APENDICES.....	76
Appendix 1.....	76
Appendix 2.....	78
Energy Demand Survey for Solar PV mini Grid Connected System-Questionnaires	78
Appendix 3.....	81
Challenges of rural electrification in northern region of Ghana.	81
Appendix 4. Photogram of PV Array and Battery Bank	83



LIST OF TABLES

	Table
Table 2.1 Generation Capacity Available for 2012	10
Table 3.1 Household Average Energy Demand Assessment for Yama	39
Table 3.2 Energy Demand Assessment for Public loads	40
Table 4.1 Warranty and Life of Product	62
Table 4.2 Estimating the Cost of PV Mini- Grid System for Yama	63
Table 4.3 Estimating the Cost of PV Mini-Grid System for 50 Households	64
Table 4.4 Material Estimate for MV/LV Construction	65
Table 4.5 Cost Estimate for MV/LV Construction	66



LIST OF FIGURES

	Table
Fig 2.1 Solar Radiation Map for Ghana	11
Fig 2.2 Diagram of a Simple Solar System	12
Fig 2.3 Schematic Diagram of a PV Mini-grid System.	14
Fig 2.4 A typical I-V Curve of a Solar Cell	28
Fig 2.5 Types of Solar Modules	29
Fig 2.6 Photograph of a Typical Inverter	33
Fig.2.7 Components of a PV Mini-grid System	34
Fig 3.1 System Design Process flow Chart	37
Fig 3.2 Diagram of System Design Configuration	38
Fig 3.3 Wiring Diagram of PV Array	52
Fig 3.4 Wiring Diagram of Battery Bank	53
Fig 3.5 Single Line Electrical Circuit Diagram	54
Fig 4.6 Graphical Representation of RETSCREEN analysis	68

MAJOR ABBREVIATIONS

A	Ampere
AC	Alternating Current
Ah	Ampere-hour
B.Eng.	Bachelor of Engineering Degree
CIDA	Canadian International Development Agency
CO ₂	Carbon Dioxide
DANIDA	Danish International Development Agency
DC	Direct Current
EC	Energy Commission
ECG	Electricity Company of Ghana
GDP	Gross Domestic Product
GDP	Gross Domestic Product
GEDAP	Ghana Energy Development and Access Project
GWh	Gigawatt-hour
HV	High Voltage
IEA	International Energy Agency
IEA-PVPS	International Energy Agency's Photovoltaic Power Systems
JICA	Japanese International Co-operation Agency
KNUST	Kwame Nkrumah University of Science & Technology
kVA	kilovolt-amps
kWh	kilowatt-hours
LOLP	Loss of Load Probability

LUCE	Levelized Unit Cost of Electricity
LV	Low Voltage
MOEn	Ministry of Energy
MPPT	Maximum Power Point Tracker
MSc	Master of Science
MV	Medium Voltage
MW	Mega-watts
NEDCO	Northern Electricity Distribution Company
O & M	Operation and Maintenance
PURC	Public Utility Regulatory Commission
PV	Photovoltaic (solar cells)
RESPRO	Renewable Energy Services Project
RETs	Renewable Energy Technologies
REEEP	Renewable Energy & Energy Efficiency Partnership
SHEP	Self Help Electrification Programme
SHS	Solar Home System
SLT	Special Load Tariff
SPV	Solar Photovoltaic
T & D	Transmission and Distribution
V	Voltage
VRA	Volta River Authority
W	Watts
Wp	Watt-peak

CHAPTER ONE

1.0 Introduction

1.1 Background

The desirability and usefulness of electrical energy to the world cannot be overemphasized. Electrical energy is useful in industrial, commercial and residential establishments. Electrical energy is useful in all manufacturing, telecommunications, residential (lighting, heating, cooling, entertainment) and commercial activities.

Electrical energy can be derived from various sources which include hydro, nuclear, wind, solar, and thermal sources. The sources of electrical energy can be grouped into two main categories renewable and non-renewable sources. Renewable sources are sources of energy which can be recovered within one's life time (70 years) (Anim-Sampong et al., (2007).

Population growth, urbanization and the introduction of numerous electrical appliances have increased the demand for electrical energy over the years. The choice of a particular source of energy depends on a number of factors including cost of generation, availability of resources, environmental effects, among other considerations.

Solar photovoltaic (PV) energy is obtained by converting sunlight into electricity (Direct Current) through a phenomenon known as the photoelectric effect. Energy from the sun as light is transformed into electricity when it touches the surface of a solar module. The more direct sunlight a solar module receives the more electricity it generates. (Harmon 2000)

Solar PV electricity is unique amongst other energy sources for the wide range of energy and non-energy benefits which can be derived from its utilization.

Solar Photovoltaic electricity can assist in securing energy supplies in both the long term and short term in Ghana. With fossil fuel resources insecurity, PV power can be a means of providing electricity to the world without concern for fuel supply security.

The utilization of solar energy can be broadly divided into two main categories; off-grid PV installation and grid-connected systems.

In this research, a mini-grid (off-grid) refers to a low-voltage (LV) network within a community or neighborhood supplied at a single point by solar PV. It does not refer to the interconnection of two or more separate mini grids into a more extensive area-wide network. The design in this research covers conventional designs that may become interconnected to the national grid within the near future.

The guiding principles for the design of mini-grid systems are that, they are safe, adequate, expandable, and efficient. Systems are **safe** if they present **no** greater hazard to the public than standard urban grid-based systems.

Systems are **adequate** when they deliver sufficient power when and where needed, with the required degree of efficiency and service quality.

System **expandability** implies the use of designs that minimize life-cycle cost by making provision for a certain degree of expansion, obviating the need to replace or rewire portions of the system as the load increases.

An **efficient** system is one that provides acceptable electric service at minimum cost over the expected life of the installation. (Allen R, (2000))

If village power systems relying on mini-grids are to be sustainable and therefore widely replicable, designs specific to the conditions found in villages must be prepared and to develop designs that most cost-effectively address those needs. Without this approach,

complexity and high costs can quickly place mini-grids beyond the reach of the typical village. The study therefore not only reviews a range of technical designs but also covers in depth some of the other issues that must be addressed for successful, affordable electrification programs.

Yama is the community selected to be used as a case study for the design of solar PV mini grids system. It is located in the Northern region of Ghana, in the West Mamprusi district and about 25km from Walewale the district capital. It has a total population of about 3,000 inhabitants and about 300 households (PHC 2010). The average energy demand per household for Yama is about 1.3kWh/day, the daily average energy demand for the community is about 390kWh/day. This study could be implemented in small remote villages in Ghana with low load factors.

1.2 Problem statement and Justification

Ghana is committed to universal access to electricity for all communities with population above 500 inhabitants by the year 2016. Ghana currently has a national average electricity access of 72% grid electricity access as at 2012. (MOEn, (2012).

Universal access by the year 2016 however may not be achieved by national grid electrification alone considering the remoteness of some parts of the country. Connecting remote and isolated communities to the national grid is becoming difficult and more expensive due to the geographic locations and settlement patterns especially in the islands communities and Northern Ghana.

The Government of Ghana renewable energy (RE) Policy have set 10% of renewable energy in the power generation mix. The Policy Frameworks would seek to encourage

investments in the development of RE resources and specifically address the barriers to investment in Renewable Energy. (MOEn, (2010).

Therefore, there is the need to develop alternative power sources such as PV mini- grids for electrification of remote and isolated communities with population below 3000 inhabitants in Ghana. The Volta River Authority Renewable Energy Program approved by VRA board in February 2010 seeks to deploy Renewable Energy plants as both grid connected and mini grid (Isolated grid) systems.

There have been several off-grid solar home systems projects in Ghana over the years but experience show that these solar projects do not survive a few years after implementation. In some situations the solar PV modules have been relocated to different community when grid electricity is extended to that community, thus adding cost to an already expensive system.

Traditionally inhabitants of the three Northern regions of Ghana live in scatted and disperse settlements making national grid extension more difficult and expensive. Therefore, using Solar PV mini-grid system will be a better alternative to grid extension in such cases.

1.3 Research objectives

1.3.1 General objective

The general research objective is to contribute to knowledge on the use of PV mini grid for rural electrification, by examining the viability of solar PV mini grid connected systems as a complement to grid extension in achieving Ghana's vision of universal access to electricity.

1.3.2 Specific objective

The specific objectives of this research are as follows:

1. To design solar PV Mini-grid System using Yama community as a case study.
2. To compare the cost of electrification using the solar mini-grid system and extension of the national grid.
3. To analyze the economic viability of the PV mini-grid
4. To make recommendations for future implementation of solar PV mini-grid in Ghana as a complement to grid extension in achieving Ghana's vision of universal access to electricity by the year 2016.

1.4 Scope

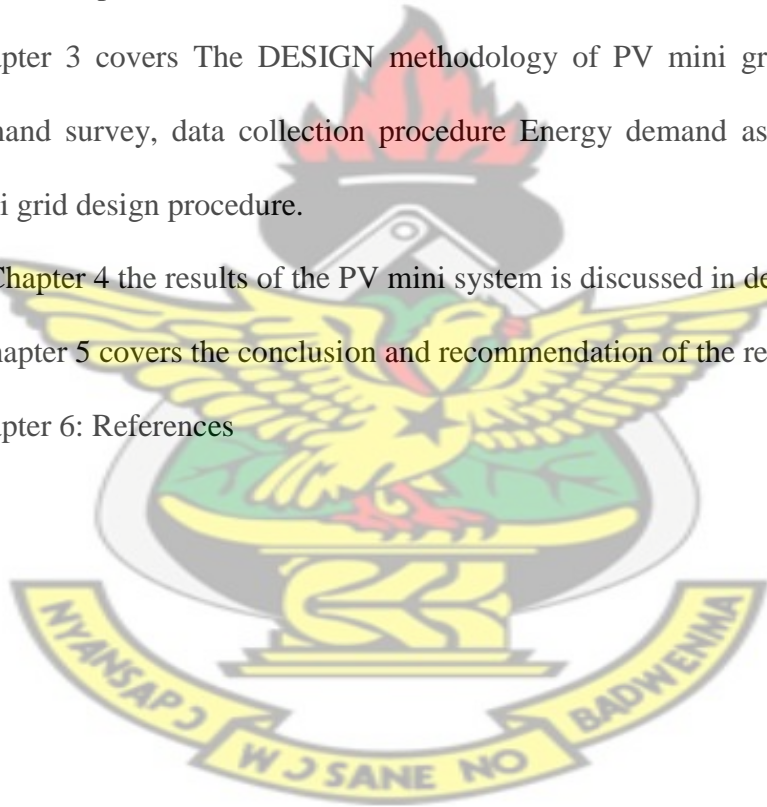
The scope of this research is to design solar PV mini-grid system for rural electrification in northern Ghana using Yama as a case study. This study seeks to determine the cost of solar PV mini-grid system as compare to extending the national grid from the nearest grid community which is about 18 km from Yama community.

In this research, a mini-grid refers to a low-voltage (LV) network within a village or neighborhood supplied at a single point by solar PV. It does not refer to the interconnection of two or more separate village grids into a more extensive area-wide network. The design covers conventional designs that may be interconnected to the national grid in future. The study does not cover details on low voltage distribution network since it is outside the scope of this research.

1.5 Chapter Outline

The following is a brief summary of the overall layout of the thesis;

- a) The chapter 1 covers research background, problem statement & justification, General objectives, specific objectives, and scope.
- b) Chapter 2 reviews the literature on Energy resources in Ghana and also reviews the literature on solar energy and particularly PV mini grid systems with battery bank and its components.
- c) Chapter 3 covers The DESIGN methodology of PV mini grid systems: energy demand survey, data collection procedure Energy demand assessments, and PV mini grid design procedure.
- d) In Chapter 4 the results of the PV mini system is discussed in detail.
- e) Chapter 5 covers the conclusion and recommendation of the research findings
- f) Chapter 6: References



CHAPTER TWO

2.0 Literature Review

2.1 Ghana Renewable Energy Policy

The Government of Ghana intends to have a significant proportion of Renewable Energy (RE) generation in the nation's power generation mix. The Policy Frameworks would seek to encourage investments in the development of RE resources and specifically address the barriers to investment in RE. Some of the policy and regulatory interventions as stated in 2011 RE policy is as follows:

- Feed-in-Tariff to be set by the Public Utilities Regulatory Commission
- Mandate the PURC to specify Renewable Purchase obligations (RPO) for distribution utility operators and future market participants
- The specification of Net-Metering Tariffs by PURC for captive generators
- The setting up of a dedicated Renewable Energy Fund to help support the promotion of grid connected RE and also investment capital subsidies

2.1.1 Various Renewable Energy Technologies

Solar PV as one way to provide off-grid electricity can be employed both in developing and developed countries for most electrical application. Moharil and Kulkarni (2009) suggest that even though providing access to grid electricity might often be cost-effective because of its low price, using Solar PV in rural areas also has advantages on a social, economic and environmental level.

Chakrabarti and Chakrabarti (2002) conducted a case study on the island “Sagar Dweep” in West Bengal, India. They took into account environmental and socio-economic factors

and reached the conclusion that Solar PV is the best option in cases like this, mostly because of the high costs incurred when transmitting electricity from conventional sources to extremely remote locations. The environmental benefit gained resulted from the fact that externality costs which using fossil fuels would have caused were not incurred with the use of Solar PV.

A study was conducted by Sinha and Kandpal (1991) on small remote villages with low load factors. They found that stand-alone solar can be an alternative to grid extension. Several studies on stand-alone Solar PV show that with the help of the levelised unit cost of electricity (LUC) this technology is not a cost-effective alternative to grid extension. Stand-alone Solar PV becomes financially attractive only when the grid would have to be extended beyond a distance of 20 km. (Ahiataku-Togobo, 2004)

In south-east Mediterranean islands, Kaldellis (2007) found a method to minimize electricity generation costs and maximize the contribution of Solar PV to the energy mix with the help of best possible storage devices. The results from this study concluded existing thermal power stations to be more expensive and unreliable than the Solar PV model.

Mayer and Heidenreich (2003) examined the reasons for the dissatisfying performance of PV stand-alone systems, pointing out that the cause are not necessarily technical problems of the system, but that systemic errors such as a misbalanced relation between load factor and generation potential or poor sizing can also lead to problems. The combination of stand-alone Solar PV with a Diesel Generator was examined by Kolhe et al (2002). It was observed that Solar PV was techno-economically more efficient and

gave an output of 15kWh/day and 68kWh/day when the economic circumstances were better, making Solar PV market-competitive.

2.2 Energy Needs and Statistics of Ghana

The Ministry of Energy is the institution charged with the implementation of the National Electrification Scheme (NES) which seeks to extend the reach of electricity to all communities in the long term.

Ghana has an installed capacity of 2186MW made up of hydro and thermal facilities as at the year 2012. Electricity demand is growing at an average of about 6% per annum for the last 10years. Expected growth for the next 10years is at an average of 7% per annum (VRA, (2012). It is estimated that Ghana requires capacity additions of about 2000MW to catch up with increasing demand in the medium to long term (VRA, (2010).

The availability of energy is vital for the economic and social development of any country. The Energy Commission's Strategic National Energy Plan (SNEP) 2006- 2020 report, Annex I of IV reports that the rate of growth of Ghana's Gross Domestic Product (GDP) since 1985 has been between 3.5 and 6 percent, yet over the same period, the demand for electricity had grown at the rate of 10 to 14 percent per annum. Ghana's energy challenge is shown in her growing economy and population. Ghana's population was 18.9 million in 2000 and it is projected to reach about 29 million in 2015, the target year for the Millennium Development Goals. (VRA, (2012). The table below shows the energy generation capacity of Ghana.

Table 2.1 Generation Capacity available for 2012.

Generation Plant	Capacity (MW)		Reliability factor	Expected Energy (GWh)
	Installed	Dependable		
Hydro Power Plants				
Akosombo	1,020	960	0.94	7,905.02
Kpong	160	140	0.90	1103.73
<i>Sub-Total</i>	<i>1,180</i>	<i>1,100</i>		<i>9,008.78</i>
Thermal Power Plants				
TAPCO (CC)	330	200	0.70	1,226.40
TICO (SC)	220	200	0.80	1,401.60
Sunon-Asogeli (gas)	200	180	0.68	1,072.22
Tema Thermal Plant-TT1P	126	100	0.85	744.60
Tema Thermal Plant-TT2P	50	45	0.85	335.07
Mines Reserve Plant-MRP	80	40	0.75	262.60
<i>Sub-Total</i>	<i>1,006</i>	<i>765</i>		<i>5,042.69</i>
Total	2,186	1,865		14,051.48

Source: VRA REDP, (2010)

2.3 Assessment of Ghana's available Solar Energy Resources and Systems

Ghana has an abundant amount of solar energy made up of about thirty (30) percent diffused radiation and seventy (70) percent direct radiation. The theoretical energy available yearly in Ghana is about 400TWh. (CREST, 2000)

The average duration of sunshine varies from a minimum of 5.3 hours per day in the cloudy forest region to about 7.7 hours per day in the dry savannah region.

The major challenges with the utilization of Ghana's abundant solar resource has been the high cost of installation and the lack of technical expertise in some sectors such as the grid and mini-grid connected systems. The figure below shows the various solar energy radiations of the Ghana.

Solar Radiation Map

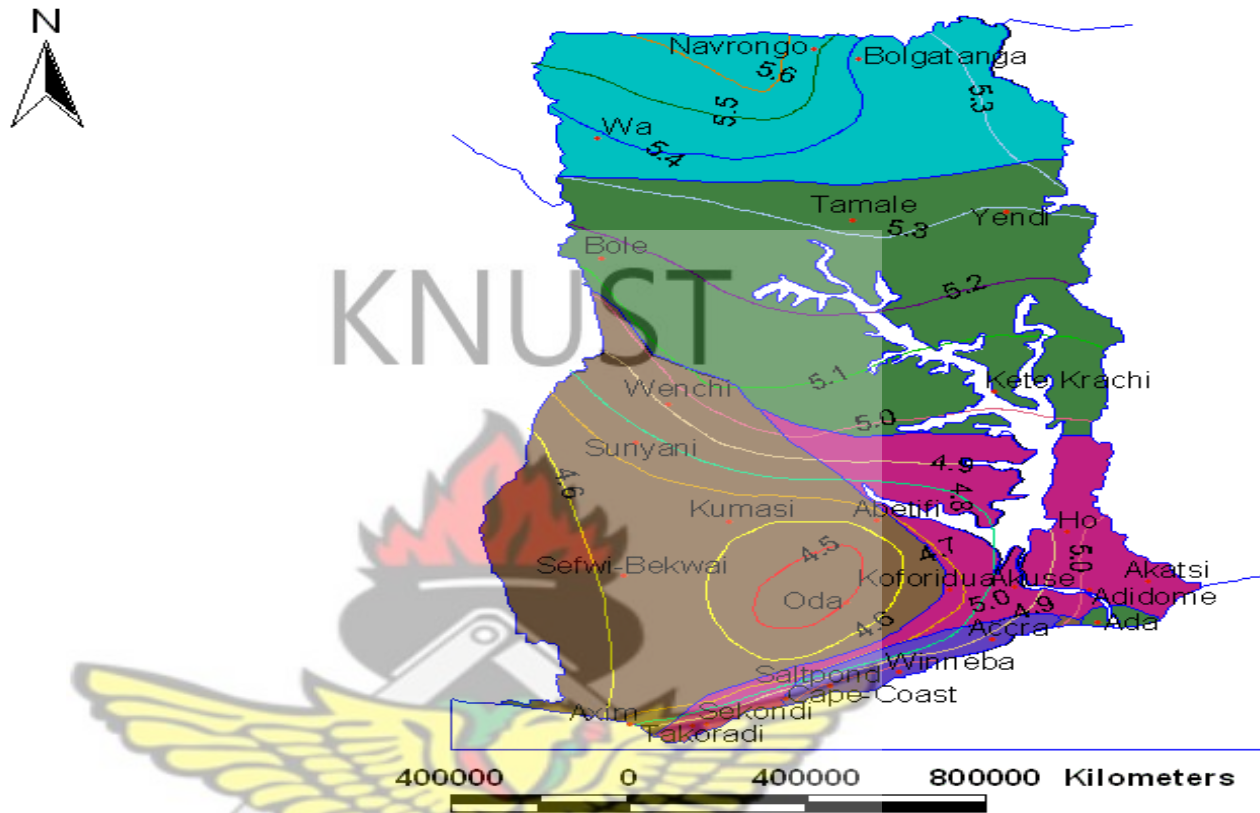


Figure 2.1 Solar Radiation Map of Ghana

2.3.1 Solar Photo-Voltaic Energy System

Solar PV is a semiconductor - based technology that converts light energy from the sun to electrical energy. It is the only source of electrical energy where there are no moving parts, noise or emissions.

Until about 1973, the only market for photovoltaic systems was its use in powering space vehicles. In 1973, the energy disruptions caused by the oil embargo caused governments around the world to begin looking for alternative energy sources. (GSES)

Solar (PV) systems are now used in almost any application where conventional electricity is used. Solar systems are used for space satellites, telecommunications, water pumping, residential and commercial activities and mainly utility grid support.

When the sun shines on a PV panel, the PV panel produces direct current but solar systems vary in complexity from its use in water pumping which requires only a PV module to be connected to a load to a solar home system, with one module, one battery, a controller and DC light and can also be a grid connected, hybrid system with a number of generating sources (e.g. wind generators, diesel gen sets etc). The most common forms of photovoltaic device have been the polycrystalline, Mono-crystalline and amorphous (Thin film) module.

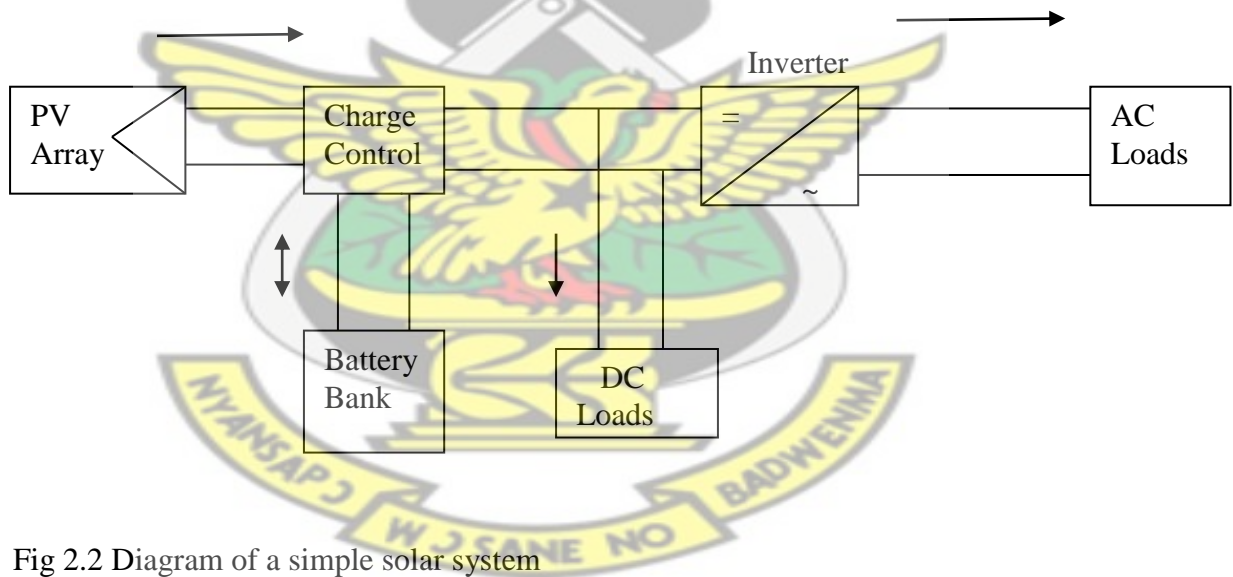


Fig 2.2 Diagram of a simple solar system

2.4 Solar PV mini grid systems

2.4.1 Relevant experiences (International)

A mini-grid connects several households to one or more sources of electric power. The conventional sources of power in existing mini-grids are diesel generators.

There are a number of examples around the world of diesel-based mini-grids where PV is used as a supplementary source of energy. One of the aims of these projects is often to design the system so that the need for large battery-capacity is avoided, in order to keep system costs down. In a small but growing number of mini-grids the PV-generators make out the prime source of energy, either in combination with battery storage solely or in combination with other energy sources.

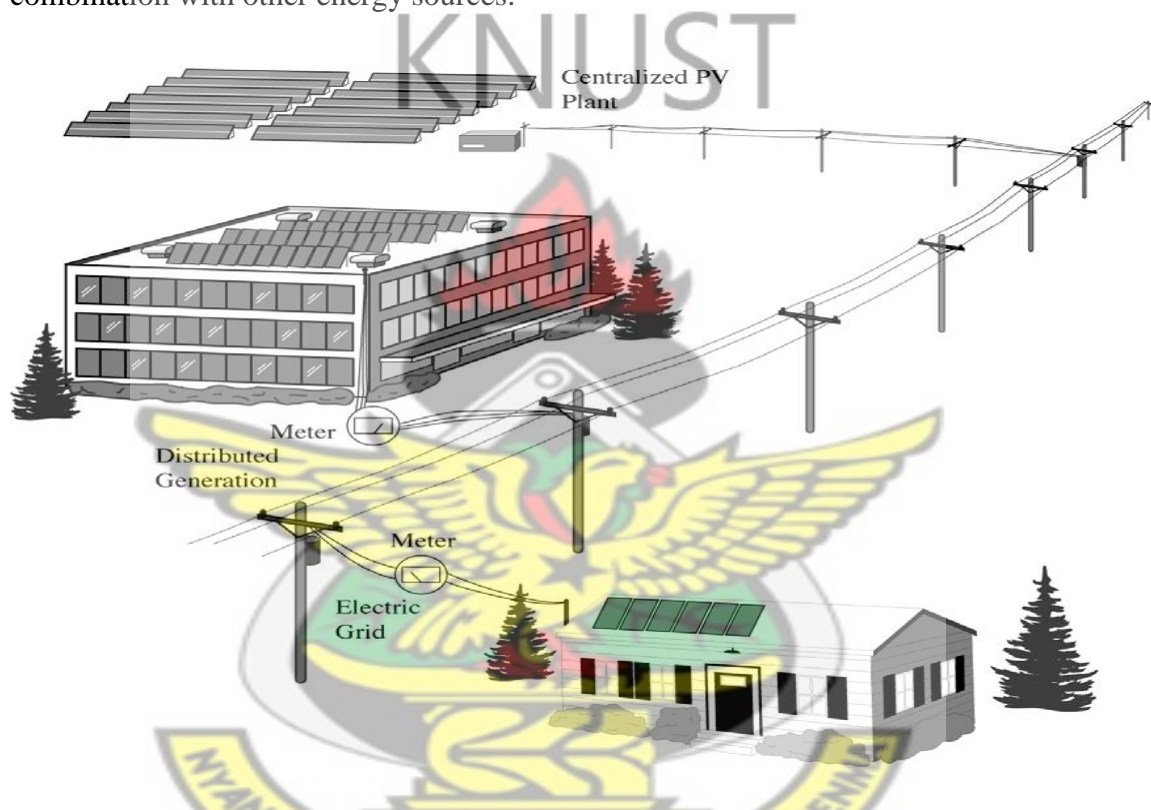


Fig 2.3 Schematic diagram of a PV mini-grid system.

Source: Ross and Royer, Photovoltaics in cold climates (Frank Y Dadzie)

2.4.2 IEA-Photovoltaic Power System Programme: Stand Alone Photovoltaic Applications– Lessons Learned

The work within IEA-PVPSTask3 is focused on stand-alone PV applications

The most recent “state-of-the-art” report within this frame work was published in 1999:“Stand-Alone Photovoltaic Applications – Lessons Learned” [1]. The publication treats different aspects of stand-alone PV systems (SAPV), which are divided into three categories; service applications (typically appliances with low energy demand); remote buildings (typically one household, 50 – 2000 Wp) and larger island systems (10 - 100households).

The report states that the island application at the time was the least developed of the three categories on a market and systems level, and that many questions remained to be resolved in order to move the application forward. Issues mentioned are sizing, economics, power, load management, management of the communal power supply and individual domestic power consumers.

The report particularly points to the social aspects of multi-user systems. It is argued that the most difficult point in the implementation of multi-user systems is to combine the interests of the potential users. Another issue is the adequate distribution of the limited energy among the users. In this context multi-user systems in rural Spain are mentioned, and the chapter contributed to the report by the Spanish team reports that an electronic device that individually counts, dispenses and limits the energy provided, has been newly developed.

The following recommendations given by the report are worth to note

On social aspects:

- The industry should further develop cheap meters and load-control equipment for multiuser SAPV or hybrid systems
- Program designers should implement technological, economic and social instruments to promote optimal load balancing over the day and over the week.

On technological aspects:

- The industry should design components so that modularity of systems becomes straightforward, in order to allow easy expansion and reduce the initial investment cost
- The industry should further develop remote monitoring systems, because these promise reductions in the maintenance costs.
- System designers should pursue optimal matching between PV and generator, which needs proper engineering.
- Industry should develop cheap individual metering systems.
- Industry should develop better controllers and user interfaces to reduce operational complexity

2.4.2.1 Task 11 – PV hybrid systems within mini-grids

Recently a new task has been added to the PVPS-programme. Approved in October 2005, Task 11 builds on the work on PV hybrid systems undertaken in the completed Task 3, and will focus on the operation of PV within mini-grids. Mini-grids are defined within the task as the interconnection of small, modular generation sources to low voltage AC-distribution systems. The source of power may be a combination of PV, wind, micro-

hydro, fossil fuel gen sets and other sources. The grid typically supplies multiple users and may be interconnected with the distribution grid of the local electric utility. (IEA)

In the program presentation of Task 11 the following objectives are stated:

- To define concepts for sustainable PV hybrid mini-grids taking into account local factors (specificity of the application, financing regimes, location, others);
- To provide recommendations on individual designs (mix of technologies, architecture, size, performances, other) in order to achieve high penetration level of PV as a mean to improve quality, reliability and economics of electrification systems such as mini-grids;
- To assess the potential of technologies to be mixed with PV for hybridization;
- To compile and disseminate best-practices on PV hybrid power systems.

2.4.3 Recent mini-grid experiences

An EU-funded project called “Mini-Grid Kit”, completed in 2003, and had the objective to design an expandable, low cost but standard quality mini-grid kit with multiple renewable and nonrenewable energy power generators. The project has identified two modular hybrid system architectures in a power range up to 30 kW: (PVPS-program; 2005)

- The centralized DC-bus system
- The distributed AC-bus system

According to the presented project results, comparison of the two concepts for several load profiles and solar fractions has shown that both system types have their advantages:

- The centralized DC-architecture is preferable in a situation of high solar fractions (e.g. PV/battery-systems) and evening loads
- The distributed AC-based system on the other hand proved to be the more efficient solution in system with smaller solar fraction and high energy use during the day.

Also, the “Mini-grid kit” project has been developing a new energy management system (abbreviated EMS), including functions for variable pricing, load and RES prediction, intelligent load control and multi-bus communication.

2.4.4 Case-studies involving mini-grids

2.4.4.1 Centralized power generation

In the IEA-PVPS Task 3 report SAPV – Lessons learned [1], a number of case-studies are presented, two of which concern what is categorized as mini-grids. One of these is a large scale hybrid system in Japan, with 750 kWp of PV, 3058 kWh of batteries and a 300 kW diesel generator, designed for a village of around 250 households. The other case-study is somewhat closer to the scale of system studied in this report, supplying power to 34 households in Korea. Again, this is a diesel-PV-hybrid system, with 60 kWp of PV, 1148 kWh of batteries and two diesel gen sets of 75 kW each. In both cases the power supply is centralized.

2.4.4.2 Bulyansungwe mini-grid System- Uganda

The Bulyansungwe system is an AC mini-grid. The installation consists of PV and gasoline hybrid generating capacity with integrated ultraviolet water purification and pumping system. It supplies both electricity and clean water to the school complex.

The primary electricity is supplied by a 3.6 kWp PV array, which is connected to the mini-grid through two SMA Sunny Boy 1700E inverters. Energy is stored in a 21.6 kWh Battery bank. The connection of the battery bank to the mini-grid, as well as the general control and orchestration of the system, is performed by a 3.3 kW SMA Sunny Island inverter (European model SI3300).

The Sunny Island communicates with the Sunny Boys via grid frequency similar to the droop system described earlier. If the batteries are fully charged, the Sunny Island will instruct the Sunny Boys to derate their power output so that the batteries will not be overcharged. Backup is provided by a 3.5 kW pull-start gasoline generator that was already owned by the school. There are plans for a self-starting diesel generator when funds are available.

The first phase of the system is now in full operation, supplying electricity and water to the girls' and boys' dormitory, classrooms, and convent. The primary use of the electricity is lighting. The dining room is open in the evening for studying, and hall lights are a huge help for midnight visits to the restroom. Another important use is kitchen appliances, such as blenders and mixers. However, the stereo is by far the students' favorite use of their new energy.

Bulyansungwe's social center was left unelectrified because it is presently only used during the day. However, plans to establish a health center and basic hospital that will require electricity are in the works. This is one of the reasons an AC PV mini-grid is so appropriate for this location.

Three years before an AC mini-grid was installed, the sponsoring organization installed a small, DC water pumping and purification system in the social center in Bulyansungwe.

The AC mini-grid topology of the Bulyansungwe system will also make future expansion of the system to meet growing energy demands easier. For example, if the school were able to acquire a few computers for classroom use, the daily energy demand would increase. This might necessitate more PV generating capacity, but not more battery capacity, since the computers are used during the day.

With the AC mini-grid, a small PV array could be added to the system by using a standard, batteryless, grid-tie inverter and connecting its output anywhere on the grid.

The PVs could be mounted near the school building, which is a couple of hundred yards from the current PV array and battery bank in the girls' dormitory. Mounting the supplemental

System near the school building would reduce line losses over that distance. This is in contrast to DC-coupled systems, where more significant reconfiguration of the system might be necessary for expansion.

2.4.4.3 Case study on the Benefits of interconnecting stand-alone PV into a mini-grid.

A small group of off-grid houses are assumed to all have their own stand-alone PV-power installation with batteries. If these houses and their power generation plants are connected to a small power grid, any excess power generated in one plant can be fed into the grid and supply other households with power or charge other batteries.

The general strategy for this so-called mini-grid is as follows:

- Each part-owner is to have an efficient power generation installed, corresponding to his/her peak power demand

- Each part-owner is to match the battery to the PV-modules in his/her own installation
- The part-owners may always charge their batteries with current from the grid, when available
- Incoming current is to be limited to stand in proportion to the mean power of the PV-modules of each household
- The part-owners are to supply power to the grid when their battery has reached an agreed level of charge (controlled by the local control unit and by measuring the battery voltage, for example)
- A part-owner with poor irradiation conditions may put up modules on an existing common building or site
- Measuring the energy consumption drawn from the grid by each user gives increased possibilities for fair distribution. It also makes it possible to detect faulty batteries that may be using excess energy for no use. A faulty battery that is no longer rechargeable may lower the grid voltage so that the other batteries risk receiving no power at all.

The desired electrical standard in the studied case has been found to include, at least, power for lighting, telephone, water pump, fridge and relatively lengthy use of TV, computer and radio. To meet these demands in the studied case, which concerns an island situated about 8 km from mainland; off-grid power has been shown to be more economical than connecting to the mainland power grid. The most economical option is a power supply solution that combines PV-power, batteries and a “back-up” gen set. E-L Hagerstedt et al (2006).

2.4.5 Approaches to mini-grid development

A large range of approaches to mini-grid development exist today. These can be classified in terms of the technologies involved and the institutional and financial arrangements. Mini-grids can include single generation technologies, such as diesel, solar photovoltaic, wind, hydropower or biomass power generation, or a hybrid system that includes two or more technologies. Hybrid systems have generated most interest because they mix ‘dispatchable’ power sources (e.g. diesel generation which can be delivered on demand) with ‘non-dispatchable’ power sources, so increasing reliability and load matching.

Institutional and financial structures for mini-grids are more diverse. Mini-grids may be owned and managed by the state, private sector or communities. Often a combination of different actors are involved, owning or managing different parts of the system, such as the production, distribution and demand management systems. Different financial models may also be applied in order to cover upfront capital costs and the ongoing operation and maintenance costs.

2.4.6 Opportunities of mini-grid implementation in developing countries

Mini-grid systems can help to increase the reliability of electricity supply. Their smaller scale and enhanced local level ownership of physical infrastructure or management systems can help to reduce problems such as power theft. These are common problems with more centralized on-grid approaches, where management is further from the customer base.

Mini-grids can help to improve environmental performance in terms of energy efficiency and carbon emissions. Hybrid mini-grid systems, for example, often incorporate a 75-

99% renewable supply (USAID/ARE, 2011). Of the renewable energy technologies, economic assessments indicate that biomass, biogas, geothermal, wind and micro-hydro systems costing US6-15 cent/kWh are the potential least-cost generation options for mini-grids in developing countries, assuming sufficient renewable energy resources are available (*ESMAP, 2007*).

Mini-grids present opportunities for countries where government grid systems are not well developed, and where there is a vibrant private sector. They are also adaptable, in that different systems can be linked up and/or connected to grids as they expand.

Mini-grid systems are also becoming more economically attractive as the cost of renewable technologies decreases and fuel prices rise. Schemes still require subsidies, but these are often a smaller percentage of investments than on-grid subsidies (*World Bank, 2008*).

2.4.7 Challenges of mini-grid implementation in developing countries

Despite the opportunities, penetration of mini-grid systems remains low in most developing countries. Their development has been greatest in Asia. China has an estimated 60,000 schemes and Nepal, India, Vietnam, and Sri Lanka, each have 100–1000 mini-grids (*Martinot et al., 2002*). The majority of schemes use Solar PV, diesel or hydro power generation and they are government run (*Palit and Chaurey, 2011*).

Building sustainable financing structures can be challenging, despite a growing understanding of financial barriers in project development and an increasing number of financial tools. While they may be more economically attractive than grid connection in remote areas, mini-grid systems can have high upfront costs. This is particularly the case

for certain renewable generation technologies, compared to more conventional options such as diesel.

It is well recognised that financing schemes need to be designed to pay for themselves in order to be sustainable by establishing realistic tariffs for consumers, despite the potential equity implications. In practice, these have been difficult to get right and have been subject to high risks. For example, consumers may fail to understand or respect the financing agreements that have been established, which may be exacerbated by inappropriate implementation of the fee-for service business model (*Gboney, 2009*).

Mini-grids in many countries have been publically financed through grants or subsidies in order to cover upfront capital costs and sometimes ongoing costs, but these can prevent the development of sustainable local electricity markets if they are not carefully designed (*ESMAP, 2000; Barnes and Foley, 2004*).

Another approach has been through supporting micro-finance schemes. However, these are limited mainly by a lack of coordination between the energy and micro-finance sectors and high perceived investment risks within local financial institutions (*Winiecki et al., 2008*).

Mini-grid development can be hampered by political priorities, such as politicians favoring extending national grid connection to their communities in urban and peri-urban areas (some schemes have simply failed because they have been superseded by connection to the national grid).

2.4.8 Requirements for developing successful mini-grids

The most successful mini-grid schemes have been developed where their design has carefully considered local economic, social and environmental conditions; where

sustainable financial models have been developed; and where the national policy and regulatory context is sensitive to the requirements of building mini-grids. Many of these factors are very context specific (ESMAP, 2007; IEG, 2008; World Bank, 2010).

Site selection based on detailed situation analysis is important in order to ensure that Mini-grids are not developed so close to grid systems that they are quickly superseded. Detailed site analysis also helps with appropriate technology selection that will give some estimate of projected output. For renewable energy this includes an understanding of hydrology, wind speeds and solar insolation, depending on the technology. For diesel generation, a clear understanding of current and future fuel availability and price at the location are important. Even where appropriate sites are identified, it is usually important to develop mini-grids alongside other initiatives that may help to increase demand and people's ability to pay (Kirubi et al., (2008).

Having a good understanding of the energy demand through field studies and demand analysis is another pre-requisite for designing sustainable systems that are economically viable. However, future demand growth also needs to be kept in mind, for example through over-sizing some components. (USAID/ARE, (2011).

Schemes need to be supported by a range of local services to facilitate maintenance and sustain local expertise, and they have generally been more successful where these exist or are promoted through separate or linked development programmes. Training programmes need to be provided for key operational staff involved in maintenance. Increasing local understanding of the technical aspects of schemes, and the rules and regulations surrounding aspects such as fee payments, can help to reduce conflict and problems such as electricity theft. The presence of companies at the local level that can provide energy

products, services, and replacement parts is also important for integrating mini-grids into a more sustainable local infrastructure (World Bank, (2008b).

It is also important to support institutions at the national level in order to increase awareness of mini-grid potential within government and legislative processes. For private sector led schemes, a well-organized private sector can be important and strong industry associations can help contribute to this. For example, in Mauritius, the involvement of the private-sector sugar industry in advocating for the continued support of a cogeneration program was found to be a key element of the programme's success (USAID/ARE, (2011).

2.5 Relevant experiences - Ghana

A review of published reports and internet search regarding PV mini grid system design and installations in Ghana has not revealed any relevant information on the subject.

There are only experiences from stand-alone and a few grid connected systems in Ghana, which does not present enough relevant information on the PV mini-grid context being studied in this research.

2.5.1 KNUST Energy Center

The late Prof. Abeeku Brew-Hammond and Prof. Akuffo have all done extensive works on renewable energy systems, especially solar PV system application but as far as solar PV mini -grid connected system is concerned there is no record or published report on the subject relevant to this research. There have been several solar PV home system projects implemented in Ghana by the support of Prof. Akuffo, Mr Edwin through department of

mechanical engineering solar energy center such DANIDA, CIDA, JICA solar projects etc.

2.5.2 Wechiau solar project.

The Wechiau solar project involved a central 2 kWp solar powered battery charging centre available for charging lead acid wet batteries. Households were provided with a set of lighting systems and a battery at subsidized cost. Batteries were used solely for home lighting, TV, cassette/radio playing. When battery power falls, the household would have its battery taken back to the solar battery centre for recharging and pay a recharging fee. The community operated the centre and maintained it cost-effectively from revenues accrued from recharging the batteries. Households who had additional resources were provided with either 50Wp or 100 Wp solar home systems. Households had the responsibility for replacing appliances, such as burnt lighting bulbs and tubes.

Other services provided with solar power included solar powered water pump serving the rural community, lighting for the community clinic and schools.

Wechiau solar power project was conceived to demonstrate universal electrification by solar power complementation. The total cost of the project was around US\$100,000 equivalent.

2.6 Cost of Solar PV systems

Although there is no documented study of the cost of one kWh of power from solar PV mini grid connected system in Ghana, studies in other parts of the world show that solar photovoltaic electricity is still more expensive than grid power (For example, in California, USA the Ministry of Natural Resources records that a 1kW system produces

1.6MWh per annum and therefore the cost of solar photovoltaic power is 35 cent/ kWh while grid power is 0.08 \$/ kWh). (Allen R, (2000)

The principal drawback to solar power for mini-grid application is that this option relies on considerably costly hardware to harness energy and make it usable. A complete power supply, with batteries, electronic controls, inverters, etc., costs at least \$10,000 per peak kilowatt. Another significant drawback is the fact that solar-PV generated electricity is direct current (DC) and must be stored in this form in a costly battery bank until it is needed. In addition to the capital costs, these battery banks need to be replaced periodically. For example, a 3-kWp solar array that might generate 10 kWh/ daily would require a 30-40 kWh bank of deep-discharge batteries costing at least \$40,000 and having to be replaced every 5 to 10 years. An inverter is also required to convert dc power to usable ac power, adding further to cost and complexity. (Allen R. (2000)

Despite the fact that a number of projects around the world show an emerging market for photovoltaic mini grid connected systems, this technology is still not common in Ghana.

2.7 Components of PV mini-grid system

2.7.1 PV array

A PV array is made up of a number of solar modules connected together. A solar module is made up of a number of solar cells. Solar cells are composed of silicon (Si). Silicon is a semiconductor with only four electrons in its outer shell. When a photon of solar radiation from the sun strikes an outer shell electron, a transfer of energy takes place. The incoming photon loses the amount of energy required to eject an electron from its shell and therefore a free electron is produced. This phenomenon is known as the photoelectric effect. The performance of a solar cell is dependent on its output voltage and current and

how they vary with each other. The typical I-V curve for a solar cell is not a straight line as expected but it is as shown in the figure below;

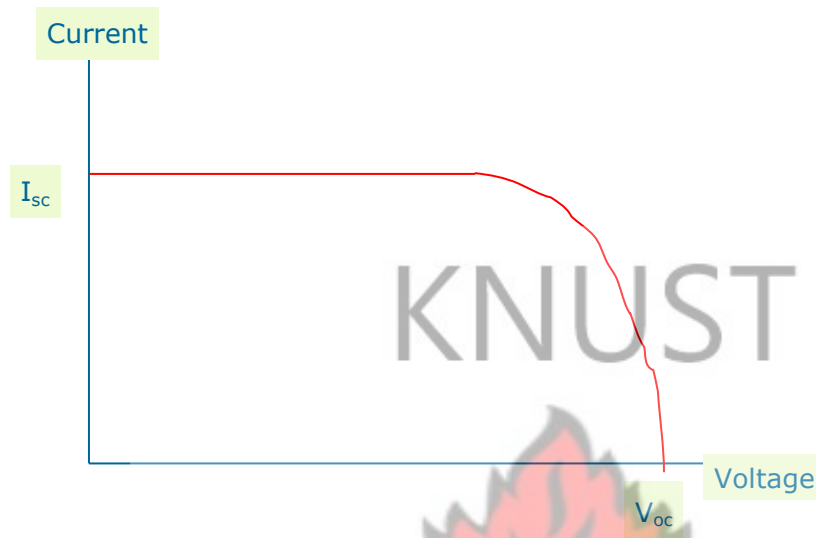


Figure 2.4 A typical I-V curve of a solar cell

The product of the output current and voltage under particular operating characteristics gives the power produced by a solar cell. At the rated voltage and current outputs, the PV module maximum power is produced. As the temperature of a solar cell increases, the open circuit voltage decreases but the short circuit current increases marginally. The combined effect is a decrease in power.

2.7.1.1 Factors that affect the performance of a solar cell

Two main factors affect the performance of solar cells. These are

1. Temperature
2. Solar Irradiance

As the temperature of a solar cell increases, the open circuit voltage decreases but the short circuit current increases marginally as stated above. The efficiency of crystalline PV cells reduces at a rate of 4-5% per °C above the STC temperature of 25°C that is

efficiency *decreases* with increasing temperature for crystalline cells. The output power changes 2.5% for every five degree variation in temperature. (CREST, 2000)

2.7.1.2 Types of solar cells

There are three main types of solar cells used in solar system today. They are mono crystalline, polycrystalline and amorphous cells/ thin film.

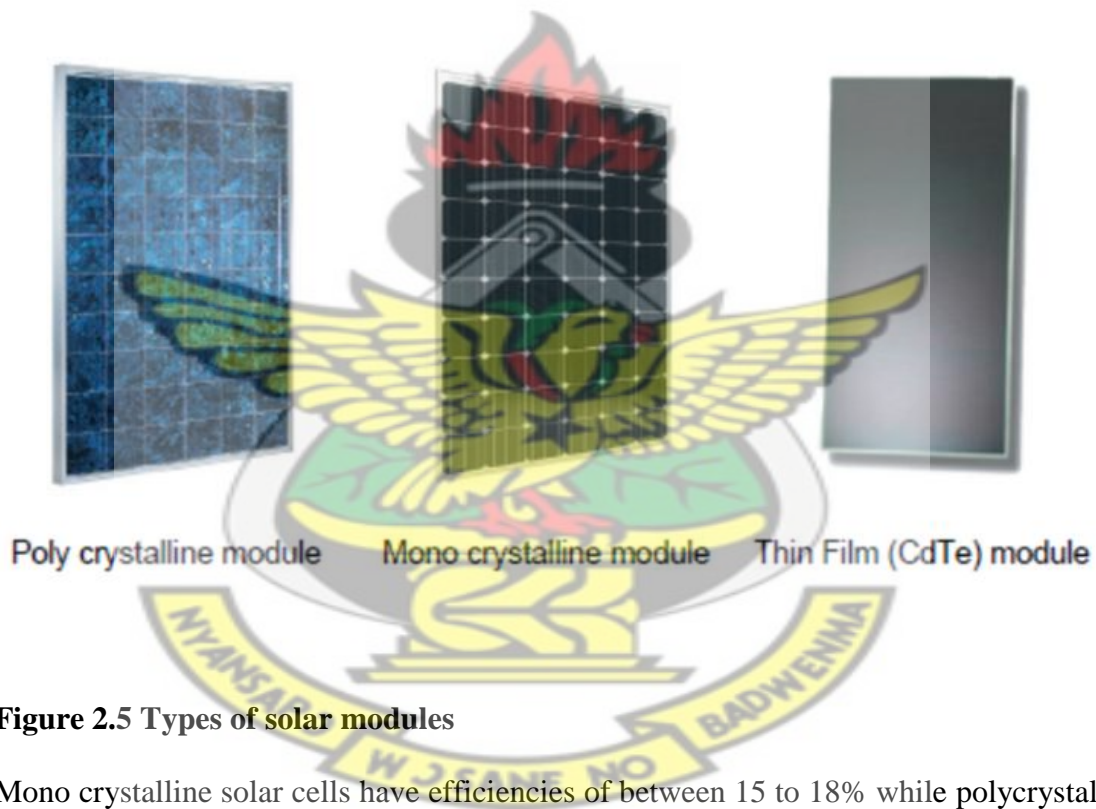


Figure 2.5 Types of solar modules

Mono crystalline solar cells have efficiencies of between 15 to 18% while polycrystalline solar cells have efficiencies of at most 12-15% and amorphous solar cells 5-8% researchers are serious working towards improvement solar cell efficiency. Amorphous solar cells are the cheapest of all the solar cells but challenges of stability and its degradation of performance over time have not made it very popular.

The efficiency of a solar cell is the ratio of the power produced by the cell to the power impinging on the cell. Reasons for the loss of efficiency include grid coverage, reflection loss and spurious absorption (some of the electrons ejected from their shell are absorbed by impure atoms in the crystal).

2.7.2 Solar Batteries

Batteries are recognized as the heart of a mini grid connected photovoltaic system with battery backup. Without proper maintenance, batteries can fail prematurely and shut the whole photovoltaic system down.

2.7.2.1 Types of Batteries

There are two main types of batteries that are mostly used in solar systems namely flooded lead acid batteries and Absorbed Glass Mat sealed lead acid battery.

2.7.2.1.1 Flooded batteries

Flooded lead acid batteries are used in majority of standalone and grid connected photovoltaic systems because they have the longest life and least cost per amp-hour of any of the choices. However, their main disadvantage is that they require regular (every 3 months) maintenance (topping the water level, equalizing charges, keeping top and terminals clean etc.). Two volt cells are mainly used for large systems.

The depth of discharge for lead acid batteries should under no circumstances exceed 80% and the battery should not be left in this condition for long.

When fully discharged a lead-acid cell will have a terminal voltage of 1.9V giving a discharged battery voltage of 11.4V. When in the fully charged condition the lead-acid

cell terminal voltage will be 2.4V and a fully charged battery will have a voltage 14.4V. Lead-acid battery capacity is reduced by approximately 0.6% per °C below 25°C. When not in use lead-acid batteries slowly discharge, typically losing 2% of nominal capacity per month, which increases with temperature.

2.7.2.1.2 Absorbed Glass Mat Sealed Lead Acid (AGM)

Absorbed glass mat sealed lead acid batteries are completely sealed and cannot be spilled therefore they do not require periodic topping of water level and emit no corrosive fumes. Their advantages include that their electrolyte do not saturify and no equalization charging is required. The main disadvantage of this battery is the cost per amp-hour.

2.7.2.1.3 Deep Cycle Battery

True deep cycle batteries are designed for a depth of discharge of 80% due to their rugged construction. They are the most expensive type of battery with the longest lifetime. Generally, deep cycle batteries are used with standalone systems. For small systems it may be appropriate to use leisure batteries due to cost considerations. Vehicle starter batteries should not be used for renewable energy systems, except in exceptional circumstances. A standalone system using renewable energy requires a highly cycleable energy store. Vehicle starter batteries cannot be cycled to any depth without reduction in life-time and damage. It is false economy to use cheap starter batteries instead of the more expensive leisure batteries since the batteries require replacement more frequently. (CREST, 2000)

2.7.2.2 Factors that affect the life of the battery bank

The following factors affect the life of the battery;

1. Corrosion (the sulphuric acid corrodes the lead plates).
2. Stratification (This is where heavier acid falls to the bottom section of the battery. This over a long period results in accelerated corrosion and non-uniform cell operation).
3. Sulphation (If a battery is left in a low state of charge for long periods, then harder crystals of solid lead sulphate can occur which are more difficult to breakdown during charging).
4. Positive plate growth (The positive plate continues to expand and contract under the charge and discharge cycles and sometimes the positive plate grows and the end as result, while the acid concentration drops, the solid $PbSO_4$ (lead sulphate) is deposited on the positive and negative electrodes. The potential difference between the positive and negative plate is about 2 volts. Positive plates are pushed up. Under this condition, the seal is broken and the acid can move up and cause corrosion.

2.7.3 Inverter

The inverter is the main determinant of a PV mini-grid connected photovoltaic system. The output of the PV array is direct current and it is not fed directly into the AC mini grid distribution network which is supposed to operate on three phase alternating current. In addition, the loads to be powered are alternating current loads and therefore there is a need for the inversion of the direct current to alternating current. The inverter is the main junction between the PV system, the distribution network and the loads. There are two main classes of inverters used in mini grid- connected photovoltaic systems with battery back-up. There are battery charger less inverters which does not charge the batteries directly whereas there are inverters chargers which can charge the batteries direct.

In this design the second class of inverters was the most appropriate choice. In this class of inverters, the inverter is programmed to convert DC power to AC power when the batteries are above a predetermined battery voltage. Typically this voltage is the float voltage of the batteries and the inverter maintains the battery at that voltage.



Fig.2.6 photograph of a typical inverter: Source: RETs Course manual



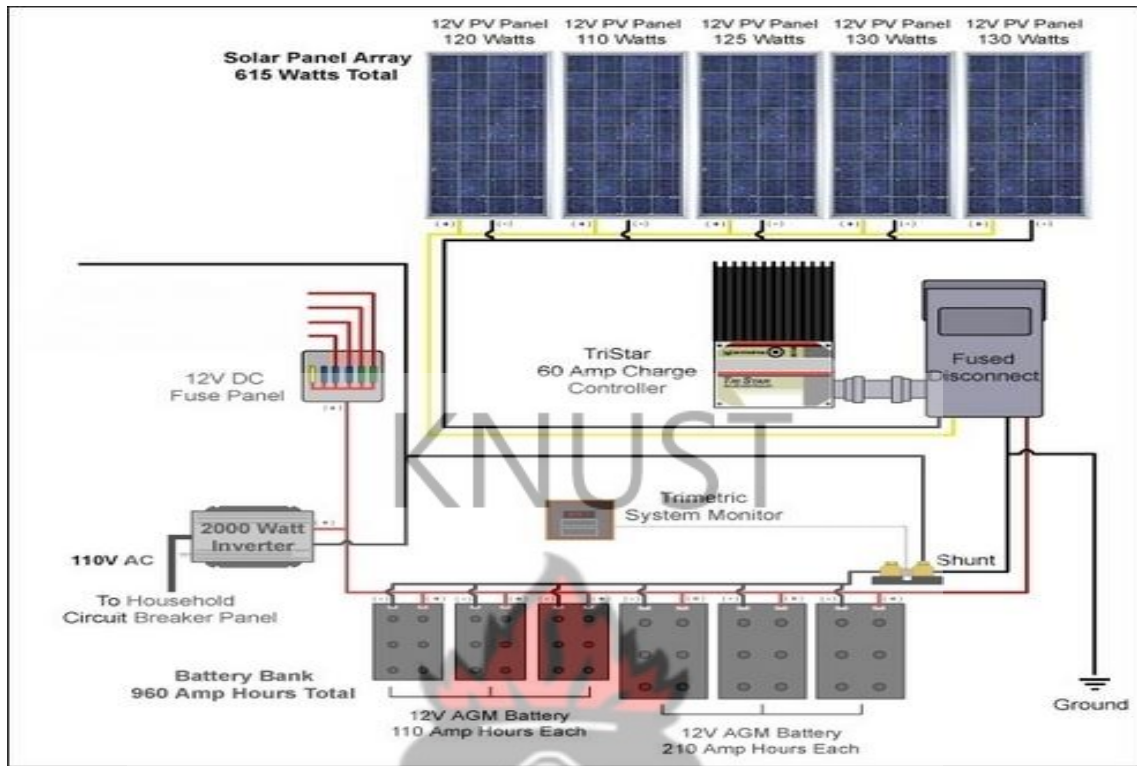


Fig.2.7 Components of a PV Mini-grid system

2.7.4 The Power Distribution Network

Necessary components in order to connect single PV-power-supplied households to a mini-grid are:

- Main cable
- Service lines for the connection of households to the main cable
- Wiring cabinet to connect service lines to the main cable
- Ground wire with earth electrode, e.g. for lightning diversion
- Cabinet for control equipment etc. between service line and household

In addition, there may be a need for connection cables and more for common equipment such as a larger PV-plant and larger battery bank.

The choice of components is made on the basis of what is commercially available, that is, what is being used in a 230/415 V heavy current grids. Components are chosen for overhead transmission lines rather than underground laying to reduce cost of the project since underground cables are more expensive.

KNUST



CHAPTER THREE

3.0 Design Methodology

3.1 PV Mini-Grid Connected Photovoltaic System with Battery Backup Design

3.1.1 System Design

In this chapter the main system design based on the daily energy demand assessment of Yama is described. The chapter also dealt with the sizing and specifying of inverter, Battery bank and PV array.

3.1.2 System Design Procedure

The system is designed from the first principles as follows:

- Energy demand assessments of Yama community
- Selection of system design voltage
- Selection of solar PV system design Configuration
- Determination of the expected system performance
- Sizing and specifying battery bank
- Sizing and specifying PV array
- Sizing and Specifying Inverter with MPPT

3.1.3 Flow Chart of design procedure

The diagram in fig. 3.1 represents the design procedure used in designing solar PV mini grid system under consideration. The design process starts with the selection of a suitable design configuration which best fit this application.

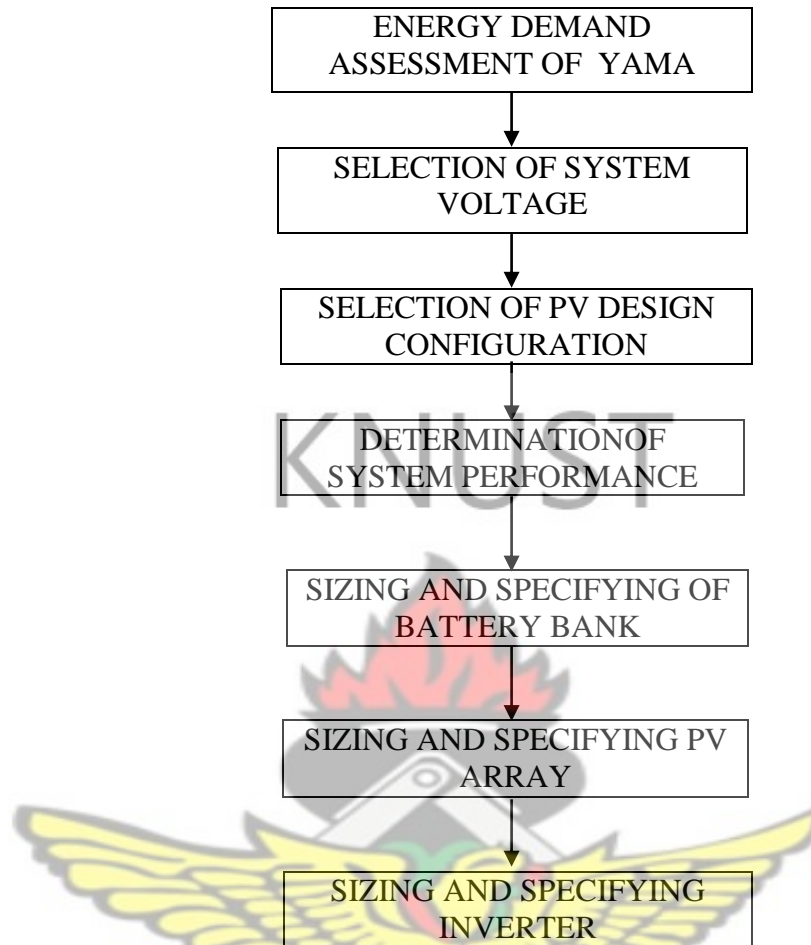


Figure 3.1 System design process flow chart

3.2 Selection of design configuration

All solar systems are designed to solve a particular power problem. There are several design configuration of PV mini-grid system based on technology and application:

- Solar PV AC mini-grid system with centralized battery bank.
- Solar PV DC mini-grid system with decentralized batteries.
- PV AC/DC mini-grid hybrid system

For the purpose of this research a mini grid solar PV power system with centralized battery bank is considered. The system is needed to supply reliable and uninterrupted electricity to the Yama community.

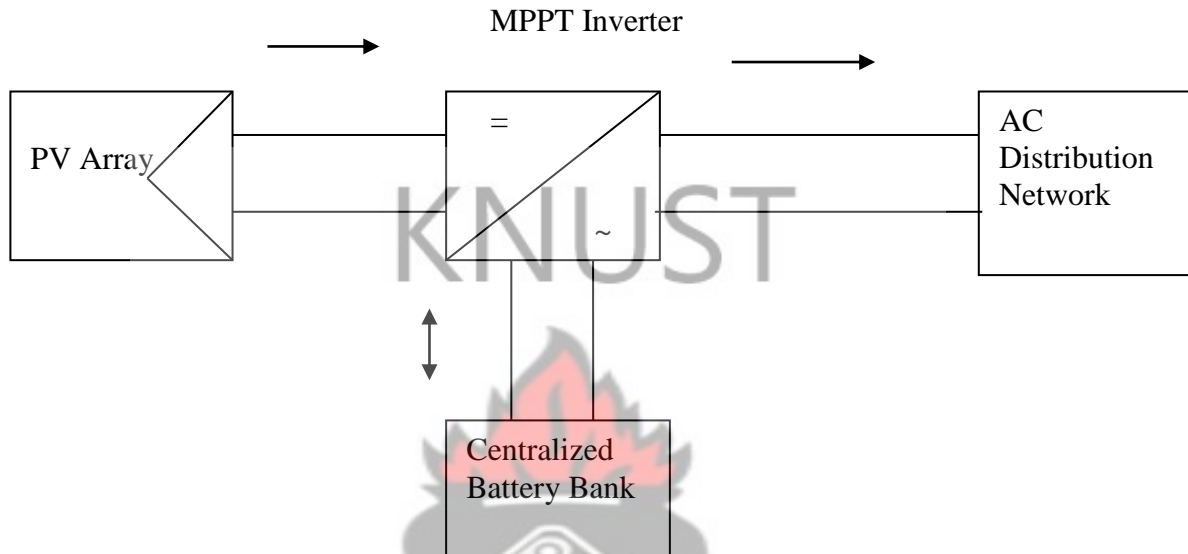


Fig 3.2 Diagram of System design configuration

3.3 Source of data and method of data collection for Load Assessment

The range of methods that were applied in this research was dictated by the research questionnaire in appendix 1&2. Taken together, these methods included survey, unstructured interviews, document gathering, direct observation, and informal conversations. Direct observation was used as supportive technique to complement the information from interviews and questionnaire surveys. A camera was used to take relevant pictures of typical households of the community.

Furthermore, Energy demand assessment of users of solar home systems that was undertaken by NEWENERGY for GEDAP in the YAMA community was considered. Data from an electrified community with similar population, socioeconomic and standard

of living was examined to study the future energy growth rate. These data were analyzed and used to arrive at the current average daily energy demand for YAMA.

3.3.1 Assessing Energy Demand Survey Questionnaire

Table 3.1 Household Average energy demand assessment for Yama

Appliances	Qty	Power (W)	Hr. of Usage	Voltage Rating	Oversize Coeff	Efficiency Of Appliance	Daily Energy Demand (kWh/day)
Inside Lights(LED)	4	11	5	240V,AC	1.1	1	200
Security Lights	2	20	12	240V, AC	1.1	1	528
Fan	1	65	3	240V,AC	1.1	1	177
TV	1	40	3	240V,AC	1.1	0.8	137
Tape/Radio	1	40	6	240V,AC	1.1	0.8	270
AVERAGE DAILY ENERGY USED PER HOUSEHOLD: $E_{TOT(wh)}$							1.3kWh/d

Total Number of household in Yama = 300

1. Average Daily Energy Demand for Yama (E_{TOT}) = $300 \times 1.3 \text{ kWh/d} = 390 \text{ kWh/day}$

2. Average Daily energy Demand for 200 Households = $200 \times 1.3 = 260 \text{ kWh/day}$

3. Average Daily energy Demand for 50 Households = $50 \times 1.3 = 65 \text{ kWh/day}$

3.3.4 Public Institution and economic activity energy usage

Table 3.2 Energy demand Assessment for public loads in Yama

Appliance/	Qty	Power (W)	Hr. of Usage	Voltage Rating	Oversize Coefficient	Efficiency Of Appliance	Daily Energy Demand (kWh/day)
3 Primary-Lights	18	20	5	240V,AC	1.1	1	5.940
1 JHS-Lights	12	20	5	240V, AC	1.1	1	1.320
1 CHIPS-Lights	10	20	6	240V,AC	1.1	1	1.320
1CHIPS-Vaccine Fridge	1	250	8	240V,AC	1.1	0.8	2.750
3 Hair Saloons – Dryers	2	750	6	240V,AC	1.1	0.8	12.375
AVERAGE DAILY ENERGY DEMAND $E_{TOT(W_h)}$							23.7kWh/d

1. Total Energy Demand for Yama = $390+23.7=413.7\text{kWh/day}$

2. Total Energy Demand for 200 Households = $260+23.7=283.7\text{ kWh/day}$

3. Total Energy Demand for 50 Households = $65+23.7=88.7\text{kWh/day}$

3.4 Selection of system voltage

In the design of PV mini grid systems, the system voltage is selected for all the components of the system inverter, battery bank, array etc.

The system voltage is selected based on the requirements of the system. As a general rule, the system voltage increases with increased daily load. However, in PV solar mini

grid systems (unlike in standalone SHS), the voltage is also dependent on the inverters that are available.

The system voltage is therefore selected based on three considerations namely;

- a) To minimize losses in cables between battery bank and the inverter.
- b) To minimize the maximum continuous current drawn from the battery and thereby reducing the cross-sectional area (size) of the cabling to be used and thereby reducing the cost and complexity of the system wiring.
- c) The nature of the PV mini grid system and the inverters available.

3.5 Determination of design daily load

It is important in this design to note that four unpredictable issues arise when designing mini grid connected photovoltaic systems.

1. The energy output from the PV system will vary from time to time during every day.
2. The energy output from the PV system will vary from day to day during each year.
3. The load put on the system is not constant over a day.
4. The daily loads vary over the year.

Considering the above unpredictable issues, calculating the exact energy usage per day is not practically possible.

3.6 Battery sizing and specifying

The main goal of this research is to investigate the suitability of the implementation of PV mini Grid connected systems as an alternative/complementary source of energy to solve the energy problem of Yama. Without the battery back up the system will only supply power to the mini grid during the day time loads only and therefore will not solve

the fundamental problem that this research seeks to solve. The battery bank is sized to cater for energy supply to the loads at night when the sun is not available.

The final battery capacity will depend on the following;

1. The total energy that the battery bank must supply to loads.
2. Maximum power demand
3. Maximum depth of discharge
4. System voltage
5. Charge current and recharge time.

3.6.1 Total energy that the battery bank must supply.

The estimated design daily energy demand is approximately **413.7 kWh**

Let this be represented by E_{dl}

The total energy that must be supplied by the battery bank is determined by the following equation;

$$E_{TOT} = \frac{E_{dl}}{\text{inverter } eff.}$$

$$E_{TOT} = \frac{413.7}{0.95} = 435.50 \text{ kWh} = \mathbf{435.50 \text{ kWh}}$$

3.6.2 Determining the required battery capacity

Batteries used in all solar systems are sized in Ampere hours under standard test conditions (Temp: 25°C). Battery manufactures usually specify the maximum allowable depth of discharge for their batteries. The depth of discharge is a measure of how much of the total battery capacity has been consumed. For most batteries the maximum allowable depth of discharge is 0.7 or 70%.

The Ah battery bank capacity required is for YAMA

$$\text{The size of battery (C}_{BB} \text{ Ah)} = \frac{\text{E}_{tot} \text{ (Wh)} \times \text{T}_{aut}}{\text{Syst(V)} \times \text{B}_{eff} \times \text{DOD}}$$

$$\text{The size of battery (C}_{BB} \text{ Ah)} = \frac{435,500 \text{ (Wh)} \times 2}{360 \text{ (V)} \times 0.8 \times 0.7} = 4320 \text{ Ah}$$

Ah battery capacity for 200 Households

$$\text{Size of battery (C}_{BB} \text{ Ah)} = \frac{\text{E}_{tot} \text{ (Wh)} \times \text{T}_{aut}}{\text{Syst(V)} \times \text{B}_{eff} \times \text{DOD}}$$

$$\text{The size of battery (C}_{BB} \text{ Ah)} = \frac{283,700 \text{ (Wh)} \times 2}{360 \text{ (V)} \times 0.8 \times 0.7 \times 0.95} = 2963 \text{ Ah}$$

Ah battery capacity for 50 Households

$$\text{The size of battery (C}_{BB} \text{ Ah)} = \frac{\text{E}_{tot} \text{ (Wh)} \times \text{T}_{aut}}{\text{Syst(V)} \times \text{B}_{eff} \times \text{DOD}}$$

$$\text{The size of battery (C}_{BB} \text{ Ah)} = \frac{88,700 \text{ (Wh)} \times 2}{240 \text{ (V)} \times 0.8 \times 0.7 \times 0.95} = 1216 \text{ Ah}$$

Where:

E_{tot} (Wh) = Daily energy demand

B_{eff}: = Battery efficient typically 80%

V_{BB} = Battery nominal voltage 2VDC

DOD= Depth of discharge: 70%

T_{aut}: = Number of days of autonomy 2

Selected Battery Ah Rating = 1500Ah

Selected system voltage = 360VDC

Selected system voltage for 50 households = 240V

3.6.3 Specifying the battery type to be used

In selecting a battery for a mini grid connected photovoltaic system the main consideration is to minimize the number of batteries in parallel.

The number of batteries in parallel must be minimized as much as possible for the following reasons;

1. For each parallel string there may be a chance of uneven charging of the batteries.
2. For safety it is recommended to fuse each parallel string in the battery bank. Remember that fuses are expensive and therefore it is recommended to keep the number of strings low.
3. Some battery manufactures state a recommended maximum number of parallel strings.

For the purpose of this study the following specification of solar battery is selected.

3.6.4 Number of batteries required for 300 households

Since the system voltage is 360VDC, the number of 2 volts batteries required in series is

Number of batteries in a string: $N_{ms} = \frac{\text{System votage}}{\text{nominal battery voltage}}$

Number of batteries in a string = $\frac{360}{2} = 180$ batteries

The number of batteries required in parallel is equal to the total capacity required divided the capacity of one of the 2-volt batteries.

Number of batteries in parallel: $N_{ps} = \frac{\text{Total Battery size}}{\text{Rating for a battery}}$

$$\text{Number of batteries in parallel} = \frac{4320}{1500} = 3 \text{ batteries}$$

Total number of batteries = Number in parallel x number in string = 180 x 3 = 540 batteries

Number of batteries required for 200 households

Since the system voltage is 360VDC, the number of 2 volts batteries required in series is

$$\text{Number of batteries in a string: } N_{ms} = \frac{\text{System votage}}{\text{nominal battery voltage}}$$

$$\text{Number of batteries in a string} = \frac{360}{2} = 180 \text{ batteries}$$

The number of batteries required in parallel is equal to the total capacity required divided by the capacity of one of the 2-volt batteries.

$$\text{Number of batteries in parallel: } N_{ps} = \frac{\text{Total Battery size}}{\text{Rrating for a battery}}$$

$$\text{Number of batteries in parallel} = \frac{2962.9}{1500} = 2 \text{ batteries}$$

Total number of batteries = Number in parallel x number in a string = 180 x 2 = 360 batteries

Number of batteries required for 50 households

Since the system voltage is 240VDC, the number of 2 volts batteries required in series is

$$\text{Number of batteries in a string: } N_{ms} = \frac{\text{System votage}}{\text{nominal battery voltage}}$$

$$\text{Number of batteries in series} = \frac{240}{2} = 120 \text{ batteries}$$

The number of batteries required in parallel is equal to the total capacity required divided by the capacity of one of the 2-volt batteries.

$$\text{Number of batteries in parallel: } N_{ps} = \frac{\text{Total Battery size}}{\text{Rating for 1 battery}}$$

$$\text{Number of batteries in parallel} = \frac{1215.9}{1500} = 1$$

Total number of batteries = Number in parallel x number in series = 120 x 1 = 120 batteries

KNUST

3.7 Sizing and specifying PV array

The main limiting criteria of the PV array in the PV mini grid connected system with battery bank are that the system must be able to operate as a standalone power system.

The system is expected to power all loads during peak hours.

There are mainly two system configurations for PV mini grid connected systems with battery bank storage;

- a. Inverter includes Maximum Power Point Tracker (MPPT) and the inverter does not charge the batteries from the mini grid.
- b. System uses switched regulator and the inverter maintains the batteries at float voltage state.

3.7.1 Selection of PV module to be used

In selection of a PV module for mini grid connected systems the main limitation is the efficiency of the module and the warranty of the product (since mini grid connected systems are designed to last for a long time. The KYOCERA technology solar 180Watt Photovoltaic module was selected for the purpose of this work.

3.7.1.1 Quality and safety

Recommended PV modules should meet ISO 9001 and ISO 14003 standard. The module should be certified to IEC 61215 or conforms to European Community Directive 89/33/EEC, 73/23/EEC and 93/68/EEC. The module's power measurements must be calibrated to World Radiometric reference through ESTI and framed modules must be certified by TUV Rheinland as Safety.

3.7.1.2 Typical electrical characteristics

The typical electrical characteristics of the KYOCERA PV module measured under Standard test conditions (irradiance of 1000W/m^2 , Air mass of 1.5G solar spectrum and effective cell temperature of 25°C) are as follows;

Warranted minimum power = 180W

Voltage at Pmax (V_{mp}) = 36.0V

Current at Pmax (I_{mp}) = 5.0A

Short circuit current = 5.3 A

Open circuit voltage = 44.2V

Temperature derating factor = $0.05\%/^\circ\text{C}$

Maximum system voltage = 1000VDC

Maximum series fuse rating = 600V DC

3.7.2 Determining the size of array required

Since the system being designed uses the maximum power point tracker, under the general design principle that input must be equal to output;

PV ARRAY SIZING

$$PV_{\text{Array}} (Wp) = \frac{E_{\text{tot}} \left(\frac{Wh}{d}\right)}{SPH \left(\frac{h}{d}\right) \times Beff \times PVder}$$

Where:

Etot: Total Daily energy demand (Wh/d)

SPH: Solar Peak Hour (h/d). = 5.5

Beff: Battery efficiency (%) = 80%

PVder: PV derating factor (%) which takes in account: = 80%

Tolerances, temperature, or aging, Module mismatches, dirt, shading, Losses due to wiring, blocking diodes, connectors

Efficiency of the charge controller

Typical η = 80%.

Array size for Yama

$$PV_{\text{Array}} (Wp) = \frac{413,700(Wh/d)}{5.5 \times 0.80 \times 0.8} = 117.5k\text{Wp}$$

120 kWp solar PV array capacity will be ideal

$$\text{Total Number of modules: } N_m = \frac{PV \text{ array size (Wp)}}{\text{Rating per module}}$$

$$\text{Total Number of modules: } N_m = \frac{120000\text{Wp}}{180\text{Wp}} = 666 \text{ modules}$$

$$\text{Number of modules in a string: } N_{ms} = \frac{\text{system voltage}}{\text{nominal module voltage}}$$

$$\text{Number of modules in a string: } N_{ms} = \frac{360}{24} = 15 \text{ modules}$$

Number of modules in parallel: $N_{ps} = \frac{\text{Number of modules}}{\text{Series string}}$

Number of modules in parallel: $N_{ps} = \frac{666}{15} = 44$ modules

Array size for 200 Households

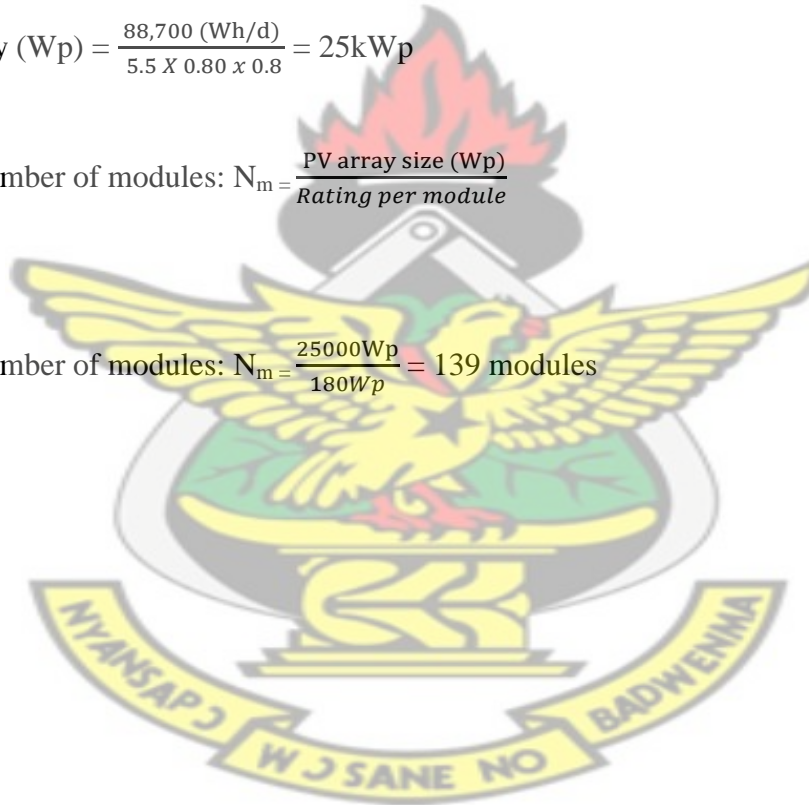
$$\text{PV Array (Wp)} = \frac{283,700 \text{ (Wh/d)}}{5.5 \times 0.80 \times 0.8} = 80.5\text{kWp}$$

Array size for 50 Households

$$\text{PV Array (Wp)} = \frac{88,700 \text{ (Wh/d)}}{5.5 \times 0.80 \times 0.8} = 25\text{kWp}$$

Total Number of modules: $N_m = \frac{\text{PV array size (Wp)}}{\text{Rating per module}}$

$$\text{Total Number of modules: } N_m = \frac{25000\text{Wp}}{180\text{Wp}} = 139 \text{ modules}$$



3.7.3 Sizing and specifying Inverter

Unlike in standalone power systems where the battery is the heart of the system and always needs to be designed first in mini-grid connected PV systems, the inverter is the main determinant of the system and can be designed first.

The inverter is the junction between the PV system, the distribution network system and the loads. The choice of an inverter in a mini-grid connected PV system with battery backup is dependent on the input and output voltages, the phase type (3-phase or single phase), output kw (power), full load efficiency, operation type and the presence of utility fault protection features. In this design the inverter must have the following characteristics;

1. Must have a D.C input voltage of between 240V and 480V to minimize cable sizes.
2. Must have an alternating current output voltage of 433V, 3 phase.
3. Must have efficiency at full load of above 95% to minimize losses.
4. Must have the ability to perform maximum power point tracking to minimize the number of panels needed.
5. Must have an in-built battery charging features.

Sizing the inverter

Total power of Ac loads = 83.25kW

Inverter size = Power of Ac loads x 1.25 (oversize factor)

Inverter size (kW) = 83.25 x 1.25 =104kW

Available inverter size = 120

The chosen inverter for this study is the sunny Central Technologies inverter with a capacity of 120kW. It is a 360VDC – 433V 3 phase AC sine wave grid tied inverter. The full load efficiency of the inverter is greater than 95%. It is fitted with solar peak power tracking (MPPT) ability and has built in utility fault protection features and meets all IEEE standards for mini-grid-tie inverters. It has an off-shelf price of \$48,700.00

KNUST



3.8 Wiring diagram of PV array

The PV array is made up of 666 modules of 44 parallel strings of 15 modules in series.

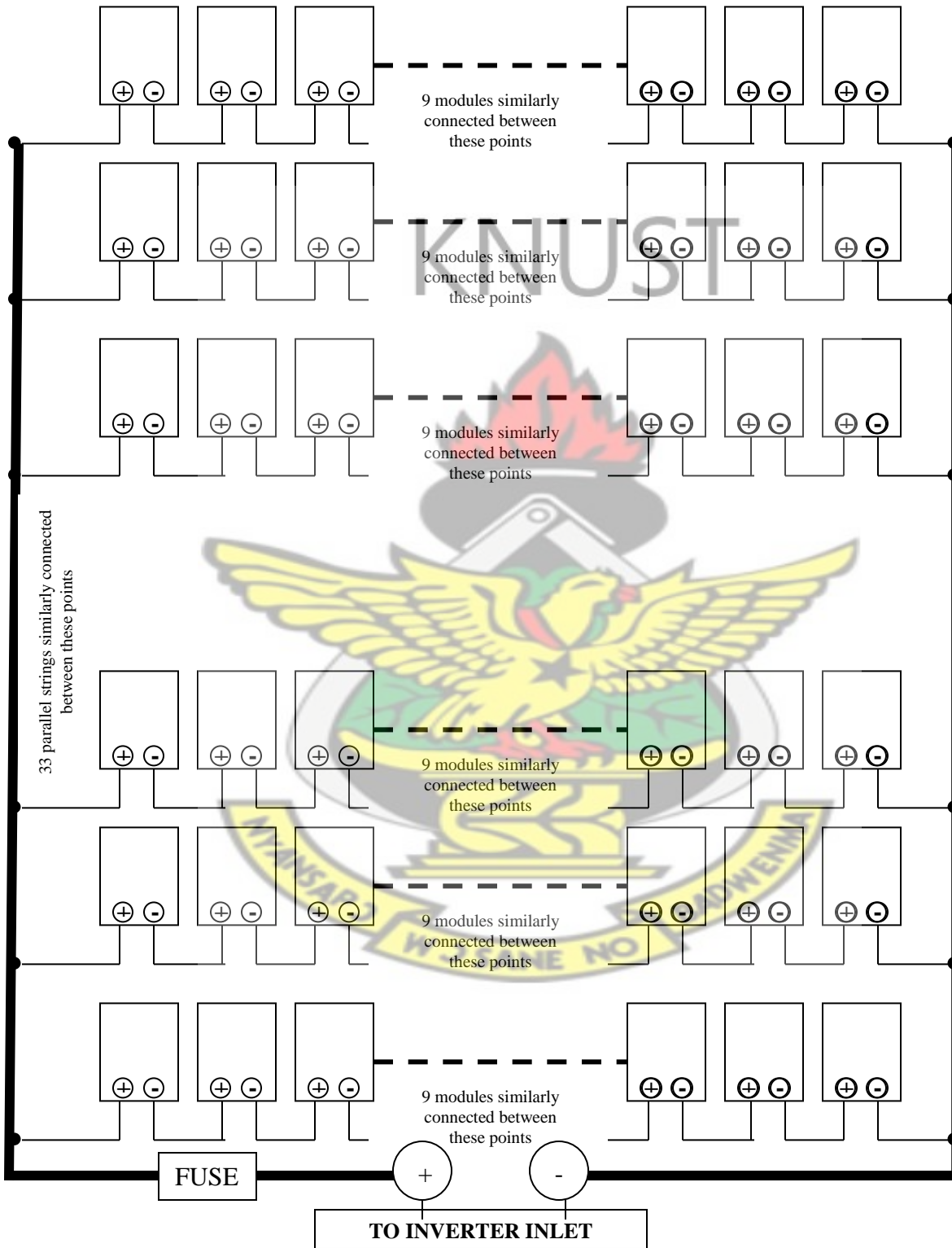


Fig 3.3 Wiring diagram of PV array

3.8.1 Wiring diagram of battery bank

The fig. 3.6 shows the wiring of the battery bank made up of 2 volts cells.

As previously determined since the system voltage is 360VDC, the number of 2 volts batteries required in series is

$$\text{Number in series} = \frac{360}{2} = 180 \text{ batteries}$$

The number of batteries required in parallel is equal to the total capacity required divided the capacity of one of the 2 volt batteries.

$$\text{Number in parallel} = \frac{4320}{1500} = 3 \text{ batteries}$$

Total number of batteries = $180 \times 3 = 540$ batteries

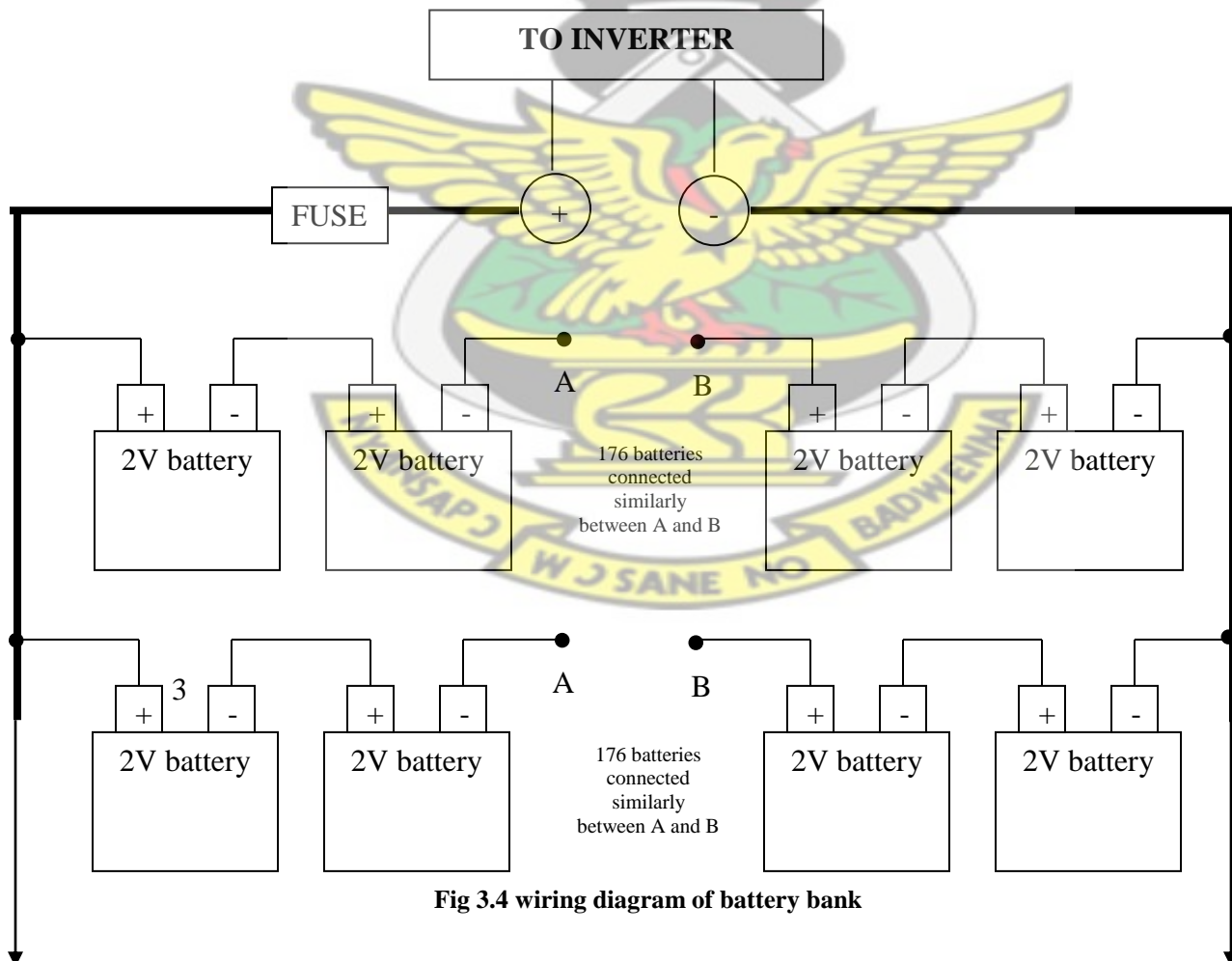


Fig 3.4 wiring diagram of battery bank

3.8.5 Single Line Electrical Circuit Diagram

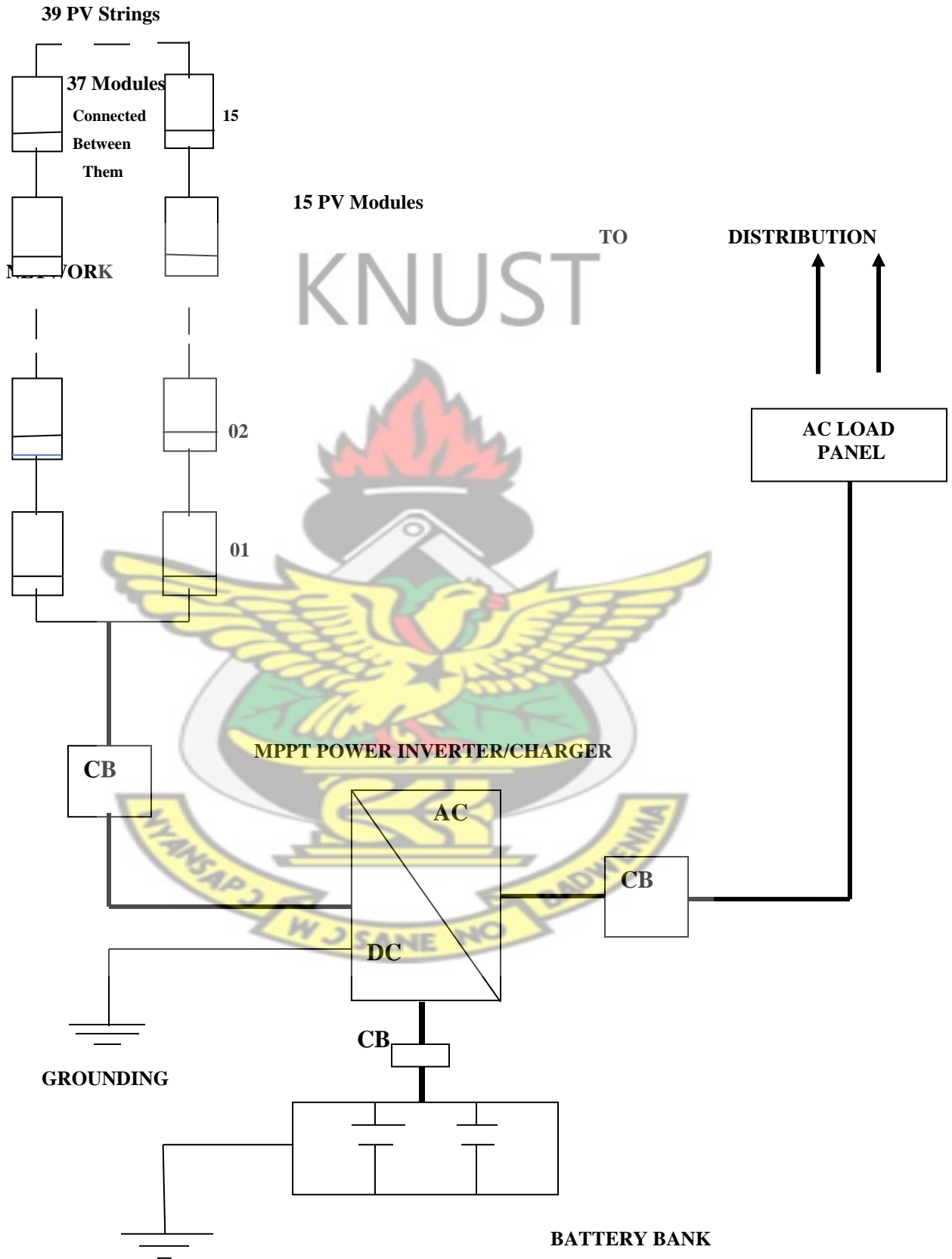


Figure 3.5 Single Line Electrical Circuit Diagram

3.8.6 Sizing of cables

As much as the design/sizing of the PV mini grid system is important, the accurate selection of system wiring cables is very essential in order that the system is safe.

The wiring must not reduce the performance of any of the components of the system. The cables in a mini grid connected system must be sized correctly to reduce the voltage drops in the cable and to make sure that the safe current handling capacity of the cable is not exceeded.

The voltage drop in a cable is given as

$$\Delta V = 2 (L \times I \times \rho) / A$$

Where ρ is the resistivity of copper wire which is normally taken to be $0.0183 \rho \text{ mm}/2\Omega$

l = the length of cables in meters

I = the current through the cables in amperes

A is the cross-sectional area (CSA) in mm^2

The multiplication by 2 accounts for total circuit wire length.

Changing the subject of the above formulae

$$A = \frac{2 \times \rho \times L \times I}{Vd}$$

In the design of the system, a maximum cable voltage drop of 5% was used and this is the maximum allowable drop in PV mini grid connected systems.

3.8.6.1 Sizing cables between PV modules

The cable is sized based on the following information

Length of cable is 1.5 m

The maximum current is 1.25 x short circuit current of modules (5.3 amperes) = 1.25 x 5.3 = 6.625A

$$V = \frac{5}{100} \times 24 = 1.2V$$

KNUST

The resistivity of copper is $0.0183\text{mm}^2/\text{m}$

$$\text{Area} = \frac{2 \times 0.0183 \times 2 \times 6.625}{1.2} = 0.40\text{mm}^2$$

This means that any cable of cross-sectional area above 0.40mm^2 can be used for the wiring between PV modules

3.8.6.2 Sizing of cable between inverter and battery bank

The cable is sized based on the following information

Maximum Length of cable is 5m

The maximum current from battery at full load supply is given by

$$I = \frac{\text{InverterVA}}{\eta_{\text{inv}} \times V_{\text{sys}}} = \frac{120\text{KVA}}{0.95 \times 360} = 351\text{A}$$

The maximum voltage drop $V = \frac{5}{100} \times 360 = 18V$

he resistivity of copper is $0.0183\text{mm}^2/\text{m}$

$$\text{Area} = \frac{2 \times 0.0183 \times 5 \times 351}{18} = 3.5\text{mm}^2$$

This means that any cable of cross-sectional area above 3.5mm^2 can be used for the wiring between battery bank and inverter.

3.9 Mini-grid Distribution Network Mapping and Layout

Once all the design loads to be served have been estimated, the distribution system can be laid out. This requires finalizing the location of the powerhouse, the placement of the lines, and the pole locations. In large part, these are determined by the layout of the village and the general nature of the loads to be served. Factors affecting this aspect of project design are explained in the following sections.

Once the nature of the power demand and the layout of the distribution system are known, the next steps will be to determine the line configuration, the conductor type and sizes to adequately supply that demand, and available pole options and size to ensure adequate line clearance and a safe system. While a few comments are made below on the placement of poles, this only serves as initial guidance. Final pole placement can be determined after the steps just mentioned have been completed.

3.9.1 Placing the lines

Once the powerhouse has been located, the distribution line is required to bring the electricity to the vicinity of the consumers. The best layout for the distribution system will be one that meets the criteria for voltage drop while minimizing cost and keeping safety and reliability in mind. In general, the shortest line will minimize cost, because this will reduce the cost of both the conductor and poles. Poles are often the most expensive component of a distribution system, and an important part of the design process is to be economical in their use.

Depending on the layout of the consumers relative to the location of the powerhouse, the best layout may be to extend lines in several directions from the powerhouse. Several factors must be taken into consideration in deciding where these lines are to be placed. The relative importance of each must be decided in each situation. These factors include the following:

- Location of roads, trails, and paths
- Presence of trees
- Topography
- Line length

3.9.2 Locating poles

Once the general layout for the distribution line has been prepared, poles must be placed along that line to support the conductors with adequate clearance to ensure a line that does not pose any hazard to people or vehicular traffic passing beneath it. Factors affecting pole location include the following:

- Location of load clusters.
- Adequate ground clearance
- Pole strength

3.9.3 Line Configuration

To distribute power around a load center, four basic distribution line configurations are possible: two single-phase configurations and two three-phase configurations. All configurations use similar materials and construction techniques. On some occasions, a

combination of these configurations can be used to achieve a more cost-effective distribution system design.

For a particular village situation, the attributes of each configuration and a rough sizing and costing of the conductor and pole top hardware for each configuration should be assessed to determine which line configuration is the most cost-effective.

3.9.4 System grounding

At medium or low voltages, system grounding is typically used to protect the electrical system and ensure safe and reliable service. With one conductor firmly bonded to the ground, it permits economies in the construction and use of various line equipment such as transformers and insulators by permitting a reduction in the required insulation levels. It increases the effectiveness of lightning arresters by providing a low-resistance path to ground and also somewhat reduces voltage drop along a line by allowing some of the return currents to flow through the earth. It increases worker and public safety, in part by facilitating the detection and subsequent isolation of any fault to ground that might occur.

3.9.5 Conductor

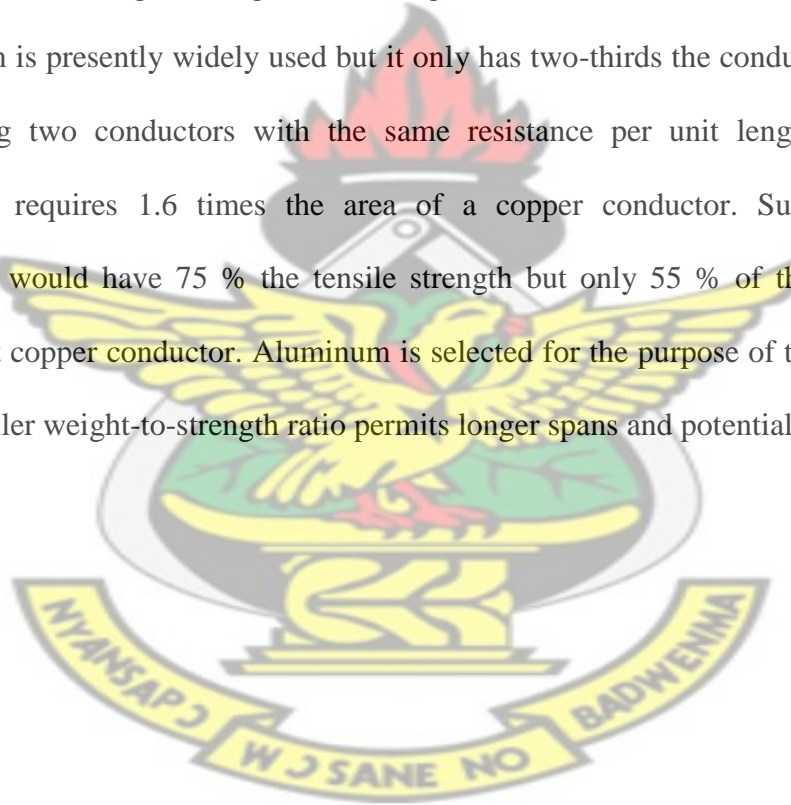
Once the nature of the loading has been determined, the selection of a conductor to most effectively serve consumer load and load growth at minimum cost can be assured by following the standard approach for properly sizing the conductor. In this process, both the voltage drop at the end of the line as well as energy (kWh) losses along the line—both of which depend on conductor size—must be kept within acceptable bounds.

3.9.6.1 Types of conductor

For electricity distribution, two materials are generally used: copper and aluminum.

Copper is available in several forms. Hard-drawn copper is used as a conductor because of its higher strength. Annealed copper is used as a ground wire and for other applications where it is necessary to bend and shape the conductor. Annealing copper—heating it to a red heat after drawing it through the drawing die—softens it and reduces its strength.

Aluminum is presently widely used but it only has two-thirds the conductivity of copper. Comparing two conductors with the same resistance per unit length, an aluminum conductor requires 1.6 times the area of a copper conductor. Such an aluminum conductor would have 75 % the tensile strength but only 55 % of the weights of the equivalent copper conductor. Aluminum is selected for the purpose of this study because of its smaller weight-to-strength ratio permits longer spans and potentially fewer poles.



CHAPTER FOUR

4.0 Results and Discussion

4.1 Cost of Design

In this chapter, the cost of design and installation of PV mini-grid for 300 and 50 households as well as the cost of extending the nation grid has been determined. This chapter will put to rest the question of which of these options is more economically viable under the circumstance to solve the problem of rural electrification in the Northern Ghana. The results of this chapter could be implemented in other communities in Ghana. No attempt is made in this chapter to compare the cost of electricity produced by the PV mini- grid system and the cost of electricity available from the national grid.

4.2 Sources of data for cost analysis

Prices that are quoted in this chapter can vary considerably depending on factors like the buyer's possibilities to achieve discounts, possibilities to do work by yourself, authority requirements, safety and other regulations. Quoted prices have been collected from a number of different sources, e.g. supplier catalogues on solar power units; verbal information from manufacturers and dealers; comparison with similar existing installations and labor elsewhere. Some sources have expressed the wish to be anonymous, wherefore references are not presented.

The cost of importation, custom duties and average margins were obtained from solar dealers in the country. All prices were sourced in May 2013.

The choice of suppliers for a project may base on the following considerations;

- i. Companies with long years of existence and superior products.

- ii. Companies with best prices for equal items.
- iii. Companies with the ability to manufacture the exact specification of the item needed.
- iv. Companies whose products meet the ISO 9001 and ISO 14003 certifications.
- v. Companies with competitive prices.

4.3 Estimation of project life.

In order to accurately estimate cost of the project, a project life time must be selected. The project life time is taken to be 25 years since it is the warranty period of the solar modules which is the most costly part of the system.

4.4 Difference between warranty period and expected life time

Although all the system components have their respective warranty period from their manufacturers, their expected life time is based on knowledge acquired on similar projects outside the country and is normally higher than the warranty period.

The table below show the respective component's warranty period and their chosen expected life time.

Table 4.1 warranty and life of products

PRODUCT	WARRANTY PERIOD	EXPECTED LIFE TIME
SOLAR MODULE	25 YEARS	50 YEARS
INVERTER	20 YEARS	25 YEARS
SOLAR BATTERY	5 YEARS	10 YEARS

4.5 Estimated investment cost for 300 households

This section deals with calculation on the investment cost of individual component or unit of the PV mini-grid system.

Table 4.2 estimating the cost of PV mini-grid system for Yama

Items	Quantity	unit cost from manufactures(\$)	Total cost at manufacturer(\$)	Shipping Cost (10%)	Custom Duties	Shipping Margin + VAT	Total Cost (\$)
120KW Inverter	1	48,700	48,700	4,870	-	-	53,570
2V Batteries	540	392	211,680	21,168	-	-	232,848
Panel KYO180W	666	350	233,100	20,510	-	-	253,610
mount Structure	666	50	-	-	-	-	33,300
SUB TOTAL(US\$)							573,328
Labour, Engineering & Supervision cost	20% of sub total						114,665.60
TOTAL							687,993.60
Estimated cost LV distribution network							175,700
Cost of battery bank housing							6,100
GRAND TOTAL(US\$)							869,793.6

4.6 Estimated investment cost for 50 household

This section deals with calculation on the investment cost of individual component or unit of the PV mini-grid system.

Table 4.3 estimating the cost of PV mini-grid system for 50 households

Items	Quantity	unit cost from manufactures(\$)	Total Cost at manufacturer(\$)	Shipping Cost (10%)	Custom Duties	+ Shipping Margin + VAT	Total Cost (\$)
25KW Inverter	1	12,350	12,350	2,435	-	-	14785
2V Batteries	120	392	47,040	4,704	-	-	51744
Panel KYO180W	139	350	48,650	507.5	-	-	49,157.5
Cost of mounting structure	139	50	6,950	-	-	-	6,950
SUB TOTAL							122,636.5
Labour, Engineering & Supervision	20% of sub total						24,527.3
TOTAL							269,800.3
Estimated cost of LV distribution network							33,600
Cost battery bank /Inverter housing							2,000
GRAND TOTAL							305,400.3

4.7 Material Estimate for MV/LV Construction

This section deals with material estimates for MV/LV network construction from the nearest grid connected community to Yama community.

Table 4.4 Material estimate for MV/LV Construction

Item	Description	Unit Measurement	Parameters
	<i>Estimated Population in 2020</i>	No	2,468
	<i>Estimated number of customers in 2020</i>	No	289
	<i>MV Distance from Connection Point</i>		18.0km
	<i>Line Type (ie either: 33-S, 33-W, 11-W or 11-C)</i>		20W
1	33KV, 3 ϕ Wood pole line complete with conductor, 10m poles, pole top hardware and accessories.		18.0km
2	33KV, 50kVA, 3 ϕ pole mounted transformer substation complete.	No	3
3	3 ϕ (4-wire) LV line complete with conductor, 9m pole, pole hardware and accessories.	Pole cct-km	1.6km
4	1 ϕ (3-wire) LV line conductor complete with 9m pole, pole hardware and accessories.	Pole cct-km	0.6km
5	1 ϕ (2-wire) LV line with conductor complete with 9m pole top hardware and accessories.	Pole cct-km	0.1km
6	3 ϕ , consumer service connection complete with energy meter, associated cut-out and aerial conductor	Per service	30
7	1 ϕ consumer service connection complete with energy meter, associated cut-out and aerial conductor	Per service	174
8	1 ϕ consumer service connection complete with 7m service pole, energy meter, associated cut-out	Per service	10

Source: National Electrification Scheme (NES) Master Plan Review (2011-2020)

4.8 Cost Estimate MV/LV Construction

This section deals with material the cost estimates for MV/LV network construction from nearest grid connected community to Yama.

Table 4.5 Cost estimate for MV/LV Construction

Item	Description	Unit Rate(\$)	Total Cost(\$)
1	33KV, 3 ϕ Wood pole line complete with conductor, 10m poles, pole top hardware and accessories.	31,804 /km	572,469
2	33KV, 50KVA, 3 ϕ pole mounted transformer substation complete.	12,615	37,846
3	3 ϕ (4-wire) LV line complete with conductor, 9m pole, pole hardware and accessories.	17,367 /km	27,787
4	1 ϕ (3-wire) LV line conductor complete with 9m pole, pole hardware and accessories.	15,397 /km	9,238
5	3 ϕ (2-wire) LV line with conductor complete with 9m pole top hardware and accessories.	13,007 /km	1,301
6	3 ϕ , consumer service connection complete with energy meter, associated cut-out and aerial conductor	628	20,101
7	1 ϕ consumer service connection complete with energy meter, associated cut-out and aerial conductor	300	52,158
8	1 ϕ consumer service connection complete with 7m service pole, energy meter, associated cut-out	653	6,530
9	Base Cost		727,430
10	Contingency (Physical and Price)	20%	145,486
11	Engineering (Design and Survey)	10%	72,743
12	Construction Supervision	20%	145,486
GRAND TOTAL			1,091,145

Source: National Electrification Scheme (NES) Master Plan Review (2011-2020)

4.9 Economic viability of solar PV mini grid

4.9.1 Estimation of relevant financial rates.

4.9.1.1 Interest rate

According to the Africa Development Bank's guidelines for economic analysis of projects, the average interest rate on funds received from foreign sources is taken as 8%.

4.9.1.2 Inflation rate

The Bank of Ghana has tried to bring inflation under control in recent years. Reductions in domestic debt moved inflation in Ghana to 9.5% in March 2006. However, owing to constantly rising international crude oil prices and the pass-through of price changes to domestic petroleum prices, inflation has risen to a three year high of 15% in April 2013. In this economic analysis, the average inflation rate of 12% is used.

4.9.1.3 Exchange rate

Despite strong international prices for gold and cocoa, the national currency continued to depreciate marginally over the first half of this year (2013).

In this economic analysis the July 2013 value of Ghc 2.00/USD is used.

4.9.1.4 Selection of financing source

The initial cost of the PV mini grid system for Yama is estimated as (US\$836,960) assuming a loan will be contracted to finance the project at an interest rate of 8%. The loan is repaid over a period of 25 years. The loan is repaid by equal payments of loan principal plus interest over the 25 year period.

4.9.2 Life cycle cost of O&M of system.

PV mini-grid systems have very minimal maintenance cost, considering the present prevailing industry rates for operation & maintenance cost of 10% of system cost, the cost of O&M for 120kWp PV grid system.

$$\text{Total cost of system} = \$869,793.60 * 10\% = \$86,979.30$$

4.9.3 Lifecycle cost of Battery Replacement

Battery may be replaced 3 times in 25 years using the warranty period of 7years, therefore

$$\text{We have initial cost @ US\$ } 232,848 * 3 = \text{US\$}698,544$$

$$\text{Total lifecycle cost of system} = 869,793.60 + 86,979.30 + 698,544 = \text{US\$}2,266,881.30$$

4.9.4 Economic Viability using Simple Payback Analysis

$$\text{Energy cost (\$/kWh)} = \text{Cost of the system (\$)} / \text{Energy generated (kWh)}$$

$$\text{Total Cost of the system} = \$ 2,266,881.30$$

$$\text{Energy generated} = 120\text{kW} \times 5.5\text{hrs} \times 0.7 \times 365 \times 25 = 4,215,750\text{kWh}$$

$$\text{Energy cost (\$/kWh)} = \$2,266,881.30 / 4,215,750 = \text{US}0.50/\text{kWh}$$

$$\text{Simple payback period} = \frac{\text{total installed cost} - \text{Incentives}}{\text{estimate of annual produced kWh} * \text{energy cost per kWh}}$$

$$\text{Simple payback} = 869793.60 / 168630 \times \$0.50$$

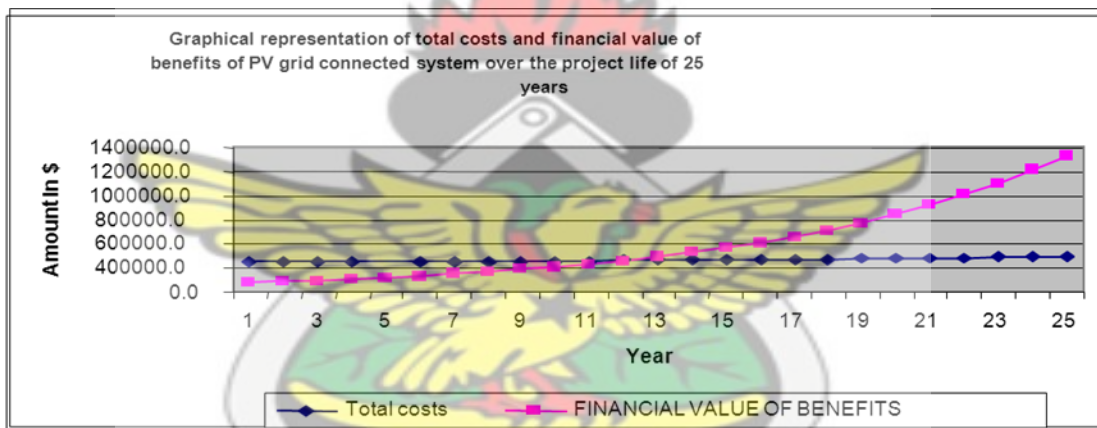
$$\text{Simple payback period} = 10 \text{ years}$$

Assuming international recognized feed-in-tariff of \$0.35/kWh for PV grid is used

$$\text{Simple payback period} = 869793.60 / 168630 * \$0.35 = 15 \text{ years}$$

4.9.5 Economic viability using RETSCREEN

- Average interest rate at the time =8%.
- Inflation rate used = 12%
- Exchange rate used at July 2013= Ghc 2.00/USD.
- The initial cost of the system =US\$869,793
- Assume Incentive of 30%.
- The loan is repaid over a period of 25 years assumed
- A result from the diagram show 13 years pay back



4.6 Graphical representation of RETSCREEN analysis

CHAPTER FIVE

5.0 Conclusions and Recommendations

5.1 Conclusions

In the design of PV mini-grid system for Yama community, the study arrived at 1.3kWh/day as the average daily energy demand for a household. With a total number of 300 households, the total average energy demand was about 390kWh per day. The commercial and public institutions have average daily energy demand of about 24kWh per day bringing the total average daily energy demand for the entire community to about 414kWh per day. This requires a PV mini-grid system capacity of 120kW with 4320Ah battery capacity estimated to cost US\$869,794.

The cost of extending the national electricity grid of 34.5kV medium voltage line over a distance of 18km to Yama is estimated to cost US\$1,091,145 whereas the PV mini-grid system including LV distribution network is estimated to cost US\$869,794. These results show that the cost of extending the national electricity grid to Yama community is higher as compare to the installation of PV mini-grid system. However, from the research it can be concluded that, the best suited and cost effective PV mini-grid for providing electricity to remote locations is to target communities which are beyond 20km from the nearest grid line with less than 300 households.

The study on economic viability arrived at a feed-in-tariff of US50 cents/kWh with a payback period of 10 years using the simple payback analysis, while RETSCREEN analysis gave a payback period of 13years. This project as in the case of solar projects worldwide has a minimum lifespan of 25years and with a payback of between 10 and 13 years as obtained in this research. Therefore the proposed solar PV mini-grid system for Yama community can be said to be economically viable for any investor.

5.2 Recommendations

From the research that was carried out, the following recommendations are made:

1. There is a considerable market for PV mini-grid systems both in remote and peri-urban areas. To meet this market demand, policies should be implemented by Ministry of Energy to promote mini-grids and also address problems, such as lack of operation and maintenance infrastructure, the need for more awareness of PV mini- grid systems and the high initial investment costs.
2. Local government should play an important role in promoting PV mini-grid systems: These can be taken into account in their decision making and planning in connection with the local infrastructure development.
3. Financial institutions should partner the national government and district assemblies in promoting PV mini-grids with the help of financial instruments such as micro-finance and consumer credit in the rural and peri-urban areas of Ghana.
4. Training institutions should be resourced and encouraged to train local experts on the installation, operations and maintenance of PV mini-grid systems.
5. The Ministry of Energy should be resourced and encouraged to include PV mini-grid system in SHEP and national electrification programmes.
6. Volta River Authority (VRA) of Ghana should be encouraged to implement their REDP on solar PV mini-grid systems as it has proven to be a viable complement to national grid extension in remote areas of Ghana.
7. Independent Power Producers (IPPs) in Ghana should explore the option of power production using PV mini-grid systems.

CHAPTER SIX

References

1. Ahiataku- Togobo (2004); challenges of solar PV for remote electrification in Ghana.
2. Ahmed .B (2012) Solar PV technology course manuals. KNUST Kumasi, Ghana pg 33-43, 56.
3. Allen .R (2000); Mini grid systems design manual, International Programs Assessing Policy Options for Increasing the Use of Renewable Energy for Sustainable Development: Ghana, Accra (2003), pg 2-9
4. Bates, J., Wilshaw, A. (1999) *Stand-alone PV systems in developing countries*, Technical report, The International Energy Agency (IEA), Photovoltaic Power Systems (PVPS) programme.
5. BCSE Designers and Installers Course for PV Grid Connect Systems with Battery Backup training manual (2000), pg 20-51
6. Chakrabarti, S., Chakrabarti, S. (2002) ‘Rural electrification programme with solar energy in remote region—a case study in an island’, *Energy Policy* 30(1), pp. 33–42
7. Ciscar, (1997), Duke et al, (2002), WEC, (2003).
8. E.L Hagerstedt et al, Benefits of interconnecting stand-alone PV into a mini grid Case Study: Vidinge, Stockholm archipelago Elforsk rapport (2006).
9. Energy Commission (2003), “Strategic National Energy Plan”, Annex I of IV
10. Energy Commission (2003), “Strategic National Energy Plan”, Annex I of IV
11. Energy Commission, (2006), Strategic National Energy Plan, Main report

12. Energy Statistics, Energy Review Issue (01-2007), pg 41-43
13. ESMAP, (2007)
14. Frank Y Dadzie, THESIS on Solar PV grid connected system with battery backup for KNUST document (2008) pg2-10, 18-34, 50-77.
15. Gavanidou, E.S., Bakirtzis, A.G. (1992) 'Design of a standalone system with renewable energy sources using trade off methods', *IEEE Trans Energy Conversions* 7, pp. 42-8
16. GSES Standalone power systems design and Installation training manual, 5th edition (2000), pg 21-33, 49-68, 101-102, 227-241
17. GVEP International Policy Briefing on mini grid system development in the developing world report (2011) pg1-8
18. Harrmon 2000 pg.2
19. IEA-PVPS (2000), Task 1 report IEA-PVPS 5-2-0 ,USA
20. Kaldellis, J.K. (2007) 'An integrated model for performance simulation of hybrid wind-diesel systems', *Renewable Energy* 32(9), pp. 1544-64
21. Kaushika et al (2005)
22. Kolhe, M., Kolhe, S., and Joshi, J.C. (2002) 'Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India', *Energy Economics* 24(2), pp. 155-65
23. Kyocera (2006) Solar Electric Products Catalog pg.2.
24. Mayer, D., Heidenreich M. (2003) *Performance analysis of stand-alone pv systems from a rational use of energy point of view*, French Agency for Environment and Energy Management
25. Ministry of Energy; national energy policy report (2010) Accra, Ghana ; pg5
26. Ministry of Energy; national energy policy report (2012),Accra, Ghana pg10
27. Moharil, R.M., Kulkarni, P.S. (2009) 'A case study of solar photovoltaic power system at Sagardeep Island, India', *Renewable and Sustainable Energy Reviews* 13(3), pp. 673-681
28. Muneer et al and Nouni et al (2006)

29. Muneer, T., Muhammad, and A., Saima M. (2005) ‘Sustainable production of solar electricity with particular reference to the Indian economy’, *Renewable and Sustainable Energy Reviews* 9(5), pp. 444 - 473.
30. National Electrification Scheme (NES) Final Report Master Plan Review (2011-2020) for (northern Region of Ghana) pg 177,197,200, 206.
31. National report on solar Radiation: National Renewable Energy Laboratory (NREL) of USA and German Aerospace Institute provided international consultancy (2002) pg3-6.
32. Off-Grid Electricity Generation with Renewable Energy Technologies in India; An application of HOMER(2011) pg 8-9
33. Ottu-Danquah K. (2007), solar energy development in Ghana; challenges and the way forward, Proceedings of 2007 National Energy Symposium, Accra, Ghana.
34. Rabah, K.V.O. (2005) ‘Integrated solar energy systems for rural electrification in Kenya’, *Renewable Energy* 30(1), pp. 23–42
35. Retscreen International Clean Energy Project Analysis, Retscreen Engineering and Cases Textbook, third edition, pg 53-71
36. Review of Existing Renewable Energy Resource Data, Energy Policies, Strategies, Plans and Projects Energy Commission, Ghana(2009) pg10-12
37. Schmitt, A., Huard, G., and Kwiatkowsk, G. (2006) ‘PV-hybrid micro plants and mini-grids for Decentralised Rural Electrification in Developing Countries’, *EDF Research and development*, France.
38. Simon Bawakillenuo, (2007).Phd Thesis on Rural electrification in Ghana: the issue of PV Energy technology Utilization. University of Hull, pg 80-81
39. Sinha, C. S., Kandpal, T. C. (1991) ‘Decentralized v grid electricity for rural India – the economic factors’, *Energy Policy* 19(5), pp. 441-448
40. USAID/ARE, (2011)
41. Volta River Authority REDP, (2010)

KNUST



APENDICES

Appendix 1

Community Profile questionnaire administered in Yama

(Key informant interview targeting: Assemblymen and NEWENERGY)

Section A: Community identity

- 1.0 Name of Community: Yama 1.1 District: West Mamprusi 1.2 Region: Northern
- 1.3 Population (2010PHC): 3000 1.4 Numbers of Households: 301
- 1.5 Distance from the nearest Grid-connected community: 18Km from Wungu
- 1.6 What is the dominant economic activity in the community: Farming
- 1.7 What developmental organizations are active in the community: New Energy

Section B: Community Facilities

- 2.0 indicate the availability and functionality of the following public facilities in the community

	Type of facility	Number	Status		Main sources of energy	Remarks
			functioning	Not functioning		
2.1	Primary School	3			NA	
2.2	Junior High School	1			NA	
2.3	Senior High School/Vocational	NIL			NA	
2.4	Teachers quarters	1			Solar Lanterns	
2.5	Doctors quarters	NIL			NA	
2.6	Nurses quarters	NIL			NA	
2.7	Health centre	NIL			NA	
2.8	Clinics	NIL			NA	
2.9	CHIPS compound	1			Solar Lanterns	
2.10	Portable water point	NIL			NA	
2.11	Custom/Police post	NIL			NA	
2.12	Other Gov't office/facility	NIL			NA	
2.13	Church/Mosque	3			Solar system	
2.14	Public streetlight	5			Solar PV	
2.15	Grain Milling	8			Diesel	

2.16	Other agro-processing	NIL			NA	
2.17	Water pumping for irrigation	NIL			NA	
2.18	General goods shop	5			SolarPV/ Kerosine	
2.19	Drug shop	2			Solar Lantern	
2.20	Repair shop	3			NA	
2.21	Chop bar/ restaurant	5			NA	
2.22	Others				NA	

KNUST



Appendix 2

Energy Demand Survey for Solar PV mini Grid Connected System- Questionnaires Community Profile

(Key informants interview targeting: Assemblymen, Committee Chairmen and individual inhabitants)

Section A: Community identity

- 3.0 Name of Community _____ 1.1 District _____ 1.2 Region _____
- 1.3 Population (2010PHC) _____ 1.4 Number of Households _____
- 1.5 Distance from the nearest Grid-connected community _____ Km
- 1.6 What is the dominant economic activity in the community _____?
- 1.7 What developmental organizations are active in the community _____?

Section B: Community Facilities

4.0 indicate the availability and functionality of the following public facilities in the community

	Type of facility	Number	Status		Main sources of energy	Remarks
			functioning	Not functioning		
2.1	Primary School					
2.2	Junior High School					
2.3	Senior High School/Vocational	High				
2.4	Teachers quarters					
2.5	Doctors quarters					
2.6	Nurses quarters					
2.7	Health centre					
2.8	Clinics					
2.9	CHIPS compound					
2.10	Portable water point					
2.11	Custom/Police post					
2.12	Other Gov't office/facility					
2.13	Church/Mosque					
2.14	Public streetlight					
2.15	Grain Milling					
2.16	Other agro-processing					
2.17	Water pumping for irrigation					
2.18	General goods shop					
2.19	Drug shop					
2.20	Repair shop					
2.21	Chop bar/ restaurant					
2.22	Others					

Section C: Energy Issues

3.1 What is the main source of energy for lighting? (Rank as 1, 2, 3 in order of importance)

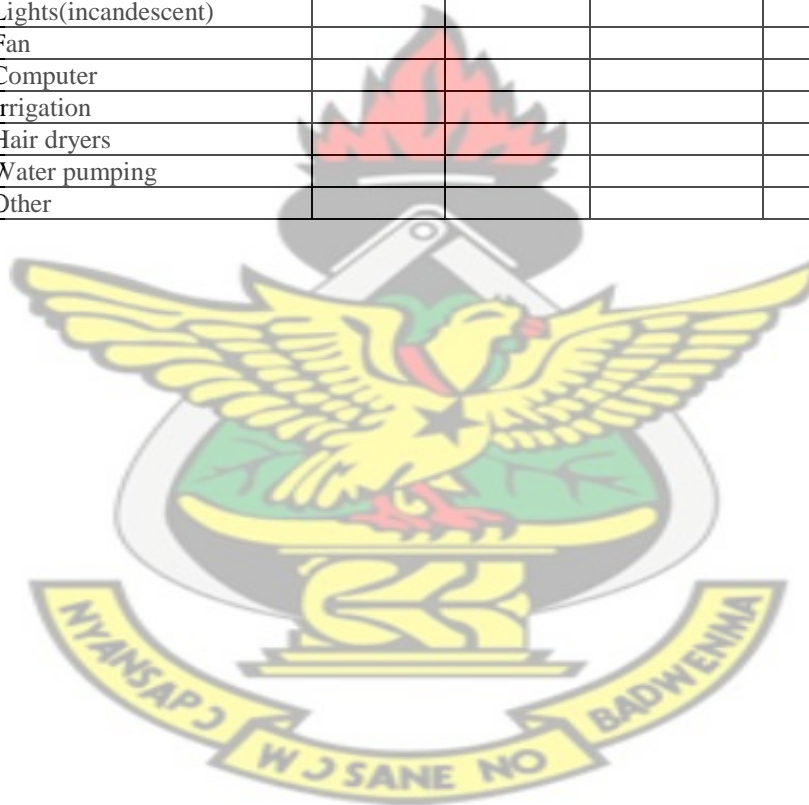
A	Electricity from own generator	
B	Kerosine	
C	Candle	
D	Dry cell batteries	
E	Solar Home System	
F	Battery charging system	
G	Solar lantern	
H	LPG	
I	None	
J	Other	

3.2 What is the monthly cost of energy for lighting and electricity for electric appliances (specify in Cedis)

	Energy source	Initial cost	Monthly running cost
A	Electricity from own generator		
B	Kerosene		
C	Candle		
D	Dry cell batteries		
E	Solar Home System		
F	Battery charging system		
G	Solar lantern		
H	LPG		
I	None		
J	Other		

3.3 Which electrical appliances do you use in this facility?

	Electrical appliance	Qty	Wattage	Hours of use/day	How appliances is currently powered. 1-solar PV, 2-Generator, 3-Battery, 4-LGP, 5- kerosine
		A	B	C	D
3.3.1	TV (colour) small				
3.3.2	TV(colour) big				
3.3.3	TV (black & white)				
3.3.4	VCR/VCD				
3.3.5	Radio				
3.3.6	Stereo				
3.3.7	Refrigerator				
3.3.8	Freezer				
3.3.9	Lights(fluorescent)				
3.3.10	Lights(incandescent)				
3.3.11	Fan				
3.3.12	Computer				
3.3.13	Irrigation				
3.3.14	Hair dryers				
3.3.15	Water pumping				
3.3.16	Other				



Appendix 3

Challenges of rural electrification in northern region of Ghana.



SOURCE: Ahiataku Togobo





Appendix 4. Photogram of PV Array and Battery Bank



Source: VRA Navrongo Solar Power Plant