DESIGN OF A GRID CONNECTED PHOTOVOLTAIC SYSTEM FOR KNUST AND ECONOMIC AND ENVIRONMENTAL ANALYSIS OF THE DESIGNED SYSTEM

by

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DECLARATION

I hereby declare that this submission is my own work towards the MPhil 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.

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ABSTRACT

This research was undertaken to investigate the economic and environmental suitability of the implementation of Grid Connected Photovoltaic Systems in comparison to the use of fuel generators/plant as an alternative source of energy to solve the regular grid failure problem in residential and commercial institutions in Ghana with KNUST as the case study. In this work a 300 kVA grid connected photovoltaic system with 100% battery back up is designed for KNUST. System wiring, installation, maintenance and trouble shooting procedures for the system designed were outlined to show that it is theoretically possible to design a PV grid connected system for KNUST. To simplify the work, the design is undertaken for the 300kVA substation (Ridge substation) and the results are replicated for the remaining substations. The results of this work show that the KNUST Ridge substation requires a 360VDC battery bank with a capacity of 2785Ah (C_{10} rating). The system requires a 300kVA Trace sun-tied 3-phase Inverter and 1575 of the BP 7180 modules. The total yearly output of the system to the grid is calculated to be 0.296GWh. The 300kVA grid connected photovoltaic system is estimated to cost 2.88 Million dollars. The cost of installing a 300kVA fuel generator is 103,477 dollars**.** Assuming a loan interest rate of 8% and inflation rate of 12% over a 25 year product life, the calculation of the Average Incremental Economic Cost (AIEC) of the two systems shows that the grid connected PV system has a lower AIEC of 0.67 compared to 12.14 of the fuel generator/plant. This results show clearly that the grid-connected system is economically preferable to a fuel generator of the same capacity as an alternative source of electricity for KNUST.

Sensitivity analysis carried out futher shows that the grid connected PV system is more economical at high inflations rates and longer project life times. Also, the net savings in

CO_2 by choosing the grid connected PV system over the Fuel generator is 180g/KWh and that makes the grid connected PV system more environmentally suitable.

It is concluded in this work that in the long term the implementation of a grid connected PV system is both economically and environmentally preferable to a fuel generator/plant.

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DEDICATION

THIS WORK IS DEDICATED TO THE LATE PROF. KWESI ANDAM (PAST VICE CHANCELLOR, KNUST), WHO DIED BELIEVING THAT I COULD EVEN DO BETTER THAN THIS.

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MAJOR ABBREVIATIONS

AC- alternating current

BSc – Bachelor of Science degree

CO_2 - Carbondioxide

DC- direct current

ECG- Electricity Company of Ghana

GDP – Gross domestic product

GWh – Gigawatt-hour

IEA – International Energy Agency

IEA-PVPS – International Energy Agency's Photovoltaic power systems

KNUST- Kwame Nkrumah University of Science and Technology

kVA- kilovolt-amps

kWh- Kilowatt-hours

MPPT – Maximum Power Point Tracker

MPhil- Master of Philosophy

PV- Photovoltaic (solar cells)

SHEP- Self help electrification project

SLT – Special low tariff

VRA- Volta River Authority

Chapter One

INTRODUCTION

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INTRODUCTION

1.1 RESEARCH BACKGROUND

The rapid economic growth of any country requires the injection of large amounts of energy and since energy cannot be created, it is necessary for every country to diversify its sources of energy.

Energy is the ability to do work and therefore it is the basic requirement for achieving all tasks.

There are many forms of energy which include; mechanical (potential and kinetic) energy, chemical energy, electrical energy, etc.

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 (Electrical energy from water sources) nuclear, wind, solar (Energy from the sun) 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 (taken to be 70 years).

The relative contribution of the different energy sources to the world's electricity generation has been changing in recent times as depicted in Tables 1.1 and 1.2.

Table 1.1 Energy and electricity share by energy source (Anim-Sampong et al., 2007)

Energy Source	% Energy Contribution	% Electricity Contribution
Fossil	87	63
Nuclear	6	17
Hydro	6	19
Other renewables	1	1

Table 1.2 Electricity supply in Developing and Industrialized Countries (Anim-Sampong et al., 2007)

Energy Source	% Energy Supply by Energy Source	
	Developing Countries	Industrialized Countries
Fossil	68	63
Nuclear	28	17
Hydro	4.0	19
Other renewables	0.4	1

The factors of population growth, urbanization and the introduction of new electrical appliances (computers etc) have increased the demand for electrical energy over the years. The world's population is estimated to grow from about 5.5 billion in 1993 to about 7 billion in the year 2010 [(4)].

The generation of electricity has been one issue that has occupied the minds of many researchers, policy makers, planners and governments. 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.

In parts of Africa including Ghana, political parties have won power in some communities due to their ability to supply electrical energy to those communities.

Photovoltaic (PV) solar energy is the conversion of energy that comes from the sun 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 a solar panel. The more sunlight a solar panel receives, the more electricity comes out of it.

Solar PV electricity is unique amongst the 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 expected to be depleted this century, PV power systems provide a means of providing electricity to the developing world without concern for fuel supply security. [12]

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

International Energy Agency’s Photovoltaic Power Systems (IEA-PVPS) Task 10 reports that a number of projects around the world show an emerging market for grid-connected photovoltaic power systems, despite the fact that solar photovoltaic electricity is still more expensive than grid power. Grid Connected photovoltaic power systems account for more than 50% of total installed capacity. The report also shows that solar photovoltaic electricity can contribute significantly to reductions in greenhouse gas emissions for the electricity sector.[12]

A grid connected solar system is a system where the photovoltaic module is connected through an inverter to the grid supply.

There are mainly two types of grid connected systems depending on whether the system has a backup or not. A solar panel only generates electricity during sunlight times and therefore a grid connected system without a battery backup only supplies power during sunshine times and cannot supply any power during the night.

Ghana's existing power plants are the Akosombo and Kpong Hydro power stations, the Takoradi Thermal Power station, the Tema diesel power station and the Ghana (Osagyefo) power barge at Effasu in the western region.

The Kwame Nkrumah University of Science and Technology(KNUST) is Ghana's second largest University and has existed for over half a century. It is named after Ghana's first president and is the only science and technology based university in Ghana. KNUST is situated in Kumasi in the Ashanti Region of Ghana.

The KNUST electrical energy distribution network receives its power supply from three incomers namely the Atonsu feeder, Bomso feeder and Boadi feeder and the typical current ranges from 70-155A at low and heavy loads in the various phases of the incomer.

The official journal of the Ghana Energy Commission reports that the total amount of energy sold by the Electricity Company of Ghana in the Ashanti Region

(Where the Kwame Nkrumah University of Science and Technology is situated) was 648.2 GWh in 2006.[7]

The total consumption of electricity for KNUST in 2006 was 10.7GWh which is about 1.65% of the total supply.

The total national consumption for the same year was 3978.4 GWh and comparing KNUST consumption means that KNUST accounts for 0.27% of Ghana's total energy consumption.

However, the major concern about electrical energy on KNUST campus has been the reliability of the supply. In 2007, during the national electric power crises all the halls of residence acquired fuel generators for their respective halls.

This researcher questions the economic and environmental suitability of that option taking into consideration the possibility of installing a grid connected photovoltaic system with battery backup instead of the fuel generator purchased.

1.2 AIMS AND OBJECTIVES

It is in light of this suggested option that this comparative study is being undertaken to investigate the economic and environmental suitability of the implementation of Grid Connected Photovoltaic Systems in comparison with the use of fuel generators/plant as an alternative source of energy to solve the regular grid failure problem in residential and commercial institutions in Ghana.

The specific objectives of the research are as follows;

1. Design a grid connected Photovoltaic system (PV) with battery backup for KNUST from first principles.

2. Outline system wiring, installation, maintenance and trouble shooting procedures for the system designed in objective one (1) above.
3. Undertake an environmental (green house emission) assessment between the grid connected PV system and a fuel generator of same capacity.
4. Undertake an economic comparative analysis between the grid-connected PV system designed and a fuel generator/plant of the same size designed to solve the grid unreliability problem.

1.3 Scope and limitations of the Research

Any research has a scope and limitation and it is never a complete compilation of all related topics in the field.

The scope of this MPhil research is to design a grid connected PV system for KNUST from first principles, determine electrical wiring, installation, and maintenance and faultfinding procedures and undertake an analysis of the economic viability and environmental suitability of the designed grid connected PV system in comparison to a fuel generator/plant of the same capacity. This MPhil thesis does not include the study of the impact of the designed grid connected PV system on the existing national grid. This section will be covered in the PhD research in future. Funds are being sought for the building of a laboratory model grid connected PV system for the PhD research. In this research the added advantage of the grid connected system supplying power to the national grid during periods of reliable power is not evaluated since it is not the main aim of this research.

1.4 OUTLINE OF THESIS

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

a) The research background, main aim, objectives, scope and limitations are outlined in Chapter 1

b) Chapter 2 reviews the literature on Energy in Ghana and also reviews the literature on solar energy and particularly grid connected PV systems with battery backup and its components.

c) The KNUST energy system and all relevant electrical design data is discussed in Chapter 3

d) In Chapter 4 the grid connected PV system is designed.

e) The wiring procedures and principles are covered in Chapter 5

f) The installation procedures and principles are covered in Chapter 6

g) In Chapter 7, the maintenance and fault finding tree for the grid connected PV system is discussed.

h) In Chapter 8, an economic and environmental comparative analysis of the designed Grid connected PV system and a fuel generator/plant of the same capacity is undertaken.

i) Chapter 9 summarizes the main findings of this research and presents recommendations for future work.

Chapter Two

LITERATURE REVIEW

CHAPTER TWO

LITERATURE REVIEW

2.0 LITERATURE REVIEW

It is important to state that the amount of literature on Ghana's energy, the solar energy system and PV grid connected systems is enormous. So much study is needed to design a grid connected PV system with battery backup accurately from first principles. The author of this thesis has attended courses on the subject, read over a hundred books, journals and papers. This chapter will cover just a little portion of that enormous amount of literature.

2.1 ENERGY NEEDS AND STATISTICS OF GHANA

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 – 6 percent, yet over the same period, the demand for electricity had grown at the rate of 10-14 percent per annum. Ghana's energy challenge is shown in her expanding economy and the growing 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 [(8)].

Ghana's present power plants are the Kpong and Akosombo hydro power stations, the Takoradi Thermal plant, the Tema diesel power station and the Ghana (Osagyefo) Power Barge at Effasu in the Western Region of Ghana.

The Hydro plants are operated by the Volta River Authority. The Akosombo and Kpong Hydro plants are reported to have produced on average electricity of 5,815 Gigawatt hours annually from 1990-2004. Maximum generation of 6,851 Gigawatt-hours occurred in 1997. Hydro plants are fully affected by climate change and this led to low output from the hydro plant in 2006/2007 and this led to the Electricity Company of Ghana undertaking a load management program which lasted for almost a year.

The Takoradi Thermal Power Plant is located at Aboadze in the Western Region of Ghana. It is made up of two generating plants; 220 Megawatt single cycle plant and a 330 Megawatt combined cycle plant. The combined cycle plant is registered under the name Takoradi Power Company (TAPCO). The other plant is also known as the Takoradi International Company (TICO). TICO is a partnership between VRA (10%) and the CMS of Michigan, USA (90%).

The Volta River Authority has a 30 Megawatt installed capacity diesel station at Tema. The Tema diesel plant was installed between 1961 and 1963 and has been used as a standby plant until 2005 where a fire outbreak completely burnt the pump.

The Ghana (Osagyefo) Power Barge is a 125 Megawatt single cycle plant. As of the time of writing this report the gas wells intended to fuel the barge were being drilled. It has never been connected to the grid [(9)].

The table below shows the total electricity generated between January and April 2007 in GWh.

Table 2.1 TOTAL ELECTRICITY GENERATED in GWh (Energy Commission Energy Review pg 41)

STATION	JAN-07	FEB-07	MAR-07	APR-07	TOTAL
Akosombo	401.1	372.7	299.6	750.2	1,823.6
Kpong	76.2	74.5	62.8	145.6	359.0

TAPCO	96.0	123.5	186.8	168.5	574.8
TICO	137.5	73	135.5	117.0	463.0
TOTAL	710.8	643.8	684.6	1,181.2	3,220.4

The hydro generation experienced drastic increase from March to April whist thermal generation was reduced. From January to April there was a constant increase in the total electricity generation in the country.

2.2 ASSESSMENT OF GHANA'S AVAILABLE ENERGY RESOURCE AND SOURCES

2.2.1 Petroleum

The existence of large and commercial fossil fuel producing fields in Mauritania, Gabon, Equatorial Guinea and neighboring Ivory Coast and Nigeria has always sustained Ghana's dream of finding commercial quantities of oil and gas. In the late part of 2007 reports were made that Ghana had finally hit commercial quantities of oil in parts of the Western Region. It is expected that it will take about three to five years for commercialization of the found oil deposits to begin.

2.2.2 Hydro source

Hydro has been Ghana's most utilized renewable energy resource. Electricity generation efficiency of hydro power plants are usually very high. However, hydro plants depend solely on the weather which is unpredictable. A feasibility study undertaken by the Energy Foundation in 2002/2003 reports that large hydropower of the size of Akosombo is no more available in the country. The remaining gross potential hydro resource including medium (more than 10MW but less than 400MW in installed capacity), small (between 1MW to 10MW) to mini (less than 1MW) hydro does not exceed 1,400

Megawatt or 2,000 Gigawatt hours a year when tapped using the available hydro generation. The most notable hydro site yet to be developed is the Bui Dam on the Black Volta and work has already begun on its construction. The work is expected to last about 7 years [8].

2.2.3 Wind

Wind resource has been used in many countries to produce large amounts of electricity. Theoretically the maximum energy that can be tapped from the available wind for electricity using today's technology is about 500-600 Gigawatt hours every year[8] A Solar and Wind Energy Resource Assessment (SWERA) project being run jointly by UNEP, Global Environment Facility and the US National Renewable Energy Laboratory (NREL) in 2004 has identified some spots within Ghana particularly the coastline.

Fig 2.1 Graphical presentation of Ghana's Wind power potential (Otu-Danquah Kwabena, Energy Symposium

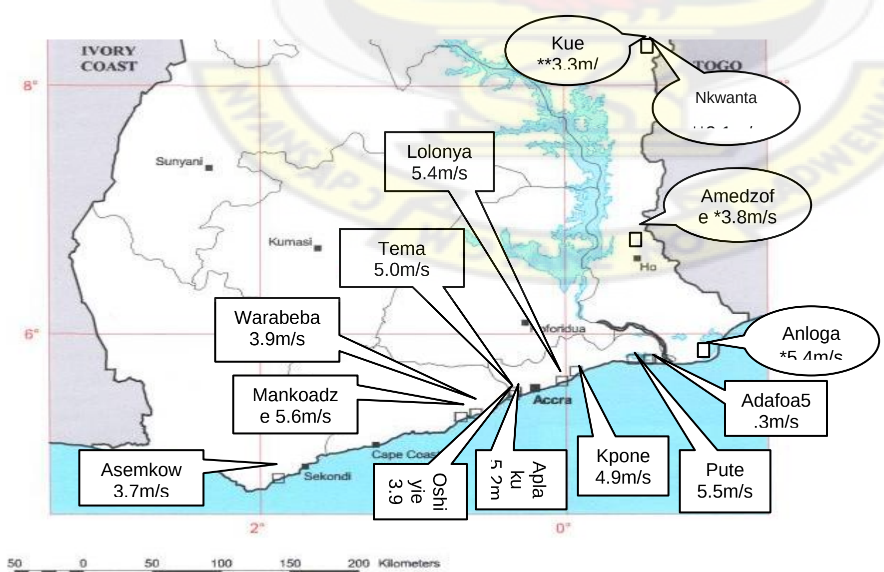


Fig 2.2 Wind power potential along Ghana's coastline [16]

The major limitation of wind power use in Ghana is that the closest electricity substations at Sogakope and Tema are very far from the favourable wind sites [16].

2.2.4 Solar Resource

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 400,000 GWh.

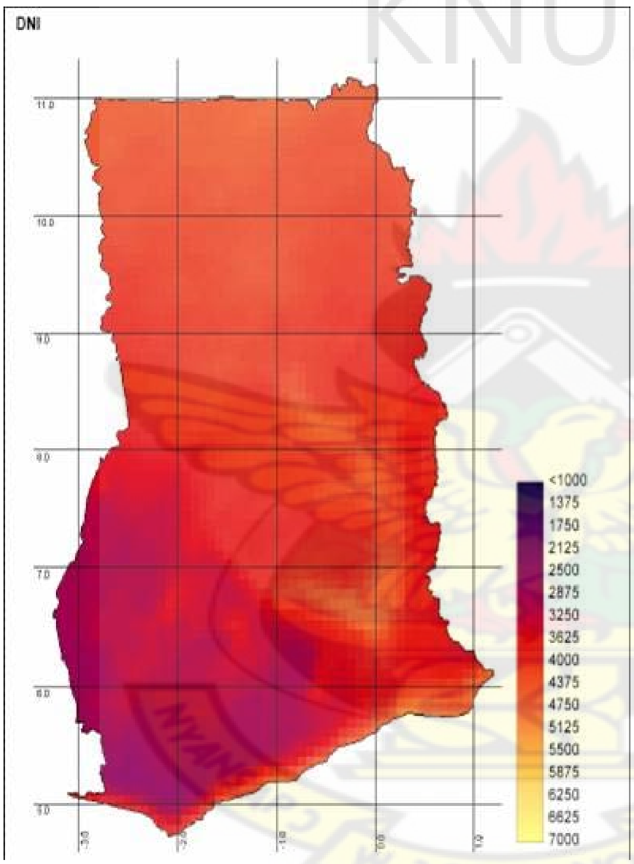


Fig 2.3 Solar radiation map for Ghana

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.

Ghana's average peak sun hours varies from 5.0 to 5.7 peak sun hours with Kumasi having average peak sun hours of 4.5. [2]

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 on some sectors like the grid connected sector of the solar industry.

2.2.5 Nuclear resource

Uranium is the major fuel source for nuclear power which is generated through the fission heat produced in nuclear power reactors. Based on the once-through cycle method, known uranium reserves are expected to last for over 60 years. Addae A.K et al in his report in the Energy Research Group Bulleting 6 (1994) said that work conducted in the early 70's indicated that there are uranium deposits in Ghana but the follow up work to establish the commercial viability of these deposits is yet to be conducted.

However, the International Atomic Energy Agency's Integrated Nuclear Fuel Cycle Information Systems (INFCIS) list of sources of uranium deposits does not include Ghana. [(1)]

2.3 Electricity consumption pattern of Ghana

Ghana's electricity consumption is mainly divided into three main sectors namely

- Households/Residential sector
- Commercial sector
- Industrial and Agricultural sector

Table 2.2 Electricity consumption in GWh from 2000 to 2005 (Energy Review Vol.1)

Sector	2000	2001	2002	2003	2004	2005
Residential	1,585.0	1,688.0	1,795	1854	1971	1957
commercial	445.4	503.3	477.3	492.9	530.2	746.9
Industry	4026.4	4336.5	3889.8	2206.1	2085.3	2542.6
Total	6056.8	6527.8	6162.1	4553.0	4586.5	5246.5
System losses	1177	1199	1244	1294	1434	1418

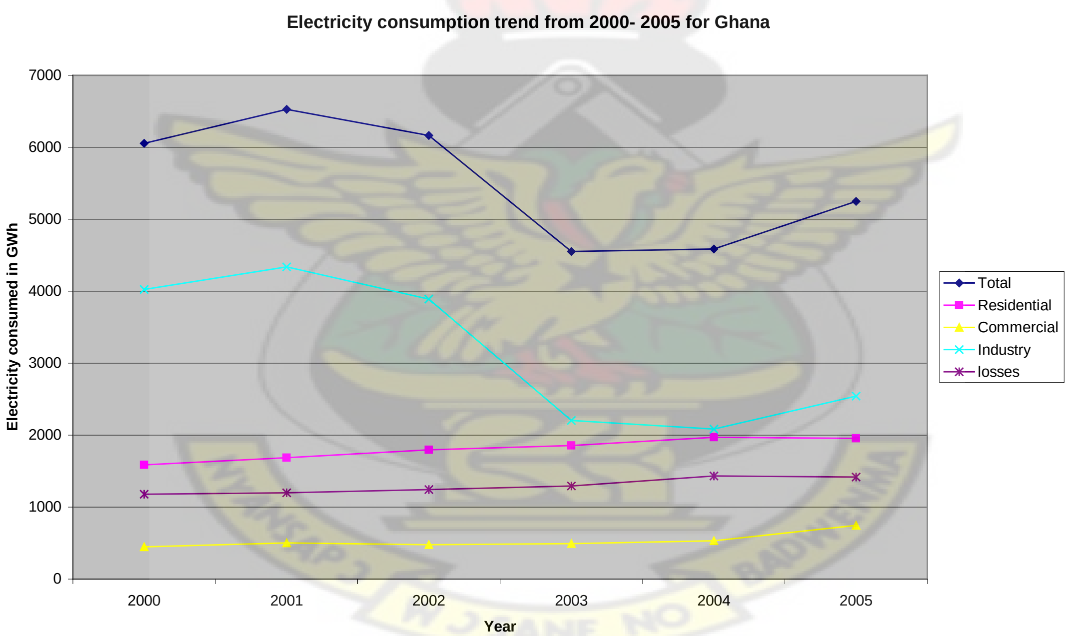


Fig 2.4 Electricity consumption trend from 2000-2005 for Ghana

The graph above shows a constant increase in residential, commercial electricity consumption but shows a significant drop in industrial consumption between 2001 and 2004.

Consumers of electricity in Ghana must conserve energy through the observance of basic energy conservation practices and the use of efficient electrical appliances. Victor Owusu of the Public Affairs Division of the Energy commission reports that it has been established that up to 30% of electricity generated in the country is lost through both negligence and the use of inefficient appliances by consumers. The amount of waste in the system is equal to the entire output of the Kpong Dam. This means that all the power that is produced from Kpong is wasted. [17]

Under the Government's Self Help Electrification Project (SHEP) 1850 communities were hooked onto the national grid in 1998 alone. The whole of Ghana is expected to be electrified by 2015 and if this dream is to become a reality, a huge amount of inflow of electricity from all the country's energy resources is needed [17].

The Energy commission and the Energy Foundation are undertaking a demand side management programme aimed at reducing total electricity demand. The programme involves replacement of incandescent lamps with high energy efficient compact fluorescent lamps throughout the country [2].

2.4 Solar Energy System

In simple terms, solar energy is energy from the sun. It 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.

In 1921, Albert Einstein won the Noble Peace Prize for Physics for his paper on the photoelectric effect (The paper was published in 1904). 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 [11]. The most common form of photovoltaic device has been the crystalline and amorphous silicon. Other technologies like Copper-indium diselenide (CIS), Cadium-telluride (CdTe) and organic solar cells (using titanium oxides and organic dyes) are still under research.

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 gensets etc.).

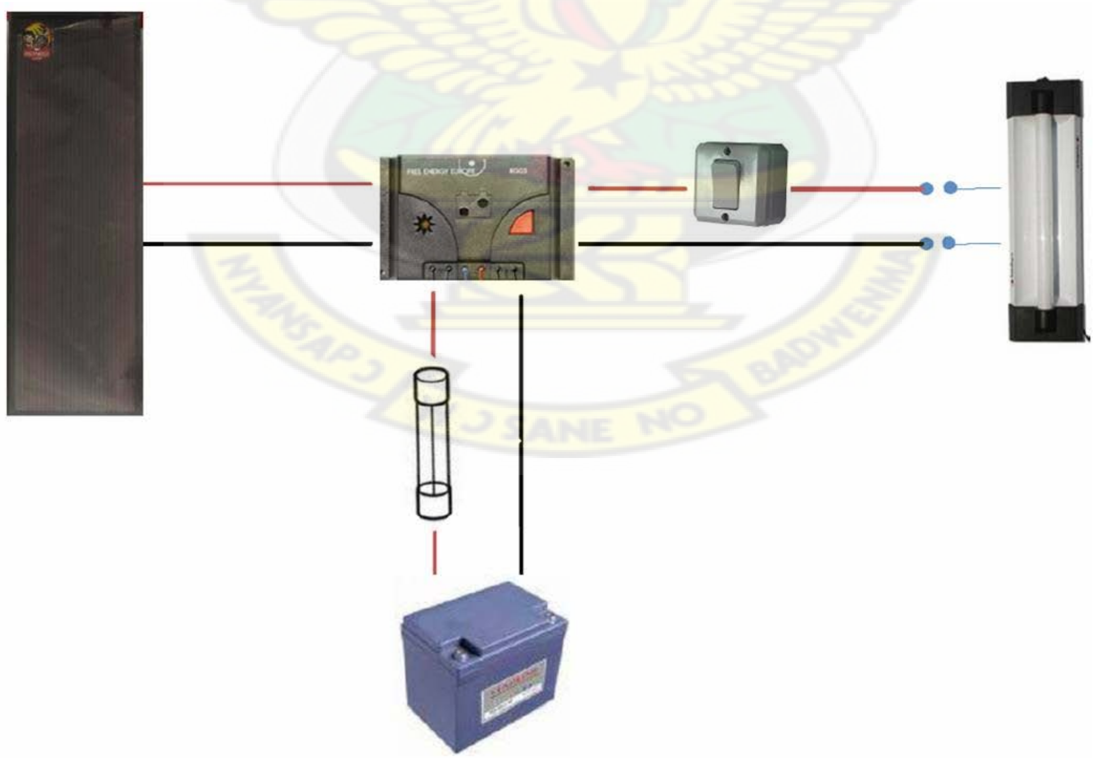


Fig 2.5 A pictorial representation of a simple solar home system

Solar energy has been utilized in so many different ways in Ghana over the past twenty years. Solar energy systems mostly installed by Non-governmental Organizations and public institutions number over 5000 across the country. The installed capacity of almost one megawatt generates between 1-2 Gigawatt-hour per annum [9]. The breakdown of the applications is as follows;

Table 2.3 Breakdown of application of solar PV in Ghana [9]

SOLAR PV SYSTEM	Installed capacity (kWp)	Generation in GWh
Rural Solar home system	450	0.70-0.90
Urban solar home system	20	0.05- 0.06
Systems for schools	15	0.01-0.02
Systems for lighting health centers	6	0.01-0.10
Vaccine Refrigeration	42	0.08-0.09
Solar Water pumps	120	0.24- 0.25
Telecommunication	100	0.10- 0.20
Battery charging stations	10	0.01- 0.02
Grid connected systems	50	0.10-0.12
Solar streetlights	30	0.04 – 0.06
Total	**843**	**1.34 -1.82**

2.5 Key barriers to the implementation of Photovoltaic power systems in Ghana.

Many have questioned why with so much abundant solar resource, Ghana has a low level of implementation of PV power systems.

The following are the key barriers;

- High initial installation cost
- Lack of Information, Market knowledge and Technical training
- Governments perceived lack of support to the solar industry.

2.5.1 High initial installation cost

Solar system when compared to grid supply and even fuel generators on purely initial cost is seen to have a higher cost. IEA PVPS task 1 report of 2000 states that in IEA countries PV electricity can now be generated at less than 0.6 USD per kWh, which is cost competitive in many off-grid applications [12]. However, PV is locked in a critical "Chicken and egg" situation between price and economy of volume. A bigger market is needed to generate economy of scale. In Ghana a 14W solar system cost about 400 Ghana Cedis (source- Deng Limited, Accra)

2.5.2 Lack of Information, Market knowledge and Technical training

In Ghana there are a lot of misconceptions about solar energy. Many see it as an inferior form of energy. There is also only a few dealers who are mainly in the Greater Accra Region of Ghana and therefore there is a general lack of awareness and information on what is available or where to source it. Until recently when the Deng Solar Training Centre was established there was no school for the training of solar energy designers and installers. There is also a lack of certification, standards and guarantees on solar installations. Many solar installations have failed due to bad installation practices and this added to the notion that PV systems are inferior.

2.5.3 Governments perceived lack of support to the solar industry.

Many practitioners in the solar field believe that as an incentive, solar systems and all its components should be tax free. While a solar system imported as a complete solar system (i.e. sourced from one manufacturer) is exempt of both duties and VAT, it is approx. 30% more expensive [(4)]. Most of the same components which are exempt of duties and VAT when imported as a complete solar system are now subject to either duties, VAT, or both. Thus the components are imported separately (i.e. the solar panels from a solar panel manufacturer, the batteries from battery manufacturer etc.) the 30% savings achieved in sourcing savings are lost on duties and VAT.

2.6 World trends in solar PV systems

Suddenly, when you walk through the streets of Ghana, one out of two people have heard of solar energy although with some misunderstanding about the cost and technology. Paula Mints, in the international renewable energy magazine (refocus) says that from 2000 through 2005 global industry sales grew at a compound annual rate of 41%, an amazing growth for any industry. Even taking current supply constraints into account, industry growth has remained strong, at 55% in 2004 over 2003, 34% in 2005 and 28% in 2006 [(12)].

The photovoltaic industry is both attractive and interesting, combining social, science and business benefits at once. On one hand, PV technology presents the best way for most of the world's very poor to enjoy the benefits of electricity. On the other hand, it is a new science technology that creates research jobs and is increasingly challenging. On another hand, solar energy is a product which can be sold for profit.

Essentially, the PV industry can be divided into three main applications. The three main applications are the off-grid application, grid connected application and consumer indoor applications.

The consumer indoor application was mainly found in watches and calculators and now represents a relatively insignificant percentage of total photovoltaic sales.

The off-grid application was once the largest global market for PV products. This situation has changed due to strong demand for grid-connected systems due to incentive programs, particularly in Germany.

The grid connected application is presently the most booming application. Ghana, although being one of the first countries in Africa to practice the application (50KWp system at the Ministry of Energy premises) does not have a booming industry in grid connected systems and even lacks basic standards for interconnection into the grid. This researcher hopes that this thesis will renew the interest in the implementation of grid connected PV systems in Ghana.

Table 2.4 Off-Grid Vs Grid-connected global application Shares (refocus 2006 pg 34)

Year	% Market for off grid	% Market for grid connected
1986	92	8
1987	96	4
1988	95	5
1989	97	3
1990	92	8
1991	92	8
1992	93	7
1993	93	7
1994	81	19
1995	87	13
1996	86	14
1997	66	34

1998	69	31
1999	61	39
2000	49	51
2001	42	58
2002	42	58
2003	28	72
2004	20	80
2005	18	82
2006	17	83

The above table shows a dramatic rise in the implementation of grid connected photovoltaic systems since 2000.

2.7 Grid connected Photovoltaic system

A grid connected photovoltaic system is solar system where the output of the PV array is connected to feed into the grid supply. Although there is no documented study of the cost of one kWh of power from grid connected PV 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 one KW of solar photovoltaic power is 0.35 $/ kWh while grid power is 0.08 $/ kWh). This study will determine the real cost of one kWh of power from a grid connected PV system in Ghana.

There are two main types of grid connected photovoltaic systems namely;

1. Grid connected photovoltaic system without battery backup.
2. Grid connected photovoltaic system with battery backup

The latter is more complicated but it is the only system which also confronts the issue of reliability of the grid supply. Its design is similar to the design of a combination between an uninterruptible power supply (UPS) and a Stand Alone Power System. In a grid connected photovoltaic system with battery backup, the system works as a stand alone power system during grid failure to eliminate the use of a fuel generator/plant. Despite the fact that a number of projects around the world show an emerging market for grid connected photovoltaic systems, grid- connected photovoltaic systems account for only 5.9% of total solar energy systems installed capacity in Ghana. [9]

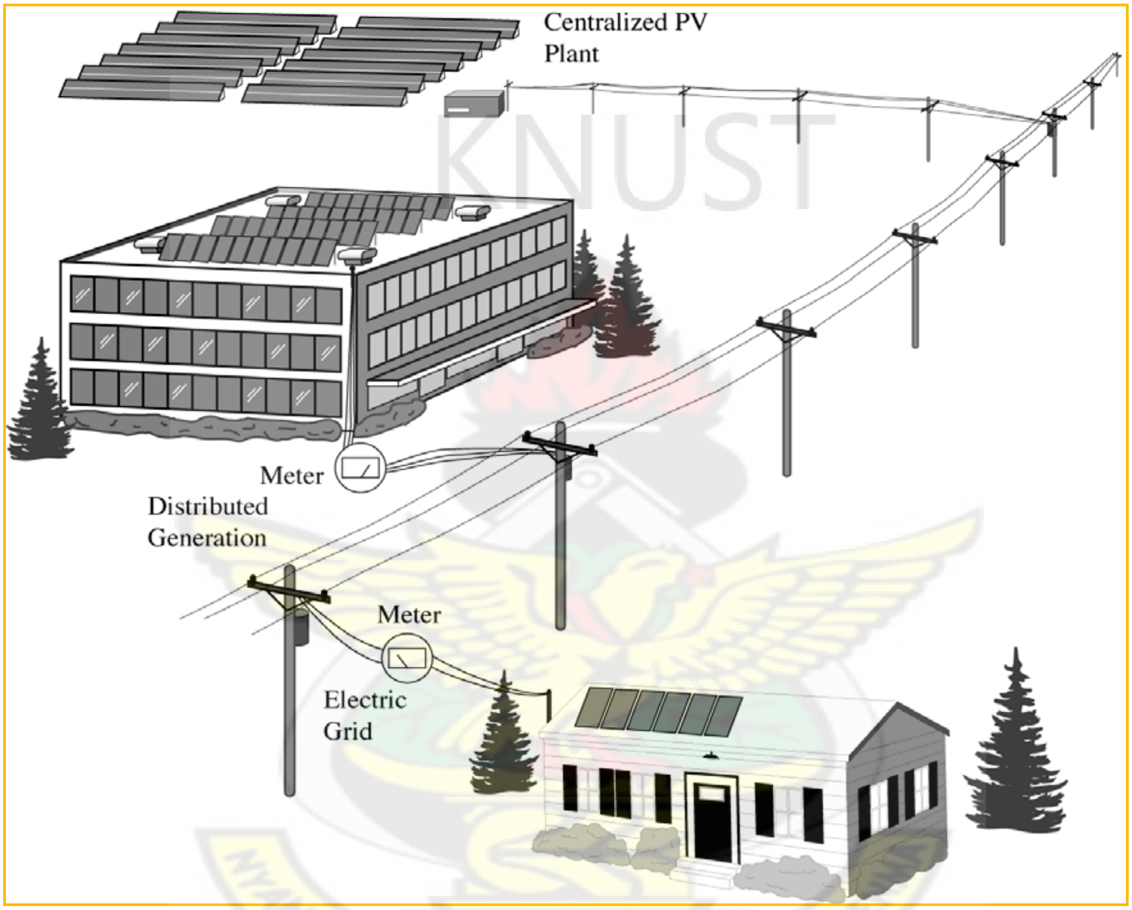


Fig 2.6 Schematic diagram of different grid- connected photovoltaic systems.

Source: Ross and Royer, Photovoltaics in cold climates [18]

2.8 Components of grid- connected photovoltaic system with battery backup

The components of a grid connected photovoltaic system with battery back up are mainly the PV array, Batteries, Inverter, Controller (if not included in inverter already), meter (if required). The connection of grid connected photovoltaic system is similar to that of a generator to the grid supply.

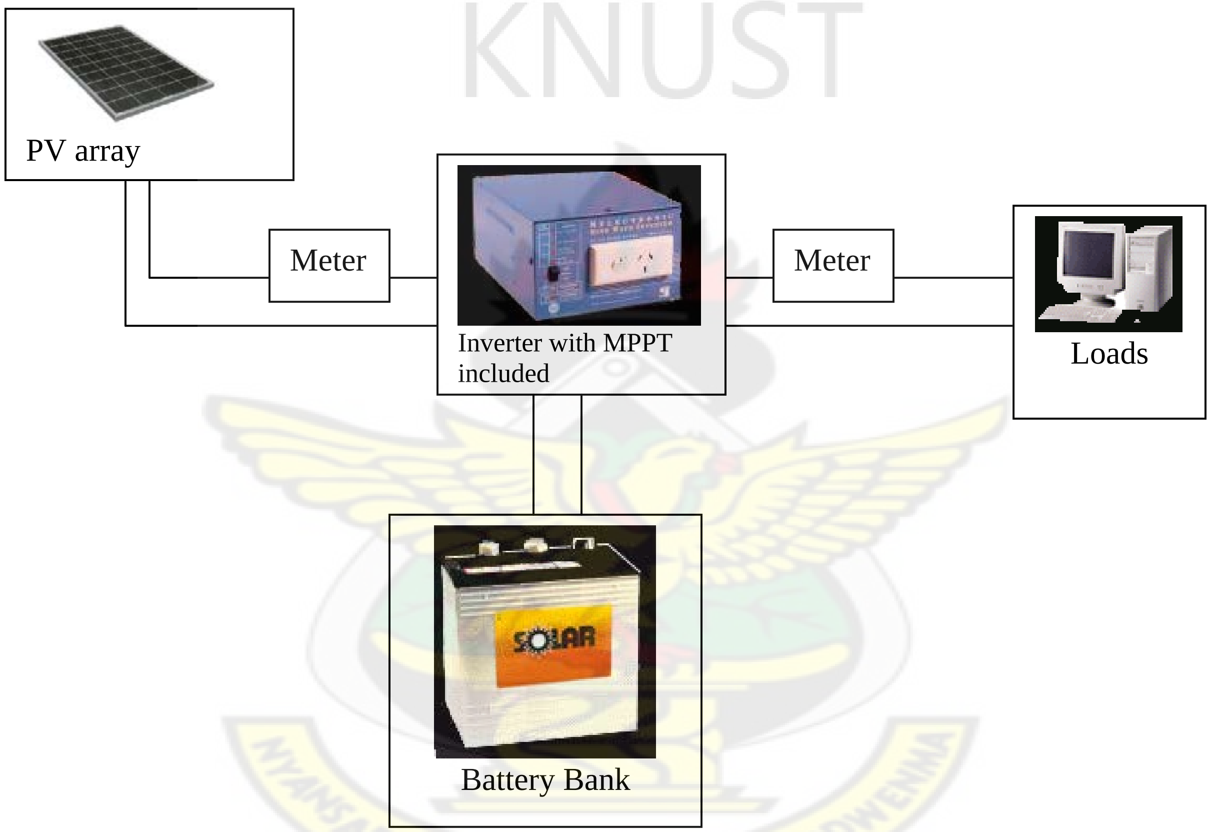


Fig 2.7 Schematic diagram of grid connected photovoltaic system with battery back

2.8.1 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 semi conductor 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 losses 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 by it is as shown in the figure below;

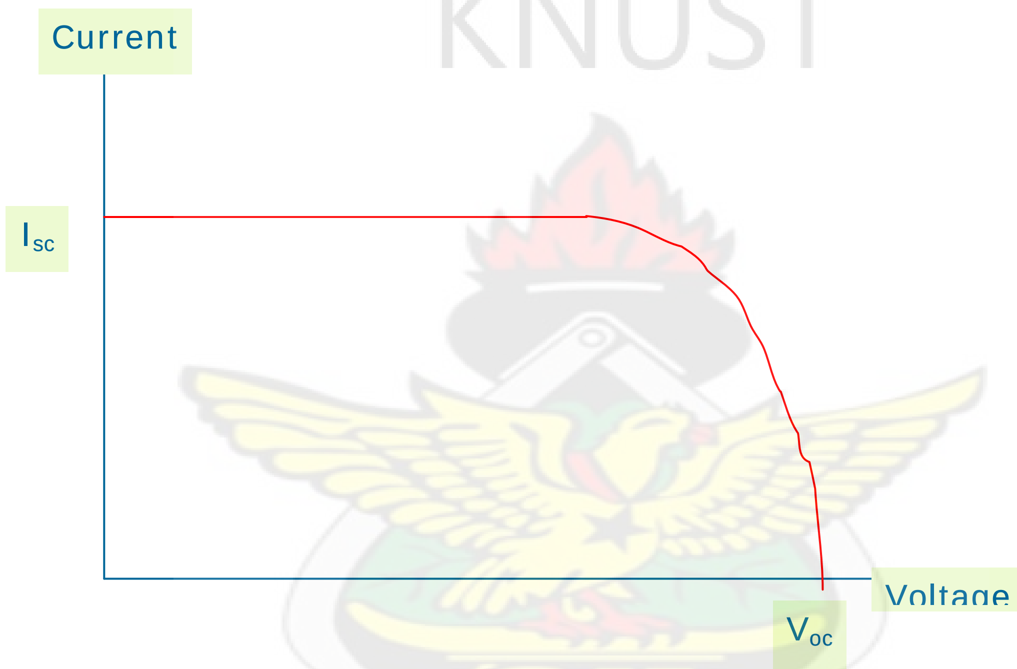


Fig 2.8 Typical I-V curve of a solar cell.

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.

If power is plotted on the I-V axes the power curve for a solar cell is derived as follows;

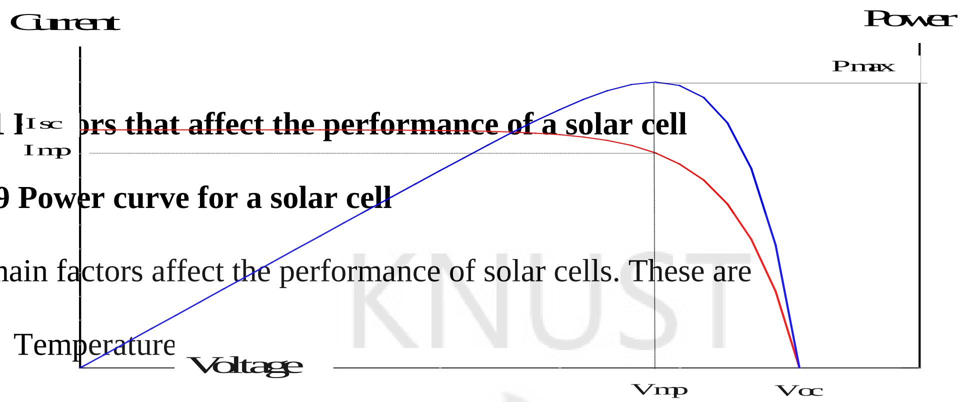


Fig 2.9 Power curve for a solar cell

2.8.1.1 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 a rule the temperature of a solar cell increases, the open circuit voltage deceases but the short circuit current increases marginally. The combined effect is a decrease in power. From previous study the rule is that the output power changes 2.5% for every five degree variation in temperature [(11)].

2

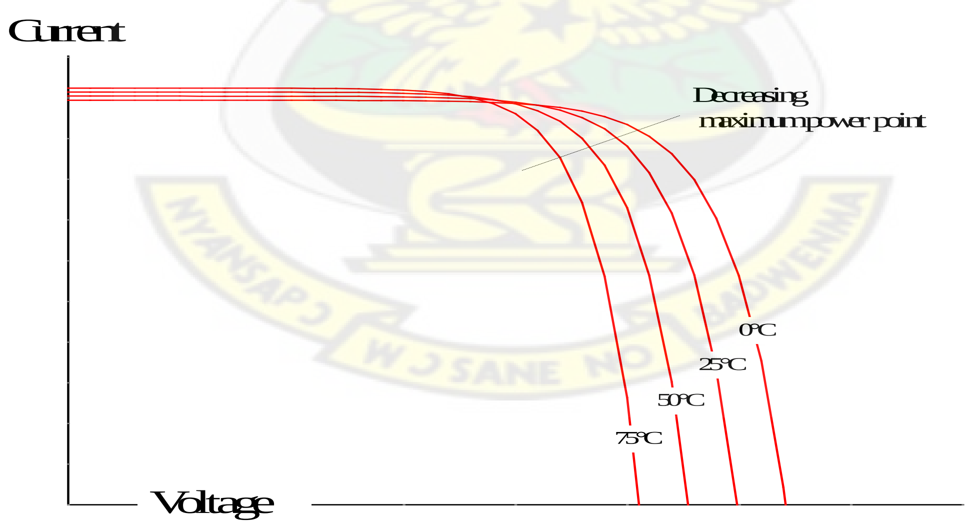


Fig 2.10 Variation of current and voltage with changes in temperature

As the solar irradiance varies there is a linear variation of the short circuit current, whilst the output circuit voltage does not change dramatically.

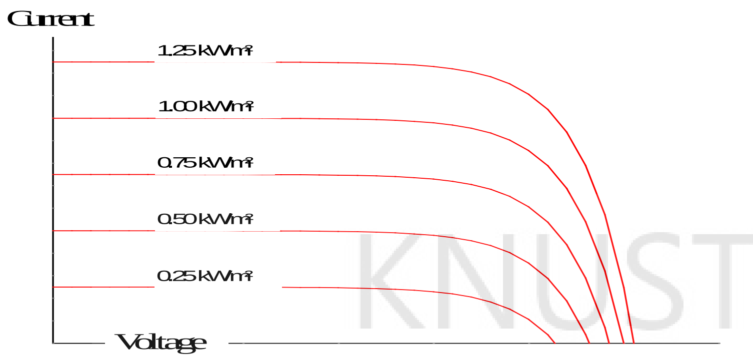


Fig 2.11 Variation of current and voltage with changes in irradiance

2.8.1.1 Types of solar cells

There are three main types of solar cells used in solar system today. They are monocrystalline, polycrystalline and amorphous cells.

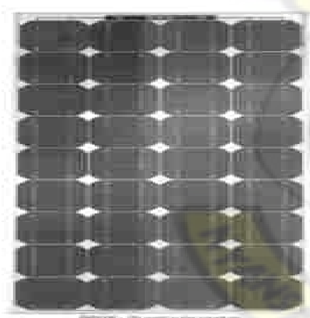


Fig 2.12 Mono-crystalline panel

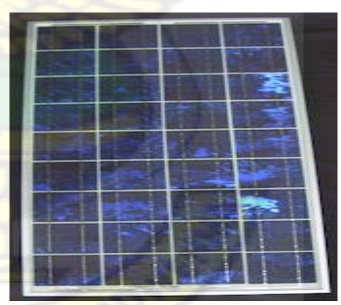


Fig 2.13 Poly crystalline panel

Fig 2.14 Amorphous panel

Mono crystalline solar cells have efficiencies of between 12 to 15% while polycrystalline solar cells have efficiencies of at most 12% and amorphous solar cells 5%. 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).

2.8.2 Solar Batteries

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

2.8.2.1 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

2.8.2.1.1 Flooded batteries

Flooded lead acid batteries are used in majority of stand alone 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.

2.8.2.1.2 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 satrify and no equalization charging is required. The main disadvantage of this battery is the cost per amp-hour.

2.8.2.1.3 Battery cycles

In battery terms, a cycle on a battery bank occurs when the battery is discharged and then charged back to the same level. A lead acid battery is designed to absorb and give direct current by a reversible electromechanical reaction.

In a fully charged lead acid cell, lead (Pb) comprises the negative plate and lead dioxide (PbO_2) is the positive plate. A solution of sulphuric acid (H_2SO_4) forms the electrolyte.

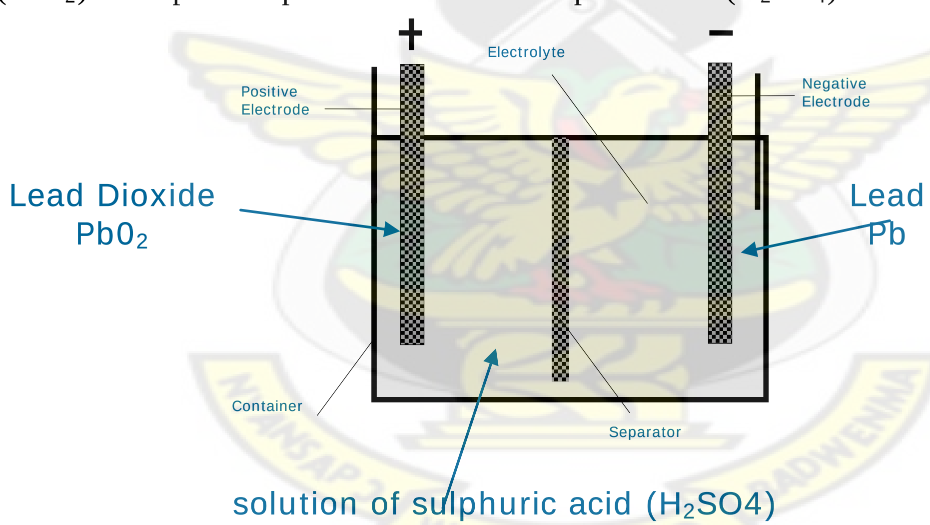


Fig 2.15 The components of a lead acid cell

The reaction that governs the discharge and charge process is as follows;

$$Pb + PbO_2 + 2H_2SO_4 \rightleftarrows 2PbSO_4 + 2H_2O$$

During discharge, the sulphuric acid reacts with both Pb and PbO_2 and 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.

During the charging process, the reaction is reversed as a result of the application of an electric potential higher than the voltage of the cell by an external charging source (in solar system it is the solar module). At the end of this process the cell achieves its initial state of charge with the two plates converted back to Pb and PbO_2. During the charging process, water is broken down into inflammable hydrogen gas and oxygen gas and therefore adequate ventilation is required.[(11)]

A battery is a combination of 2 volts in series eg. a 24 volt battery is made up of 12 cells connected in series.

2.8.2.2 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

positive plates are pushed up. Under this condition, the seal is broken and the acid can move up and cause corrosion).

2.8.3 Inverter

The inverter is the main determinant of the grid connected photovoltaic system. The output of the PV array is direct current and it is not suitable to be fed directly into the national grid which is three phase alternating. In addition, the loads to be powered during grid failure 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 grid and the loads.

The inverter converts DC voltage to AC voltage. There are two main classes of inverters used in grid- connected photovoltaic systems with battery back-up. There is one class (Sunprofi class) which only uses the PV array to charge the batteries. The inverter does not act as a battery charger. In the other class of inverters (AES, PSA and Trace class) the inverter chargers the battery.

In this design the second class of inverters is the most useful. 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.

2.8.3.1 Operation of Inverter

At the start of each day, the solar array charges the battery bank through the charge controller (sometime fitted in the inverter). When the battery voltage rises above float voltage, the inverter will convert the excess solar power into AC power to be supplied to the load circuit. The inverter will also ensure that the batteries are held at this voltage, and this will be directly from the solar power during the day.

On the AC side, the inverter is both connected to the grid and the loads. If the excess solar power supplied to the load circuit is not enough for its performance, the grid will supplement it. If, on the other hand, the solar power output is more than that required by the loads, the remaining AC power is fed into the grid.

When the grid power fails, the standard protection devices within the inverter will disconnect the inverter from the grid. The system then becomes like a stand alone power system and the batteries supply power to the load circuits.

When the grid power returns, the inverter will act as a battery charger and it, along with the PV array (if it is during sunshine time) will charge the batteries up to the equalization voltage. After the equalization charge has occurred, the batteries will then be held at float voltage. The system will then return to the standard operation, that is, if the battery voltage is raised above the float voltage due to the PV array, then the excess power will be exported to the AC grid connection side of the inverter.

The following settings for the charging of the battery are set within the inverter;

1. Equalization voltage
2. Float voltage
3. Period between equalization
4. How long the equalization voltage is maintained.

Chapter Three

The KNUST electrical distribution system and all relevant electrical design data

CHAPTER THREE

THE KNUST ELECTRICAL DISTRIBUTION SYSTEM AND ALL RELEVANT ELECTRICAL SYSTEM DESIGN DATA

3.0 THE MAIN KNUST DISTRIBUTION SYSTEM

The KNUST distribution network can receive its power supply from (3) different 11kV feeders tied on the 11kV, 3MVA Tamco switchgear at the intake point situated behind the Continental Unity Hall of Residence. This place is popularly referred to as the power house. The supply is mainly taken from the VRA transmission line T_5 through the Station D incomer (specifically D-31) from Atonsu. The choice of the D-31 incomer over the C incomer from Bomso is because the D-31 incomer provides better voltages. A dedicated feeder F-21 from the Electricity Company of Ghana Primary Substation at Boadi has been connected to the KNUST distribution system but is yet to be commissioned for dedicated use.

The typical current ranges from 70-155A at low and heavy loads in the various phases of the incomer.

The major components of these substations are the transformers, ring main unit (RMU), fuses, distribution pillar and low voltage Feeders.

The KNUST 11kV distribution network is a ring circuit made up of fifteen (15) different 11/0.433kV 3-phase distributions transformer substations including the newly installed Architecture and Science Substations. The loads are quite evenly distributed between the substations.

Table 3.1 KNUST's substations and loads connected to it

Name and size of substation	Loads connected to the substation
Exams Hall Substation (500kVA)	KNUST Hospital, Photocopy Building, Administration Block II, Commercial Area, Maintenance Area
Unity Hall Substation (500kVA)	Africa Hall, Unity Hall, SRC Hostel, Non-Residential Facility I, Printing Press, Law school building, Hall 7
Ridge Substation (300kVA)	Link Road, Ridge, New Ridge Road, Beposo Road, Beposo Flats, low cost and Allotei Konuah Flat
Buroburo Substation (300kVA)	Akrosu Road, Okodee Road, Buroburo Road, Part of Printing Press, Senior Staff Club, Guest Flat Areas
Library Substation (800kVA)	Library Block, Great Hall, Administration Block I, Finance Block
Sewage Substation (500kVA)	KCCR, VC's lodge, SMS Guest House, Engineering Guest House, IRNR Guest House, GUSS 2 & 3
Independence Hall Substation (500kVA)	Independence Hall, Queens Hall, Republic Hall
IRNR Substation (500kVA)	Animal Science, IRNR Block, New Auditorium

Agric Substation (500kVA)	Agricultural Engineering, Agric science block, Pharmacy block, Social Science block at CCB , Housing and Planning
Hall 6 Substation (500kVA)	E- Line House, F- Line Houses, Hall 6 Houses
Pump House Substation (500kVA)	KNUST Primary School, Community Center Primary School Road, KNUST JSS, A Line Houses, B Line Houses, C Line Houses, D Line Houses, G Line Houses
University Hall Substation (500kVA)	Part of Asuogya Road, University Hall, Spring Hostel, Shaba Hostel, GUSS 1, Steven Paris Hostel
Engineering Substation (500kVA)	Chemistry Block, Physics Block, SMS Block, Biological Science, College of Engineering, Non-Residential Facility.
Architecture Substation (315kVA)	Architecture Substation, BT Block
Science Substation (500kVA)	Yet to be loaded

Further study of the KNUST electrical power distribution system is being undertaken under the supervision of Mr. E.K Anto, a lecturer of the Electrical/ Electronic Department. That work will undertake load monitoring of the distribution transformers using a three phase power quality analyzer. The work will obtain the respective current and voltage waveforms of the feeders. The power data will be analyzed with respect to the voltage levels, power flows on the feeders, power factors, Total Harmonic Distortion, K-factors for currents, peak or crest factors for current and voltage. The work will conclude with determination of the extent of overloading or otherwise of the transformers. The results of this further study are not vital to the design stage of the grid connected PV system with battery backup. The results of this further study will be used in the PhD section of this study where an electrical impact analysis will be undertaken.

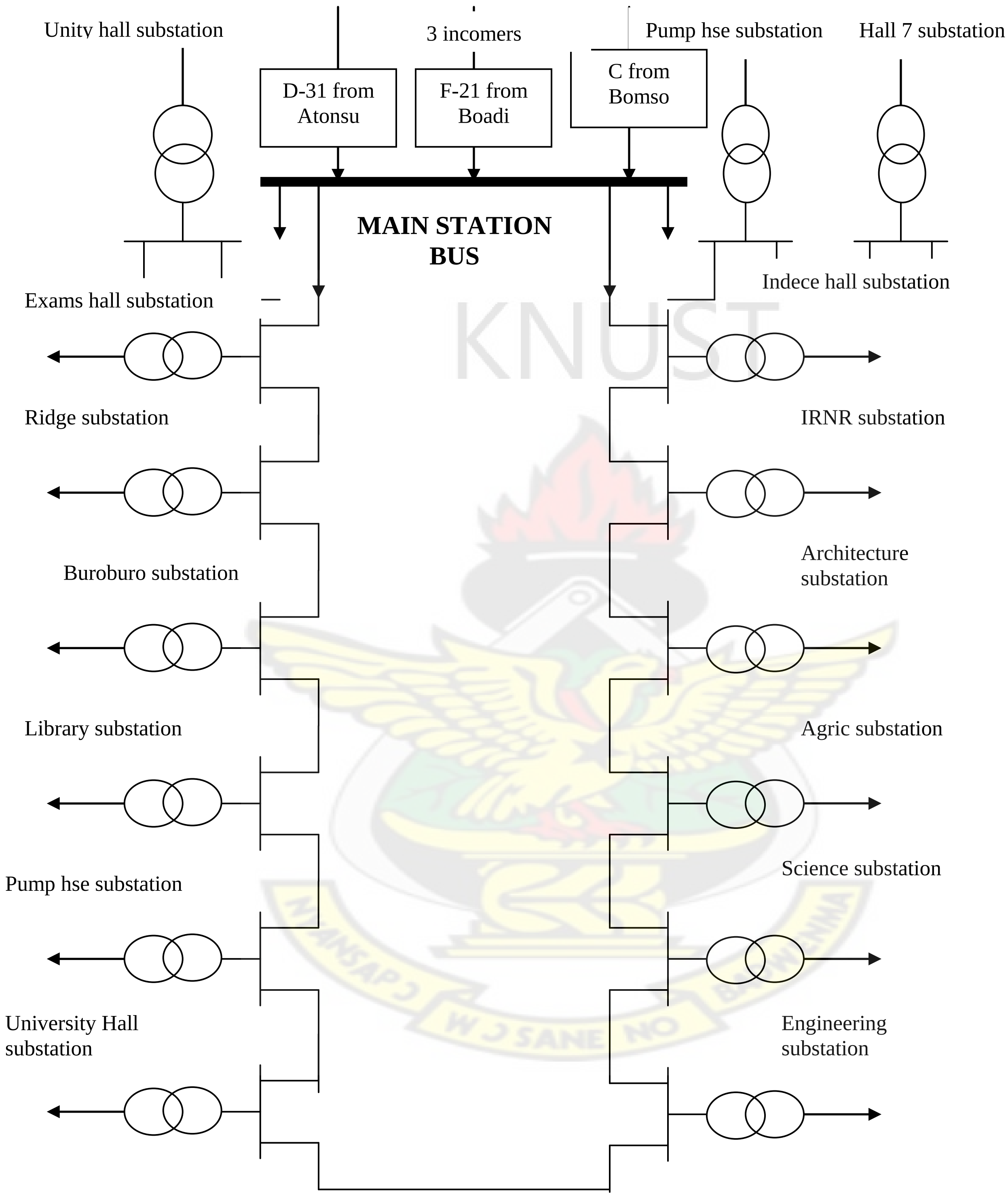


Fig 3.1 Schematic diagram of the ring system of the KNUST distribution system

3.1 Energy Consumption pattern of KNUST

KNUST is one of the largest consumers of electricity in the Ashanti Region of Ghana. They are rated on the tariff class 42 and treated as Special Low Tarrif (S.L.T) costumers. KNUST is charged for its kVA reading and its kWH reading. KNUST pays a total of 9 Ghana Cedis per kVA of its maximum demand plus a power factor surcharge of 0.1 Ghana Cedis per kVA. In addition to the above KNUST pays service charge, government special levy, Value Added Tax, National Health Insurance Levy. KNUST pays 0.905 Ghana Cedis per kWh consumed in the University.

KNUST's total bill for November 2007 was a huge 158,240.93 Ghana cedis.

The table below shows the Maximum Demand and kWh consumed from January 2006 to November 2007.

Table 3.2 Maximum Demand and kWh consumed for KNUST from January 2006 to November 2007

2006 and 2007 data for Maximum Demand and kWh consumed				
	2006		2007	
Month	Maximum Demand	kWh Consumed	Maximum Demand	KWh Consumed
January	2831	784496	2799	761434
February	3045	1084846	2966	992060
March	3052	1285395	3125	1169167
April	3228	1157158	2968	788265
May	2934	940517	2533	667521
June	2095	718983	1768	471093
July	1667	588436	1590	407336
August	1969	631426	1909	659370
September	2670	667138	2686	874945
October	2892	885709	2963	1186619
November	2807	1123678	2998	1215784
December	2644	773558	N/A	

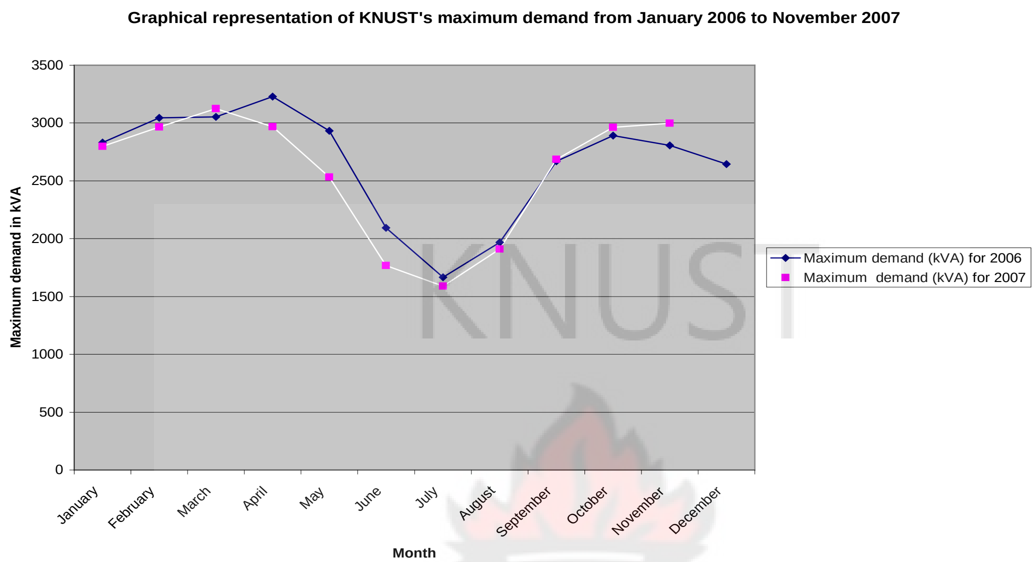


Fig 3.2 Graphical representation of KNUST maximum demand from January 2006 to November 2007

It is realized from the above graph that KNUST has a well defined maximum demand pattern which remains largely the same for 2006 and 2007.

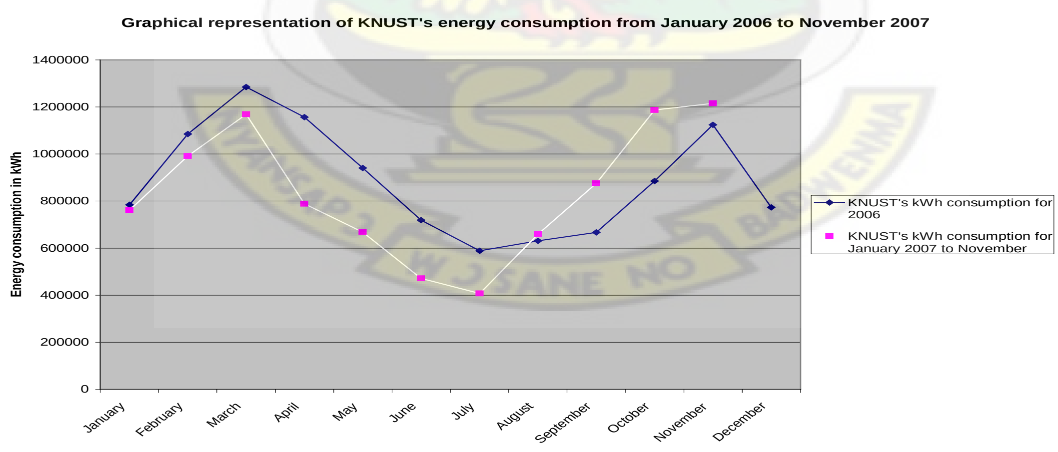


Fig 3.3 Graphical representation of KNUST energy consumption from January 2006 to November 2007

It is realized from the above graph that KNUST has a well defined load consumption pattern. It is also realized that the graph for maximum demand is similar to the graph for kWh consumed over the same period and that justifies the researcher's view that there is a correlation between maximum demand and kWh consumed.

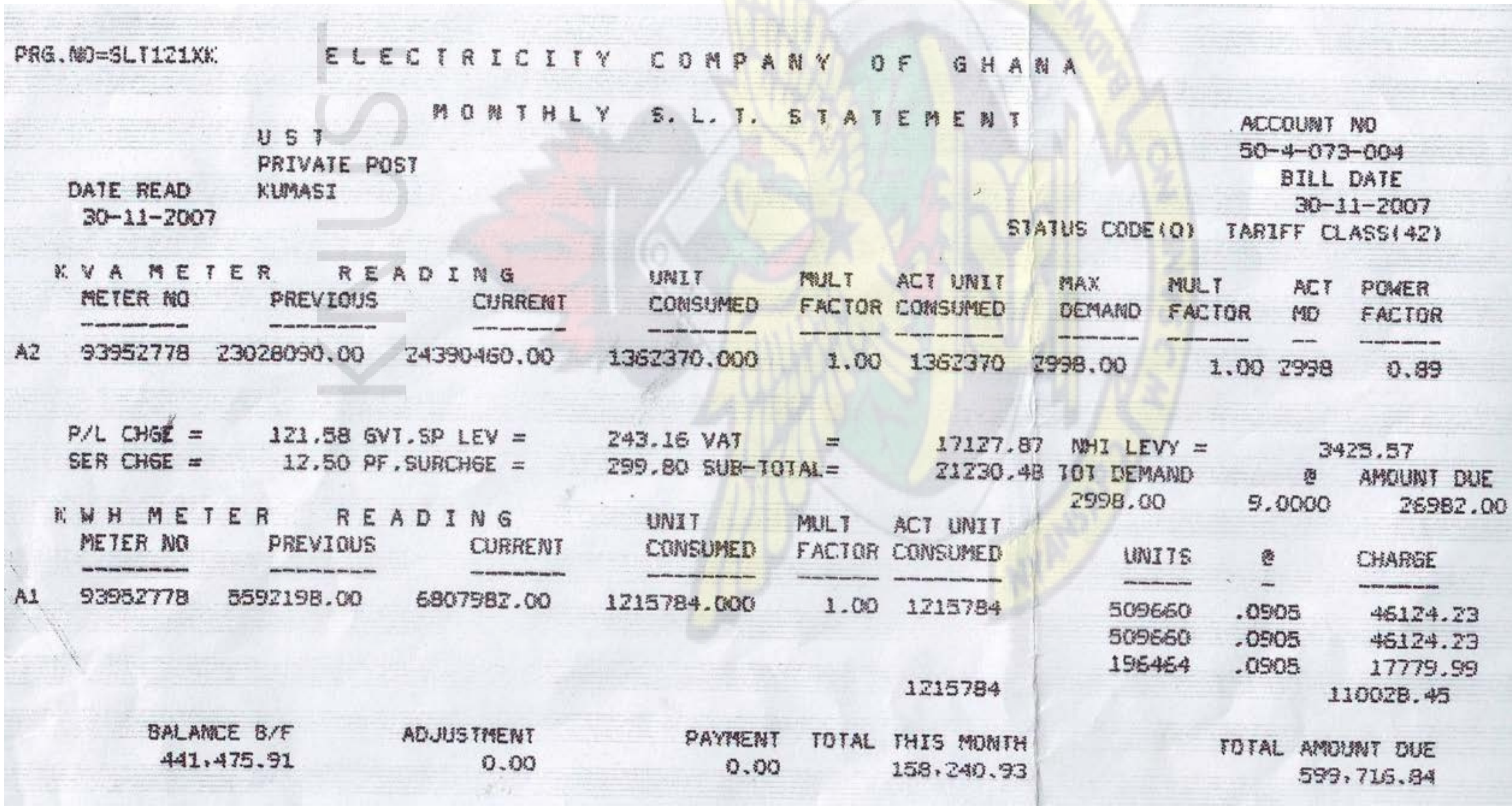
A regression analysis of the data for maximum demand and kWh consumed shows the following output;

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.839661781
R Square	0.705031906
Adjusted R Square	0.690985806
Standard Error	282.748222
Observations	23

A further analysis of the data for maximum demand and kWh shows a straight line relationship with an equation **Y= 0.0017X + 1148**

Where Y is the maximum demand and X is the kWh consumed.

KNUST's consumption peaks during the months of March, October and November and is lowest in the month of July. This pattern corresponds to the fact that school activities peak during the month of March for the second semester and October and November in the first semester. In July, the students are on vacation and consumption due to the students is taken out.



PRG.NO=SLT121XK

ELECTRICITY COMPANY OF GHANA

MONTHLY S. L. T. STATEMENT

U S T
PRIVATE POST
KUMASI

DATE READ
30-11-2007

ACCOUNT NO
50-4-073-004
BILL DATE
30-11-2007

STATUS CODE(O) TARIFF CLASS(42)

K V A METER READING

	METER NO	PREVIOUS	CURRENT	UNIT CONSUMED	MULT FACTOR	ACT UNIT CONSUMED	MAX DEMAND	MULT FACTOR	ACT MD	POWER FACTOR
A2	93952778	23028090.00	24390460.00	1362370.000	1.00	1362370	2998.00	1.00	2998	0.89

P/L CHGE = 121.58 GVT.SP LEV = 243.16 VAT = 17127.87 NHI LEVY = 3425.57
SER CHGE = 12.50 PF.SURCHGE = 299.80 SUB-TOTAL= 21230.48 TOT DEMAND @ AMOUNT DUE
2998.00 9.0000 26982.00

K W H METER READING

	METER NO	PREVIOUS	CURRENT	UNIT CONSUMED	MULT FACTOR	ACT UNIT CONSUMED	UNITS	@	CHARGE
A1	93952778	5592198.00	6807982.00	1215784.000	1.00	1215784	509660	.0905	46124.23
							509660	.0905	46124.23
							196464	.0905	17779.99
						1215784			110028.45

BALANCE B/F	ADJUSTMENT	PAYMENT	TOTAL THIS MONTH	TOTAL AMOUNT DUE
441,475.91	0.00	0.00	158,240.93	599,716.84

Fig 3.4 KNUST electricity bill for November 2007

3. 2 KNUST's regular grid failure problem

The main challenge to KNUST's electricity system is the regular occurrence of grid failure. This regular grid failure affects the work on the campus. The grid failure data was derived by adding the grid failure times (fault times) on the D-31 incomer and the VRA transmission line T5.

Table 3.3 Grid failure data from November 2006 to November 2007

GRID FAILURE DATA FROM NOVEMBER 2006 TO NOVEMBER 2007		
DATE	Duration in hrs	Grid failure on T5 or D31
5/11/2006	0.65	D31
8/1/2007	1.78	T5
9/1/2007	0.92	T5
10/1/2007	5.95	T5
13/1/2007	0.33	D31
25/1/2007	0.12	T5
26/1/2007	6.68	T5
16/3/2007	6.78	D31
21/3/2007	0.27	T5
25/3/2007	0.12	T5
15/4/2007	0.02	T5
17/4/2007	0.13	T5
21/4/2007	2.35	T5
22/4/2007	3.47	D31
30/4/2007	2.23	D31
3/5/2007	6.17	T5
27/5/2007	4.97	D31
4/6/2007	2.75	T5
5/6/2007	1.03	T5
6/6/2007	0.42	D31
9/6/2007	1.62	D31
18/6/2007	1.60	D31
25/6/2007	3.72	T5
26/6/2007	1.22	T5
27/6/2007	0.05	T5
29/6/2007	4.78	T5
23/7/2007	4.12	D31
15/8/2007	0.43	T5
31/8/2007	0.75	T5
24/9/2007	0.50	T5
25/9/2007	0.23	T5

27/9/2007	0.08	T5
28/9/2007	0.20	T5
1/10/2007	1.00	T5
2/10/2007	0.87	T5
4/10/2007	0.13	T5
5/10/2007	0.57	T5
6/10/2007	0.10	D31
15/10/2007	1.00	T5
16/10/2007	0.10	T5
17/10/2007	0.47	T5
18/10/2007	0.32	T5
13/11/2007	0.20	D31
14/11/2007	0.10	T5
15/11/2007	0.05	T5
18/11/2007	0.12	T5
Total grid failure	71.45	

3.3 Important notes from data

* The total number of hours of grid failure over the design year (November 2006 – November 2007) is 71.45 hours.

* The highest grid failure occurred on the 16th of March, 2007 and lasted for 6 hours 50 minutes.

* The shortest grid failure occurred on the 15th November, 2007 and lasted for only one minute.

* There was a total of 48 days of grid failure in the design year.

* Of the 48 grid failure days, 12 grid failures occurred as the result of faults on the D31 incomer and the rest was due to faults on the VRA transmission line load/frequency relay.

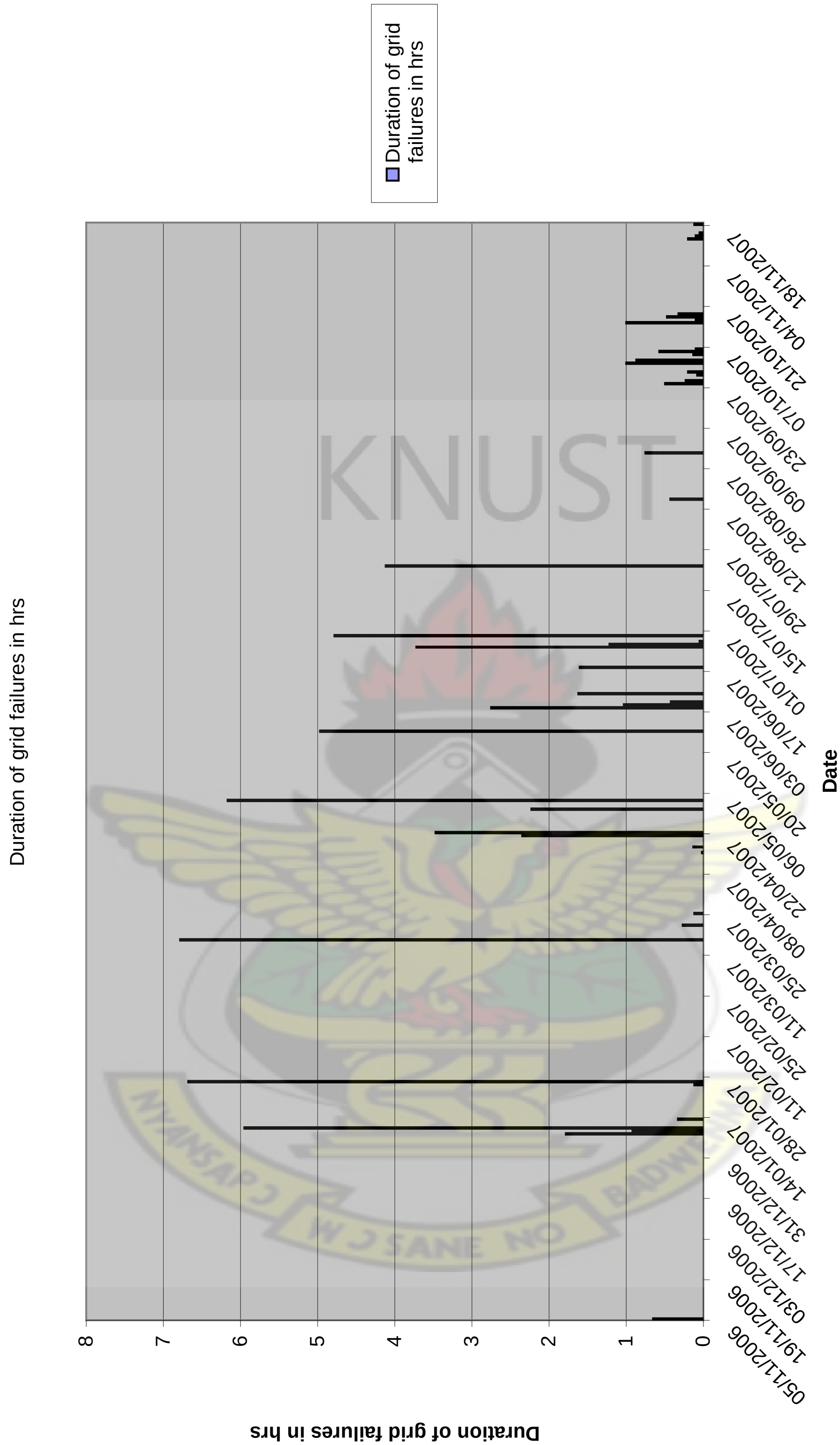


Fig 3.5 Graphical representation of KNUST grid failure data.

Chapter Four

GRID CONNECTED PHOTOVOLTAIC SYSTEM WITH BATTERY BACKUP DESIGN

CHAPTER 4

GRID CONNECTED PHOTOVOLTAIC SYSTEM WITH BATTERY BACKUP DESIGN

4.0 SYSTEM DESIGN

In this chapter the main system design is undertaken based on the data received on KNUST. The chapter begins with energy conservation recommendations for KNUST and ends with the determination of the output of the PV grid connected system.

In this chapter, the Inverter, Battery bank and panels are sized and specified.

4.1 System Design Procedure

The system design process from first principles is as follows;

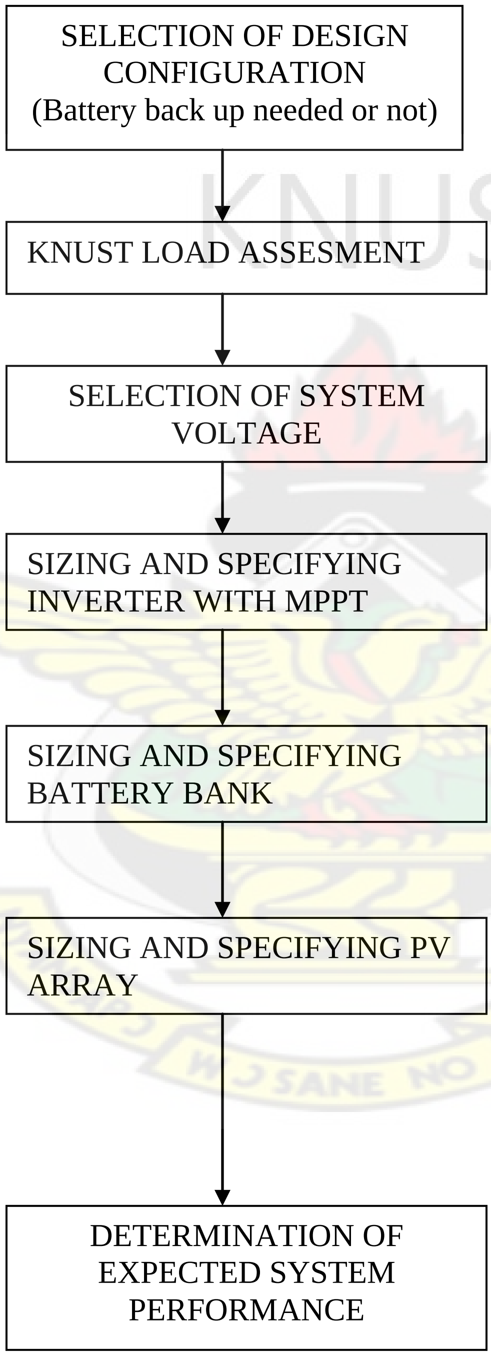


Fig 4.1 System design process from first principles

4.2 Selection of design configuration

All solar systems are designed to solve a particular power problem. There are three main types of solar power systems namely;

a. Stand alone power system

b. Grid- connected photovoltaic system without a battery back up

c. Grid-connected photovoltaic system with a battery back up.

Considering the fact that the system is needed to mainly solve the power unreliability (regular loss of grid supply) problem of the university, the third option is the most suitable.

The grid connected system with a battery back up to be designed has two main functions;

1. To supply power to all the loads when the grid has failed for a specified period.
2. To supply a.c power to the national grid when there is excess power.

There are two configurations available for grid connected PV systems with battery back up. In the first configuration, the charge controller and the inverter are one unit whiles in the second configuration they are different units

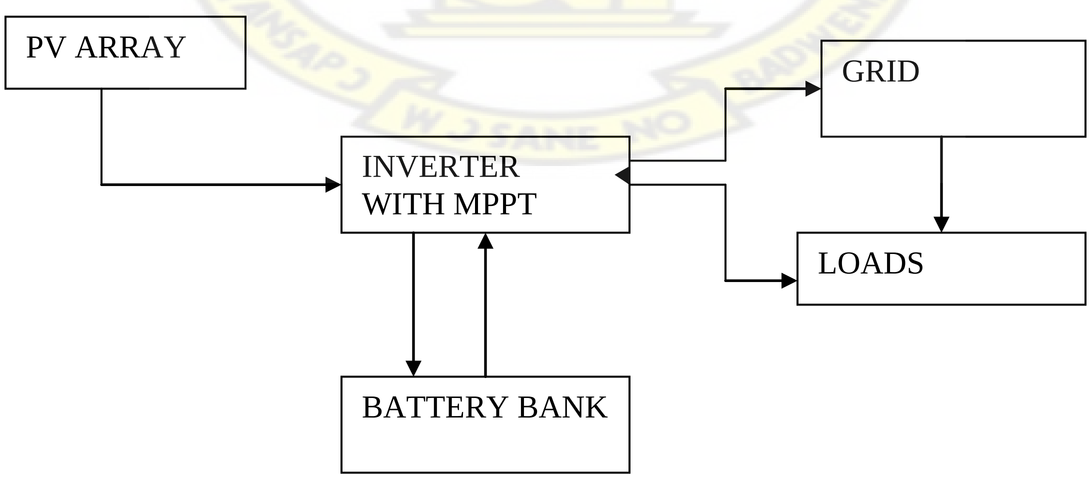


Fig 4.2 System configuration with charge controller and the inverter as one unit

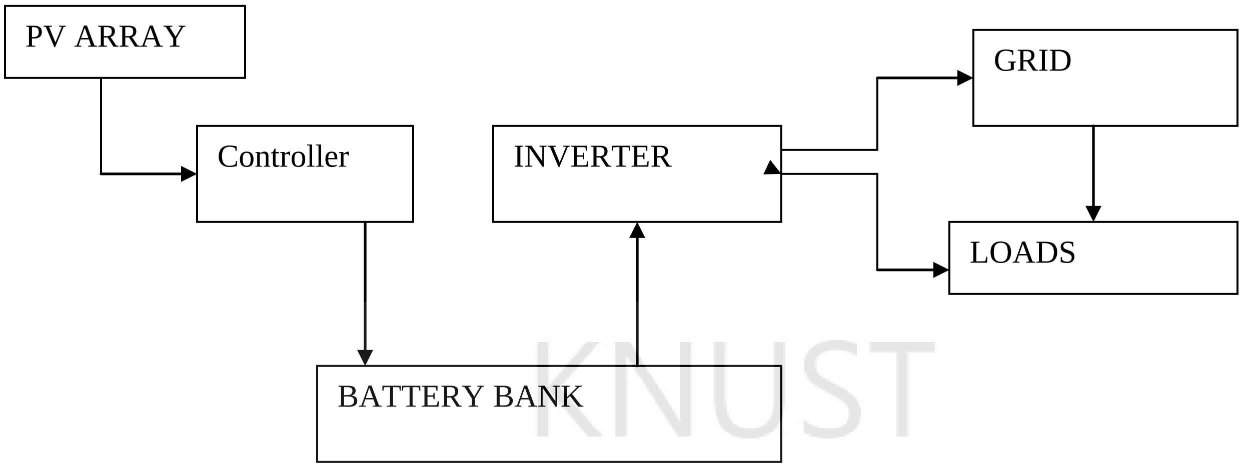


Fig 4.3 System configuration with charge controller and the inverter as separate units

4.3 Load Assessment

Since the grid connected Photovoltaic system with battery back up to be designed has one main function (supply power during grid failures) it is necessary to undertake a load assessment to determine the amount of energy required when the grid fails.

4.3.1 Assessing average yearly electrical energy usage

There are two main ways of assessing the average yearly electrical energy usage namely;

a) Using the existing electrical energy records from the bills or

b) Undertaking a load assessment analysis using a load assessment sheet.

The first way is more accurate and in this design that option will be used.

Table 4.1 Assessing daily energy use per day by KNUST

Date of Meter reading	Energy consumed (kWh)	Number of billing days	Average energy use per day (kWh)
31st Dec 2006	773558	31	24935.5
31st Jan 2007	761434	31	24562.4
28th Feb 2007	992060	28	35430.7
31st March 2007	1169167	31	37715.0
30th April 2007	788265	30	26275.5
31st May 2007	667521	31	21532.9
31st June 2007	471093	30	15703.1
31st July 2007	407336	31	13139.8
31st August 2007	659370	31	21270
30th September 2007	874945	30	29164.7
31st October 2007	1186619	31	38278.0
30th November 2007	1215784	30	40526.1
Total for design year	9967152	365	

4.3.2 Assessing the energy required during grid failure

The assessment of the energy required during grid failure is based on the nature of the grid failure and how the system must operate during grid failure.

Considering the grid failure data on KNUST and also considering that the system is expected to supply power to all the loads during grid failure, the energy need during grid failure is typically similar to that for a stand alone power system design and can be derived from the readings of the bills obtained and the table 4.1.

From the grid failure data for KNUST, it is observed that the maximum grid failure duration per day is six hours and 50 minutes.

4.4 Selection of system voltage

In the design of grid connected PV systems, a 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 grid connected PV systems (unlike in stand alone power systems), 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 of the system wiring.
c) The nature of the grid and the inverters available.

Taking inverter efficiency at full load of 95% as in the case of the available Trace 3-Phase sun-tied DC to AC inverters, the apparent power that will be drawn from the battery will be as follows;

Let A_{bi} be the total estimated apparent power that will be drawn from the battery to the inverter at full load.

Therefore $A_{bi} = \frac{300}{0.95} = 315.8kVA$ -----------------------------------(1)

The trace 3-phase Suntie DC to AC inverters can be easily paralleled for higher power and allow a voltage of up to 360VDC.

Selecting a system voltage of 360VDC the maximum current drawn from the battery bank will be

$$\frac{315.8x10^3VA}{360V} = 877A$$ ---(2)

The choice of 360VDC as the system voltage will reduce the current drawn from the battery bank and thereby reduce the cost of cabling needed.

Assuming a lower voltage of 120VDC was chosen, the maximum current drawn will have been 2631 Amperes for the same DC power level.

4.6 Determination of design daily load

It is important in this design to note that four unpredictable issues arise when designing 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 (battery back up) during grid failure is not constant over a day.
4. The daily load varies over the year.

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

Taking note of the ring system design of the KNUST electrical system, the most practical way is to design individual system to be connected to each section of the KNUST electrical system.

For the essence of this work, the design will be for a 300kVA grid- connected system (similar to the Ridge Substation) and this will be replicated for all the other sections of the ring system of KNUST.

The highest recorded load per day is 40526.1 kWh (From Table 4.1). A further analysis of the data for maximum demand and kWh shows a straight line relationship with an equation **Y= 0.0017X + 1148.**

Where Y is the maximum demand and X is the kWh consumed. Therefore it can be assumed that for smaller sizes of transformers, there will be a lower level of energy consumption.

Therefore for the 300kVA substation, out of the possible total 6715kVA KNUST maximum demand from its 15 substations, the estimated daily load is taken to be

$$\frac{300}{6715} \times 40526.1 = 1810.54kWh \quad \text{-----------------------------------(3)}$$

To allow for future growth and variation in load during grid failure times the estimated design daily load is taken to be **2000kWh.**

4.6 Battery sizing and specifying

The main goal of this research is to investigate the suitability of the implementation of Grid connected PV systems as an alternative source of energy to solve the regular grid failure problem in KNUST.

Without the battery back up the grid connected system will only supply to the grid and therefore will not solve the fundamental problem that this research seeks to solve. The battery bank is sized to cater for supply to load during grid failure. Therefore the system will work as a stand alone power system during fault conditions on the grid. The final battery capacity will depend on the following;

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

The battery bank will only be used during grid failure and considering the grid failure data for KNUST over the design year, it is realized that apart from load shedding periods (as experienced from August 2006 to September 2007), the longest grid failure for the design year was six hours and fifty minutes on 16th March, 2007.

The grid failure design hours is taken as 8 hours. The choice of 8 hours is taken to cater for future growth in load, variation of loads during grid failure and periods of poor irradiation.

To make the specifying of the battery easier since most batteries are rated at their 10hr, 20hr and 100hr discharge rate, a discharge rate of 10 hours will be most appropriately taken as the typical discharge rate.

4.6.1 Total energy that the battery bank must supply during grid failure.

The estimated design daily energy demand is **2000 kWh** and let this be represented by E_{dl}

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

$$E_{tot} = \frac{E_{dl}}{\eta_{inv}} \text{--}(4)$$

Where E_{tot} = total energy in watt hours to be supplied by battery bank during grid failure.

E_{dl}= total AC energy to be supplied by grid connected PV system which is determined from estimated daily load table and allowance for future load growth.

$$E_{tot} = \frac{2000}{0.95} = 2105.3kWh \text{-----------------------------------}(5)$$

4.7.2 Determining the required battery capacity

Batteries used in all solar systems are sized in Ampere hours under standard test conditions (Temp: 25^0C). 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 battery bank capacity required is

$$C_x = \frac{E_{tot}}{V_{dc}} \times \frac{G_{ft}}{DOD_{\max}}$$ --(6)

Where C_x = battery capacity, for a specified discharge rate in ampere hours.

E_{tot}= total energy in watt hours to be supplied by battery bank during grid failure

G_{ft} = the number of days the battery bank needs supply during grid failure. It is important to remember that in hours this will be divided by 24.

DOD_{max}= design maximum depth of discharge

Therefore $C_x = \frac{2105.3 \times 10^3 Wh}{360V} \times \frac{8/24}{0.70} = 2785Ah$ -------------(7)

Since x is the typical average discharge hours which was selected as 10 hours earlier. It is taken as C_{10} = 2785Ah

4.6.3 Temperature corrections

It is realized that battery capacities are specified at standard test conditions of 25 degrees Celsius. The capacity depends on the average operating temperature of the batteries.

To determine the correction factor, the average temperature is used in conjunction with a typical temperature correction graph as shown below;

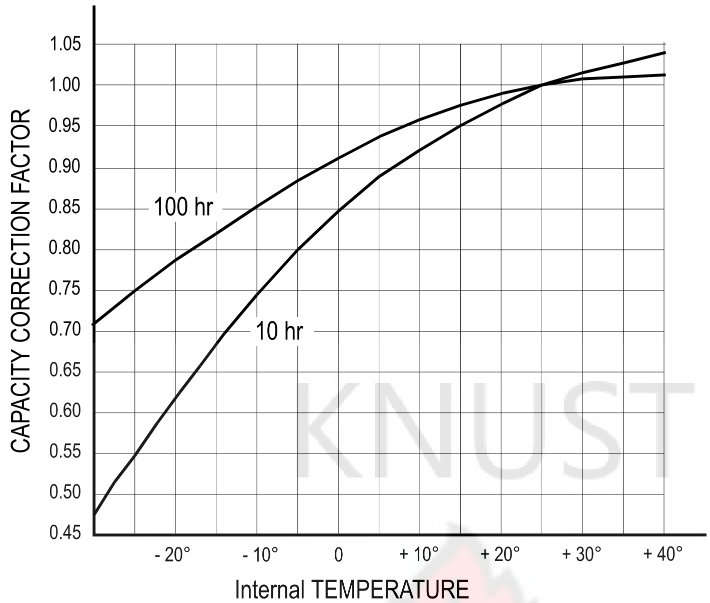


Fig 4.4 Temperature correction graph (reproduced from GSES training manual for stand alone power systems)

For Ghana, particularly Kumasi where KNUST is situated the average temperature is 25 degree Celsius and therefore the temperature correction factor is 1 and therefore the required capacity will be;

C_{10} = 2785x 1= 2785Ah -------------------------------(8)

4.6.4 Specifying the battery type to be used

In selecting a battery for a 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. Some battery manufactures state a recommended maximum number of parallel strings.

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. For each parallel string there may be a chance of uneven charging of the batteries.

The battery type must be suitable for the inverter chosen. Therefore the battery bank must be able to provide the maximum power required by the inverter to the loads without the voltage droping below the inverter cut off voltage.

The two requirements to be met when choosing a battery for an inverter are;

1. The inverter must not charge the battery at a higher current than the discharge current at C_{10}.
2. That the maximum discharge, based on kVA rating of inverter should be less or equal to the discharge current at C_5.

Based on the above requirements and information gathered on the internet on solar batteries the following solar battery range is selected.

Fig 4.5 Rolls battery

The 2-KS-33PS Deep cycle, flooded lead acid battery feature a high cycle life, thick plates, a large liquid reserve and it is designed to offer up to a 20 year lifetime. This battery is manufactured by Rolls Battery Engineering, a company which has been manufacturing deep cycle lead-acid batteries for more than 60 years. This series has been designed specifically for large renewable energy applications.

4.7.4.1 Mechanical characteristics of battery chosen

The battery 2-KS-33PS deep cycle has a non-breakable dual container construction which prevents acid leakage. It has thick plates with the highest density active material which provides unsurpassed cycling service.

The battery has a length of 34.923 centimeters, width of 20.955 centimeters and height of 63.01 centimeters. The weight of the battery is 94.3488kg.

4.7.4.2 Capacity of battery chosen

The battery has a ten year warranty and expected performance of 3000+ cycles to 50% depth of discharge and 2000+ cycles to 80% depth of discharge. The 2-KS-33PS deep cycle battery has a nominal voltage of 2 volts. The amp-hour rating is 1,500 at the 10hr rate, 1,750 at the 20hr rate and 2,470 at the 100hr rate. The off-shelf price for the battery is $861.

4.7.4.3 Number of batteries required

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

Number in series $= \frac{360}{2} = 180 batteries$ --------------------------------(9)

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 in parallel = $\frac{2785}{1500} = 1.856 \approx 2 batteries$ ---------------------(10)

Please note that this approximation also accounts for allowance for future growth and inaccuracies in the design assumptions.

Total number of batteries = Number in parallel x number in series = 180 x 2 = 360 batteries---(11)

4.8 Sizing and specifying PV array

The main limiting criteria of the PV array in the grid connected PV system with battery backup is that the system must be able to operate as a stand alone power system when there is no grid power available. The system is expected to supply all the loads during grid failure.

There are mainly three system configurations for grid connected PV systems with battery backup storage;

1. Inverter includes Maximum Power Point Tracker (MPPT) and the inverter does not charge the batteries from the grid. (eg in the case of Sunprofi inverters)
2. System uses switched regulator and the inverter maintains the batteries at float voltage (as is in the case in some AES inverters)
3. System uses MPPT (Maximum power point tracker) and the inverter maintains the batteries at float voltage (as is the case in Trace 3-Phase SunTie DC to AC inverters)

Since the Trace 3-phase Sun-Tie DC to AC inverter is selected, the configuration 3 is used.

4.7.1 Selection of PV module to be used

In selection of a PV module for grid connected systems the main limitation is the efficiency of the module and the warranty of the product (since grid connected systems are designed to last for a long time. The BP solar 180Watt Photovoltaic module (Saturn technology) is chosen. The BP 7180 forms part of the high efficiency Saturn 7 series "real power" range of solar modules. Being the largest, most powerful module manufactured by BP Solar, the BP 7180 is ideal for this installation since high power is required in a very limited area. The BP 7180 has been especially designed for grid connected applications such as the PV plant being designed in this research.

4.7.1.1 Performance

The module has a rated power of 180W and a module efficiency of 14.35 and nominal voltage of 24 Volts

4.7.1.2 Configuration

Clear universal frame with output cables and polarized multi-contact (MC) connectors.

4.7.1.2.1 Quality and safety

This module was manufactured in ISO 9001 and ISO 14003 certified factories. The module is certified to IEC 61215 and conforms to European Community Directive 89/33/EEC, 73/23/EEC and 93/68/EEC. The module's power measurements have been calibrated to World Radiometric reference through ESTI and framed modules have been certified by TUV Rheinland as Safety Class II equipment for use in systems up to 1000VDC and the Underwriter's laboratories for electrical and fire safety have given it a Class C fire rating.

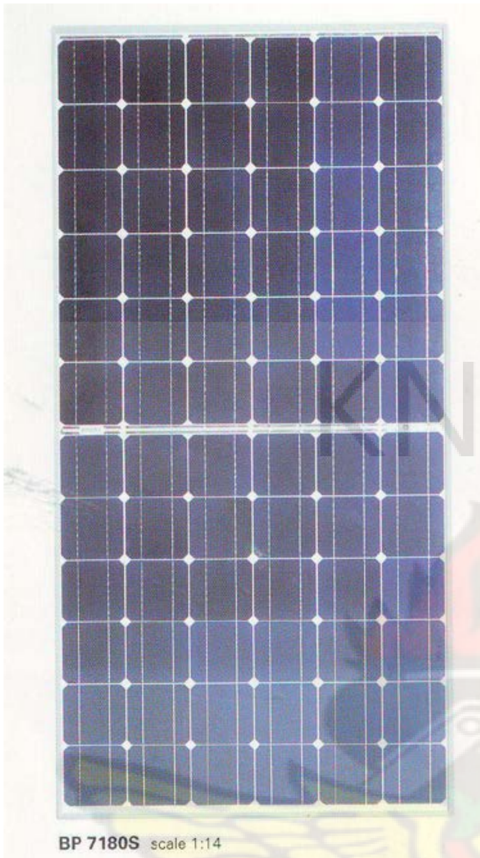


Fig 4.6 module picture

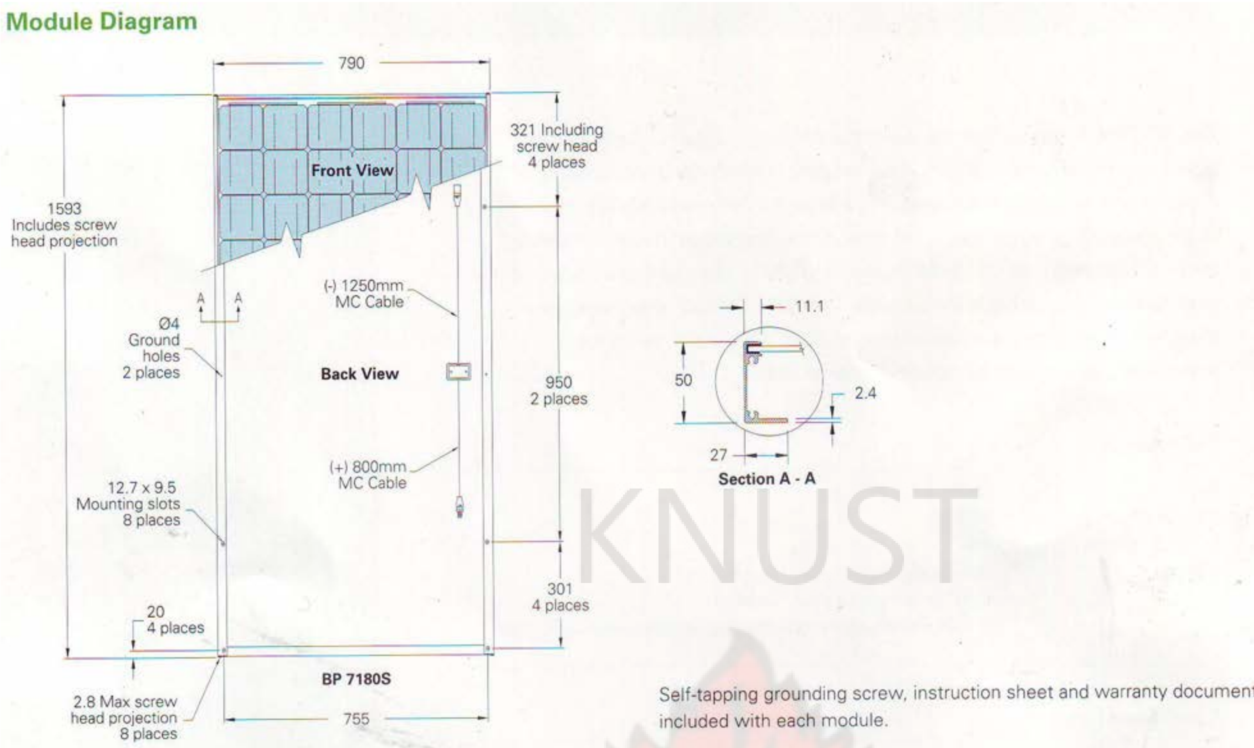


Fig 4.7 Module diagram from BP leaflet

4.7.1.2.2 Typical electrical characteristics

The typical electrical characteristics of the PV module BP 7180S measured under Standard test conditions (irradiance of 1000W/m^2 ,Air mass of 1.5G solar spectrum and a effective cell temperature of 25^{0}C) are as follows;

Warranted minimum power	- 180W
Voltage at Pmax (Vmp)	- 36.0V
Current at Pmax (Imp)	- 5.0A
Short circuit current	- 5.3 A
Open circuit current	- 44. 2V
Temperature derating factor	-0.05%/ ^{0}C
Maximum system voltage	- 1000VDC
Maximum series fuse rating	- 600V DC

4.7.1.2.3 Mechanical characteristics

The module is made up of 72 cells connected in series with a weight of 15.4kg and dimensions of 1593 x 790 x 50 and its frame is clear anodized aluminum alloy type.

4.7.2 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;

$$N \times P_{\mathrm{mod}} \times H_{tilt} \times \eta_{pvss} = E_{gf} \times f_o \text{ -----------------------------------(12)}$$

Where N = total number of modules required

P_{mod} = the derated output power of the module in watts.

H_{tilt}= average daily irradiation in peak sun hours for the specified tilt angle.

η_{pvss} = efficiency of the PV subsystem, dimensionless

E_{gf}= design energy demand at the DC bussbar during grid failure per day (this is actually the daily energy demand for 8hrs out of the 24hrs of a day. Therefore E_{gt} is one third of E_{tot}

E_{gf}= E_{tot} / 3 = 2105.3 X 10^3/ 3 = 701.76 x 10^3Whrs

Undertaking a change of subject on equation 12

$$N = \frac{E_{gt} \times f_0}{P_{\mathrm{mod}} \times H_{tilt} \times \eta_{pvsss}} \text{ ---(13)}$$

Where all terms take up their same meaning as in (12)

4.7.2.1Determination of η_{pvps}

The efficiency of the PV subsystem depends of the efficiency of the cables, the MPPT and the watt-hour efficiency of the battery.

$$\eta_{pvss} = \eta_{pv-batt} \times \eta_{mppt} \times \eta_{batt} \text{ ----------(14)}$$

Where $\eta_{pv-batt}$ = The cable losses (transmission losses) which in this design is kept above 95%

η_{mppt} = The efficiency of the MPPT which is 95% for Trace 3-phase sun-tie DC to AC inverters.

η_{batt} = the watt-hour efficiency of the battery. The watt-hour efficiency of the batteries is typically 80%.

$$\eta_{pvss} = 0.95 \times 0.95 \times 0.80 = 0.722 \text{ -----------(15)}$$

4.7.2.2 Determination of the real power output of the module in this design

In solar systems the module output is affected by the tolerance of the manufacturer, dirt (shading) and temperature, therefore the module does not give its rated module power output in real operation.

$$P_{\text{mod}} = P_{stc} \times f_{man} \times f_{temp} \times f_{dirt} \text{ ---------------------------(16)}$$

Mono-crystalline modules typically have a temperature co-efficient (γ) of 0.45%/ degree Celsius. This is for every ambient temperature.

In this design the ambient temperature is 25 degree Celsius.

Therefore, f_{temp}= 1-(γ x 25)-------------------------(17)

Therefore $f_{temp} = 1-(\frac{0.45}{100}\times 25) = 1-0.1125 = 0.8875$ ----------(18)

Manufacture's tolerance is taken to be 0.90 for BP 7180

Since KNUST is an area with regular rain fall and not very dusty the derating factor for dirt is taken to be 0.97

Therefore substituting in equation (16) above

$P_{\text{mod}} = 180\times 0.9\times 0.8825\times 0.97 = 136.67W$ ---------------(19)

For the H_{tilt} , from BP solar design records and works done at the Department of Mechanical Engineering of KNUST, it is known that the peak sun hours for Kumasi at the approved tilt of between 10-15^0 is 4.5

Therefore substituting in equation (13)

$N = \frac{701.76\times 10^3 \times 1}{136.67\times 4.5\times 0.722}$ = 1580 modules----------------------(20)

Since each of the modules are rated at a nominal voltage of 24VDC, to get a system voltage of 360V

The number of modules in series = $\frac{360}{24} = 15\,\text{mod}\,ules$ ----------------(21)

Therefore the number in parallel will be = $\frac{1580}{15} \cong 105\,\text{mod}\,ules$ ----(22)

4.7.3 Sizing and specifying Inverter

Unlike in stand alone power systems where the battery is the heart of the system and always needs to be designed first in 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 grid system and the loads. The choice of an inverter in a grid connected PV system with battery back up is dependent on the input and output voltages, the phase type (3-phase or single phase), output kVA (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 to synchronize with the grid voltage of 433V.
3. Must be a three phase alternating current sine wave grid tied inverter and suitable for battery backup connection.
4. Must have an efficiency at full load of above 95% to minimize losses.
5. Must have the ability to perform maximum power point tracking to minimize the number of panels needed.
6. Must have an in-built utility fault protection features.
7. Must have a capacity of 300kVA or above and can be easily paralleled for higher power.

Considering the conditions above and the available inverters on the market, the PI/TE-PV range of inverters is selected.

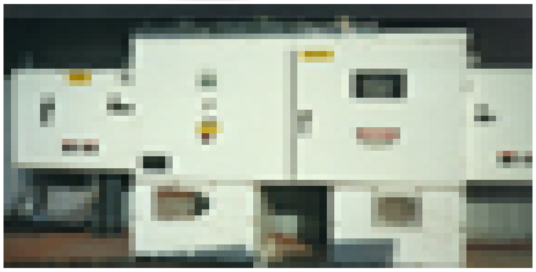


Fig 4.8 300KVA Trace technologies floor mounted inverter

The chosen inverter is the PI/TE- PV 300 Trace Technologies inverter with a capacity of 300kVA. 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 grid-tie inverters.

It has an off-shelf price of $116,144.00

4.8 Estimation of the output of the grid connected PV system with battery backup.

The output of a grid connected PV system with battery backup is affected by

a) Effects of dirt on the module
b) Temperature effects
c) Manufacturer's tolerance of modules
d) System losses
e) Watt hour efficiency of battery (Losses due to charging battery)
f) Inverter efficiency
g) Average solar irradiation for selected tilt angle and orientation.

In the grid connected PV system it is the duty of the inverter when the PV array is connected to the grid to maintain the battery bank voltage at float voltage (fully charged voltage). The power output needed from the PV array to maintain the float voltage is dependent on the amount of energy required to overcome self discharge of the battery.

While there is no PV input (at night) the inverter uses power from the grid to maintain the batteries at float voltage.

The Australia Business Society Council for Education (BSCE) course handbook for Designers and installers of grid connected PV systems records that this power consumption is between 20W and 50W.

From calculation (19) above, the derated output power of the module P_{mod} = 136.67W

Therefore the average daily energy output of the PV array, E_{array}

$E_{array} = P_{mod}$ X H_{tilt} X N--------------------------------(23)

Where all terms are as previously defined

E_{array} = 136.67 X 4.5 x 1575 = 968648.63Wh = 0.96MWh----------(24)

Let the average daily energy output of the grid connected PV system that is delivered to grid be E_{system}

Then $E_{array} \times \eta_{inv} \times L_s - E_{LBCI} = E_{system}$ ---------------------------------(25)

Where η_{inv} = efficiency of the inverter

L_s = losses in the system cabling

E_{LBCI} = Energy lost in charging the batteries

The energy loss in charging the batteries is actually the energy required to cater for self discharge of the battery bank.

The self discharge of batteries is about 1% per month.

Therefore, the ampere hours required per day is about 0.033% of the battery bank capacity.

Considering the battery bank capacity of 2785Ah from equation (8)

The ampere hours required per day will be

$= \frac{0.0333}{100} \times 2785Ah = 324Wh$ -------------------------------(26)

The average daily energy output of the grid connected PV system is

E_{system} = 968648.63 X 0.95 X 0.95 – 324Wh -------------(27)

Note that the losses in the system cabling is taken to be a maximum of 5%

E system = 873881.39 Wh = 0.87MWh ------------------(28)

Let the average yearly output of the PV grid system be $E_{sys.yr}$

$E_{sys.yr}$ = E_{system} X 365 – E_{BC} X $N_{grid\ failures}$ ----------------(29)

$N_{grid\ failures}$ = number of grid fails per year.

E_{BC} = energy required to recharge batteries after grid failure.

$E_{BC} = DOD_{\max} \times C_{10} \times \eta_{batt} \times V_{sysem}$ -----------------------(30)

Where all terms have their previously defined meanings.

$E_{BC} = 0.7 \times 2785 \times 0.7 \times 360 = 491274Wh$ -------------(31)

Using the grid failure data for the design year, the number of grid failures was 46

$E_{sys.yr}$ = 873881.39Wh X 365 – 491274 X 46------------(32)

=318MWh-22MWh

= 296MWh = 0.296GWh

Chapter Five

SYSTEM WIRING

CHAPTER FIVE

SYSTEM WIRING

5.0 INTRODUCTION

This chapter outlines the wiring layout of the system, determines cables sizes suitable for installation and selects fuses/circuit breakers for installation. Earthing and lightning protection is also discussed. It is important to note that the system wiring is as important as the system design since a lot of systems fail because of poor wiring.

5.1 Wiring layout of grid connected PV system and its components

It is vital in all large system works to have a clear understanding of the wiring connections required in the system. Some components do not allow for trial and error since they burn out immediately when not connected properly.

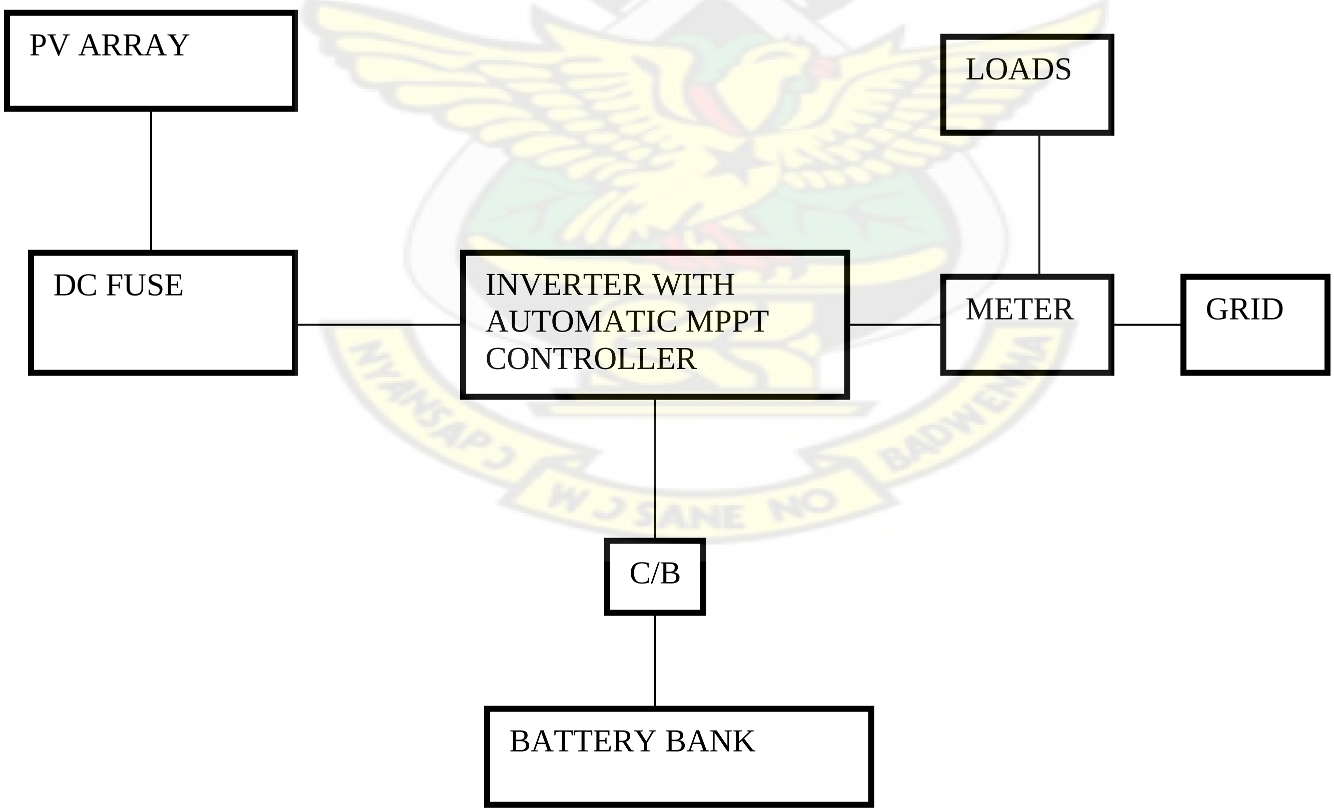


Fig 5.1 Single wiring diagram of grid connected PV system

5.1.1 Wiring diagram of PV array

The PV array is made up of 1575 modules of 105 parallel strings of 15 modules in series.

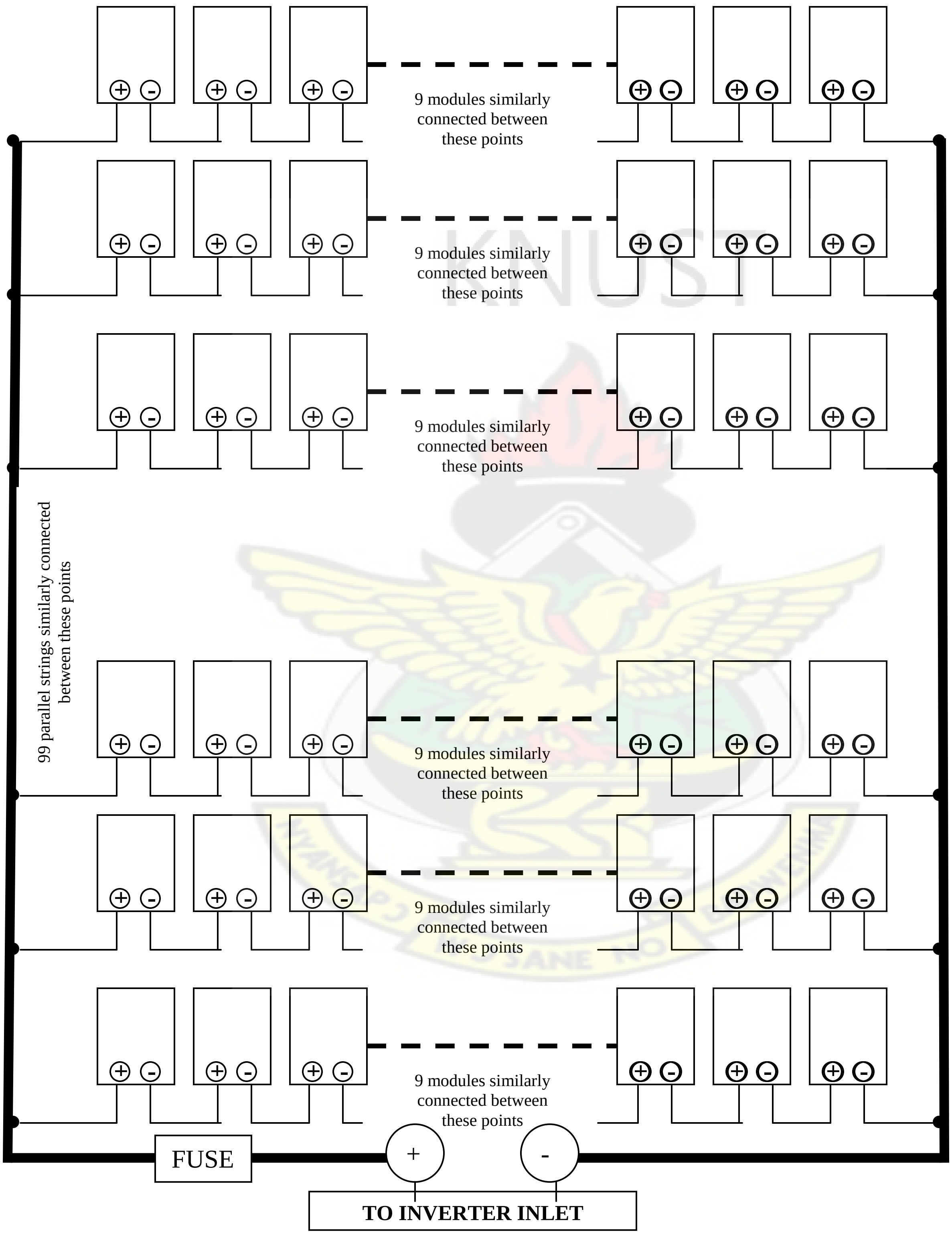


Fig 5.2 Wiring diagram of PV array

5.1.2 Wiring diagram of battery bank

The figure below 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

Number in series $= \frac{360}{2} = 180 batteries$ --------------------------------(9)

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 in parallel = $\frac{2785}{1500} = 1.856 \approx 2 batteries$ --------------------(10)

Total number of batteries = 360 batteries---(11)

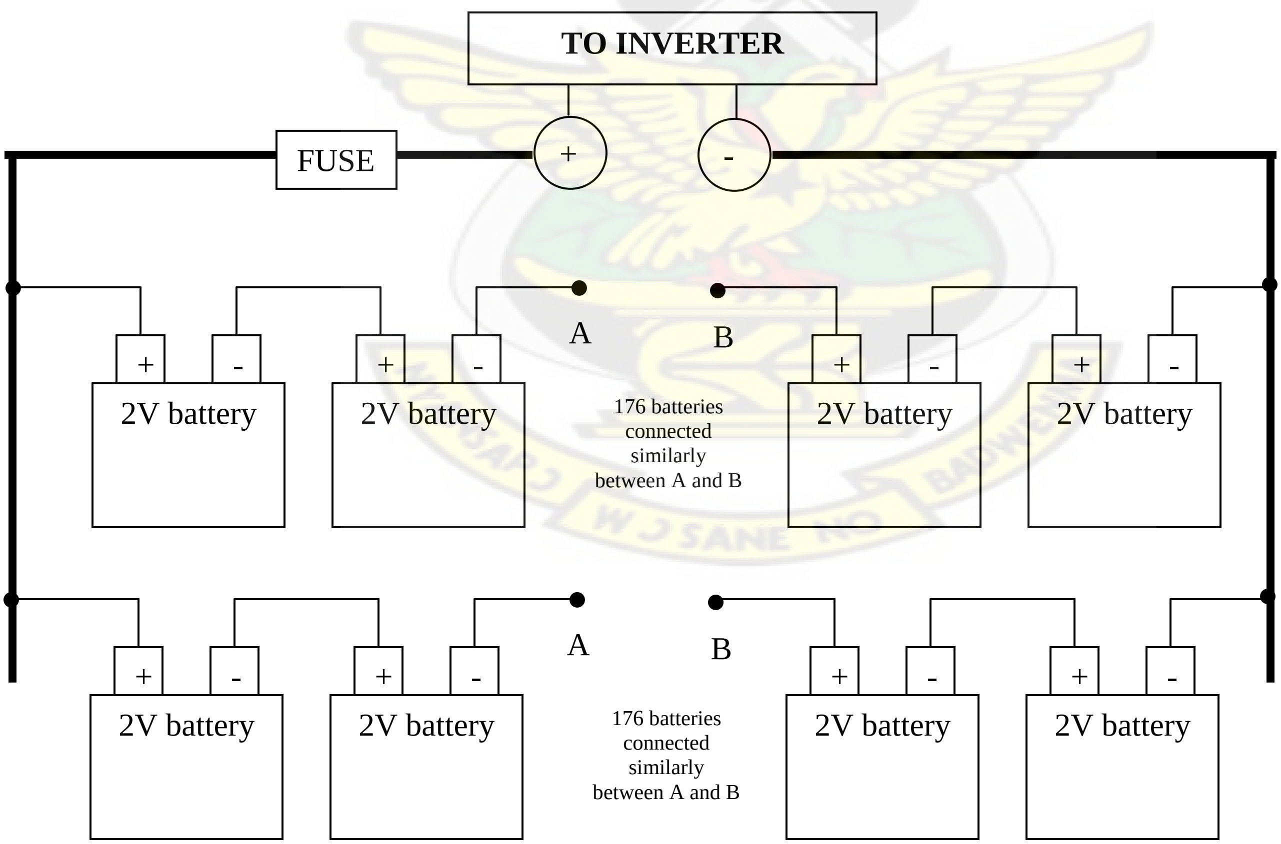


Fig 5.3 wiring diagram of battery bank

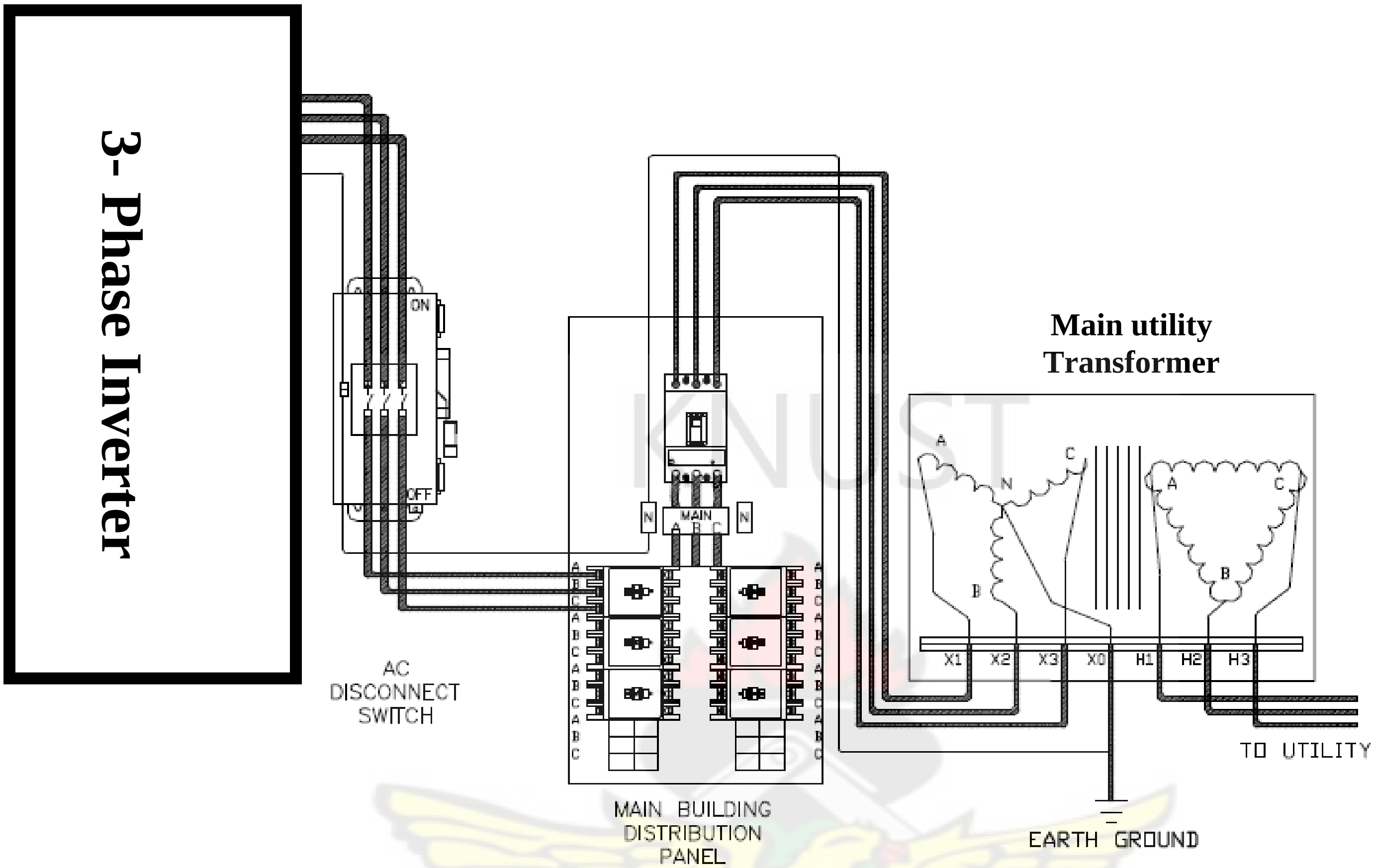


Fig 5.4 wiring diagram of connection of inverter output to main junction distribution panel

5.2 Sizing of cables

As much as the design/sizing of the grid connected PV 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 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

$$V_d = \frac{\rho l}{A} \times I \times 2 \text{ --(33)}$$

Where ρ is the resistivity of copper wire which is normally taken to be 0.0183 $\Omega mm^2 / m$

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

$$A = \frac{\rho l \times I \times 2}{V_d} \text{ ---(34)}$$

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

5.2.1 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

The maximum allowable voltage drop is $\frac{5}{100} \times 24 = 1.2V$

The resistivity of copper is $0.0183\,\Omega mm^2/m$

$$A = \frac{\rho l \times I \times 2}{V_d} = \frac{0.0183 \times 1.5 \times 6.625 \times 2}{1.2} = 0.30mm^2$$

This means that any cable of cross-sectional area above 0.30mm^2 can be used for the wiring between PV modules

5.2.2 Sizing of cable from PV array busbar (DC current from array collection point) to Inverter

The cable is sized based on the following information

*Length of cable is 20m

The maximum current from array is 5.3 x 105 x1.25 = 695.625amperes

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

The resistivity of copper is $0.0183\,\Omega mm^2/m$

$$A = \frac{\rho l \times I \times 2}{V_d} = \frac{0.0183 \times 20 \times 695.625\text{x}2}{18} = 28.28mm^2$$

This means that any cable of cross-sectional area above 28.28mm^2 can be used for the wiring between PV array busbar and inverter.

5.2.3 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

$$I = \frac{InveterVA}{\eta_{inv} \times V_{system}} = \frac{300KVA}{0.95 \times 360} = 877.2A$$

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

The resistivity of copper is $0.0183\,\Omega mm^2 / m$

$$A = \frac{\rho l \times I \times 2}{V_d} = \frac{0.0183\times 5\times 877.2\times 2}{18} = 8.9mm^2$$

This means that any cable of cross-sectional area above 8.9mm^2 can be used for the wiring between battery bank and inverter.

5.2.4 Sizing of cable from inverter to main junction (inverter/grid/loads) distribution panel

Maximum Length of cable is 20m

The maximum current from inverter at full load on each phase (line) is given by

$$I_{phase} = \frac{InveterVA}{V_{output}\times\sqrt{3}} = \frac{300kVA}{240\times\sqrt{3}} = 721A$$

The maximum voltage drop is $\frac{5}{100}\times 240 = 12V$

The resistivity of copper is $0.0183\,\Omega mm^2 / m$

$$A = \frac{\rho l \times I \times 2}{V_d} = \frac{0.0183\times 20\times 721\times 2}{12} = 43.981mm^2$$

This means that any cable of cross-sectional area above 43.981mm^2 can be used for the between inverter to main junction distribution panel.

5.3 Sizing of system circuit breakers

Circuit breakers are installed in the system to cater for over current protection and sized to not be below 125% of the current flowing through the wiring. The circuit breakers used in this installation must be bi-directional.

5.3.1 Sizing of circuit protection between Inverter and battery bank

The required circuit protection is equal to 125% of maximum current drawn under full load condition. The maximum current from battery at full load supply is given by

$$I = \frac{InveterVA}{\eta_{inv} \times V_{system}} = \frac{300KVA}{0.95 \times 360} = 877.2A$$

Therefore minimum rating of DC circuit protection is $\frac{125}{100} \times 877.2 = 1096.5A$

5.3.2 Sizing of circuit protection between PV array and Inverter

There are generally two ways of undertaking the circuit protection between PV array and Inverter.

* Each parallel string of modules can be fused before entering DC collection point or
* The total output of the PV array is fused before being joined to the inverter

In this installation, the first option is used because that makes it easier to find suitable DC circuit breakers.

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

Therefore minimum rate of DC circuit protection is $\frac{125}{100} \times 6.625 = 8.28A$ per parallel string.

5.3.3 Sizing of circuit protection on every phase output of inverter

The maximum current from inverter at full load on each phase (line) is given by

$$I_{phase} = \frac{InveterVA}{V_{output} \times \sqrt{3}} = \frac{300kVA}{240 \times \sqrt{3}} = 721A$$

Therefore the minimum rating of circuit breaker is $\frac{125}{100} \times 721 = 901.25A$

5.3.4 Sizing of Inverter (AC) output disconnect

A lockable disconnect switch for isolation during maintenance and fault conditions is required for the system. This switch is placed between the inverter output and the main junction distribution panel. The switch should have a rating greater than the over-current protection devices in the circuit. Therefore in this design a disconnect switch rated at 300A will be suitable.

5.3.5 Wiring and current carrying capacity

In addition to noting the cross-sectional area of cables it is necessary to note that cables have a rated current carrying capacity and when purchasing cables for this installation, all cables must have a current carrying capacity higher than the current rating of the protection device connected to it so that the over current protection devices clears before any of the current carrying components in a over current condition.

5.4 Summary of wiring ratings of system

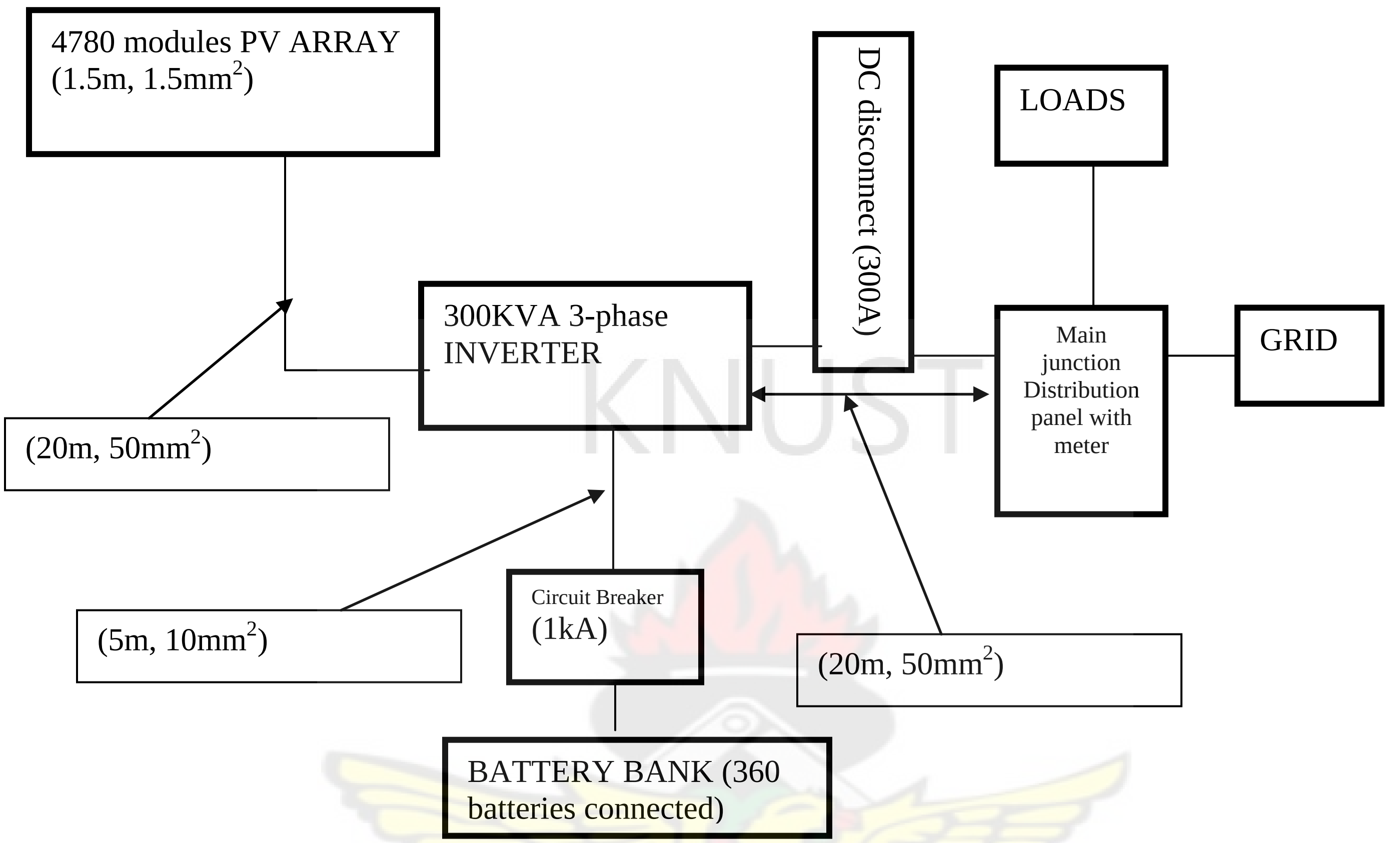


Fig 5.5 Summary of wiring ratings and lengths of the system.

Chapter Six

SYSTEM INSTALLATION

CHAPTER SIX

SYSTEM INSTALLATION

6.0 INTRODUCTION

The system installation section is the final step to the full installation and putting into operation the grid connected PV system.

This chapter includes installation preparation practices, Equipment installation practices, signage required, safety equipment and practices and finally system commissioning activities.

6.1 Installation preparation

The preparation for installation involves two main steps

1. Determination of equipment location
2. Preparation and use of installation checklist

6.1.1 Equipment location

Maximum wiring distances between all components of the system have been determined and used for cable sizing and these distances must be maintained in the installation.

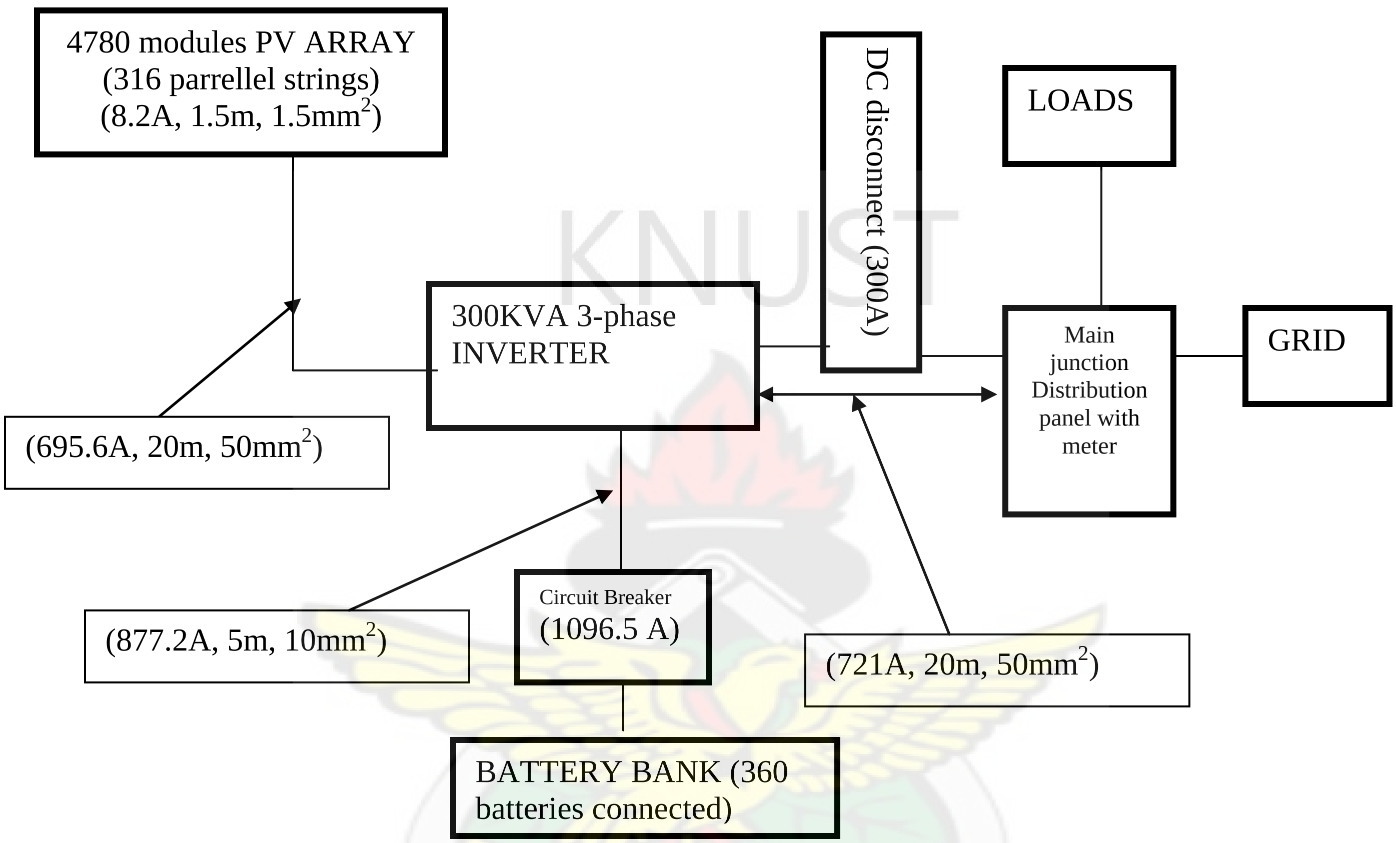


Fig 6.1 System installation diagram based on wiring calculations

6.1.2 Installation checklist

To prevent the halting of the installation process due to the absence of any installation equipment, an installation checklist is prepared.

The installation checklist is prepared to

a) obtain all the relevant equipment

b) Ensure all tools and equipment is loaded and ready for transport to site.

The checklist is ticked to represent the presence of the tool or equipment.

Table 6.1 Installation checklist

Item No	Type of item	Number required	OK
1	PV module- BP 7180 model	1575	
2	Solar array mounting structure/ frame	-	
3	Hardware for connecting module to frame	-	
4	Hardware for connecting frame to floor	-	
5	Cable between PV modules (1.5mm^2)	8000m	
6	Cable between PV array and Inverter (85mm^2)	40m	
7	Conduit	8000m	
8	Fastening hardware for cables/ conduit	-	
9	300kVA Trace sun-tied Inverter	1	
10	Wooden stand for inverter	1	
11	Circuit breaker on each parallel PV array string	316	
12	Batteries (360, 2V, 1500Ah batteries)	360	
13	Cable between Inverter and Battery (10mm^2)	10m	
14	Circuit breaker on battery to inverter cable	1	
15	Battery stands/racks for battery	360	
16	Coverings for battery terminals	720	
17	Fasteners for cable connection between	-	

	inverter and battery		
18	AC disconnect switch (230A)	1	
19	Fasteners for AC disconnect switch	As provided	
20	Cable runs from Inverter to main junction ($10mm^2$)	40m	
21	Reversible meter	1	
22	Installation toolbox	5	
23	All safety equipment (safety goggles, leather gloves, water washing bottle, Bicarbonate soda, water bucket etc)		

6.2 Equipment installation

In this section the main rules with respect to the installation of the individual components of the grid connected PV system are summarized.

6.2.1 Solar Array

The solar array should be

* Mounted facing true south + or – 5 degrees.

*Mounted at a tilt angle of between 10^0 to 15^0 to the horizontal.

*Sited to minimize shading by trees and buildings.

*Mounted to meet wind loading standards.

6.2.2 Battery Bank

The battery bank is installed carefully as follows;

*The battery bank is installed in a room that is suitably ventilated and where the batteries are well protected.

*The battery bank is installed in a place where the batteries are not in direct sunlight and in as cool and environment as practically possible.

*The terminals are well covered to prevent short circuiting of the terminals.

*The batteries should be mounted on acid resistant battery trays.

6.2.2.1 Calculation of ventilation for Battery bank

From previous study it has been identified that the natural ventilation area (inlet and outlet sizes) required for a battery bank is given by

$$A = 100 \times 0.006nI$$

Where n is the number of 2 volt cells and I is the maximum current drawn from the battery.

For this system

A = 100x 0.006 x 360 x 877.2 = 189475.2 sq cm

Say 380cm by 500cm at both inlet and outlet

The outlet is placed above and the inlet below

6.2.3 Inverter and the AC disconnect switch

The inverter and the AC disconnect switch will generally be installed as follows;

*Installed in a dust free environment

*Mechanically supported where placed

*Not installed in a wet or damp environment

*Installed in a location where the inverter and AC disconnect switch are not in excessive temperature.

*Mounted in an area that is free from hydrogen accumulation

Chapter Seven

SYSTEM MAINTENANCE AND TROUBLE SHOOTING

CHAPTER SEVEN

SYSTEM MAINTENANCE AND TROUBLESHOOTING

7.0 SYSTEM MAINTENANCE

In a solar system, like any other equipment installation, the life time of the system is dependent is shortened if the system is not well maintained. Considering the cost of such a large system, it is more than essential for the system to be maintained. In addition, like any other electrical equipment or system, troubles do occur and trouble shooting if not well planned can become both tedious and time consuming. This chapter seeks to outline the major maintenance activities and also create a fault finding tree that makes it easier to identify faults and solve them in the shortest possible time.

7.1 Maintenance schedule for each component

For each major component in the grid connected PV system, the major maintenance schedule is outlined as follows;

7.1.1 Solar Array

Table 7.1 Maintenance schedule for Solar Array

Maintenance activity	Period recommended
Clean modules	Every three months
Check all cabling for loose connections and mechanical damage	Every three months
Check mechanical security of the array structure	Every three months
Check output voltage and current of each	Every three months

parallel string of the array and compare to the expected output under the same conditions	
Check for shading by trees and houses around modules	Every three months

7.1.2 Battery Bank

Table 7.2 Maintenance schedule for Battery Bank

Maintenance activity	Recommended period
Check specific gravity of electrolyte	Every two months
Check electrolyte level and top up where necessary	Every two months
Check all battery connections and cable terminations for corrosion and security	Every two months
Check for any mechanical damage to battery cases	Every two months
Clean battery area for any liquid spillage	Every two months

7.1.3 Inverter, AC disconnect and AC main junction (service) panel.

Table 7.3 Maintenance schedule for Inverter, AC disconnect and Service panel

Maintenance activity	Recommended period
Check if the all the units have not been invaded by spiders, rodents or insects	Every month

Cleaning all units to minimize dust build up	Every month
Check that all electrical connections are clean and tight	Every month

7.2 Maintenance logbooks

To have historical information about each of the equipment which can help show abnormal variations, future problems and changes in performance over time, all maintenance activities and their records must be kept.

A book usually called a log book made up of loose sheets is used to keep these records.

The following are the individual log books prepared for this system. These sheets are ticked to show that that particular activity has been undertaken.

7.2.1 Solar array log sheet

Table 7.4 Solar array log sheet

Date	Modules cleaned	Cabling in good condition	Array structure OK	Output voltage	Output Current	No shading	Comments

7.2.2 Battery Bank log sheet

Table 7.5 Battery Bank log sheet

		Date	Date	Date	Date
Battery Bank voltage output					
Ambient temperature					
Battery 1	Average Specific Gravity				
	Is Electrolyte level OK?				
	All battery terminals and connections intact				
	Battery cases Ok?				
	All liquids around battery cleaned				
Continue for battery 2- 359	------------------------				
Battery 360	Average Specific Gravity				
	Is Electrolyte level OK?				
	All battery terminals and connections intact				
	Battery cases Ok?				
	All liquids around battery cleaned				

7.2.3 Inverter, AC disconnect and AC main junction (service) distribution panel log sheets

Table 7.6 Inverter, AC disconnect and service panel log sheets

Appliance	Activity	Date	Date	Date	Date
Inverter	No insect evasion				
	All connection tight				
	The appliance is cleaned				
AC disconnect switch	No insect evasion				
	All connection tight				
	The appliance is cleaned				
AC main junction (service) distribution panel	No insect evasion				
	All connection tight				
	The appliance is cleaned				

7.3 System Faultfinding

The faultfinding process for a system as large as this can be both tedious and time consuming (remember time is money!). In this section major fault occurrences likely to be encountered by operating each of the components is stated and the logical process to ascertain the fault cause is listed.

7.3.1 Solar Array Faults

* Most likely fault occurrence – Solar array does not give similar current output under similar irradiation conditions in the past.

Logical process for identifying fault cause

1. Check for shading of the modules
2. Check for dirt on modules
3. Check for any loose wires
4. Check current output for each string and check if any of the strings give an unrealistic low figure.
5. If an under performing string is identified, identify the particular module by shading each module successively and checking the relative changes in the ammeter reading. **The module that when shaded does not result in any change in ammeter reading is faulty.**

7.3.2 Battery Bank faults

* Most likely fault occurrence – Battery bank voltage is low after a long period of grid supply.

Logical process for identifying fault cause

1. Check that the battery bank fuse is intact

2. Check that all terminal connections are tight and clean.
3. Measure the battery voltage for the whole bank at the output terminals with no load or inverter connected to it.
4. If the battery terminal voltage is as expected then the fault only appears under load.
5. The voltage of each battery is checked with a heavy load connected. If the battery voltage drops significantly on connections then it means one or more battery cells might have a short circuit which only appears under load.

7.3.3 Inverter faults

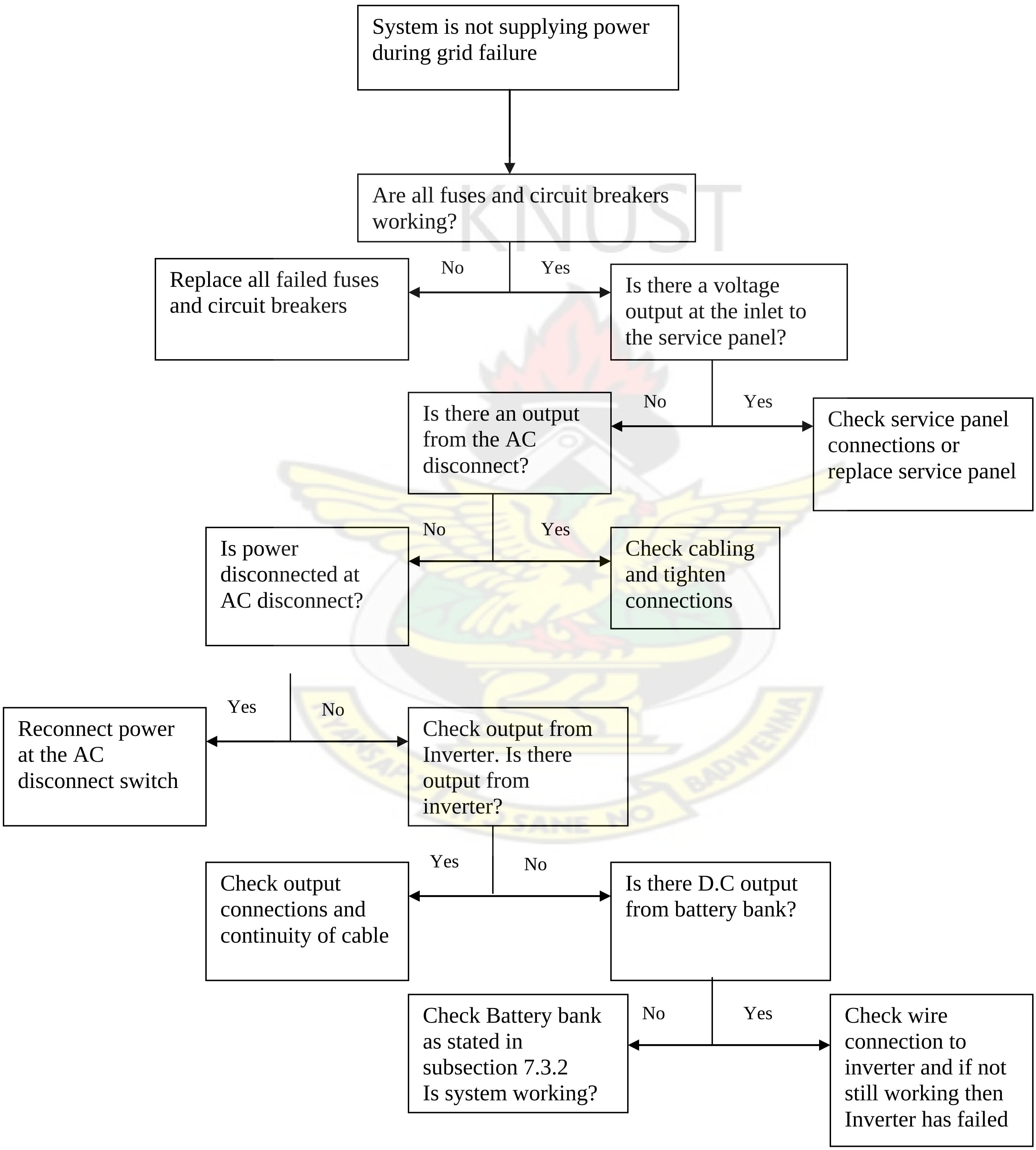
* Most likely fault occurrence – Inverter does not give required voltage output

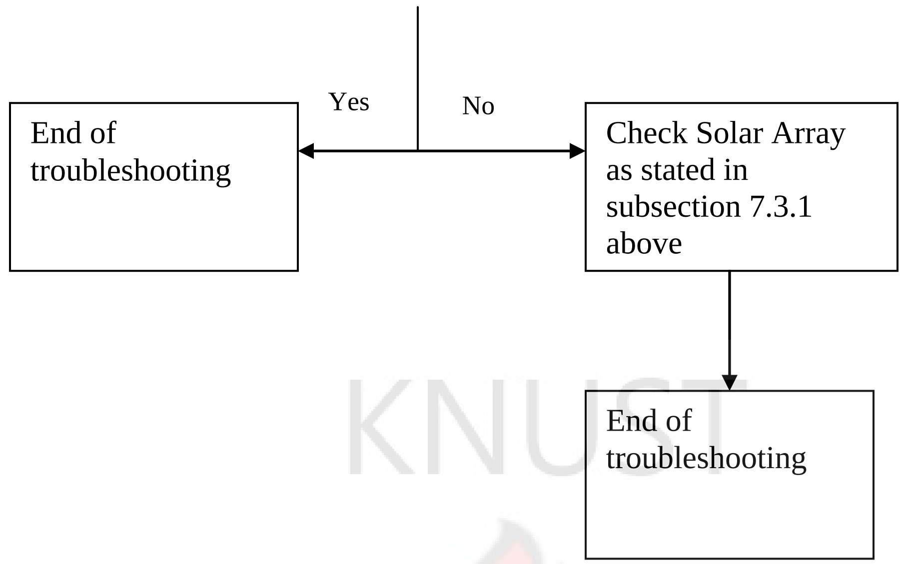
Logical process for identifying fault cause

1. Check for loose connections at input of Inverter
2. Then the fault is in the circuit board of the inverter and since the Trace sun-tied inverter comes with a 10 year warranty, the manufacturers are contacted for further instructions.

7.4 Grid Connected PV system troubleshooting tree

Fig 7.7 Troubleshooting tree




Yes
No
End of troubleshooting
Check Solar Array as stated in subsection 7.3.1 above
End of troubleshooting

Chapter Eight

Economic and environmental analysis of PV grid connected system with battery back-up

CHAPTER 8

ECONOMIC AND ENVIRONMENTAL ANALYSIS OF PV GRID CONNECTED SYSTEM WITH BATTERY BACKUP

8.0 ECONOMICAL AND ENVIRONMENTAL ANALYSIS

In this chapter, an economic and environmental comparative analysis will be undertaken between the 300 kVA PV grid connected system with 100% backup and a 300 kVA fuel generator.

This chapter will put to rest the question of which of this system is more economically and environmentally acceptable to solve KNUST's regular grid failure problem. The results of this chapter are actually applicable to all such systems in Ghana.

No attempt is made in this chapter to compare the cost of electricity produced by the PV grid connected system and the cost of electricity produced directly from the national grid.

8.1 Scope of economic analysis and methodology

An economic analysis is undertaken to choose the means using the least resources for a given output. All resource inputs and output are made up of their financial cost and their opportunity cost. In this comparative analysis, the focus is on the financial cost of the inputs and outputs since the main output (production of electricity to solve KNUST's grid failure problem) is the same for the two alternatives being compared. In financial analysis all expenditures incurred under the project and revenues resulting from it are taken into account.

In this economic analysis between the two mutually exclusive, technically feasible project options, the least cost analysis is used. The least cost analysis be itself does not provide an indication of the availability of funds for the project.

The Asian Development Bank's guidelines to economic analysis states that for project alternatives whose outcome is a homogenous product of the same quality, the average incremental economic cost (AIEC) method stands out. The consideration of AIEC aims to establish the project alternative with the lowest per unit costs. The AIEC is the ratio of the present value of the incremental investment and annual costs (Total costs) to the present value of the incremental output over the project life expected.

8.2 Sources of data

Information on the cost of the components of the grid connected PV system were derived from the manufacturers (BP Solar, Trace Engineering, Rolls Engineering etc) and the respective cost of importation, custom duties and average margins were obtained from DENG Ltd and Ecozone Ltd (Ghana's two largest solar companies). The information on the fuel generator was obtained from Mantrac Ghana Limited (Caterpillar Ghana Ltd) (one of Ghana's largest generator companies). All the above mentioned companies are situated in the Greater Accra Region of Ghana (about 300 kilometers from Kumasi where the university is situated).

All prices were sourced in January 2008 from manufacturers directly or through their respective websites.

The choice of the above mentioned suppliers was based on the following considerations;

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

ii. Companies with best prices for equal items e.g (Rolls Engineering)

iii. Companies with the ability to manufacture the exact specification of the item needed. For example, Trace Engineering

iv. Companies whose products meet the ISO 9001 and ISO 140003 certifications. For example, BP Solar.

v. Companies with lowest prices (BP Solar 180W module is $810 while that of Kyocera (Japan) is $927)

vi. Companies who were willing to provide breakdown of prices.

8.3 Estimation of project life.

In order to accurately estimate the average incremental economic cost of the project alternatives, 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 panel which is the most costly part of the system.

8.4 Estimation of relevant financial rates.

8.4.1 Interest rate

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

8.4.2 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 2008. In this economic analysis, the average inflation rate of 12% is used.

8.4.3 Exchange rate

Despite strong international prices for gold and cocoa, the national currency continued to depreciate marginally over the first half of this year (2008).

In this economic analysis the April 2008 value of Ghc 1.00/USD is used.

8.4.4 Selection of financing source

Considering KNUST's bill payment per month of about 150,000 dollars, it can be deduced that KNUST can not finance the initial cost of the PV grid connected system (2,188,000 dollars) and foreign financial support will be required. The loan is placed 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.

Actually, in this economic analysis, the payment plan does not affect the average incremental economic cost.

8.4.5 Sunk cost

While several types of cost need to be included in the economic analysis of a project, some types of financial costs (sunk costs) must be excluded. The underlying principle of economic analysis is that the project costs comprise the difference in costs between the without and with project situation, that is, the extra use of resources necessary to achieve the corresponding benefits.

Sunk costs are those costs that would exist both without and with the project, and this is not additional cost for achieving project benefits. In this analysis, the only sunk cost is the cost of land.

8.4.6 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 8.1 Warranty period and expected life time of system components

ITEM	WARRANTY PERIOD	EXPECTED LIFE TIME
SOLAR PANEL	25 YEARS	50 YEARS
INVERTER	20 YEARS	25 YEARS
SOLAR BATTERY	20 YEARS	25 YEARS
GENERATOR	1 YEAR	10 YEARS

8.5 Estimated investment cost of PV grid connected system

The investment cost of the PV system is shown in the table below.

Table 8.2 Estimating the overall cost of PV system in Ghana

Item	quantity	Unit cost from manufacturer ($)	Total cost at manufacturer	Shipping cost (10%)	Custom duties	Suppliers margins + VAT	Total cost in 1000$
300 KVA inverter	1	116,144	116,144	10,000	7,500	46,458	180.1
2V	360	861	309,960	30,996	23,247	123,876	488.07

batteries							
Panels BP 180W	1575	810	1,518,750	151,875	-	341,718	2012.3
Installation cost including mounting equipment	1575	40	-	-	-	-	63.00
SUB TOTAL							2743.07
Wiring, Transport and other incidental costs	5% of sub total						137.15
TOTAL							2880.22

The total estimated cost of the designed system is 2,88 million dollars.

8.6 Estimated investment cost of Fuel generator/plant

MANTRAC CAT

Ref: GE025/08

Monday, February 11, 2008

Attn: Mr. Frank Yeboah

Engineering consultant (KNUST)
KUMASI

frank9love@yahoo.com

PROFORMA INVOICE

One (1) Caterpillar model 550F generator Set in CANOPY ARRANGEMENT, powered by Caterpillar Diesel Watercooled C.18 engine. **Rated 500 KVA, 550 eKW,** 3 phase, 50Hz, 415/240 volts, 0.8 power factor at 1500 RPM.

Price ex T&E, Accra	US$100,200.00
15% VAT & NHIL	US$0
Total Price Ex Mantrac Accra	**US$100,200.00**

One Caterpillar Model 3406TA Generator Set powered by Caterpillar 406DEN8 Engine, **Prime Rated 320kVA, Standby rated 350kVA** 328e Kw, 3 phase, 50Hz, 415/240 volts, 0.8 power factor at 1500 RPM

Price Ex T&E, Accra	US$75,200.00
15% VAT +NHIS	US$11,280.00
Estimated Price ex T&E Accra	US$86,480.00

1 x ATI800 Automatic Transfer Switch rated 800 Amps.

Price Ex T&E, Accra	US$6,600.00
15% VAT +NHIS	US$ 990.00
Estimated Price ex T&E Accra	**US$7,590.00**

Country of Origin	UK
Delivery	10 – 12 weeks Ex factory.
Payment Terms	50% deposit with order and 50% on arrival before delivery.
Warranty	Caterpillar engines and attachments are covered by Caterpillar's warranty against faulty workmanship or material for a period of twelve months, commencing at the delivery date to the end user.
Validity:	Prices will remain valid for 30 days from the date o this Proforma Invoice.

11/02/08
Kwame Gyan-Tawiah
Power Systems Manager

All quotations, acceptance of orders contracts are subject to the General Conditions of Sale Endorsed on the back Hereof which shall prevail over other provisions inconsistent therewith unless the contrary is expressly stated

Accra
P. O. Box 5207, Accra-North
Tel.: +233 21 221900, 221916 221980, 225822, 232385 239625/26/29
Fax: +233 21 221950

Kumasi
P. O. Box 3000, Kumasi
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Takoradi
P. O. Box 386, Takoradi
Tel: +233 31 22900 23450, 24213
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Tarkwa
P. O. Box 200, Tarkwa
Tel: +233 362 20706 20707, 20708
Fax: +233 362 20709

Website: www.mantracgroup.com

DIRECTORS: Ishmael Evans Yamson, Steven Andrew Scott, Tarek Shata, Omar Ahmed Fouad Elbakary

This information was received from Mantrac Ghana Limited. Upon further discussions, the cost of transport, installation, wiring and other incidental costs was agreed to be 10% of the estimated price.

Therefore the cost of the Fuel generator will be;

(86,480 + 7,590) * 1.1 = $103,477

8.7 Estimation of energy needed during grid failure times.

The estimated total power required to power loads during grid failure is as follows;

E_{dl}= total AC energy to be supplied by grid connected PV system which is determined from estimated daily load table and allowance for future load growth.

$$E_{tot} = \frac{2000}{0.95} = 2105.3KWh$$ ----------------------------------(5)

But this is the supply for a whole day, for the estimated number of eight (8) hours of grid failures.

The estimated total power required to power loads during grid failure is

$\frac{8}{24} \times 2105.3 = 701KWh$ per grid failure day

For 46 grid failures per year, the total power needed will be

46 X 701KWh= 32,281KWh

8.8 Financial value of energy output (benefit) in running PV grid- connected system in the first year.

Reproducing former calculation, the average yearly output of the PV into the KNUST system is

$E_{sys.yr}$ = 873881.39Wh X 365 – 491274 X 46------------(32)

=318MWh-22MWh

= 296MWh = 0.296GWh

Total energy supplied to KNUST during grid active times per year = 0.296 GWh

Cost of KNUST's electricity = 0.0905 per KWh + about 25% for maximum demand surcharges

The total accrued benefit = $\frac{125}{100} \times 296000 \times 0.0905 = 33{,}485$

The total accrued benefit in first year during grid active time = 33,485 dollars

In economic analysis, the accrued benefit of supply of power during the grid failure in the first year should be estimated.

The total electricity supplied to KNUST during the first year in grid failure is 32,281Wh

Therefore, the total additional accrued benefit = $\frac{125}{100} \times 32281 \times 0.0905 = 3651$

The total accrued benefit in the first year is 33485 + 3651=37136 dollars

8.9 Financial value of energy output (benefit) in running Fuel generator in the first year.

In economic analysis, the accrued benefit of supply of power during the grid failure in the first year should be estimated as the benefit of the fuel generator

The total electricity supplied to KNUST during the first year in grid failure is 32,281kWh

Therefore, the total additional accrued benefit = $\frac{125}{100} \times 32281 \times 0.0905 = 3651$

The total accrued benefit in the first year is 3651 dollars

8.9.1 Running cost (including maintenance and minor replacements) of Fuel generator/plant

Total estimated number of hours of grid failure per year = 8 x 46 =368

Total estimated fuel consumption is about 73L/ hr of fuel generator operation (Mantrac Ghana Limited).

Total fuel consumed in year = 368 X 73 = 26,864 Litters

Cost of one liter of diesel is about 1.176 dollars (Goil service station, Maxima on 10th April, 2008)

Total cost of fuel consumed in first year = 1.176 X 26,864 = 31,592.06 dollars

The cost of maintenance (changing oil, changing filters etc) for the generator per year is given as 3% of the cost of the generator

Therefore the cost of maintenance in first year = 3/100 X 86,480 = 2,594 dollars = 2,386 dollars.

Total running cost = 33978.06 dollar in first year

8.9.2 Running cost (including maintenance and replacement) of the grid-connected PV system.

Grid connected PV systems have very minimal maintenance cost as covered in Chapter 7 of this report. Considering the present prevailing industry rates for maintenance of one Ghana Cedi/dollar per solar panel per year for large systems, the cost of maintenance of for this system per year will be 1 x 1575 panels= **1,575 dollars.** This cost is mainly for battery maintenance.

8.10 Calculation of Average Incremental Economic cost of PV grid connected system over the 25 year project life.

Table 8.3 Calculation of the AIEC of the PV grid connected system.

ECONOMIC ANALYSIS OF TWO ALTERNATIVES USING THE CALCULATION OF THEIR RESPECTIVE AVERAGE INCREMENTAL ECONOMIC COSTS							
Calculation of AIEC of PV grid connected system							
YEAR	INVESTMENT	INTEREST PAYABLE	RUNNING COST	REPLACE MENT COSTS	TOTAL COSTS	VALUE OF BENEFITS	COSTS - BENEFITS
1	115200	9216	1575		125991.0	37136.0	88855.0
2	115200	9216	1764.0		126180.0	41592.3	84587.7
3	115200	9216	1975.7		126391.7	46583.4	79808.3
4	115200	9216	2212.8		126628.8	52173.4	74455.4
5	115200	9216	2478.3		126894.3	58434.2	68460.1
6	115200	9216	2775.7		127191.7	65446.3	61745.4
7	115200	9216	3108.8		127524.8	73299.9	54224.9
8	115200	9216	3481.8		127897.8	82095.9	45802.0
9	115200	9216	3899.6		128315.6	91947.4	36368.3
10	115200	9216	4367.6		128783.6	102981.1	25802.5
11	115200	9216	4891.7		129307.7	115338.8	13968.9
12	115200	9216	5478.7		129894.7	129179.4	715.3
13	115200	9216	6136.2		130552.2	144681.0	-14128.8
14	115200	9216	6872.5		131288.5	162042.7	-30754.2
15	115200	9216	7697.2		132113.2	181487.8	-49374.6
16	115200	9216	8620.9		133036.9	203266.3	-70229.5
17	115200	9216	9655.4		134071.4	227658.3	-93586.9
18	115200	9216	10814.0		135230.0	254977.3	-119747.3
19	115200	9216	12111.7		136527.7	285574.6	-149046.9
20	115200	9216	13565.1		137981.1	319843.5	-181862.4
21	115200	9216	15192.9		139608.9	358224.7	-218615.8
22	115200	9216	17016.1		141432.1	401211.7	-259779.6
23	115200	9216	19058.0		143474.0	449357.1	-305883.1
24	115200	9216	21344.9		145760.9	503280.0	-357519.0
25	115200	9216	23906.3		148322.3	563673.6	-415351.2
				NPV	3320400.8	4951486.6	
				AIEC	0.670586		

Notes on table 8.2

1. The interest rate of the loan is taken as 8% and the loan is paid in equal installment over the 25 year period.

2. The rate of inflation is taken to be 8%.

3. The expected life time of all the panels, inverter and battery are taken to above 25 years.

4. The Average Incremental Economic Cost is 0.67 meaning the net present value of the cost and investment in the system is lower than the net present value of the benefits in the system.

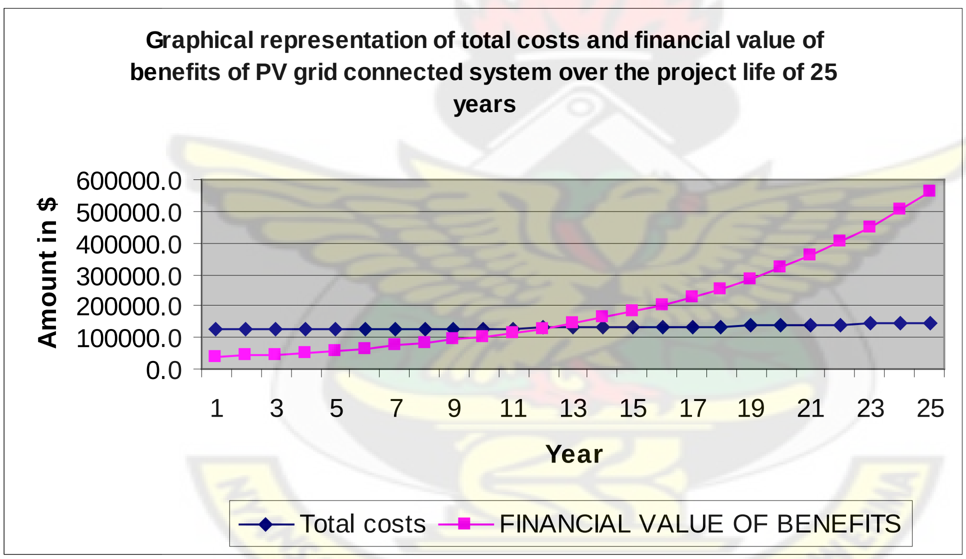

Fig 8.1 Graphical representation of total costs and financial value of benefits over project life of 25 years

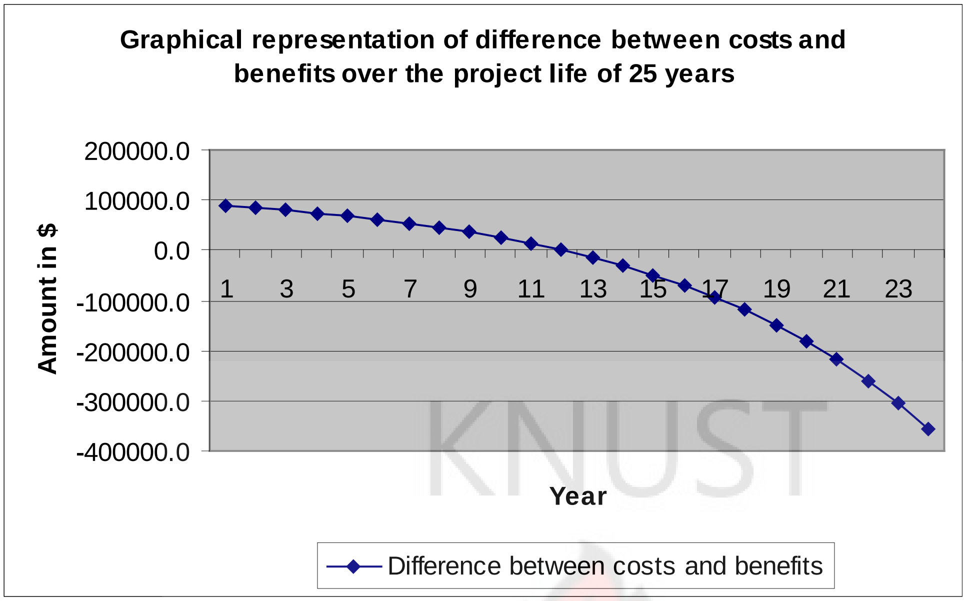

Fig 8.2 Graphical representation of difference between costs and benefits over the project life of 25 years

<u>Notes on figure 8.2</u>

1. The graph shows that the financial value of the benefits outweigh the costs in the 13th year of operation.

8.11 Calculation of Average Incremental Economic cost of the fuel generator over the 25 year project life.

Table 8.4 Calculation of the AIEC of the fuel generator

ECONOMIC ANALYISIS OF TWO ALTERNATIVES USING THE CALCULATION OF THEIR RESPECTIVE AVERAGE INCREMENTAL ECONOMIC COSTS							
Calculation of AIEC of fuel generator							
YEAR	INVESTMENT	INTEREST PAYABLE	RUNNING COST	REPLACEMENT COSTS	TOTAL COSTS	VALUE OF BENEFITS	COSTS - BENEFITS
1	103477	8278.2	33978		145733.2	3651.0	142082.2
2			38055.4		38055.4	4089.1	33966.2
3			42622.0		42622.0	4579.8	38042.2
4			47736.6		47736.6	5129.4	42607.3
5			53465.0		53465.0	5744.9	47720.1
6			59880.8		59880.8	6434.3	53446.5
7			67066.5		67066.5	7206.4	59860.1
8			75114.5		75114.5	8071.2	67043.3
9			84128.3		84128.3	9039.7	75088.5
10			94223.7	309905	404128.7	10124.5	394004.2
11			105530.5		105530.5	11339.5	94191.1
12			118194.2		118194.2	12700.2	105494.0
13			132377.5		132377.5	14224.2	118153.3
14			148262.8		148262.8	15931.1	132331.7
15			166054.3		166054.3	17842.8	148211.5
16			185980.8		185980.8	19984.0	165996.8
17			208298.5		208298.5	22382.1	185916.4
18			233294.3		233294.3	25067.9	208226.4
19			261289.7		261289.7	28076.1	233213.6
20			292644.4	962520	1255164.4	31445.2	1223719.2
21			327761.7		327761.7	35218.6	292543.1
22			367093.2		367093.2	39444.9	327648.3
23			411144.3		411144.3	44178.2	366966.1
24			460481.7		460481.7	49479.6	411002.0
25			515739.5		515739.5	55417.2	460322.3
				NPV	5914598.4	486802.0	
				AIEC	12.149907		

Note on table 8.3

1. The interest rate of the loan is taken as 8% and the loan is paid in one year.

2. The rate of inflation is taken to be 8%.

3. The expected life time of the fuel generator is taken to be 10 years or about 3000 hrs of operation.

4. The Average Incremental Economic Cost is 12.15 meaning the net present value of the costs is greater than the net present value of the benefits.

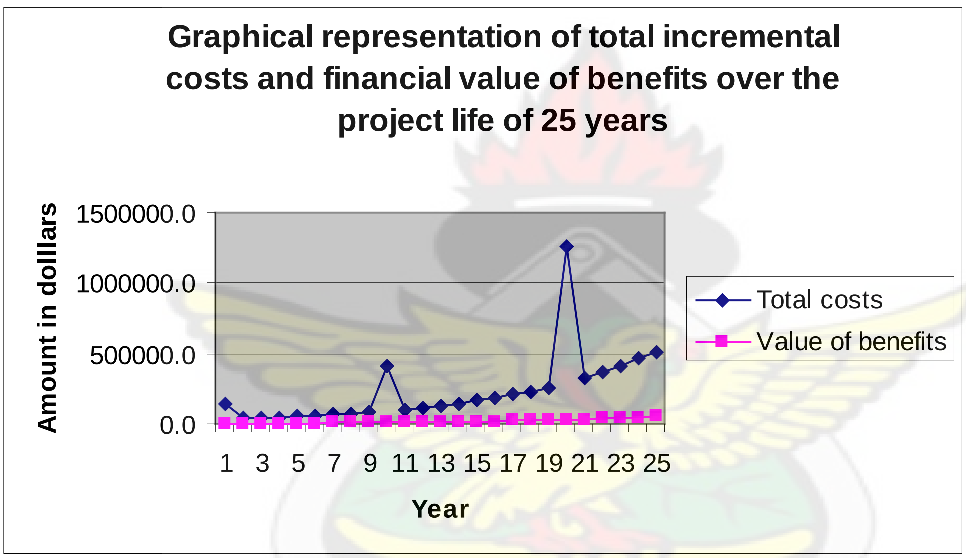

Fig 8.3 Graphical representation of the total incremental costs and financial value of benefits

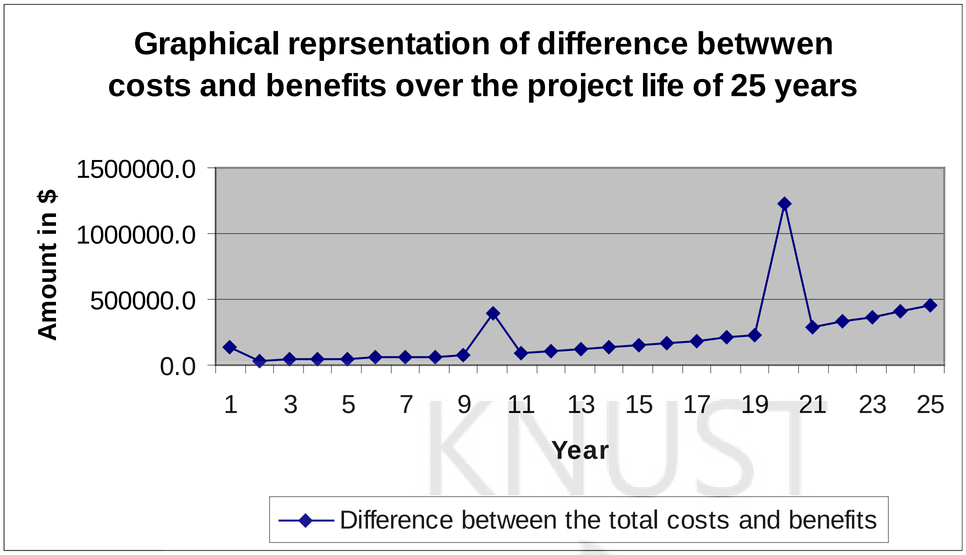

Fig 8.4 Graphical representation of difference between costs and benefits of the project

8.12 Conclusion on economic analysis

It is realized that PV grid connected systems are presently economically preferable as a solution to providing power during regular grid failure at KNUST and other large institutions since it has an Average Incremental Economic Cost which is lower than that of the fuel generator (0.67 < 12.14) over a project life of 25 years at an inflation rate of 12% per annum and a loan interest rate of 8%.

8.13 Sensitivity Analysis

Sensitivity analysis is undertaken to help identify the key variables that can influence the project cost and benefit streams. It involves the recalculating of the above results for different values of major assumed variables.

The major assumed variables in the above economic analysis are;

a. Project life time

b. Inflation rate

8.13.1 Sensitivity Analysis by varying project life time.

It is argued by the manufactures that although the PV panel has a warranty of 25 years it is expected to have a life time of 50 years.

Table 8.5 Calculation of the AIEC of the PV grid connected system over 50 years

ECONOMIC ANALYSIS OF TWO ALTERNATIVES USING THE CALCULATION OF THEIR RESPECTIVE AVERAGE INCREMENTAL ECONOMIC COSTS							
Calculation of AIEC of PV grid connected system							
YEAR	INVESTMENT	INTEREST PAYABLE	RUNNING COST	REPLACEMENT COSTS	TOTAL COSTS	VALUE OF BENEFITS	COSTS - BENEFITS
1	115200	9216	1575		125991.0	37136	88855.0
2	115200	9216	1764.0		126180.0	41592.32	84587.7
3	115200	9216	1975.7		126391.7	46583.398	79808.3
4	115200	9216	2212.8		126628.8	52173.406	74455.4
5	115200	9216	2478.3		126894.3	58434.215	68460.1
6	115200	9216	2775.7		127191.7	65446.321	61745.4
7	115200	9216	3108.8		127524.8	73299.879	54224.9
8	115200	9216	3481.8		127897.8	82095.865	45802.0
9	115200	9216	3899.6		128315.6	91947.369	36368.3
10	115200	9216	4367.6		128783.6	102981.05	25802.5
11	115200	9216	4891.7		129307.7	115338.78	13968.9
12	115200	9216	5478.7		129894.7	129179.43	715.3
13	115200	9216	6136.2		130552.2	144680.96	-14128.8
14	115200	9216	6872.5		131288.5	162042.68	-30754.2
15	115200	9216	7697.2		132113.2	181487.8	-49374.6
16	115200	9216	8620.9		133036.9	203266.34	-70229.5
17	115200	9216	9655.4		134071.4	227658.3	-93586.9
18	115200	9216	10814.0		135230.0	254977.29	-119747.3
19	115200	9216	12111.7		136527.7	285574.57	-149046.9
20	115200	9216	13565.1		137981.1	319843.52	-181862.4
21	115200	9216	15192.9		139608.9	358224.74	-218615.8
22	115200	9216	17016.1		141432.1	401211.71	-259779.6
23	115200	9216	19058.0		143474.0	449357.11	-305883.1
24	115200	9216	21344.9		145760.9	503279.97	-357519.0
25	115200	9216	23906.3		148322.3	563673.56	-415351.2
26			26775.1	490705	517480.1	631314.39	-113834.3
27			29988.1	490705	520693.1	707072.12	-186379.0
28			33586.7	490705	524291.7	791920.77	-267629.1

29			37617.1	490705	528322.1	886951.27	-358629.2
30			42131.1	490705	532836.1	993385.42	-460549.3
31			47186.9	490705	537891.9	1112591.7	-574699.8
32			52849.3	490705	543554.3	1246102.7	-702548.4
33			59191.2	490705	549896.2	1395635	-845738.8
34			66294.2	490705	556999.2	1563111.2	-1006112.0
35			74249.5	490705	564954.5	1750684.5	-1185730.1
36			83159.4	490705	573864.4	1960766.7	-1386902.3
37			93138.5	490705	583843.5	2196058.7	-1612215.1
38			104315.2	490705	595020.2	2459585.7	-1864565.6
39			116833.0	490705	607538.0	2754736	-2147198.0
40			130852.9	490705	621557.9	3085304.3	-2463746.4
41			146555.3	490705	637260.3	3455540.8	-2818280.6
42			164141.9	490705	654846.9	3870205.7	-3215358.8
43			183838.9	490705	674543.9	4334630.4	-3660086.5
44			205899.6	490705	696604.6	4854786.1	-4158181.5
45			230607.6	490705	721312.6	5437360.4	-4716047.8
46			258280.5	490705	748985.5	6089843.7	-5340858.2
47			289274.1	490705	779979.1	6820624.9	-6040645.8
48			323987.0	490705	814692.0	7639099.9	-6824407.9
49			362865.5	490705	853570.5	8555791.9	-7702221.4
50			406409.3	490705	897114.3	9582486.9	-8685372.6
			Net Present Value		19158053.7	89127078	
		AIEC	0.214952				

Table 8.6 Calculation of the AIEC of the fuel generator over 50 years

ECONOMIC ANALYISIS OF TWO ALTERNATIVES USING THE CALCULATION OF THEIR RESPECTIVE AVERAGE INCREMENTAL ECONOMIC COSTS							
Calculation of AIEC of 300kVA fuel generator							
YEAR	INVESTMENT	INTEREST PAYABLE	RUNNING COST	REPLACE MENT COSTS	TOTAL COSTS	VALUE OF BENEFITS	COSTS - BENEFITS
1	103477	8278.2	33978		145733.2	3651.0	142082.2
2			38055.4		38055.4	4089.1	33966.2
3			42622.0		42622.0	4579.8	38042.2
4			47736.6		47736.6	5129.4	42607.3
5			53465.0		53465.0	5744.9	47720.1
6			59880.8		59880.8	6434.3	53446.5
7			67066.5		67066.5	7206.4	59860.1
8			75114.5		75114.5	8071.2	67043.3
9			84128.3		84128.3	9039.7	75088.5
10			94223.7	309905	404128.7	10124.5	394004.2
11			105530.5		105530.5	11339.5	94191.1

12			118194.2		118194.2	12700.2	105494.0
13			132377.5		132377.5	14224.2	118153.3
14			148262.8		148262.8	15931.1	132331.7
15			166054.3		166054.3	17842.8	148211.5
16			185980.8		185980.8	19984.0	165996.8
17			208298.5		208298.5	22382.1	185916.4
18			233294.3		233294.3	25067.9	208226.4
19			261289.7		261289.7	28076.1	233213.6
20			292644.4	962520	1255164.4	31445.2	1223719.2
21			327761.7		327761.7	35218.6	292543.1
22			367093.2		367093.2	39444.9	327648.3
23			411144.3		411144.3	44178.2	366966.1
24			460481.7		460481.7	49479.6	411002.0
25			515739.5		515739.5	55417.2	460322.3
26			577628.2		577628.2	62067.2	515561.0
27			646943.6		646943.6	69515.3	577428.3
28			724576.8		724576.8	77857.1	646719.7
29			811526.0		811526.0	87200.0	724326.0
30			908909.1	2989442	3898351.1	97664.0	3800687.1
31			1017978.2		1017978.2	109383.7	908594.6
32			1140135.6		1140135.6	122509.7	1017625.9
33			1276951.9		1276951.9	137210.9	1139741.0
34			1430186.1		1430186.1	153676.2	1276509.9
35			1601808.5		1601808.5	172117.3	1429691.1
36			1794025.5		1794025.5	192771.4	1601254.1
37			2009308.5		2009308.5	215904.0	1793404.6
38			2250425.6		2250425.6	241812.5	2008613.1
39			2520476.6		2520476.6	270830.0	2249646.7
40			2822933.8	9284755	12107688.8	303329.5	11804359.3
41			3161685.9		3161685.9	339729.1	2821956.8
42			3541088.2		3541088.2	380496.6	3160591.6
43			3966018.8		3966018.8	426156.2	3539862.6
44			4441941.0		4441941.0	477294.9	3964646.1
45			4974973.9		4974973.9	534570.3	4440403.6
46			5571970.8		5571970.8	598718.7	4973252.1
47			6240607.3		6240607.3	670565.0	5570042.3
48			6989480.2		6989480.2	751032.8	6238447.4
49			7828217.8		7828217.8	841156.7	6987061.1
50			8767603.9		8767603.9	942095.5	7825508.4
			Net Present Value		95206197.2	8762466.626	
		AIEC	**10.8652**				

It is realized from the above tables that over the 50 year period, the AIEC of the PV grid connected system is still more economically wise than the fuel generator.

8.13.2 Sensitivity analysis by varying the inflation rate.

Considering the fact that most of the components in both system are not produced in Ghana. We can undertake a sensitivity analysis to see the effect on the system if the inflation rate is reduced to 7% over the 25 year period.

Table 8.7 Recalculating AIEC of fuel generator based on the inflation rate of 7%

ECONOMIC ANALYSIS OF TWO ALTERNATIVES USING THE CALCULATION OF THEIR RESPECTIVE AVERAGE INCREMENTAL ECONOMIC COSTS							
Calculation of AIEC of fuel generator							
YEAR	INVESTMENT	INTEREST PAYABLE	RUNNING COST	REPLACEMENT COSTS	TOTAL COSTS	VALUE OF BENEFITS	COSTS - BENEFITS
1	103477	8278.2	33978		145733.2	3651.0	142082.2
2			36356.5		36356.5	3906.6	32449.9
3			38901.4		38901.4	4180.0	34721.4
4			41624.5		41624.5	4472.6	37151.9
5			44538.2		44538.2	4785.7	39752.5
6			47655.9		47655.9	5120.7	42535.2
7			50991.8		50991.8	5479.2	45512.6
8			54561.2		54561.2	5862.7	48698.5
9			58380.5		58380.5	6273.1	52107.4
10			62467.2	190238.2	252705.4	6712.2	245993.2
11			66839.9		66839.9	7182.1	59657.8
12			71518.7		71518.7	7684.8	63833.8
13			76525.0		76525.0	8222.8	68302.2
14			81881.7		81881.7	8798.3	73083.4
15			87613.4		87613.4	9414.2	78199.2
16			93746.4		93746.4	10073.2	83673.1
17			100308.6		100308.6	10778.3	89530.3
18			107330.2		107330.2	11532.8	95797.4
19			114843.3		114843.3	12340.1	102503.2
20			122882.4	374227.4	497109.8	13203.9	483905.8
21			131484.1		131484.1	14128.2	117355.9
22			140688.0		140688.0	15117.2	125570.8
23			150536.2		150536.2	16175.4	134360.8
24			161073.7		161073.7	17307.7	143766.0
25			172348.9		172348.9	18519.2	153829.7
					2825296.6	230922.2	
				AIEC	12.23484		

Note on table 8.6

1. The interest rate of the loan is taken as 8% and the loan is paid in one year.

2. The rate of inflation is taken to be 7%.

3. The expected life time of the fuel generator is taken to be 10 years or about 3000 hrs of operation.

4. The Average Incremental Economic Cost is 12.234 meaning the net present value of the costs is greater than the net present value of the benefits.

Table 8.8 Recalculating AIEC of PV grid connected system based on the inflation rate of 7%.

ECONOMIC ANALYSIS OF TWO ALTERNATIVES USING THE CALCULATION OF THEIR RESPECTIVE AVERAGE INCREMENTAL ECONOMIC COSTS							
Calculation of AIEC of PV grid connected system							
YEAR	INVESTMENT	INTEREST PAYABLE	RUNNING COST	REPLACEMENT COSTS	TOTAL COSTS	VALUE OF BENEFITS	COSTS - BENEFITS
1	115200	9216	1575		125991.0	37136.0	88855.0
2	115200	9216	1685.3		126101.3	39735.5	86365.7
3	115200	9216	1803.2		126219.2	42517.0	83702.2
4	115200	9216	1929.4		126345.4	45493.2	80852.2
5	115200	9216	2064.5		126480.5	48677.7	77802.8
6	115200	9216	2209.0		126625.0	52085.2	74539.9
7	115200	9216	2363.7		126779.7	55731.1	71048.5
8	115200	9216	2529.1		126945.1	59632.3	67312.8
9	115200	9216	2706.1		127122.1	63806.6	63315.6
10	115200	9216	2895.6		127311.6	68273.0	59038.6
11	115200	9216	3098.3		127514.3	73052.1	54462.1
12	115200	9216	3315.1		127731.1	78165.8	49565.4
13	115200	9216	3547.2		127963.2	83637.4	44325.8
14	115200	9216	3795.5		128211.5	89492.0	38719.5
15	115200	9216	4061.2		128477.2	95756.4	32720.7
16	115200	9216	4345.5		128761.5	102459.4	26302.1
17	115200	9216	4649.7		129065.7	109631.6	19434.1
18	115200	9216	4975.1		129391.1	117305.8	12085.4
19	115200	9216	5323.4		129739.4	125517.2	4222.2

20	115200	9216	5696.0		130112.0	134303.4	-4191.3
21	115200	9216	6094.8		130510.8	143704.6	-13193.8
22	115200	9216	6521.4		130937.4	153763.9	-22826.5
23	115200	9216	6977.9		131393.9	164527.4	-33133.5
24	115200	9216	7466.3		131882.3	176044.3	-44162.0
25	115200	9216	7989.0		132405.0	188367.4	-55962.4
				totals	3210017.2	197785.8	
				AIEC	16.2297667		

The results of the above AIEC recalculations show that if an inflation rate of 7% per annum is chosen the fuel generator is seen to be more economical than the PV grid connected system.

8.13.3 Sensitivity analysis by varying project life and inflation rate.

Now the two variations are combined and the AIEC is calculated.

Table 8.9 Recalculating AIEC of fuel generator based on the inflation rate of 5% and a project life of 50 years

ECONOMIC ANALYSIS OF TWO ALTERNATIVES USING THE CALCULATION OF THEIR RESPECTIVE AVERAGE INCREMENTAL ECONOMIC COSTS							
Calculation of AIEC of 300kVA fuel generator							
YEAR	INVESTMENT	INTEREST PAYABLE	RUNNING COST	REPLACE MENT COSTS	TOTAL COSTS	VALUE OF BENEFITS	COSTS - BENEFITS
1	103477	8278.2	33978		145733.2	3651.0	142082.2
2			36356.5		36356.5	3906.6	32449.9
3			38901.4		38901.4	4180.0	34721.4
4			41624.5		41624.5	4472.6	37151.9
5			44538.2		44538.2	4785.7	39752.5
6			47655.9		47655.9	5120.7	42535.2
7			50991.8		50991.8	5479.2	45512.6
8			54561.2		54561.2	5862.7	48698.5
9			58380.5		58380.5	6273.1	52107.4
10			62467.2	190238	252705.2	6712.2	245993.0
11			66839.9		66839.9	7182.1	59657.8
12			71518.7		71518.7	7684.8	63833.8
13			76525.0		76525.0	8222.8	68302.2
14			81881.7		81881.7	8798.3	73083.4
15			87613.4		87613.4	9414.2	78199.2

16			93746.4		93746.4	10073.2	83673.1
17			100308.6		100308.6	10778.3	89530.3
18			107330.2		107330.2	11532.8	95797.4
19			114843.3		114843.3	12340.1	102503.2
20			122882.4	374227	497109.4	13203.9	483905.4
21			131484.1		131484.1	14128.2	117355.9
22			140688.0		140688.0	15117.2	125570.8
23			150536.2		150536.2	16175.4	134360.8
24			161073.7		161073.7	17307.7	143766.0
25			172348.9		172348.9	18519.2	153829.7
26			184413.3		184413.3	19815.6	164597.7
27			197322.2		197322.2	21202.6	176119.6
28			211134.8		211134.8	22686.8	188448.0
29			225914.2		225914.2	24274.9	201639.3
30			241728.2	736161	977889.2	25974.2	951915.1
31			258649.2		258649.2	27792.3	230856.9
32			276754.6		276754.6	29737.8	247016.8
33			296127.5		296127.5	31819.5	264308.0
34			316856.4		316856.4	34046.8	282809.6
35			339036.3		339036.3	36430.1	302606.2
36			362768.9		362768.9	38980.2	323788.7
37			388162.7		388162.7	41708.8	346453.9
38			415334.1		415334.1	44628.4	370705.7
39			444407.5		444407.5	47752.4	396655.1
40			475516.0	1448142	1923658.0	51095.1	1872562.9
41			508802.1		508802.1	54671.7	454130.4
42			544418.3		544418.3	58498.8	485919.5
43			582527.6		582527.6	62593.7	519933.9
44			623304.5		623304.5	66975.2	556329.2
45			666935.8		666935.8	71663.5	595272.3
46			713621.3		713621.3	76680.0	636941.4
47			763574.8		763574.8	82047.5	681527.2
48			817025.0		817025.0	87790.9	729234.2
49			874216.8		874216.8	93936.2	780280.5
50			935412.0		935412.0	100511.8	834900.2
			Net Present Value		16673563.1	1484237.122	
		AIEC	**11.2337597**				

Table 8.10 Recalculating AIEC of PV grid connected system based on the inflation rate of 7% and a project life of 50 years

ECONOMIC ANALYSIS OF TWO ALTERNATIVES USING THE CALCULATION OF THEIR RESPECTIVE AVERAGE INCREMENTAL ECONOMIC COSTS							
Calculation of AIEC of PV grid connected system							
YEAR	INVESTMENT	INTEREST PAYABLE	RUNNING COST	REPLACEMENT COSTS	TOTAL COSTS	VALUE OF BENEFITS	COSTS - BENEFITS
1	115200	9216	1575		125991.0	37136	88855.0
2	115200	9216	1685.3		126101.3	39735.52	86365.7
3	115200	9216	1803.2		126219.2	42517.006	83702.2
4	115200	9216	1929.4		126345.4	45493.197	80852.2
5	115200	9216	2064.5		126480.5	48677.721	77802.8
6	115200	9216	2209.0		126625.0	52085.161	74539.9
7	115200	9216	2363.7		126779.7	55731.122	71048.5
8	115200	9216	2529.1		126945.1	59632.301	67312.8
9	115200	9216	2706.1		127122.1	63806.562	63315.6
10	115200	9216	2895.6		127311.6	68273.021	59038.6
11	115200	9216	3098.3		127514.3	73052.133	54462.1
12	115200	9216	3315.1		127731.1	78165.782	49565.4
13	115200	9216	3547.2		127963.2	83637.387	44325.8
14	115200	9216	3795.5		128211.5	89492.004	38719.5
15	115200	9216	4061.2		128477.2	95756.444	32720.7
16	115200	9216	4345.5		128761.5	102459.4	26302.1
17	115200	9216	4649.7		129065.7	109631.55	19434.1
18	115200	9216	4975.1		129391.1	117305.76	12085.4
19	115200	9216	5323.4		129739.4	125517.16	4222.2
20	115200	9216	5696.0		130112.0	134303.37	-4191.3
21	115200	9216	6094.8		130510.8	143704.6	-13193.8
22	115200	9216	6521.4		130937.4	153763.92	-22826.5
23	115200	9216	6977.9		131393.9	164527.4	-33133.5
24	115200	9216	7466.3		131882.3	176044.32	-44162.0
25	115200	9216	7989.0		132405.0	188367.42	-55962.4
26			8548.2	135534	144081.8	201553.14	-57471.3
27			9146.6	135534	144680.2	215661.86	-70981.6
28			9786.8	135534	145320.5	230758.19	-85437.7
29			10471.9	135534	146005.6	246911.26	-100905.7
30			11205.0	135534	146738.6	264195.05	-117456.5
31			11989.3	135534	147522.9	282688.7	-135165.8
32			12828.6	135534	148362.2	302476.91	-154114.7
33			13726.6	135534	149260.2	323650.3	-174390.1
34			14687.4	135534	150221.1	346305.82	-196084.8

35			15715.5	135534	151249.2	370547.22	-219298.1
36			16815.6	135534	152349.3	396485.53	-244136.3
37			17992.7	135534	153526.3	424239.52	-270713.2
38			19252.2	135534	154785.8	453936.28	-299150.4
39			20599.9	135534	156133.5	485711.82	-329578.3
40			22041.8	135534	157575.5	519711.65	-362136.2
41			23584.8	135534	159118.4	556091.47	-396973.1
42			25235.7	135534	160769.3	595017.87	-434248.5
43			27002.2	135534	162535.8	636669.12	-474133.3
44			28892.4	135534	164426.0	681235.96	-516810.0
45			30914.8	135534	166448.5	728922.48	-562474.0
46			33078.9	135534	168612.5	779947.05	-611334.5
47			35394.4	135534	170928.0	834543.34	-663615.3
48			37872.0	135534	173405.6	892961.38	-719555.7
49			40523.0	135534	176056.7	955468.67	-779412.0
50			43359.6	135534	178893.3	1022351.5	-843458.2
			Net Present Value		7139024.1	1073469.1	
		AIEC	6.650424				

From the above sensitivity analysis it is clear that PV grid connected systems are more economically efficient if they have longer project lives and the rate of inflation is high. In Ghana which normally has a high inflation rate, PV grid connected systems are more economically efficient than fuel generators of the same capacity.

8.14 Environmental comparative analysis of PV grid connected system and Fuel generator/plant

Many have questioned if it is important to consider environmental issues when considering the options for producing power in Ghana. They argue that climate change is a foreign issue and it is being championed by the developed countries that don't have problems with power supply. The author believes that it is not adequate for academia to solve one problem and create another in the process for the future.

Therefore the environmental comparative analysis is being undertaken.

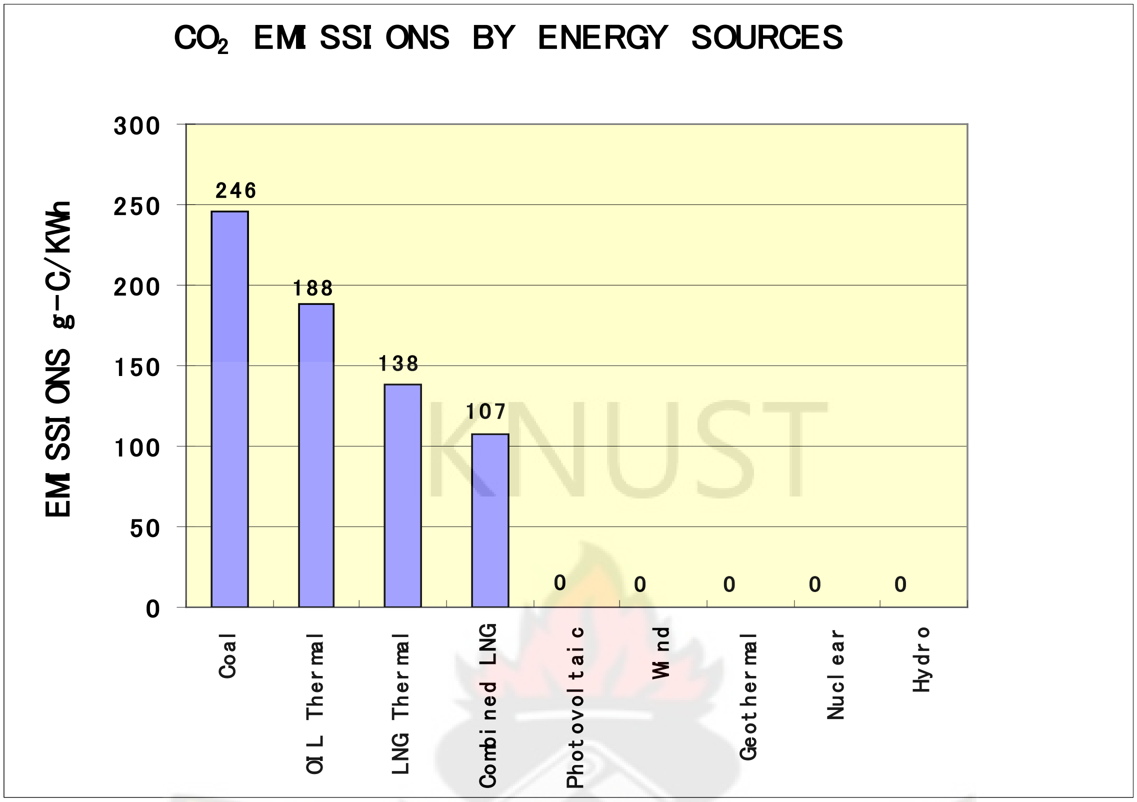

Fig 8.5 CO_2 emissions by energy sources (Source: Central Research Institute of Electric Power Industry)

It is clear for the graph above that the implementation of a grid connected PV system is environmentally friendly and save about 180g/KWh produced and in the future it is expected that special monetary benefits will be derived for producing power from environmentally friendly sources.

8.15 Recommendations

From the economic and environmental analysis undertaken above it is recommended by the researcher that PV grid connected systems should be implemented instead of fuel generators since they are more economically and environmentally efficient.

Chapter Nine

REFERENCES

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REFERENCES

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