TECHNICAL AND ECONOMIC ANALYSIS OF A 1MW GRID-CONNECTED SOLAR PHOTOVOLTAIC POWER SYSTEM AT KNUST-KUMASI

By

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DECLARATION

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

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(Head of Department)	Signature	Date

DEDICATION

This work is dedicated to

Madam Grace Tettey (my mother)

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First and foremost acknowledgement goes to the Almighty God for making it possible for me to live to undertake this study.

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ABSTRACT

Grid-connected solar PV systems, though the fastest growing renewable energy technology in the world, have not been fully exploited in Africa; one of the reasons being the very high initial investment. Prices of solar PV systems have however been on a decline for the past few years due to technological innovations which have led to improvements in cell efficiencies and the economies of scale resulting from increase in production.

The main purpose of this thesis is to present a technical and economic analysis of a 1MW grid-connected solar photovoltaic power system for the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi using rooftops of buildings on the campus. A solar resource assessment done to know the amount of solar radiation available at KNUST showed that KNUST receives about 4.30kWh/m^2/day. A roof assessment which considered parameters such as the surface orientation and pitch of roofs, roof area and the possibility of shading of the roof, also revealed there is about 43,697m^2 of roof space available for grid-connected solar PV installations.

In technical analysis of the 1MWp solar PV system, the three (3) commonest solar PV module technologies were selected and their performance simulated using PVsyst software. Amorphous silicon modules were found to perform better than monocrystalline and polycrystalline modules over the one (1) year simulation period.

The financial analysis carried out using RETScreen revealed that at a solar PV market price of US$4.45/Wp and a tariff of US$0.11/kWh (tariff paid for Asogli Power Plant which happens to be the most expensive generation source in the country), the project is not viable unless feed-in tariffs greater than US$0.43/kWh are paid.

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LIST OF ABBREVIATIONS

AC	Alternating current
a-Si	Amorphous silicon
CdTe	Cadmium Telluride
CI (G) S	Copper Indium Gallium Selenide
CO_2	Carbon dioxide
CPV	Concentrator Photovoltaic
DC	Direct current
GWh	Gigawatt hour
kW	Kilowatt
kWp	Kilowatt peak
kWh	Kilowatt hour
kWh/m^2/day	Kilowatt hour per metre squared per day
MWh	Megawatt hour
MWh/year	Megawatt hour per year
m^2	Metre squared
Mono-Si	Monocrystalline Silicon
NPV	Net Present Value
Poly-Si	Polycrystalline Silicon
PV	Photovoltaic
Sq	Square
SWERA	Solar and Wind Resource Assessment
TWe	Terawatt electricity
UNEP	United Nations Environment Programme
US$	United States Dollar
Wp	Watt peak

CHAPTER ONE- GENERAL OVERVIEW

1.1 BACKGROUND

Issues bordering on sustainable energy development and climate change have taken centre stage in major world discussions in recent times. The International Energy Agency, in 2009, estimated that, if current government policies don't change, the world's primary energy demand is expected to increase by 1.5% annually from the year 2007 to the year 2030; an overall increase of about 40% (IEA, 2009). World electricity demand, on the other hand, is expected to increase by 2.5% annually over the same period (IEA, 2009). However, fossil fuels continue to dominate the world's fuel mix and this trend has led to a continued growth of carbon dioxide in the atmosphere, aggravating the adverse effects of global warming. It is reported that, the current thinking of stabilizing greenhouse gas emissions in the atmosphere at 450ppm, is expected to give rise to a global temperature increase of $2^{o}C$, and this can be achieved by cutting down on the volume of fossil fuels used (IEA, 2009).

Conventional energy sources like fossil fuels are fast depleting and these call for world leaders to put in place more sustainable energy policies to curb this trend. Renewable energy has been identified as one of the major solutions to this global energy problem. Renewable energy sources are generally carbon free or carbon neutral and hence provide one of the best ways to help mitigate the effects of climate change. The major setback with renewable energy technologies, however, is the very high initial capital it requires. The costs of these renewable energy technologies have, however, been on the decline over the past few years due to technology improvement and market maturity (REN21, 2010). This cost reduction comes as a big boost for most economies since it will encourage patronage of these technologies, which will eventually lead to sustainable energy development as well as the mitigation of the effects of climate change.

Globally, renewable energy capacity grew at rates of 10–60% annually for many technologies over the five-year period from the end of 2004 through 2009 (REN21 2010). However, grid-connected solar photovoltaic systems remain the fastest growing energy technologies in the world, with 60% annual increases in cumulative installed capacity during the five-year period from the end of 2004 through 2009 (REN21, 2010). Grid-connected solar Photovoltaic (PV) systems employ the direct conversion of sunlight into electricity which is fed directly into the electricity grid without storage in batteries. The solar PV modules used are a number of solar cells connected in series. Typical flat-plate modules achieve efficiencies between 10 – 15% (WEC, 2004)

1.2 JUSTIFICATION

Ghana has experienced a number of power crises over the last two decades, partly due to the heavy reliance on hydroelectric power which is more often than not dependent on the rain fall pattern of the country and partly also due to insufficiency in the generation capacity of the country. It has been estimated that grid electricity demand would grow to about 18,000GWh by 2015 and even up to about 24,000GWh by the year 2020 from about 6,900GWh in the year 2000 (Energy Commission, 2006). In order for Ghana to ensure secured uninterrupted electricity supply by the year 2020, the existing installed capacity of 1760MW as at 2006 must be doubled by 2020 (Energy Commission, 2006). The government of Ghana is targeting 10% of the country's electricity generation to come from renewable energy, such as solar, small and medium sized hydros, wind, biomass and municipal solid wastes, by the year 2020 (Energy Commission, 2006).

The economy of Ghana is expected to grow at a GDP of between 8-10% if it is to attain the status of a middle income country and these growth rates require significant amounts of electricity (Brew-Hammond et al., 2007).

A look at the world map of mean solar radiation reveals that, Africa as a continent receives the highest amount of solar radiation between 300 and 350 W/m^2 annually (Brew-Hammond et al., 2008). This makes the African continent of which Ghana is a part, exceptionally suitable for solar energy projects including grid-connected solar photovoltaic systems. In spite of this huge potential, Africa still trails the rest of the world in terms of solar energy applications and energy services in general; thus Africa is often referred to globally as the Dark Continent.

The installation of a 1 MW grid-connected solar photovoltaic system on the Kwame University of Science and Technology (KNUST) campus in Kumasi will help boost the existing electricity production capacity in the country, which is mainly from hydro and thermal sources. Solar energy, being a renewable source, provides energy with no pollutant and greenhouse gas emissions. This can go a long way to help mitigate the adverse effect of global warming as well as contribute to sustainable energy development. It will also set the pace for similar projects to be developed in other institutions, thereby, helping to attain the target of 10% renewable energy in the electricity generation mix set by the government.

1.3 OBJECTIVES

The main objective of the project is to perform a technical and economic analysis of a 1MW grid-connected solar photovoltaic power system for the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi using rooftops of buildings and car parks.

The specific objectives are as follows:

- To develop a standard project development framework for the planning of institutional large scale grid-connected solar PV systems. This would include;
  - The determination of the total area required for the project.
  - Assessing the suitability of roofs of buildings and car parks, in terms of roof surface orientation, roof strength and the possibility of shading, for PV installations.
  - Assessing the financial viability of the project.
- To validate the framework in planning a 1MW grid-connected solar photovoltaic system for KNUST.
- To simulate the performance of the 1MW grid-connected solar PV system using suitable software packages and conducting technical as well as economic analysis based on the software simulation results

1.4 METHODOLOGY

The project began with a literature review of existing grid-connected solar photovoltaic systems in the country and elsewhere around the world. Solar and wind resource assessment data for Ghana, including the dataset developed by the Mechanical Engineering Department, KNUST for the Energy Commission of Ghana was also studied and the average solar radiation for Kumasi determined. Private enterprises already in the solar business were contacted for information on the costs of solar PV systems as well as the technical specifications of the systems. However, general information regarding the project was sourced from various areas including the Ministry of Energy, Ghana Energy Commission, the Energy Center-KNUST, KNUST library, internet, etc.

A prefeasibility study for the 1 MW grid-connected solar photovoltaic systems was conducted with the help of RETScreen software, which comes with inbuilt solar radiation data for various locations including Kumasi as well as solar PV system specifications from various manufacturers. The results of the prefeasibility included the total estimated area required for the installation of the 1MW system as well as the basic economics of the project including the simple payback period and net present value for the project. The prefeasibility studies also included a greenhouse gas emissions analysis (See Appendix F for Prefeasibility Study results).

A "zero-order" draft framework was initially developed to include the various steps required for the achievement of the project objectives. This framework which included steps such as roof area assessment, assessment roof surface orientation, roof strength assessment and the assessment of the possibility of shading of the roofs was updated during the course of the project into a standard project development framework which could be replicated in other institutions. The results of roof assessments and the technical specifications of the solar PV system components were used to design the layout of the system for the selected roofs after which the technical and economic performance of the system was simulated with PVSyst and RETScreen software packages and the results analysed.

The technical and economic analyses were conducted, after all the design parameters were settled, to estimate the amount of energy to be generated and also the cost and benefits of the project. PVsyst a software developed by the Group of Energy at the Institute for the Sciences of the Environment in the University of Geneva in Switzerland was used for the technical analysis and RETScreen was used for the financial analysis of the project. The methodology is diagrammatically shown in Figure 1.1.

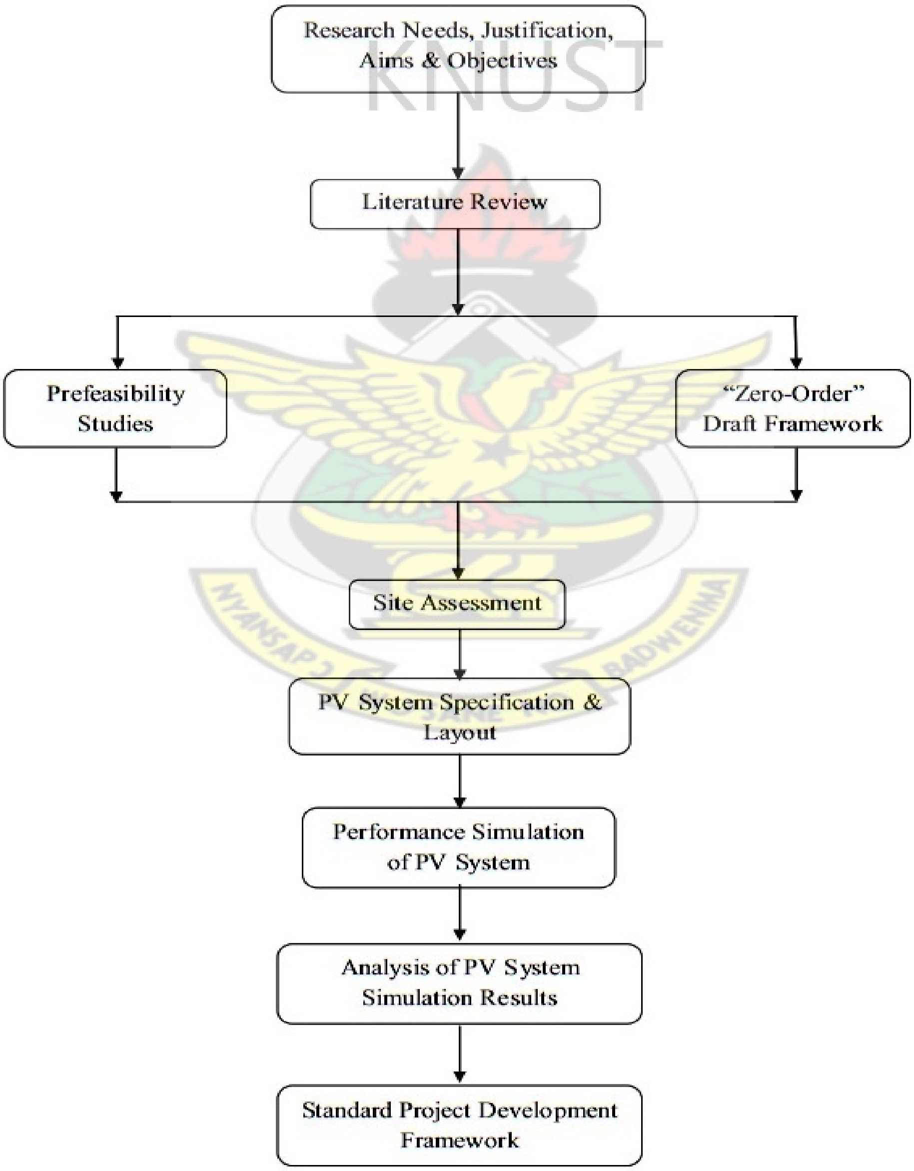

Figure 1.1: Project Execution Plan

1.5 SCOPE AND ORGANISATION OF THESIS

This report covers the development of a standard project development framework to aid the planning, technical and economic analysis of institutional large-scale grid-connected solar photovoltaic power systems. The framework developed which included steps such as roof area assessment, assessment roof surface orientation, roof strength assessment and the assessment of the possibility of shading of the roofs was employed in the planning, technical and economic analysis of a 1MW solar photovoltaic system for the KNUST campus. The work however does not cover the detail design of the 1MW grid-connected solar PV power system.

The background to the project as well as the objectives are contained in chapter one. Chapter one also looks at the methodology employed as well as brief description of the scope and organization of the project. Chapter two contains a review of the literature on solar PV system installations in Ghana, Africa and the world at large. It also contains a brief description of solar PV systems and their applications. A detailed assessment of the roof properties as well as PV system specifications is contained in chapter 3. Chapter 3 ends with a detailed layout design of the PV system ready for installation. The technical and economic analyses of the project were carried out using the following software packages; PVsyst and RETScreen and the results analyzed in chapter 4. Figure 1.2 shows the organization of the thesis.

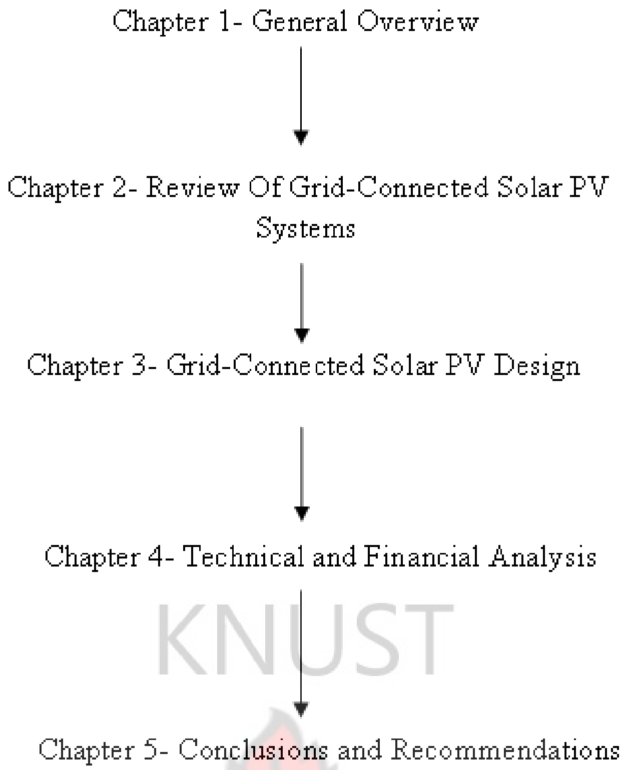

Figure 1.2: Organization of Thesis

CHAPTER 2 –REVIEW OF GRID-CONNECTED SOLAR PV SYSTEMS

2.1 INTRODUCTION TO SOLAR ENERGY AND APPLICATIONS

2.1.1. Basics of Solar Energy

Solar energy is the energy produced by the sun through a nuclear fusion reaction in which two hydrogen atoms combine to form a helium nucleus with the release of energy. Several of these reactions take place in the sun and the energy released is transmitted in the form of electromagnetic radiation (including visible light, infra red light and ultra-violet radiation) (Quaschning, 2005).

Solar energy is unarguably the greatest source of energy for the earth and is regarded by many as the indirect source of energy for nearly every other form of energy on the earth with the exception of geothermal energy and nuclear energy. It plays a very important role in the formation of fossil fuels and its effect on weather and climate greatly influences other energy sources such as wind, wave, hydro and biomass. It also serves as a direct energy source for solar thermal as well as photovoltaic devices for both heating and electricity applications (Quaschning, 2005).

2.1.2 Solar Radiation

The energy produced by the sun is transmitted to the planets and other celestial bodies through electromagnetic radiation. Most of these electromagnetic radiations emitted from the sun's surface are within the visible band of the radiation spectrum with a wavelength of about 500nm as shown in Figure 2.1. The amount of energy emitted by the sun's surface is approximately 63,000,000 W/m^2. This energy is transmitted through space where it is intercepted by planets, other celestial bodies and particulate matter. The intensity of solar radiation that strikes the surface of these celestial bodies is determined by the Inverse Square Law, which states that the intensity of radiation absorbed by a celestial body varies inversely with the square of the distance from the source (Pidwirny et al, 2010).

$$intensity = \frac{I}{d^2}$$

Where: I=Intensity of radiation at one unit distance

d= Distance from source

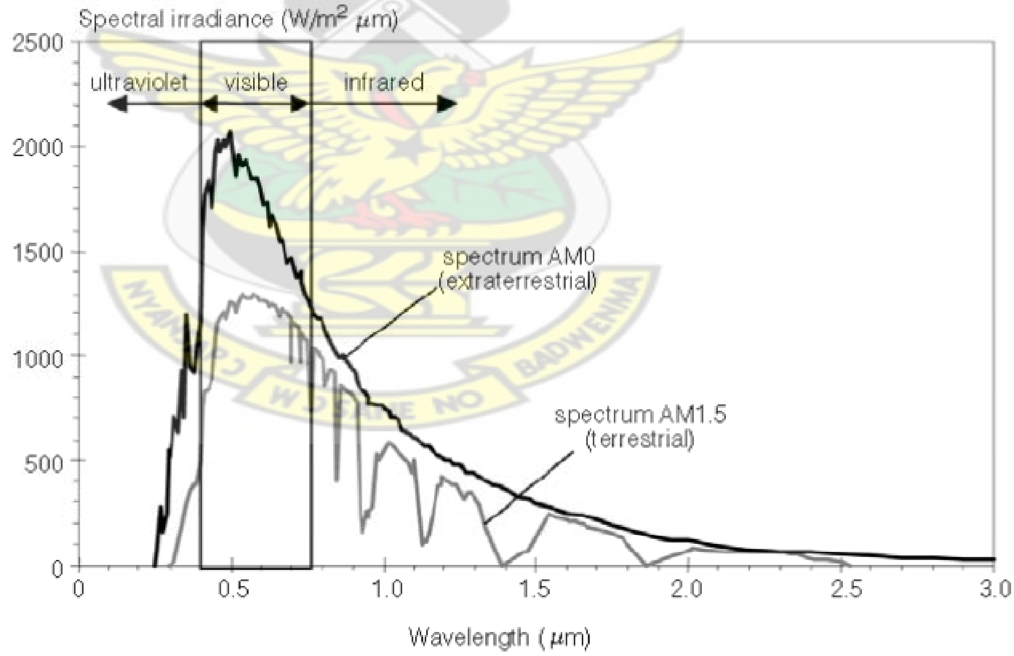

Figure 2.1: Solar radiation spectrum

Source: Quaschning (2005)

Given the amount of energy radiated by the sun and the Earth-sun distance varying from 1.47×10^{11}m and 1.52×10^{11}m, throughout the year, the amount of radiation intercepted by the outer limits of the atmosphere is calculated to be between 1,325 W/m^2 and 1,420 W/m^2 (Quaschning, 2005). The average of these values, 1,373 W/m^2 is known as the solar constant, G_{SC}. Only about 40% of the solar energy intercepted at the top of Earth's atmosphere passes through to the surface. The atmosphere reflects and scatters some of the received visible radiation (Quaschning, 2005). About 30% of the sun's visible radiation, with wavelengths from 400 nm to 700 nm, is reflected back to space by the atmosphere (Pidwirny et al, 2010). Figure 2.2 shows the amount of solar radiation reaching the different parts of the earth.

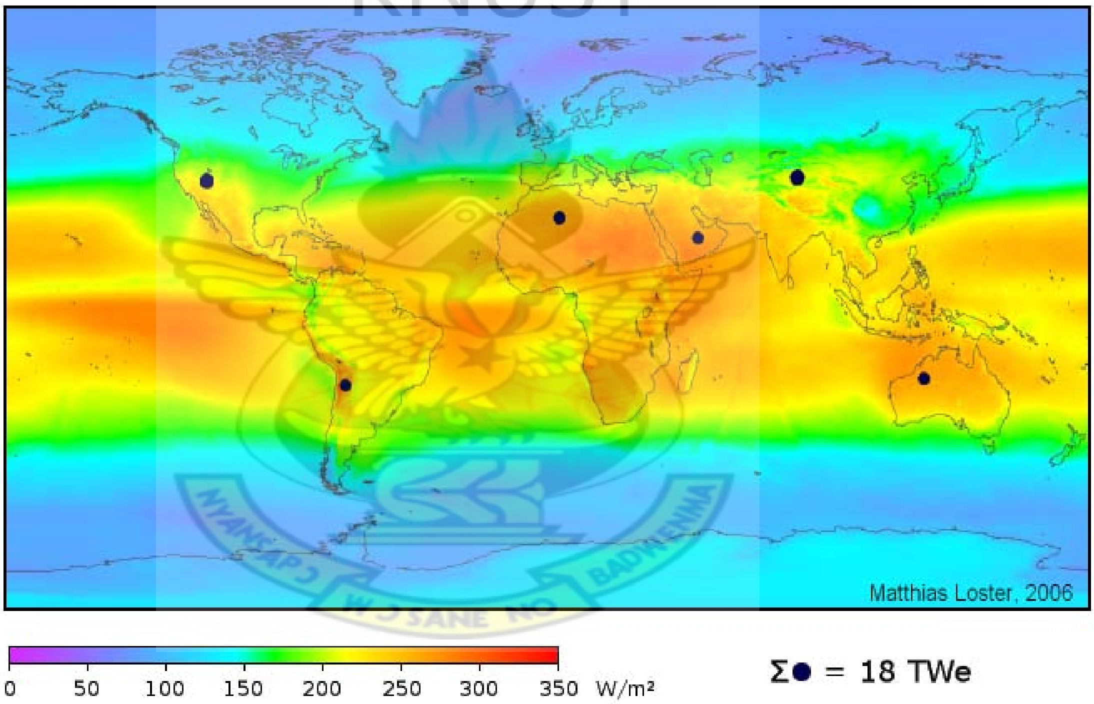

Figure 2.2: Solar radiation map of the world

Source: Mathias Loster (2006)

2.1.2.1 Solar Radiation Components

Solar radiation from the sun reaches the earth in two main forms namely direct and diffuse radiation. The sum of the diffuse and direct solar radiation on a surface is often referred to as global insolation or total solar radiation and the energy flux is measured in W/m^2.

2.1.2.2 Direct Solar Radiation

Direct solar radiation is the solar radiation received directly from the sun without having been scattered by the atmosphere. This radiation comes from the direction of the sun and casts strong shadows of objects in its path. It is sometimes referred to as beam radiation. On clear days, direct radiation accounts for a greater portion of the total solar radiation (Duffie et al, 1980).

2.1.2.3 Diffuse Solar Radiation

This is the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere. This radiation usually has no defined direction. On very cloudy days, the total solar radiation is almost entirely diffuse. Diffuse radiation is also referred to as sky or solar sky radiation (Duffie et al, 1980).

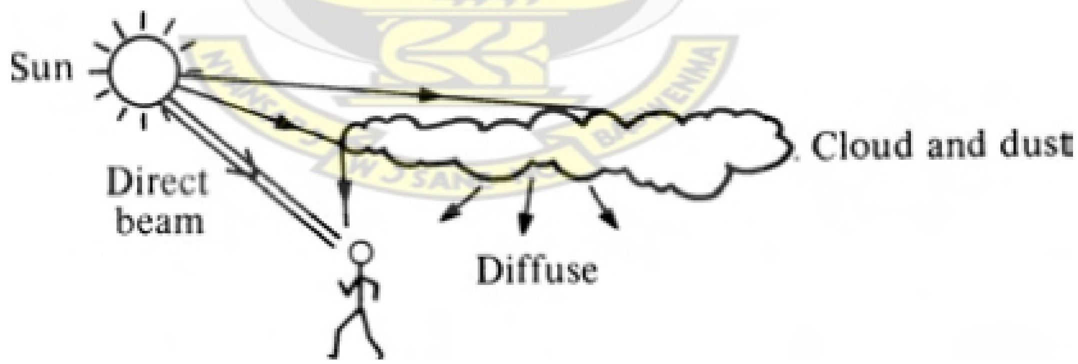

Figure 2.3: Illustration of Direct and Diffuse Radiation
Duffie et al (1980)

2.1.2.4 Daily and Seasonal Variations of Solar Radiation

Solar radiation is largely affected by the angle of incidence; the angle at which the sun rays strike the earth surface (such that the intensity is higher when the sun is directly overhead at 90^o from the horizon and reduces as the angle above the horizon reduces). This angle of incidence is affected by the location on the earth's surface (i.e equator, northern hemisphere and southern hemisphere), the rotation of the earth on its axis and the orbital motion of the earth about the sun (Pidwirny et al, 2006).

The rotation of the earth on its axis causes day and night for all locations on the earth's surface. However, the length of the day varies for every location except the equator, which experiences equal lengths of day and night on everyday of the year. Locations north of the equator experience longer days during the summer solstice whereas locations south of the equator experience longer days in the winter solstice. Seasonal variation in day length is also affected by increasing latitude. These variations are caused by the movement of the earth in its elliptical orbit about the sun. These variations also explain why areas around the equator have higher solar irradience values than those in the northern and southern hemispheres (Pidwirny et al, 2006).

2.1.2.5 Orientation and Inclination of Surfaces

The amount of solar radiation reaching a solar device depends on the angle (of incidence) at which the solar radiation hits the surface of the device. This angle is affected by the orientation as well as the inclination of the solar device.

The orientation defines the direction in which the panel faces, in terms of north, south, east or west. As a rule of thumb, solar collectors (in the northern hemisphere) must be oriented southward and inclined at a certain angle to be able to absorb the maximum amount of solar radiation reaching its surface and those in the southern hemisphere must also be oriented northward. The azimuth angle specifies how many degrees the surface of the solar device diverges from the exact south-facing direction (SolarServer, 2010).

The inclination, on the other, defines the position of the solar device with respect to the horizontal. The angle of inclination describes the divergence of the solar device from the horizontal. The orientation and inclination, when properly set for a particular location, enables solar collectors to receive the maximum amount of solar radiation reaching the surface (SolarServer, 2010).

2.1.3 Solar Energy Applications

There are two major applications of solar energy: solar thermal energy systems and solar photovoltaic systems. Solar photovoltaic systems are systems that convert sunlight directly to electricity. They are usually made of Semiconductor materials such as silicon.

Solar thermal systems on the other hand collect thermal energy in solar radiation and use it at high, medium or low temperatures for various applications using different technologies. These technologies can be classified into the following groups based on their working temperature;

- Low-temperature technologies (working temperature < 70^{o}C) examples include; solar space heating, solar pond, solar water heating, and solar crop drying.
- Medium-temperature technologies (70^{o}C < working Temperature < 200^{o}C) examples include; solar distillation, solar cooling and solar cooking.

- High-temperature technologies (working temperature > $200^{o}C$) examples include; solar thermal power generation technologies such as parabolic trough, solar tower (central receiver system) and parabolic dish (Asif et al, 2007).

The main focus of this project, however, is in grid-connected solar photovoltaic power systems.

2.2 SOLAR PHOTOVOLTAIC SYSTEMS

Photovoltaic systems are solar energy systems, which convert sunlight directly to electricity. The major component in PV systems is the solar panel which is formed by putting together several PV cells. Several modules form arrays and several arrays form a panel. Solar PV cells can be used for a wide range of power applications ranging from a few milliwatts in wrist watches and scientific calculators to several megawatts in central power stations. Solar cells are usually made of semiconductor materials such as silicon, gallium arsenide, cadmium telluride or copper indium diselenide.

2.2.1 Types of Solar Cells

Solar cells come in two major forms based on the nature of the material used in their production. The two main forms are crystalline solar cells and thin film solar cells.

Silicon is the most important material in crystalline solar cells and also happens to be the second most abundant element on Earth. It is, however, not present in a pure form, but in chemical compounds, with oxygen in the form of silicon dioxide (quartz or sand). This is taken through a series of chemical processes under varying conditions of temperature and pressure to form silicon wafers, which are then turned into solar cells. Crystalline solar cells, so far, have the highest conversion efficiencies when it comes to photovoltaic cells. The main types are monocrystalline and polycrystalline cells. Monocrystalline are the most efficient with efficiency ranging between 15-18% whiles polycrystalline cells have efficiency ranging from 13-16% (DGS, 2008).

Thin-film solar cells, on the other hand, are manufactured by applying thin layers of semiconductor materials to a solid backing material. The composition of a typical thin-film cell is shown in Figure 2.4. Although less efficient than crystalline silicon, thin-film solar cells offer greater promise for large-scale power generation because of ease of mass-production and lower materials cost. The commonest example of thin film cells is the amorphous silicon cell with efficiency ranging between 5-7%.

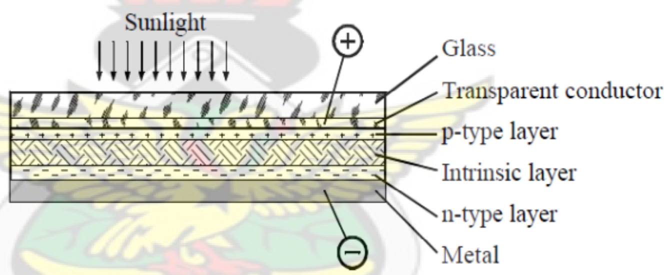

Figure 2.4: Typical thin-film amorphous silicon construction

2.2.2 Types of Photovoltaic Systems

Photovoltaic systems can be grouped under two main headings; namely grid-connected systems and off-grid systems.

2.2.2.1 Grid-Connected PV Systems

Grid-connected systems are systems connected to an independent grid usually the public electricity grid and feeds electricity into the grid. These systems are usually employed in decentralised grid-connected PV applications and central grid-connected PV applications. Decentralised grid-connected PV applications include rooftop solar PV generators (where the solar PV systems are mounted on rooftops of buildings) and building integrated system (where the PV systems are incorporated into the building). In the case of residential or building mounted grid connected PV systems, the electricity demand of the building is met by the solar PV system and the excess is fed into the grid. Their capacities are usually in the lower kilowatts range (DGS, 2008).

Central grid-connected PV applications have capacities ranging from the higher kilowatts to the megawatt range.

A typical grid-connected PV system comprises the following components:

- Solar PV Modules: these convert sunlight directly to electricity.
- Inverter: converts the DC current generated by the solar PV modules to AC current for the utility grid.
- Main disconnect/isolator Switch
- Utility Grid

2.2.2.2 Off-Grid Systems

Off-grid PV systems are systems that are not connected to the public electricity grid. These systems require energy storage devices for the energy generated since the energy generated is not usually required at the same time as it is generated. They are mostly used in areas where it is not possible to install an electricity supply from the main electricity grid, or where electricity grid extension is not cost-effective or desirable. They are therefore preferable for developing countries where vast areas are still frequently not supplied by an electrical grid. Off-grid systems are usually employed in the following applications; consumer applications such as watches and scientific calculators, industrial applications such as telecommunications and traffic signs and remote habitations such as solar home systems and water pumping applications (DGS, 2008).

A typical off-grid system comprises the following main components:

- Solar PV Modules: these convert sunlight directly to electricity.
- Charge Controllers: manage the charging and discharging of the batteries in order to maximize their lifetimes and minimize operational problems
- Battery Or Battery Bank: Stores the energy generated by the PV modules
- Inverter: converts the DC current generated by the solar PV modules to AC current for AC consumer load.

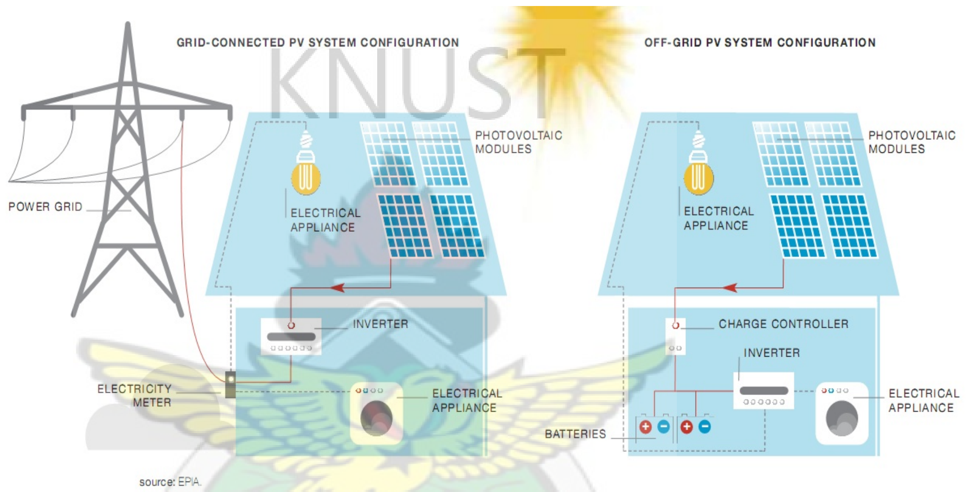

Figure 2.5: Grid-connected and Off-grid PV system configuration

Source: EPIA (2011)

2.3 DEVELOPMENTS IN THE SOLAR PHOTOVOLTAIC INDUSTRY

Solar PV is currently the fastest power generation technology in the world with about 15,000MW capacity installed in the year 2010 (EPIA et al, 2011). In all, the total installed capacity of solar PV systems is close to 40,00MW, with Europe alone contributing about 70% of this amount and North America, Japan, China and Australia following in that order. Grid-connected systems make up the majority of these figures and this is as a result of favourable incentives such as feed-in tariff schemes, tax rebates and investment subsidies available to the industry (EPIA et al, 2011; REN21, 2011).

The solar PV industry has also seen tremendous improvement in efficiencies for the various technologies available on commercial scale as shown in Table 2.1 below. This improvement in technology and the continuous growth of the PV market has led to drastic reduction in the cost of solar PV systems (EPIA et al, 2011).

Table 2.1: Commercial Module Efficiency

<table>
<tr><th>Technology</th><th colspan="5">Thin Film</th><th colspan="2">Crystalline silicon</th><th>CPV</th></tr>
<tr><th></th><th>a-Si</th><th>CdTe</th><th>CI(G)S</th><th>a-Si/μc-Si</th><th>Dye-S</th><th>Mono</th><th>Multi</th><th>III-V Multi junction</th></tr>
<tr><td>Cell eff.</td><td rowspan="2">4-8%</td><td rowspan="2">10-11%</td><td rowspan="2">7-12%</td><td rowspan="2">7-9%</td><td rowspan="2">2-4%</td><td>16-22%</td><td>14-18%</td><td>30-38%</td></tr>
<tr><td>Module eff.</td><td>13-19%</td><td>11-15%</td><td>~25%</td></tr>
<tr><td>Area/kW</td><td>~15 m²</td><td>~10m²</td><td>~10m²</td><td>~12m²</td><td></td><td>~7m²</td><td>~8m²</td><td></td></tr>
</table>

Source: EPIA 2011. Efficiency based on Standard Test conditions

2.3.1 Grid-Connected Solar PV in Developed Countries

The development of the global grid-connected solar PV systems' market has largely been driven by the developed countries with Germany, Italy, Japan, USA and Spain among the top five countries with total installed capacities ranging from 24.7GW in the case of Germany to 4.2GW in the case of Spain (EPIA et al, 2011).

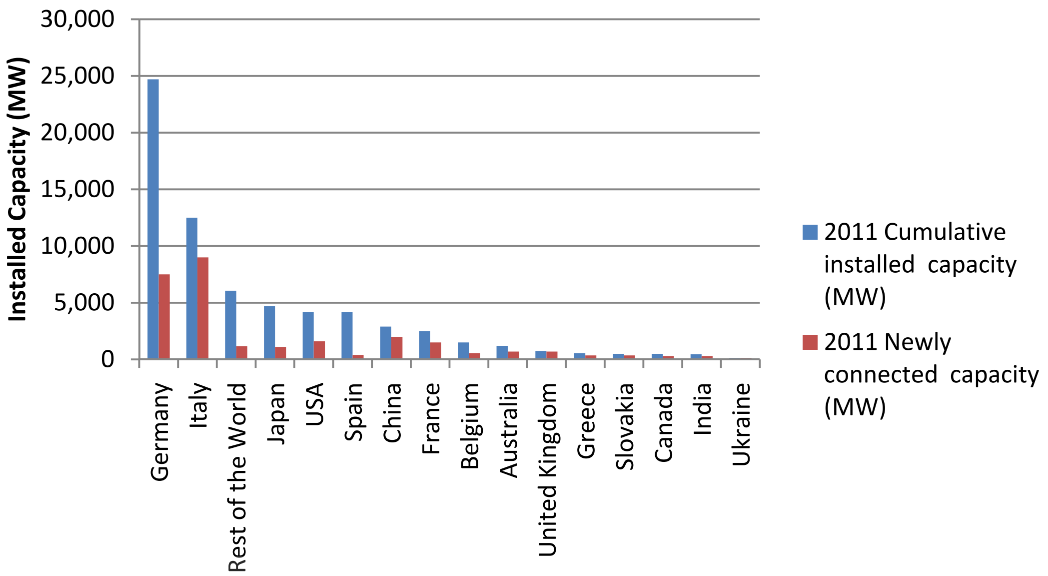

Figure 2.6: Total global installed capacity of solar PV systems

Source: EPIA et al (2011)

In the year 2011 alone, about 27.7GW of installed grid-connected solar PV systems were added. The developed countries alone contributed about 90% of the total capacity added as can be seen in Figure 2.7.

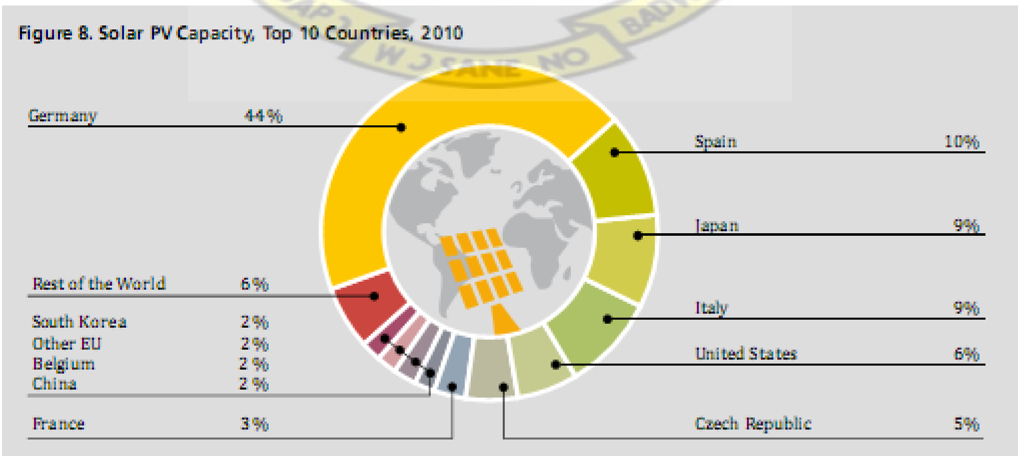

Figure 2.7: Total installed solar PV capacity as of 2010

Source: REN21 (2011)

2.3.2 Grid-Connected Solar PV in Developing Countries

The developing world, most of which lie within the Sunbelt region of the globe, offers a huge potential market for solar photovoltaic (PV) systems. The primary market for solar PV systems in developing countries has been off-grid applications such as solar home systems (SHS), mostly employed in rural electrification projects. It is however important to note that a far larger market in developing countries is expected to emerge for grid-connected solar PV systems, which currently are not cost-competitive with other power generation sources such as hydro and thermal power.

In spite of the huge market potential for solar PV systems in developing countries, the successes of PV manufacturers and dealers to date have been few with most solar PV sales in the developing world made possible through donor-funded procurement programs, which provide the solar PV systems on a concessional basis to users with very little sales made directly to end-users. Currently, very few PV manufacturers or dealers provide financing to users or work with private lending institutions to do so and this has also contributed in the very small numbers in terms of solar PV deployment in developing countries.

Figure 2.7 reveals that, the rest of the world (most of which are developing countries) contributed only about 6% of the newly installed capacity of solar PV systems in the world in the year 2010 (EPIA et al, 2011). Currently, developing countries are contributing only about 6GW out of a total installed capacity of about 67GW in the world (EPIA et al, 2011).

Africa as a continent contributed less than 1% of the world's total installed solar PV systems with an installed capacity of 163MW as at the end of 2010 (EPIA et al, 2011) as can be seen in Figure 2.8. This is as a result of the lack of policy instruments that help promote renewable energy technologies in general. Grid-connected solar PV systems are not that popular in Africa since most solar PV applications are employed in off-grid rural electrification projects to rural communities (for lighting, educational and health applications) that are far from the national grid (EPIA et al, 2011). Presently, Cape Verde can boast of the largest grid-connected solar PV system capacity adding about 7.5MW of grid-connected solar PV systems by the end of the year 2011.

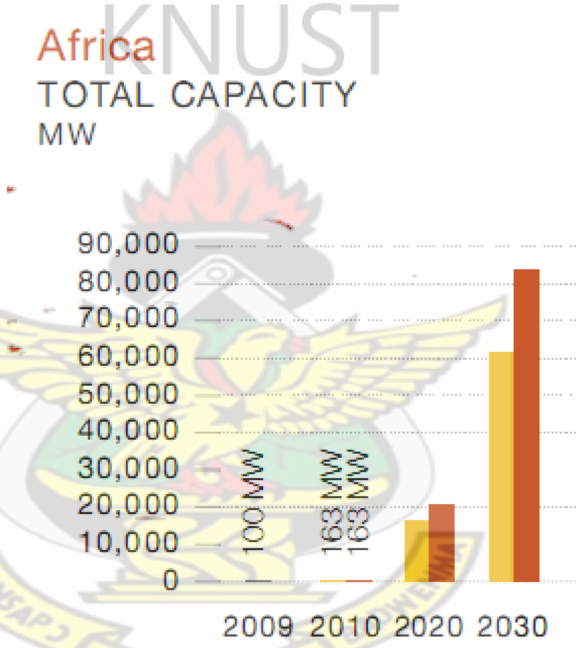

Figure 2.8: Total installed capacity of grid-connected solar PV in Africa

Source: (EPIA et al, 2011)

The effort at promoting grid-connected solar PV systems in Ghana is spearheaded by the Energy Commission of Ghana. The total installed capacity of grid-connected solar PV systems in the country is about 160kWp; 50kWp at the Ministry of Energy, 4.25kWp at the Ghana Energy Commission premises, 4kWp at the College of

Engineering KNUST, and a total of about 101.75kWp on individual home sponsored by the Energy Commission of Ghana. The Energy Commission together with KNUST both have installed 4kWp grid-connected solar PV systems donated by the German state of North Rhine Westphalia (MoE, 2010; Energy Commission, 2011).

2.3.3 Lessons from the KNUST 4kWp Grid-Connected Solar PV System

The German State of North-Rhine Westphalia, in 2008, donated a 4kWp grid-connected solar PV system to the College of Engineering, KNUST to facilitate research into the impact of grid-connected solar PV on the national utility grid as well as the performance of grid-connected solar PV systems in the middle part of the country. The system comprised of the following;

- 2kWp poly-crystalline and 2kWp amorphous PV modules
- 2 inverters (2.5 kW each)
- Protection devices
- A communication interface

The results of a study carried out on the system are presented graphically in Figures 2.9 and 2.10.

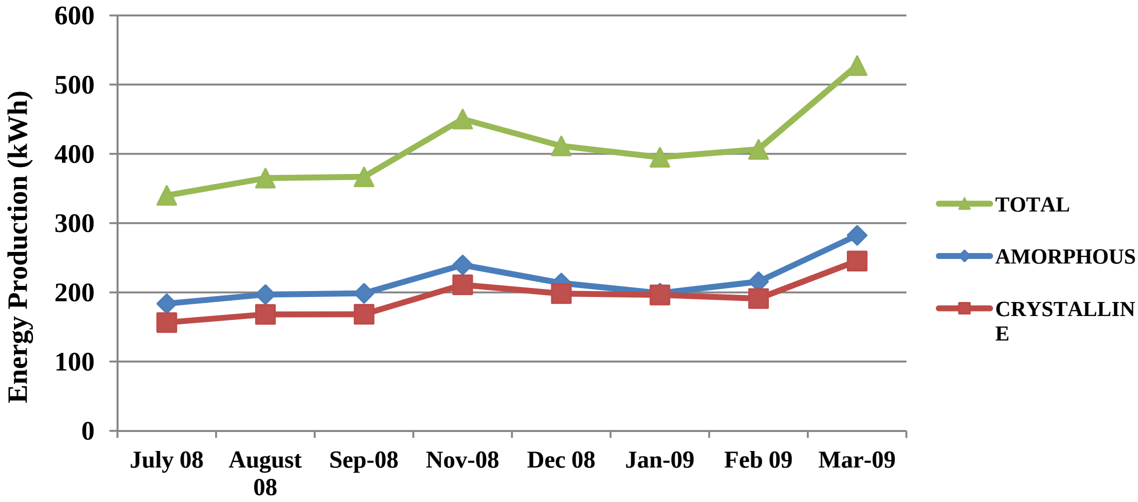

Figure 2.9: Comparison of monthly energy generated by the 4kWp PV system

Source: Bagre (2011)

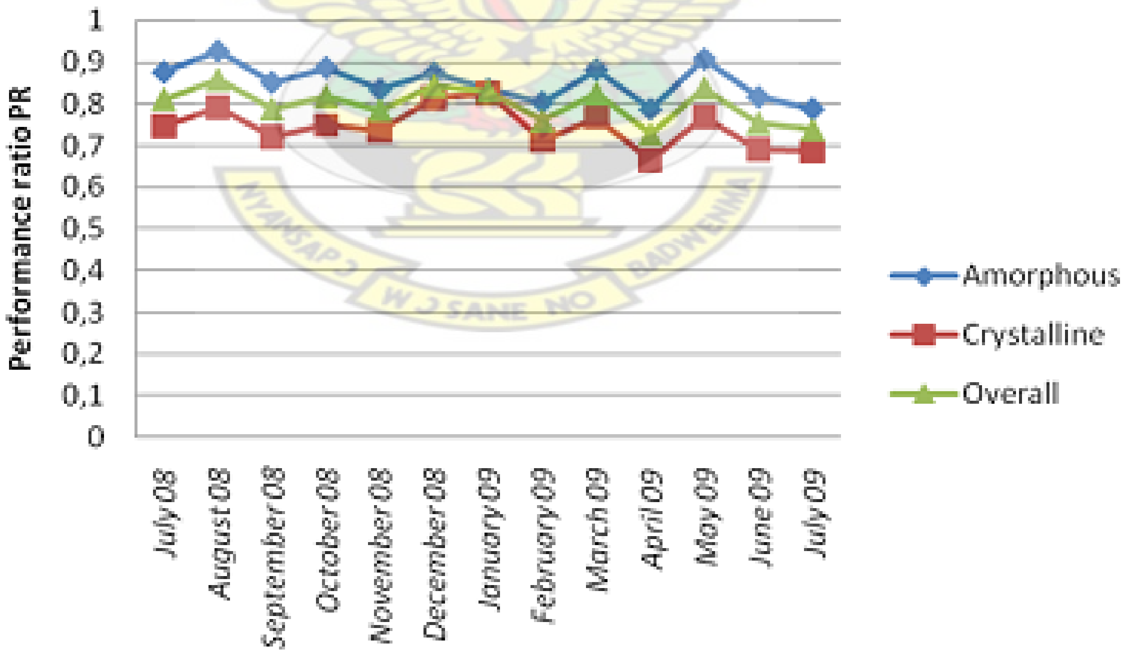

Figure 2.10: Comparison of performance ratio for the Solar PV systems

Source: Bagre (2011)

The results show that for the same capacity of panels, amorphous silicon modules perform better then polycrystalline silicon modules in terms of electricity output as can be seen in Figure 2.9. The performance ratio, which is the ratio of the actual amount of PV energy delivered to the utility grid in a given period of time to the theoretical amount of energy according to standard test conditions (STC) of the modules, for the amorphous silicon modules was higher than the for the crystalline modules as shown in Figure 2.10. It is worth noting that, for the same capacity of system, amorphous silicon modules require twice as much area as the crystalline modules.

CHAPTER THREE – GRID-CONNECTED SOLAR PV DESIGN

The planning of a grid-connected solar PV system consists of the following stages; site assessment; which includes solar resource assessment for the area under consideration, assessment of the possible grid connection points as well as the requirements for grid connection and assessment of roof properties such as the roof type, area, pitch/slope, the strength of the roof.

Shading analysis to determine the extent of shading on the buildings under consideration was carried out, before finally selecting the most suitable roofs for the design of the PV system. Selection of solar PV system components, including modules and inverters, was done using manufacturers' catalogue from both local and international solar system dealers. These provided some basic information such as the area and weight of the panels as well as their electricity output specifications. They also provided information about the input as well as output specifications of the inverters, which was helpful in designing the layout of the system.

3.1 Site Assessment

The project site for this study is the Kwame Nkrumah University of Science and Technology (KNUST) campus in Kumasi. KNUST was chosen because it is the only science and technology university in Ghana and as such a major installation would help enhance further study and research into grid-connected solar PV systems in the country.

KNUST is located on latitude 6.67^o north and longitude 1.57^o west and covers a total land area of 18,129,916 m^2. It is located about 20,719,904 m^2 to the east of Kumasi, the capital city of the Ashanti region of Ghana. There are six colleges in the university with a total student population of about 32,198 students as at April 2012 and six halls of residence, each housing an average of about 960 students.

3.1.1 Electricity Consumption and Grid Access for KNUST

KNUST is one of the largest consumers of electricity in the Ashanti Region of Ghana and is considered as a Special Load Tariff-Medium Voltage (SLT-MV) consumer. This category of consumers are supplied electricity at a level exceeding 415 Volts but less than 11 kilo Volts and have maximum demand above 100 kilo Volts Ampere (PURC, 1999).

The monthly average electricity consumption for KNUST for the period between January 2006 and October 2012 is about 1,058,264 kWh (ECG, 2012).

The energy consumption profile for KNUST for the period under consideration shown in Figure 3.1 reveals that, electricity consumption in KNUST peaks twice around March and October, when students are in school and dropping steeply in July and January when students are on vacation.

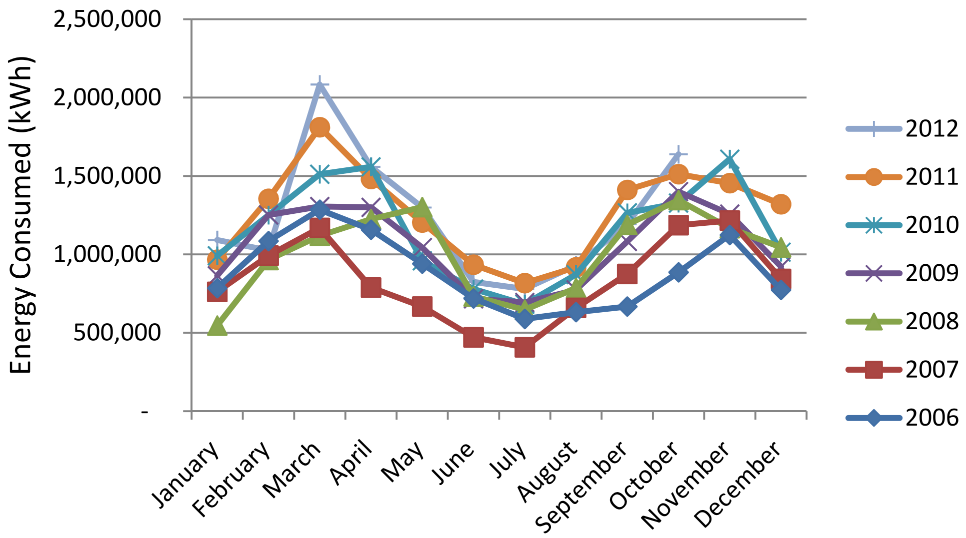

Figure 3.1 : Electricity Consumption trend for KNUST between 2006 and 2011

Source: ECG (2012)

The electricity distribution network in KNUST receives its power supply from the Electricity Company of Ghana through three different feeders, 11kV each, tied on 11kV, 3MVA switch gear at the intake point behind Unity Hall. The distribution network is a ring circuit made up of 18 different 11kV/415V 3-phase distribution transformer substations from which the loads are quite evenly distributed. Figure 3.2 shows the ring electricity distribution network with the various transformer substations and the loads they serve on the KNUST campus. The location of the substations as well as the paths of both the low voltage and high voltage electricity lines on the KNUST campus is presented in Figure 3.3.

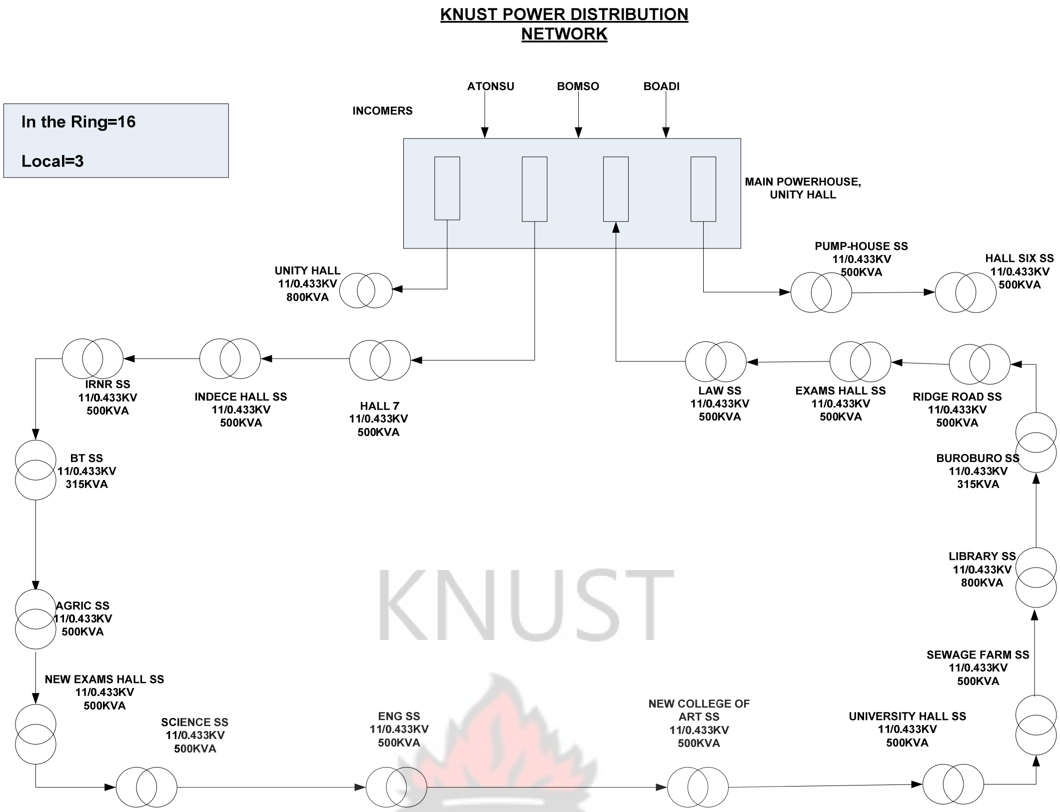

Figure 3.2: Ring electricity distribution network for KNUST
(source: KNUST Electrical Consultant)

The Ghana Grid Company Ltd specifies, in the Ghana Grid Code, the main requirements for the connection of an electricity generation source to the grid to be in the area of the voltage and frequency. Other requirements include the power quality of the electricity delivered to the grid and the safety of grid maintenance personnel (GRIDCO, undated). Electricity distribution from the substations to the various buildings on the KNUST campus is done by 3-phase alternating current (AC) of 415V/50Hz and as such the electricity to be fed into this same grid should be 3-phase alternating current (AC) of 415V and frequency of 50Hz with a ±0.2Hz degree of freedom and a normal deviation of electric time ranging from ± 10seconds to ±60 seconds, as specified in the Ghana Grid Code (GRIDCO, undated). The power quality also takes into account the harmonics of the sinusoidal AC wave, the power factor, and also voltage flickers; therefore the inverters used in grid-connected PV systems must have the potential of controlling these parameters within the acceptable limits. It is important to note that, current inverter technologies come with mechanisms that are able to address power quality problems.

Like any source of electricity, solar PV systems are potentially dangerous to both people and property, and much attention has been given to finding ways to reduce these inherent safety risks. The main safety concern is about the safety of grid maintenance personnel during maintenance works on the grid. This is due to islanding, a situation where a portion of the utility grid that contains both load and generation source is isolated from the remainder of the utility grid but remains energized due to the presence of a generation source on that part of the grid (Collinson et al, 1999). However, inverter technology has developed over the years such that there is no chance of a PV-supported island stemming from interconnected residential or small commercial systems since inverters come with built-in anti-islanding safety features (Collinson et al, 1999).

The 1MW grid-connected solar photovoltaic power system can be connected to the KNUST network through any of the transformer substations scattered around the campus or at the main electricity intake point behind the Unity Hall.

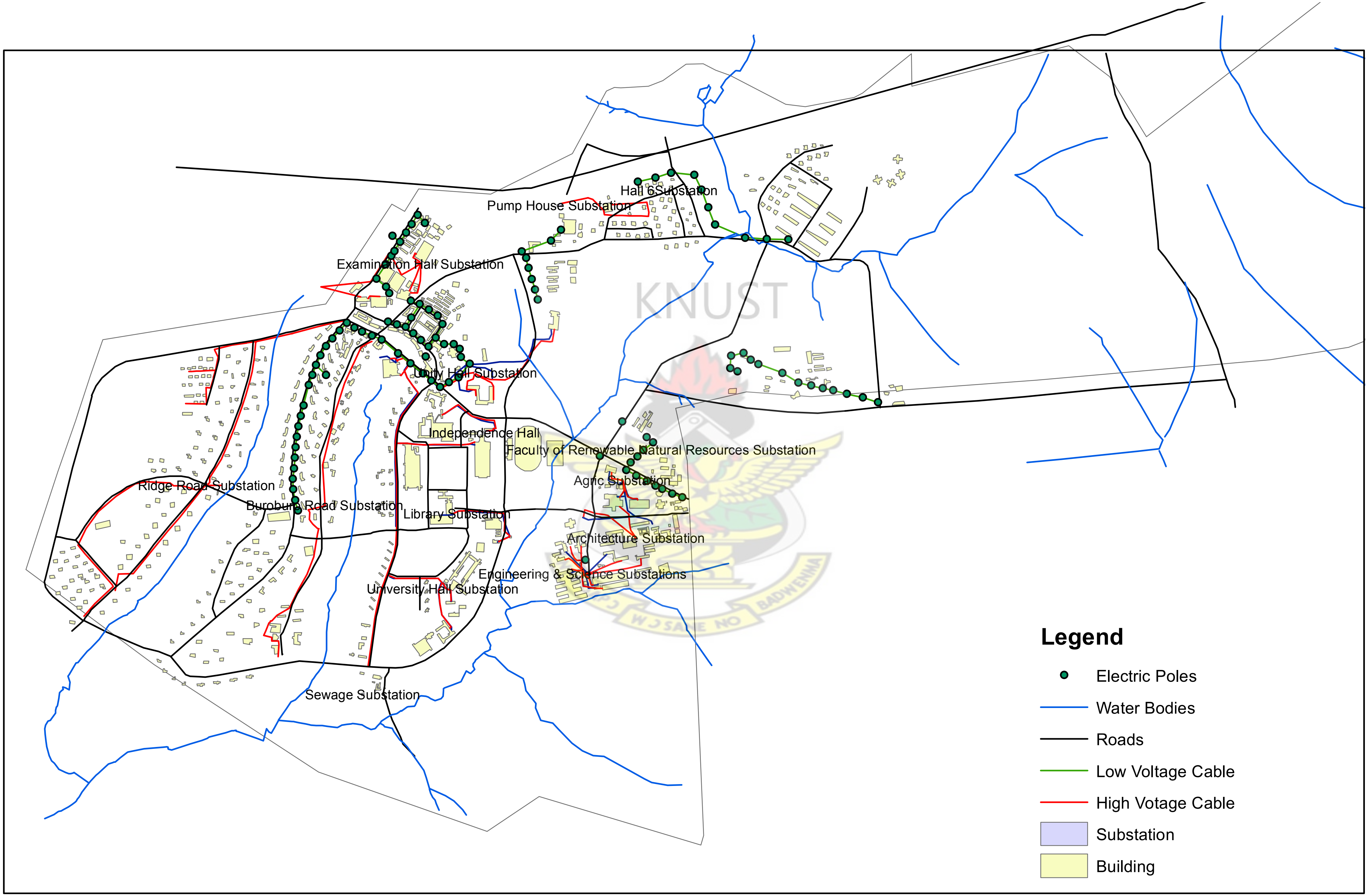

Figure 3.3: Electricity Distribution Network for KNUST

Source: Ladzagla (2010)

3.1.2 Solar Resource Assessment

There are two main sources of data for solar radiation at the surface of the earth; ground measurements and calculations based on satellite data.

Direct measurements of the solar radiation at ground level can be done with a number of different instruments including the pyranometer, which is the most widely used solar radiation measuring device. The instrument measures all the radiation coming from the sun and from the sky or clouds at a specific location. Ground station measurements give the best results.

In the calculations based on satellite data, satellites are used to measure the light (visible or infrared) coming from the Earth, which is mainly the light reflected from the ground or from clouds. The calculation of the solar radiation at ground level must therefore be able to take into account the radiation absorbed by the atmosphere as well as that reflected by clouds.

The solar radiation data used for this study was from the Solar and Wind Resource Assessment (SWERA) report for Ghana, developed by the Mechanical Engineering Department of the Kwame Nkrumah University of Science and Technology for the United Nations Environment Programme (UNEP). This data is from actual ground measurements of solar radiation using a solar radiation measuring device. This data was however compared to some satellite data from NASA (used in the RETScreen Software), the American Space Agency and also PVGIS-Helioclim developed by the Joint Research Centre of the European Commission and is shown in Figure 3.4. The comparison of solar radiation data reveal that, satellite solar radiation data (in the case of NASA/RETScreen) are much higher that actual data from ground measurements (SWERA).

The daily horizontal solar irradiance for Kumasi (KNUST) used for this study was 4.30kWh/m^2/day based on radiation data in the SWERA database.

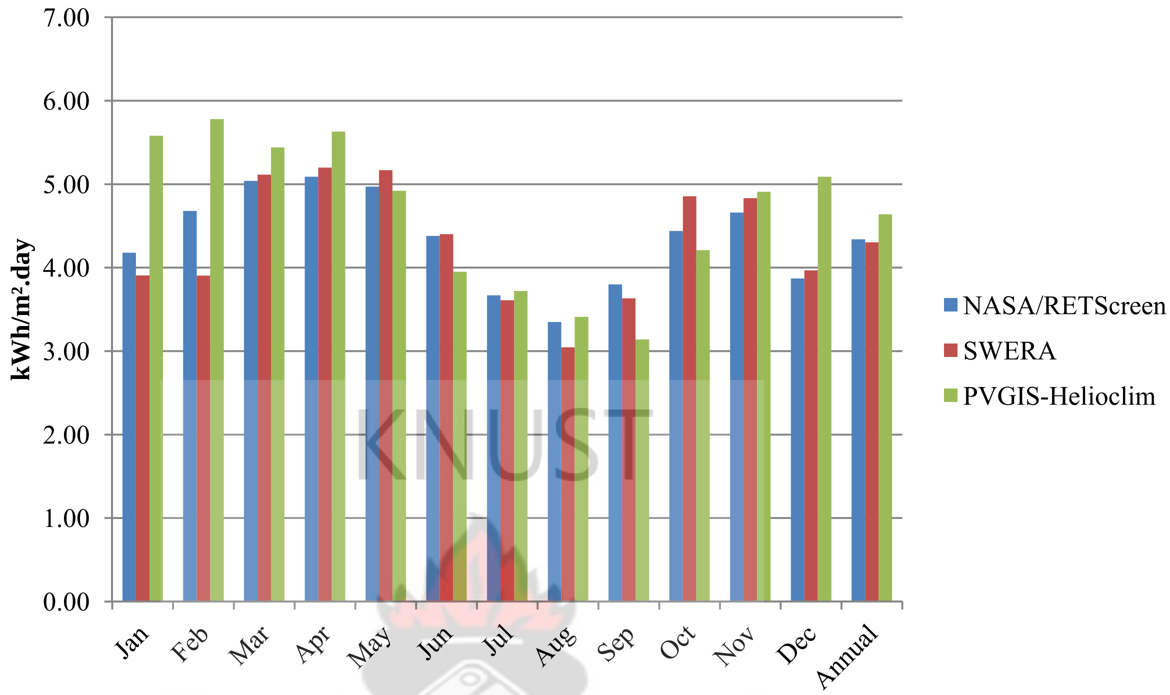

Figure 3.4: Comparison of solar radiation data from 3 different sources

The amount of solar radiation on the surface of a solar device depends on the orientation and inclination of the device. For every location, there is an optimum orientation and inclination which would enable a solar radiation device to receive maximum amount of solar radiation. It is always best to orient the solar device to face south at an optimum angle of inclination for locations in the northern hemisphere and vice versa. However, for roof mounted systems, the maximum amount of radiation is limited by the properties of the roof such as pitch/slope and orientation which can't be changed. Gable and hipped roofs in KNUST have slopes estimated to be about 15°. Figure 3.5 shows the PVsyst simulation results for solar radiation at the different orientations (south, north, east and west) for a 15° angle of inclination and also for flat roofs. The figure shows that south facing roofs receive more solar radiation annually followed by east/west facing roofs, flat roofs and then north facing roofs.

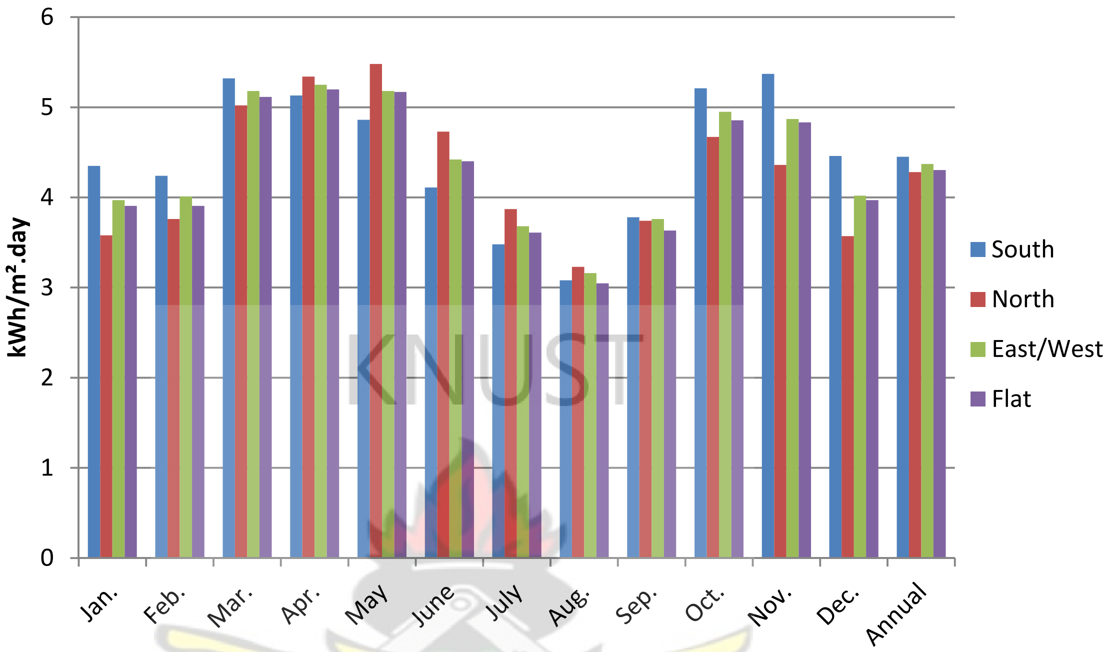

Figure 3.5: Solar radiation for different roof orientation including flat roofs[1]

3.2 Assessment of Roof Properties

The assessment of roof properties such as roof type, orientation and pitch, area, structural strength and the effect of shading on the roof is important because it helps one to know whether or not the roof will be suitable for the installation of grid-connected systems, in terms of carrying the weight of the solar PV system and also the amount of energy that can be generated from system installed on it. In all, one hundred and four (104) buildings were assessed including academic/faculty buildings, non-academic/administrative buildings, halls/hostels of residence on the

[1]Angle of inclination for sloping roofs have been estimated to be 15 degrees

campus. The study however did not take into consideration staff residence, uncompleted buildings as well as partly complete buildings.

3.2.1 Roof Type Assessment

There are seven (7) conventional types of roofs, namely: Flat, Gable, Hipped, Shed, Mansard, Gambrel and Arch-shaped roofs as shown in Figure 3.6 (Scharff et al, 2001). Roofs on the KNUST campus can be grouped under four (4) of the categories mentioned based on the shape of the roof. The three categories are Flat, Gable, Hipped and Arch-shaped roofs. The layout of the buildings on KNUST campus showing the four (4) main roof types is presented in Figure 3.7.

Gable roofs are the commonest type of roofs on the KNUST campus, making up about 74% of the total number of roofs on the campus. A Gable roof has two upward sloping sides that meet in the middle at the ridge as shown in Figure 3.6. To be a true gable roof, both sides of the roof must slope at the same angle. Viewed from the end, the shape of a gable roof appears as a symmetrical triangle.

Flat roofs on the other hand make up about 15% of the total roofs and are mostly found on the Annex building of the halls of residence and also the Unity Hall. Flat roofs, as the name implies, are usually made flat but often given a slight slope of about 5^o to enable rainwater to run-off the roof. The flat roofs on KNUST campus usually have very little free space since they mostly have water storage tanks and other equipment installed on them. Flat roofs are found on Pharmacy block and annex blocks of University Hall, Queen Elizabeth Hall, Independence Hall and the Republic Hall.

Hipped roofs accounted for only 5% of the buildings and are mostly found on the Great hall, Law auditorium and the Non-Resident students' facilities on campus. A hipped roof has many similarities to a gable roof but has four sloping surfaces instead of two. The intersection between the various surfaces is referred to as a hip (Scharff et al, 2001).

Arch-shaped roofs cover about 6% of buildings considered and are found on the old library block, the central classroom block and the dining halls of University Hall, Queen Elizabeth Hall, Independence Hall and the Republic Hall.

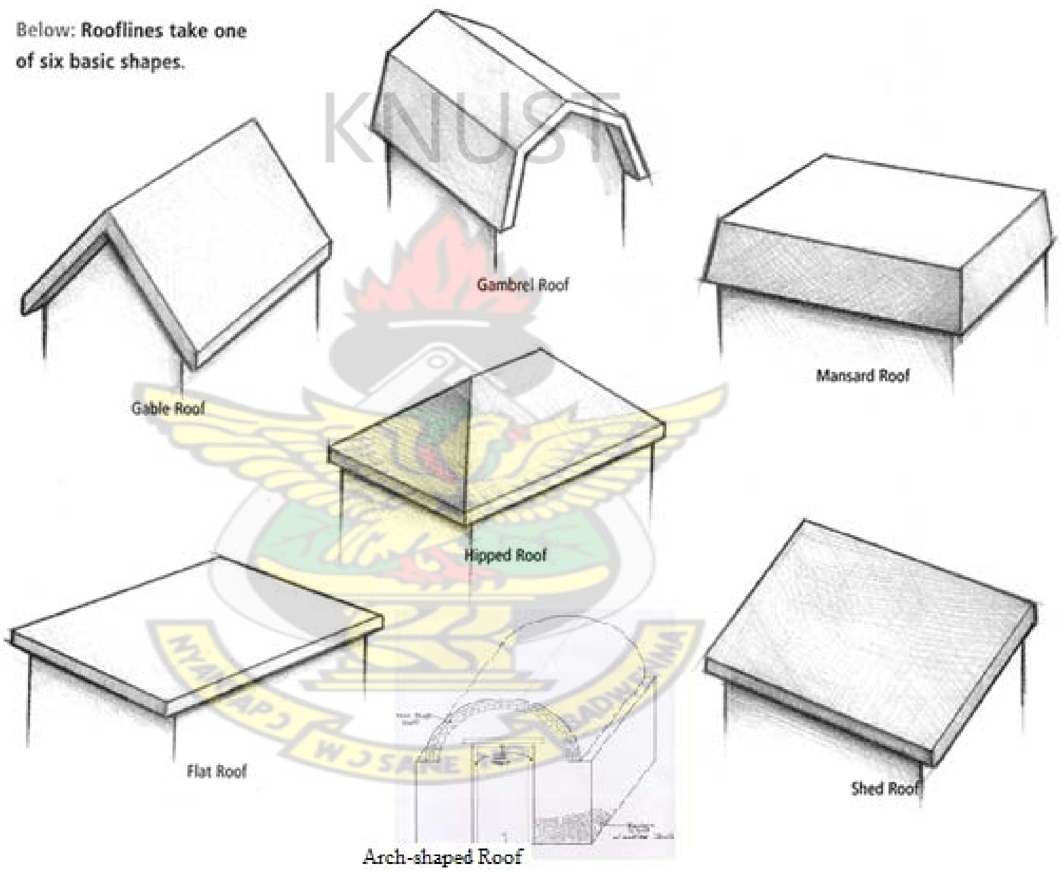

Figure 3.6: Types of roofs

Source: Scharff et al (2001)

3.2.2 Roof Area Assessment

The European Photovoltaic Industry Association (EPIA) estimates the total area required for the installation of solar PV systems to range between 7m^2/kWp and 15m^2/kWp depending on the technology used (EPIA et al 2011). Estimating the area of roofs for PV installations can be a very difficult task, particularly when the actual building drawings are not available and this is a very common phenomenon in Ghana. In the absence of building drawings as was experienced during this study, the roof areas were estimated with the help of Google Earth, an internet based software package which shows the actual location of the buildings and also provide a tool to measure the ground area covered by the building and land use map from the Geomatic Engineering Department of KNUST. The estimated ground area is then multiplied by the cosine of the roof slope to get the actual roof area. For the purpose of this work, a roof slope of 15 degrees (which is estimated to be the average slope of most of the roofs on the campus) was used. Multiplying the actual ground area covered by the buildings with the cosine of the roof slope increases the actual roof area by less than 4% as a result, it was ignored. The estimated roof area was assumed to be equal to the ground area covered by the building. In all, there is about 62,554m^2 roof areas available: 16,372m^2 facing north, 16,372m^2 facing south, 10,990m^2 facing east, 10,990m^2 facing west and 7,830 m^2 flat and arch-shaped roofs. The detailed list of roof properties for the buildings assessed is presented in Appendix C.

3.2.3 Assessment of Orientation and Pitch/Slope of Roof

The orientation of a roof surface refers to the direction in which the roof faces, i.e. north, south, east or west whereas the roof pitch/slope refers to the angle of inclination of the roof to the horizontal. Apart from the flat and arch-shaped roofs, which are not oriented in any particular direction, the gable roofs have roof orientations in either the north-south or the east-west directions and hipped roofs have all four. Out of the total area of roofs considered, 26% have north-south orientations, 18% in the east-west orientation and 12% have flat roofs. The gable and hipped roofs which have north-south or east-west or all four orientations however have slopes/pitches around 15^o.

3.2.4 Roof Strength Assessment

The main function of roofs among other things is to protect buildings from adverse weather conditions such as storms; as such it is designed to withstand a certain amount of load caused by severe weather conditions. The strength of roofs is mainly dependent on the properties of the materials used in constructing the frame of the roof as well as the roofing materials. Most roof frames on the KNUST campus are made from timber, in the case of smaller buildings, and steel, in larger buildings; all the building assessed have roof frames made of wood except the following buildings; Great Hall, Social Science New Auditorium, College of Engineering New Auditorium and the Agric Engineering Workshop, which have roof frames made of steel. The commonest roofing materials found on the roofs assessed are aluminum roofing sheets, concrete and asbestos roofing tiles; the latter (which is no longer in use because of its associated health risks) can only be found on four buildings including the College of Engineering lecture theatre, all the Faculty of Arts buildings and the Department of Economics building.

For the purpose of this study, the method used to assess the strength of the existing roofs included an assessment of the roofing material as well as the type of roof frame. The weight of the solar PV system is also considered in this assessment. The 2006 international building code specifies the maximum design load for ordinary flat and gable roofs as $960N/m^2$ (International Code Council, 2006). However, the average weight of solar PV systems together with accompanying mounting structures is about 150N/m^2, which is clearly below the maximum design load for ordinary flat and gable roofs. Therefore apart from the very old buildings with asbestos roofs, all the other building roofs were considered structurally suitable for solar PV installations.

LAYOUT OF BUILDINGS AT THE KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY-KUMASI

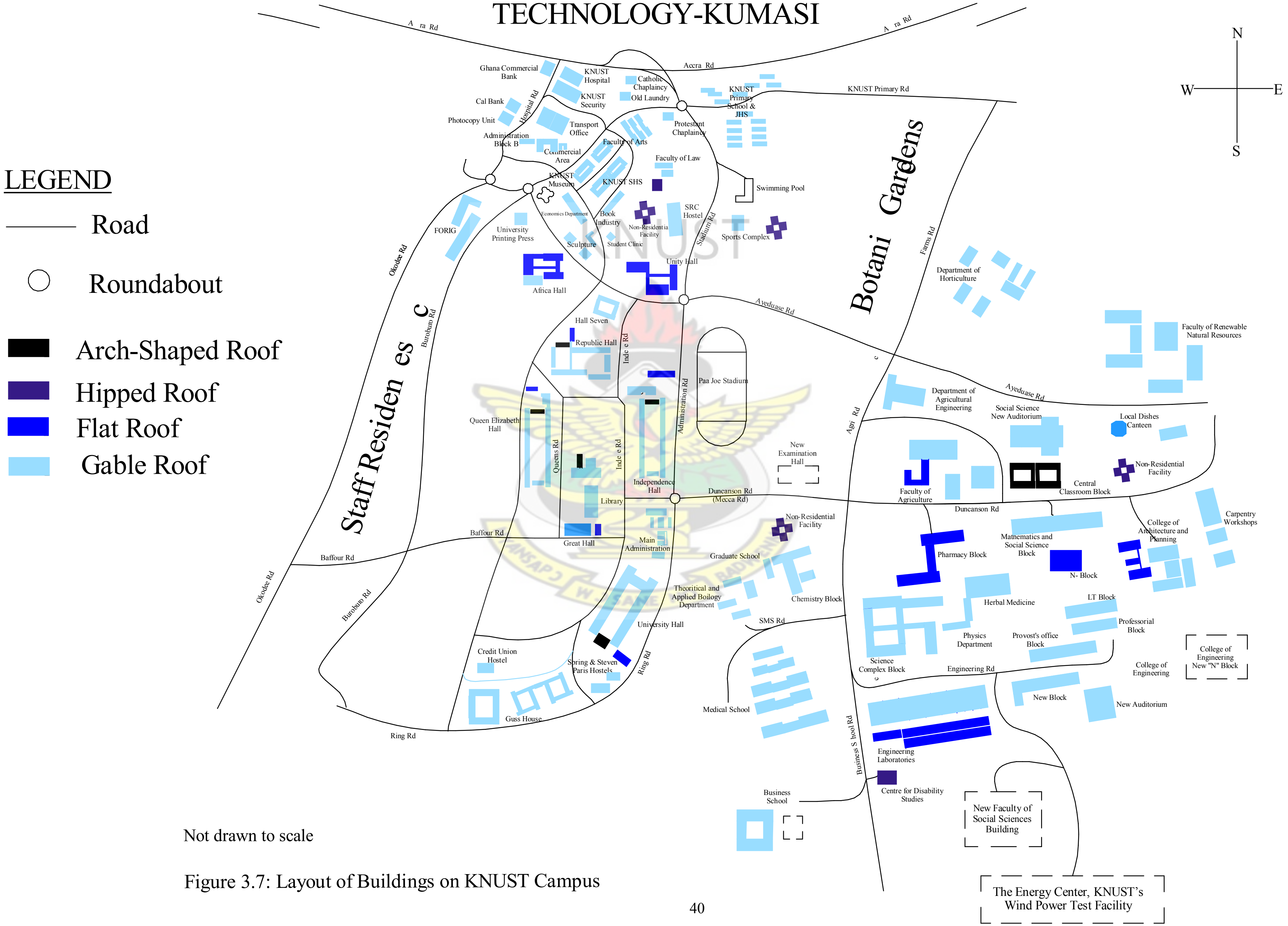

Figure 3.7: Layout of Buildings on KNUST Campus

3.2.5 Possibility of Shading of Roofs

Shading analysis is one of the most essential steps in solar energy system design. In photovoltaics, it is important to analyse shading caused by surro unding objects and/or vegetation since it can reduce the module output by as much as 50% depending on the type of solar cells; with thin film technologies having more tolerance for shading than crystalline silicon cells (Lenardic, 2011).

Shading analysis can be done in three main ways: using basic calculations involving some simple geometric equations, shading analyser or sun path diagram on acetate and computer software packages. Shading analysis for this work was done through a visual inspection of the various buildings at different times of the day and the possibility of shading assessed based on the results of physical observations.

Out of a total of about one hundred and four (104) buildings considered, only five buildings showed signs of possible shading of their roofs either by neighbouring vegetations or other buildings and these include the Drawing block for the College of Architecture and Planning, Graduate school, Agric Engineering workshop and the Professorial block of the College of Engineering.

3.2.6 Selection of Suitable Roofs

The selection of suitable roofs for grid-connected solar PV installations was done based on the following criteria: roof area, roof surface orientation and the possibility of shading from neighbouring buildings, vegetation or other obstacles.

In this work, large south-facing roofs devoid of shading of any sort from neighbouring buildings and other obstacles were preferred over others because they will not only house a larger number of installations but will also generate the maximum amount of electricity.

An initial prefeasibility study (see appendix F) suggested that a total of about 9,000m^2 of roof area will be required to mount the 1MW grid-connected solar PV system. The roof assessment revealed that there is a total of about 16,372m^2 facing north, 16,372m^2 facing south, 10,990m^2 facing east, 10,990m^2 facing west and 7,830 m^2 flat and arch-shaped roofs available. In total, the amount of roof space available for solar PV installations is about 43,697m^2 comprising of only faculty and administrative buildings. Out of these, south facing roofs are preferred because they receive the highest amount of solar radiation for the location followed by flat roofs, east/ west facing roofs and north facing roofs in that order.

3.3 Selection of PV System Components

Grid connected solar PV systems are usually made up of the following components: solar PV modules, inverters and other accessories including cables and metering devices. The selection of these components can be done with the help of catalogues from both local and international dealers.

3.3.1 Solar PV Module Selection

There are three main types of solar PV modules available on the market commercially. These include monocrystalline, polycrystalline and amorphous silicon modules. Table 3.1 gives a comparison of the three module types in terms of efficiency, area/kW$_p$ and cost/W$_p$.[2] The three main common modules available commercially were selected including monocrystalline, polycrystalline and amorphous silicon modules from Schott Solar were selected after which the results were compared.

[2] Cost includes of transportation to project site

Table 3.1: Comparison of PV module types

Module Type	Efficiency (%)	Area/kWp (m^2)	Cost/Wp ($)
Monocrystalline	13-19	7	2.33
Polycrystalline	11-15	8	2.46
Amorphous Silicon	4-8	15	2.02

Source: EPIA et al 2011 and Energiebau Sunergy Ghana Ltd

Schott solar modules (Schott Mono 190, Schott PROTECT Poly 185, Schott ASi 100) were selected because they have high efficiencies, can work better under high temperature conditions and were also recommended by Energiebau Sunergy Ghana Ltd, the leading installer of grid-connected solar PV systems in Ghana. Appendix E contains the datasheets of the three module types with all their properties outlined.

The mono-Si module selected for this work is Schott Mono 190 with the following specifications:

Nominal power	190W	Voltage at Nominal Power (Vmpp)	36.4V
Efficiency (ŋ)	14.1%	Current at Nominal Power (Impp)	5.22A
Area (A)	1.31m^2	Open Circuit Voltage (V_{oc})	45.2V
Cell type	Mono-Si	No of Cells	72

The poly-Si module selected for this work is Schott PROTECT Poly 185 with the following specifications;

Nominal power	185W	Voltage at Nominal Power (Vmpp)	23.5V
Efficiency (ŋ)	13.9%	Current at Nominal Power (Impp)	7.80A
Area (A)	1.34m^2	Open Circuit Voltage (V_{oc})	29.2V
Cell type	Poly-Si	No of Cells	48

The A-Si module selected for this work is Schott ASi 100 with the following specifications;

Nominal power	100W	Voltage at Nominal Power (Vmpp)	30.7V
Efficiency (ŋ)	6.9%	Current at Nominal Power (Impp)	3.15A
Area (A)	$1.45m^2$	Open Circuit Voltage (V_{oc})	40.9V
Cell type	a-Si	No of Cells	24

See Appendix E for manufacturers' data sheet

3.3.2 Grid-Tie Inverter

Inverter selection for grid-connected solar PV systems is a very important step because of the role the inverter plays in the whole system; as the main connecter to the utility grid. It is important that the inverter output parameters fall within the grid operators' specifications. The following criteria were considered for the selection of inverters for this work:

- The output alternating current of the inverter must be a three phase AC current with a voltage of 415V at 50Hz to facilitate synchronization with the grid
- The inverter capacity must be selected to match the capacity of the PV array; usually the same as the PV array capacity. The input DC voltage of the inverter must be the same as the array output voltage.
- The inverter efficiency at full load should be above 95% to minimize losses
- An in-built maximum power point tracker (MPPT) is important to maximize the power output of the PV array
- An in-built utility fault protection feature should also be included to help protect the system

Based on the set of criteria listed above, various capacities of Sunny Central and Sunny Tripower inverters from SMA Technology were selected. These inverters are 3-phase and come with inbuilt maximum power point tracker (MPPT) and have maximum efficiency of about 95% and 98.2% for Sunny Central and Sunny Tripower respectively. Sunny Central inverters come in capacities of 60kW, 90kW, 100kW and 125kW whiles the Sunny Tripower inverters come in capacities of 8kW, 10kW, 12kW, 15kW and 17kW (SMA, 2010). Since the array capacities would require a combination of inverters, a matlab algorithm was developed to do this combination (see Appendix D for algorithm).

3.3.3 Auxiliary Components

The components classified under this group include cables, metering devices: alternating current (AC) and direct current (DC) disconnect switches, and the mounting structures for the PV system.

Cables are required for the connection of the various components together to form a system. The type of cables to be used depends on the type of current (either AC or DC) that flows through the system. DC cables will be required for the interconnections between the various modules and also the connection of the PV array to the DC input end of the inverter. The connection from the AC output end of the inverter to the utility grid requires the use of AC cables. The sizes of the cables depend on the length of cable required and also the amount of current which would flow through them.

Metering devices are important in the system because they help to measure the amount of energy injected into the grid. For the purpose of this project, a 3-phase meter is required since the electricity generated is converted from DC to 3-phase AC before injection into the grid. The specifics of each meter will be selected based on the exact specification of the system such as the current flowing through the system.

AC and DC disconnect switches are required to enable isolation of the various components from the main system for maintenance.

Mounting structures help secure the PV arrays to the roofs of the buildings on which they are mounted. They are usually made of aluminum (the common material for the manufacture of mounting structures by most solar installers) since it is light in weight, strong, and resistant to corrosion. The means of fastening these mounting structures to the roofs however, depends on the roof frame as well as the roofing material.

3.4 System Layout Design

The configuration of the various components in a grid-connect solar PV system can be done in four different ways, namely AC module, String, Multi-String and Centralised systems; based on the way the PV arrays are connected to the inverters. These configurations can be seen in the Figure 3.8 (Kjaer et al, 2005).

In the AC module configuration, one large PV cell is connected to an inverter. In this case, the selected inverter should be able to amplify the very low voltage of the PV array for the grid whiles maintaining a high efficiency of conversion. This configuration is mostly suitable for smaller home systems and therefore would not be appropriate for larger systems since it increases the number of inverters required and in turn increase the total investment cost (Kjaer et al, 2005).

The string configuration involves the connection of single strings of PV modules to inverters. A string is a grouping of modules wired in series to increase the voltage of the system. Most modern solar-electric systems operate at 48-volts nominal, and high-voltage grid-tied systems can use up to 600 volts meanwhile the modules available have voltages of 12- and 24-volts. This therefore requires joining together modules to attain this higher voltage before connecting to an inverter and subsequently to the grid (Kjaer et al, 2005).

The multi-string inverter is a further development of the string inverter, where several strings are interfaced with their own DC–DC converters and subsequently connected to a common inverter. The advantage of this system is that each string can be controlled individually without disrupting the operations of the whole array and also provides room for new strings to be added to the system. It is also less expensive compared to the string and the AC module configurations because the number of inverters used reduces (Kjaer et al, 2005).

Centralized system configurations involve dividing the PV modules in to series connections (strings), with each generating a sufficiently high voltage to avoid further amplification. These strings are then connected in parallel, through string diodes, in order to obtain high power levels. This configuration, though cheaper than the others, comes with some very serious limitations including high-voltage DC cables between the PV modules and the inverter, power losses due to a centralized MPPT, mismatch losses between the PV modules, losses in the string diodes, and a non flexible design which is a disadvantage to mass production (Kjaer et al, 2005).

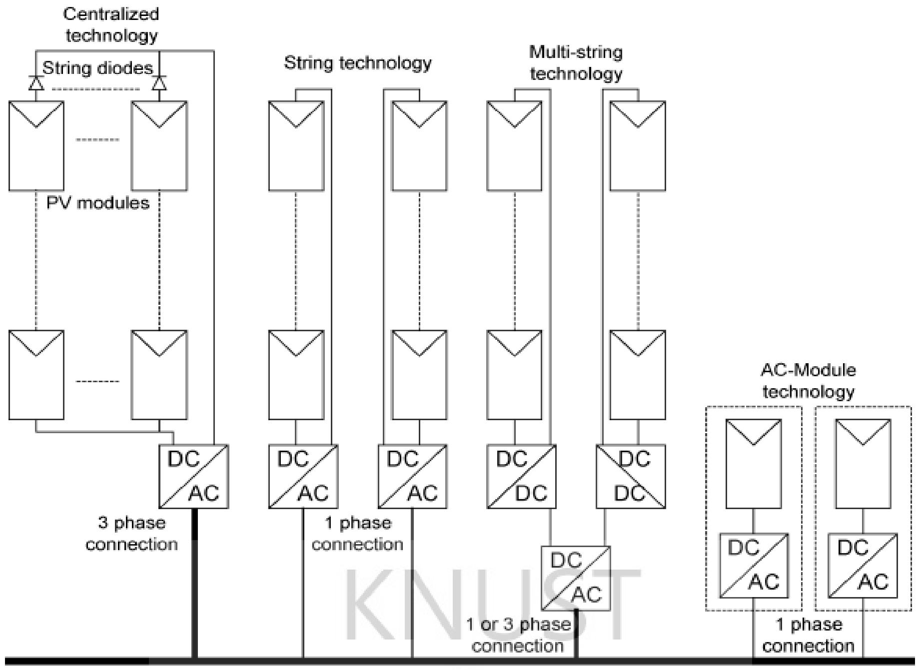

Figure 3.8 Types of PV array-Inverter configurations

Source: Kjaer et al (2005)

3.4.1 Design of 1MW Grid-Connected Solar PV System

The planning of the 1MW grid connected solar PV system was carried out for the three main solar PV technologies; monocrystalline, polycrystalline and amorphous silicon modules. These will be installed on roofs inclined at an angle of about 15 degrees to the horizontal. The system is also made up of module numbers ranging between 5,263 and 10,000 depending on the chosen technology. It is expected that the system will require a total area ranging between 6,906m^2 and 14,493m^2 depending on the solar PV module technology chosen. Each module has area between 1.31m^2 and 1.45m^2 depending on the type of module used as can be seen in the datasheet presented in Appendix E. Sixty (60) 3-phase inverters with capacities ranging from 8kW to 100kW (depending on the size of the PV array) will be used to convert the DC electricity from the PV modules to AC to be fed into the electricity grid. Table 3.2 presents a summary of the design specifications.

Table 3.2: Summary of design specifications

Module Type	**Mono-Si**	**Poly-Si**	**A-Si**
Module capacity	190W	185W	100W
Total array capacity	1MW	1MW	1MW
Area required	6,906m^2	7,247 m^2	14,493m^2
No of Modules	5,263	5,404	10,000
No of inverters	60	60	60

3.4.2 Layout of System

The layout selected for the system was the multi-string system configuration; several strings of PV modules were connected to a single inverter. This will help minimize the total investment cost whiles maintaining high system efficiency as well as increase flexibility in the operation of the system. In this design, each building will be classified as a subsystem with each subsystem comprising of several strings connected to a series of inverters and subsequently to the grid. Figure 3.9 shows the electrical layout of each of the systems.

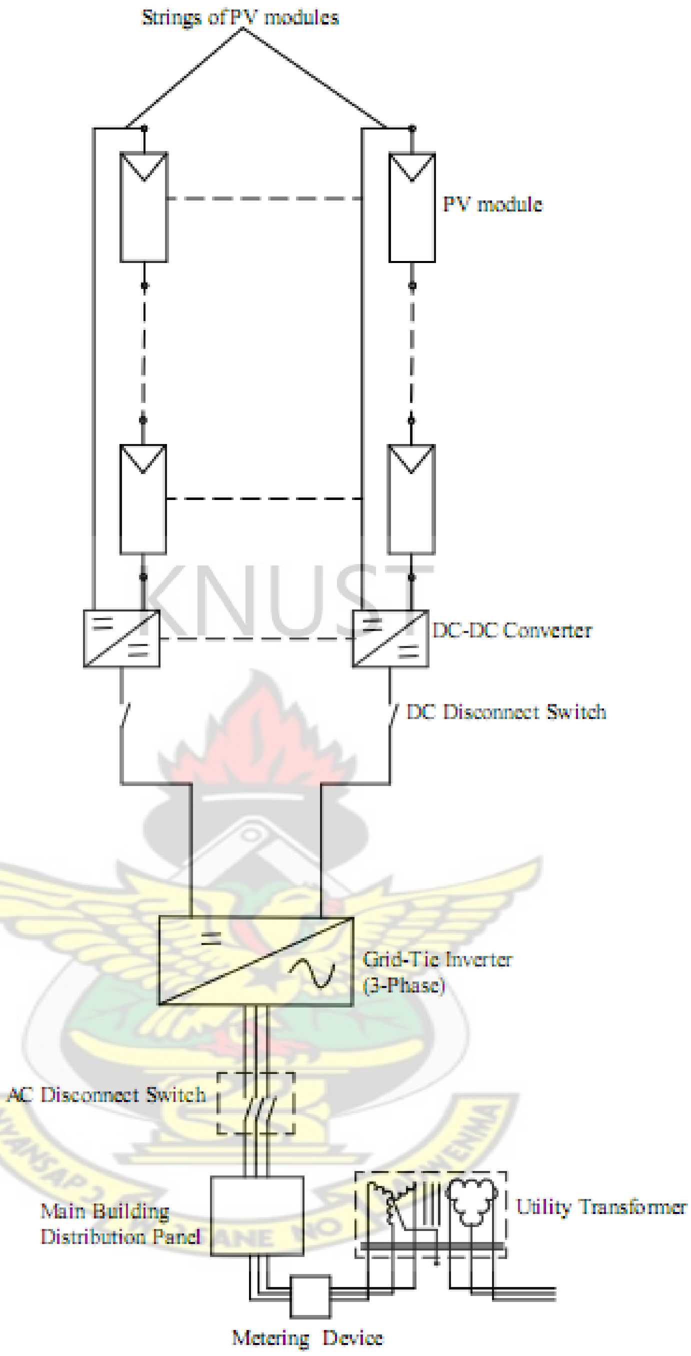

Figure 3.9: Layout of the proposed grid-connected PV system

CHAPTER FOUR – TECHNICAL AND ECONOMIC ANALYSIS

The preliminary studies of the 1MW Grid-Connected Solar PV System in Kumasi was carried out to analyse the technical performance of the system based on the results the PVsyst computer software simulation. PVsyst, developed by the Group of Energy of the Institute for the Sciences of the Environment of the University of Geneva in Switzerland, was used.

The economic analysis on the other hand was carried out to determine the cost and intended benefits of the project. This section also looks at the various financing options and their implications on the project. RETScreen Clean Energy Project Analysis Software was used for this simulation because it has strong financial modeling capabilities.

4.1 Technical Analysis

The International Energy Agency (IEA) Photovoltaic Power Systems Program describes, in its IEC Standard 61724, parameters used to assess the performance of solar PV systems (Marion et al, 2005). These performance parameters are used to define the system performance with respect to the energy production, solar resource, and the overall effect of system losses. These parameters include final PV system yield, reference yield, and performance ratio. The capacity factor of the system was also considered among the key parameters so that the system can be compared with other electricity generation sources in the country. These performance criteria were assessed for all three systems i.e. monocrystalline silicon, polycrystalline silicon and the amorphous silicon systems and the results compared.

This assessment was done with the help PVsyst software package which has an extensive database of meteorological data for different locations but can also take weather data specified by the user (SWERA data in this case), system components and their specifications from manufacturers and can simulate the performance of the PV system, taking into consideration the possible losses the system would suffer. More information on the software can be obtained from the developer's website.

4.1.1 Total Energy Yield

The total energy yield is the total amount of electricity that is injected into the utility grid by the 1MWp grid-connected solar PV system.

The 1MWp amorphous silicon system is capable of injecting 1,299MWh of electricity into the utility grid annually as compared to 1,206MWh and 1,197MWh by the monocrystalline silicon and polycrystalline silicon modules respectively. This is due to the fact that amorphous silicon suffers fewer losses as compared to monocrystalline and polycrystalline as explained in Section 4.1.6 of this report. The results presented graphically in Figure 4.1 show that, the months of March and October (both in the dry season of Ghana) record the highest electricity generation and the month of August recording the lowest amount of electricity generation for all three module types matching quite well the load curve presented earlier in Figure 3.1. The monthly average electricity generation by the 1MW grid-connected solar PV system will be able to make up for about 11% of KNUST's monthly electricity consumption.

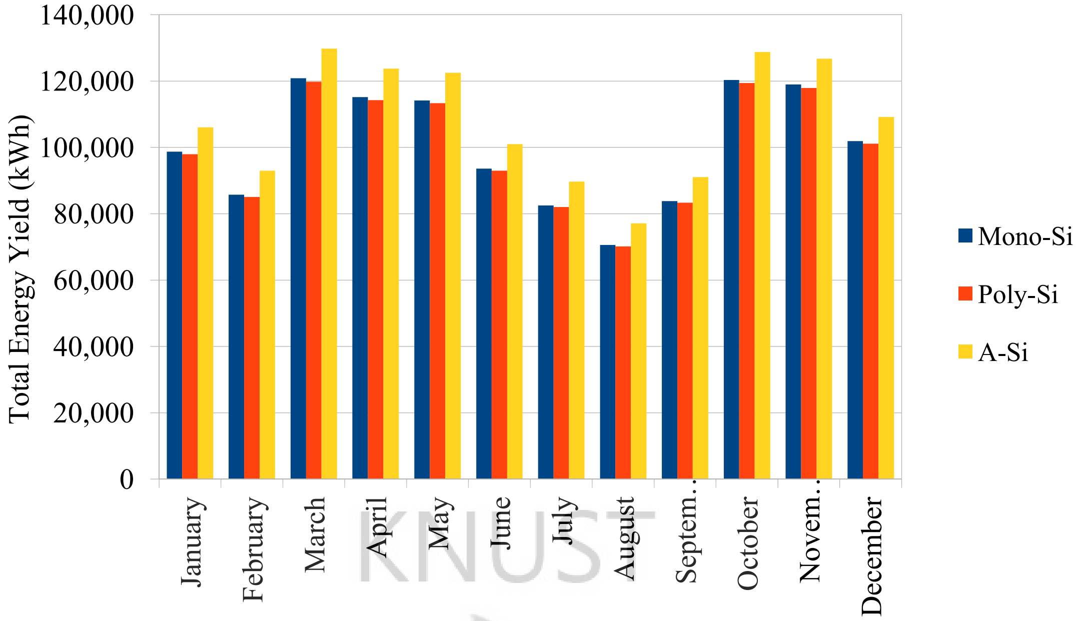

Figure 4.1: Total energy yield

4.1.2 Reference Yield

The reference yield, Y_r, is the ratio of the daily total irradiance reaching the surface of the PV array (in-plane irradiance) in kWh/m^2 to the PV array's reference irradiance (which is 1,000W/m^2 for Standard Testing Conditions) (Marion et al, 2005). It represents the number of daily peak sun-hours or an equivalent number of hours at the reference irradiance in a day. Its unit is hours. The reference yield also defines the amount of solar radiation available to a particular installation at a particular location and is a function of the location, orientation of the PV array, and weather variability.

$$Y_r = \frac{Daily\ total\ In - plane\ irradiance}{Reference\ Irradiance}$$

All three module technologies receive the same amount of solar radiation as a result of which they all have the same reference yield of 4.29 hours with the months of

November and March recording values as high as 5.18 hours and 5.12 hours respectively. The month of August recorded the lowest yield of 2.94 hours. Figure 4.2 shows the profile of the reference yield and compares it to the final PV system yield for the three module technologies under consideration.

4.1.3 Final PV Array Yield

The final PV system yield also referred to as the yield factor or specific yield, Y_f, is the ratio of the net energy output (total energy yield) to the nameplate DC power of the installed PV array (Marion et al, 2005). It represents the number of hours that the PV array would need to operate at its rated power and orientation in a given situation to provide the same amount of net energy output. The units are kWh/kW_p/day or hours/day. This parameter helps to compare the energy outputs of PV systems of different sizes.

$$Y_f = \frac{Net\ Energy\ Output}{Array\ DC\ Power}$$

It can be observed from the results in Figure 4.2 below that for the same rated capacity of system, amorphous silicon yields more in terms of energy output than monocrystalline silicon and polycrystalline silicon because. This is so because amorphous silicon experiences less losses compared to monocrystalline and polycrystalline as discussed in section 4.1.6. The average PV system yield is 3.56kWh/kWp/day for amorphous silicon, 3.31kWh/kWp/day for monocrystalline silicon and 3.28kWh/kWp/day for polycrystalline silicon. The months of November and March recorded the highest values of PV system yield whereas August recorded the lowest for all three module technologies. A comparison between the reference yield and the final PV system yield, gives an indication of the losses suffered by the system. The difference between the reference yield and the final PV system yield is equal to the losses suffered by the three module technologies.

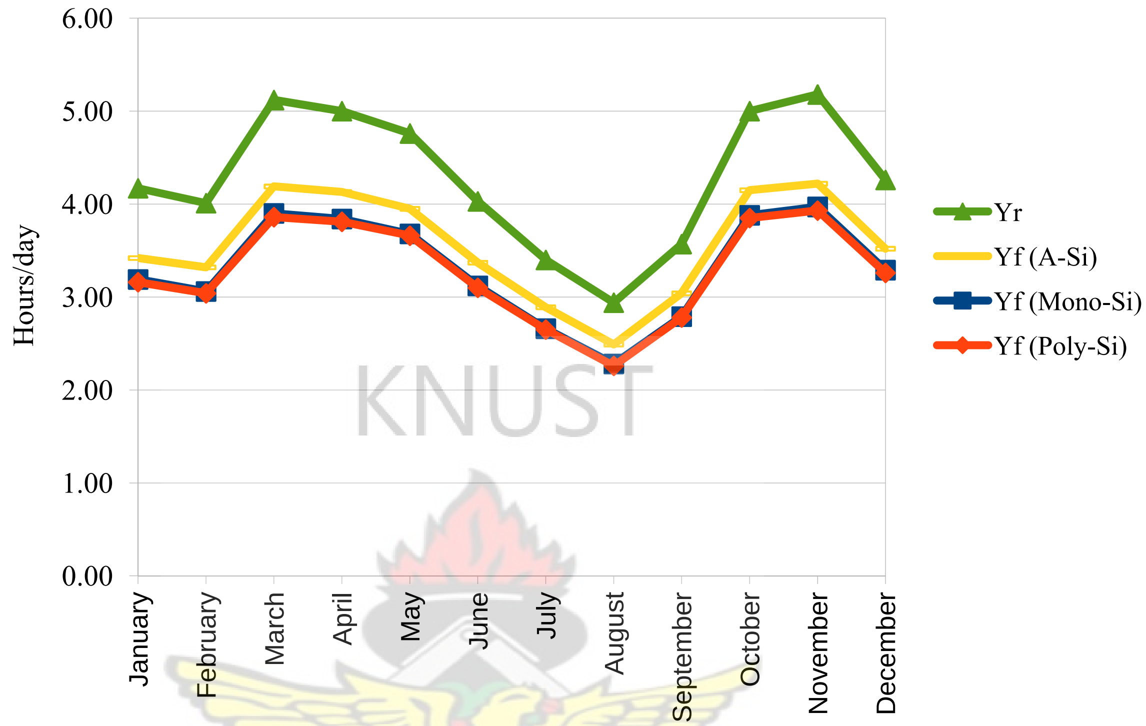

Figure 4.2: Comparison between reference yield and final PV array yield

4.1.4 Performance Ratio

Performance ratio (PR) is defined as the ratio of the actual amount of PV energy delivered to the utility grid in a given period of time to the theoretical amount of energy generated by the PV modules under standard test conditions (STC) (Marion et al, 2005). It is also referred to as the ratio of the final PV system yield to the reference yield.

$$PR = \frac{Y_f}{Y_r}$$

The average performance ratio recorded for the module technologies being considered is 0.831, 0.772 and 0.766 for amorphous silicon, monocrystalline silicon and polycrystalline silicon respectively as presented graphically in Figure 4.3.

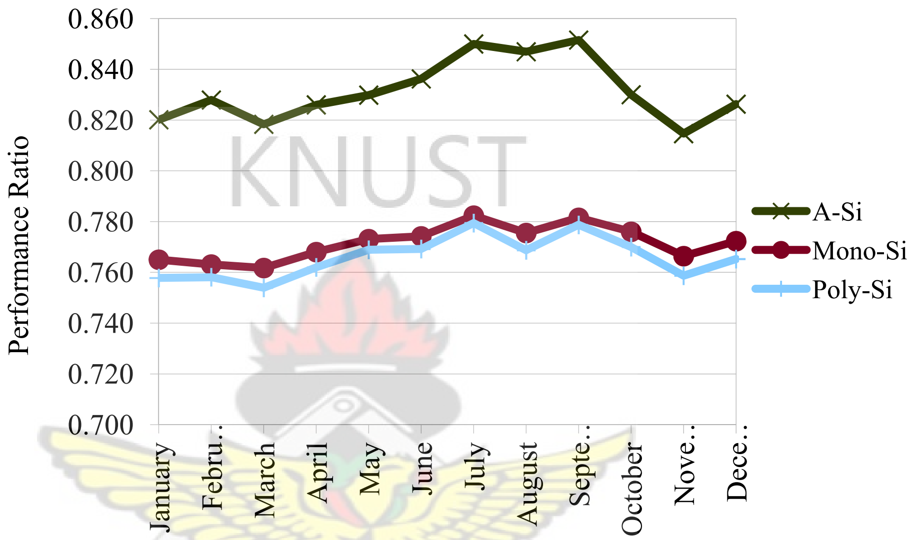

Figure 4.3: Average performance ratio for the system

4.1.5 Capacity Factor

The Capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its potential output if it had operated at full nameplate capacity the entire time. Mathematically, capacity factor is the total amount of energy the plant produced during a period of time divided by the amount of energy the plant would have produced at full capacity. Capacity factors vary greatly depending on the type of fuel that is used and the design of the plant. It also provides a tool for the comparison of the performance of different types of electricity generation plants.

$$\text{Capacity Factor} = \frac{\text{Annual Energy Output}}{\text{Nameplate Capacity} \times \text{No of Days in a year} \times \text{No of Hours/Day}}$$

The capacity factors are 14.8% for amorphous silicon, 13.8% for monocrystalline silicon and 13.7% for polycrystalline silicon. The graphic representation in Figure 4.4 has a profile is similar to that of the total energy yield presented in Figure 4.1.

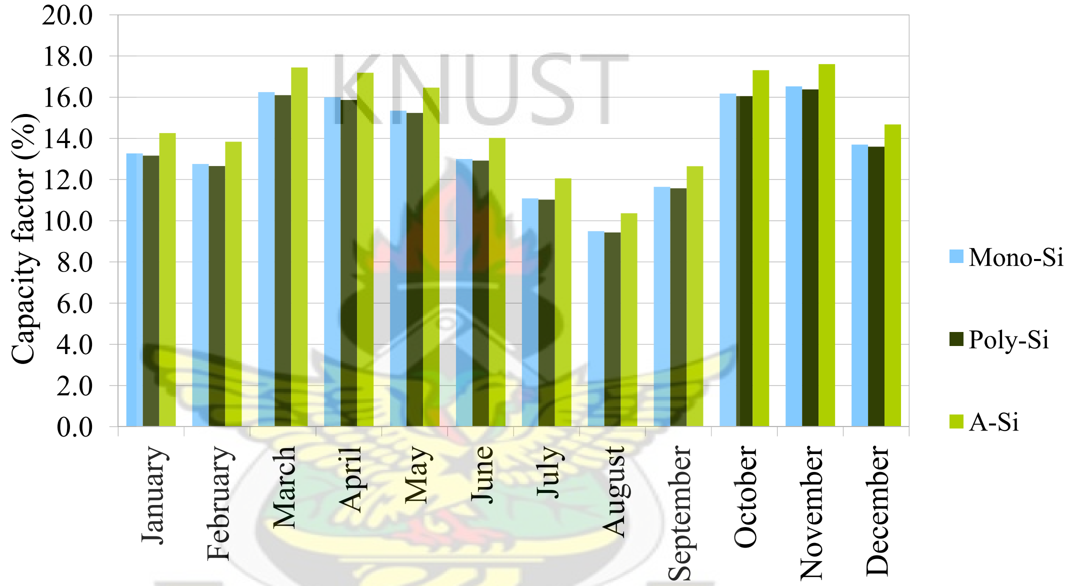

Figure 4.4: Capacity Factor for the system

4.1.6 Losses

Losses suffered by grid-connected solar PV systems can be classified under two main headings, namely collection/array losses and system losses. Collection/array losses are associated with the collection and conversion of sunlight into D.C. electricity whereas system losses are associated with the conversion of D.C. electricity to A.C. electricity and subsequent feeding into the grid (PVsyst, 2012).

The PVsyst simulation results showing the total losses suffered by each of the three module technologies presented in Figure 4.5. The results show that, monocrystalline and polycrystalline modules operate with much higher losses than amorphous silicon modules specifically 11.779kWh/kWp/day and 12.067kWh/kWp/day for monocrystalline module and polycrystalline modules respectively as compared to 8.75kWh/kWp/day by amorphous silicon modules.

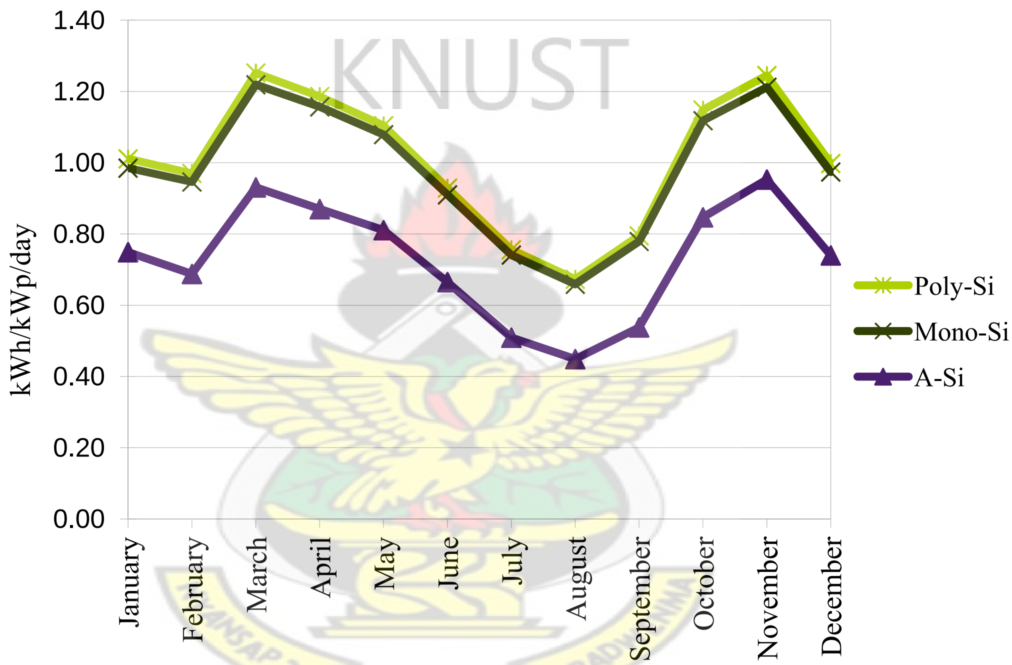

Figure 4.5: Total losses suffered by the three main PV module technologies

4.1.6.1 Collection/Array Losses

Collection/ array losses are the losses associated with the collection of solar radiation and its conversion into electricity by solar panels. They include irradiance losses, Incidence Angle Modifier (IAM) losses, thermal losses, module quality losses, module array mismatch losses and ohmic wiring loss.

The Incidence Angle Modifier (IAM) is an optical effect which corresponds to the weakening of the irradiation really reaching the PV cells' surface, with respect to irradiation under normal incidence (PVsyst, 2012).

Thermal losses are the losses associated with the operation of the solar PV system under very high temperature conditions. The standard test conditions are specified for a cell temperature of 25°C, but the modules usually work at higher temperatures, hence the source of this type of loss (PVsyst, 2012).

The Module Quality losses are the losses due to the usage of the low quality material. It is typically around 0.1 % to 0.2% (PVsyst, 2012).

Losses due to "mismatch" are related to the fact that the real modules in the array do not rigorously present the same I/V characteristics as specified by manufacturers. Mismatch losses are the losses due to the varying tolerance level of the modules power capacities as specified by manufacturers (PVsyst, 2012).

The wiring ohmic resistance induces losses (I^2R) between the power available from the modules and that at the terminals of the array. These losses can be characterised by just one parameter R defined for the global array

PVsyst simulation results reveal that, collection/array losses account for as high as 22.1% of the global horizontal irradiation available to the location of the PV systems. The comparison of the losses suffered by the three technologies presented in Figure 4.6 show that amorphous silicon suffers much less collection/array losses than monocrystalline and polycrystalline modules. This is because as can be seen in the datasheets presented in Appendix E, the amorphous silicon modules have a lower temperature coefficient than monocrystalline and polycrystalline.

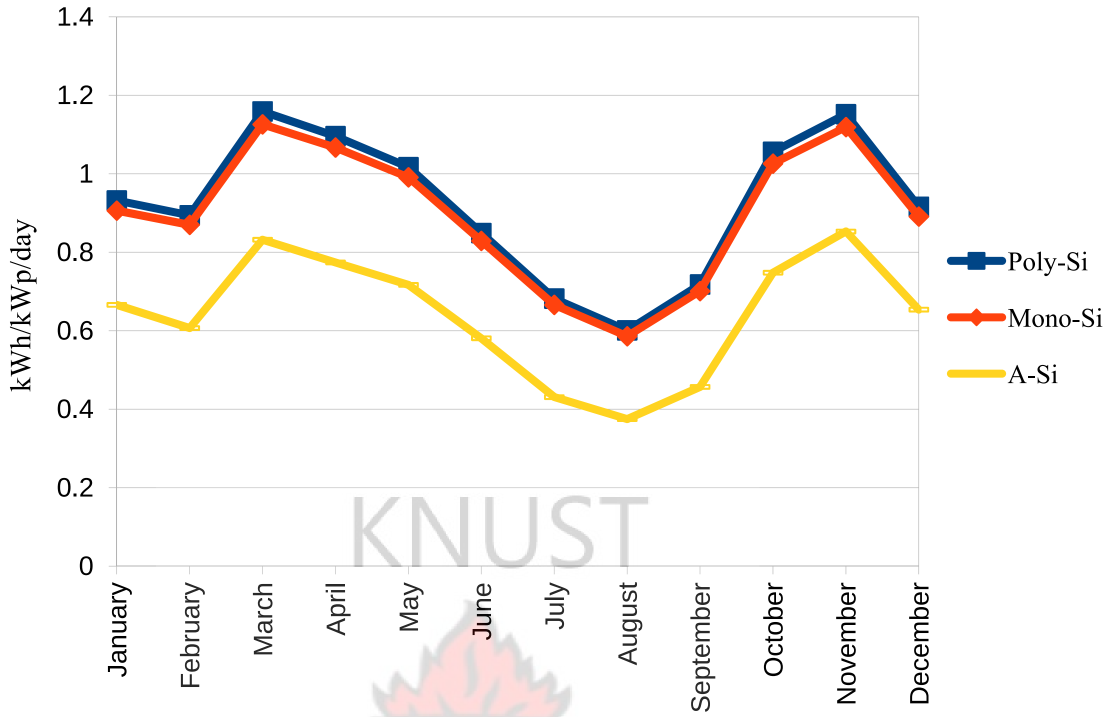

Figure 4.6: Collection losses for the system

4.1.6.2 System Losses

System losses on the otherhand are associated with the conversion of the D.C produced by the solar modules to A.C by the inverters for feeding into the utility grid. They comprise of mainly of inverter losses. The system loss curves present in Figure 4.7 show that amorphous silicon cells suffer higher system losses/kWp for the same rated capacity than the other two technologies under consideration.

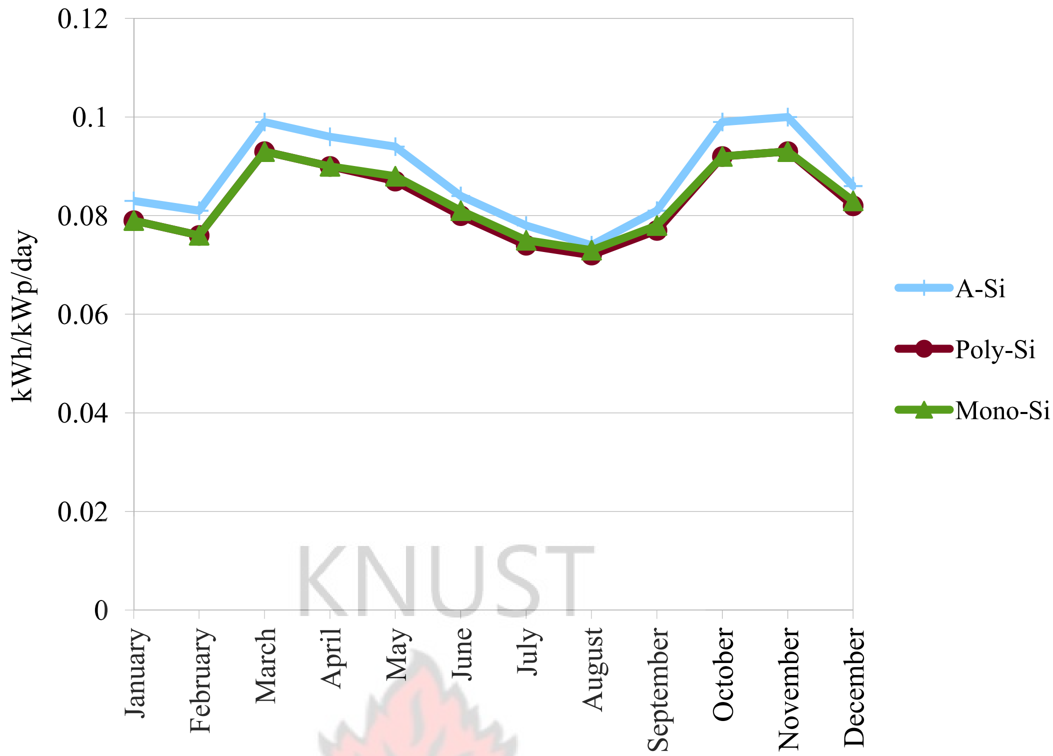

Figure 4.7: System losses

The loss flow chart presented in Figure 4.8 was generated through the PVsyst simulation and shows the details of the losses suffered by the three systems. A detailed comparison of the losses for the three systems in Figure 4.8 show that the thermal loss for amorphous silicon is lower compared to monocrystalline silicon and polycrystalline silicon; an indication that amorphous silicon modules perform better than the other two under high temperature conditions.

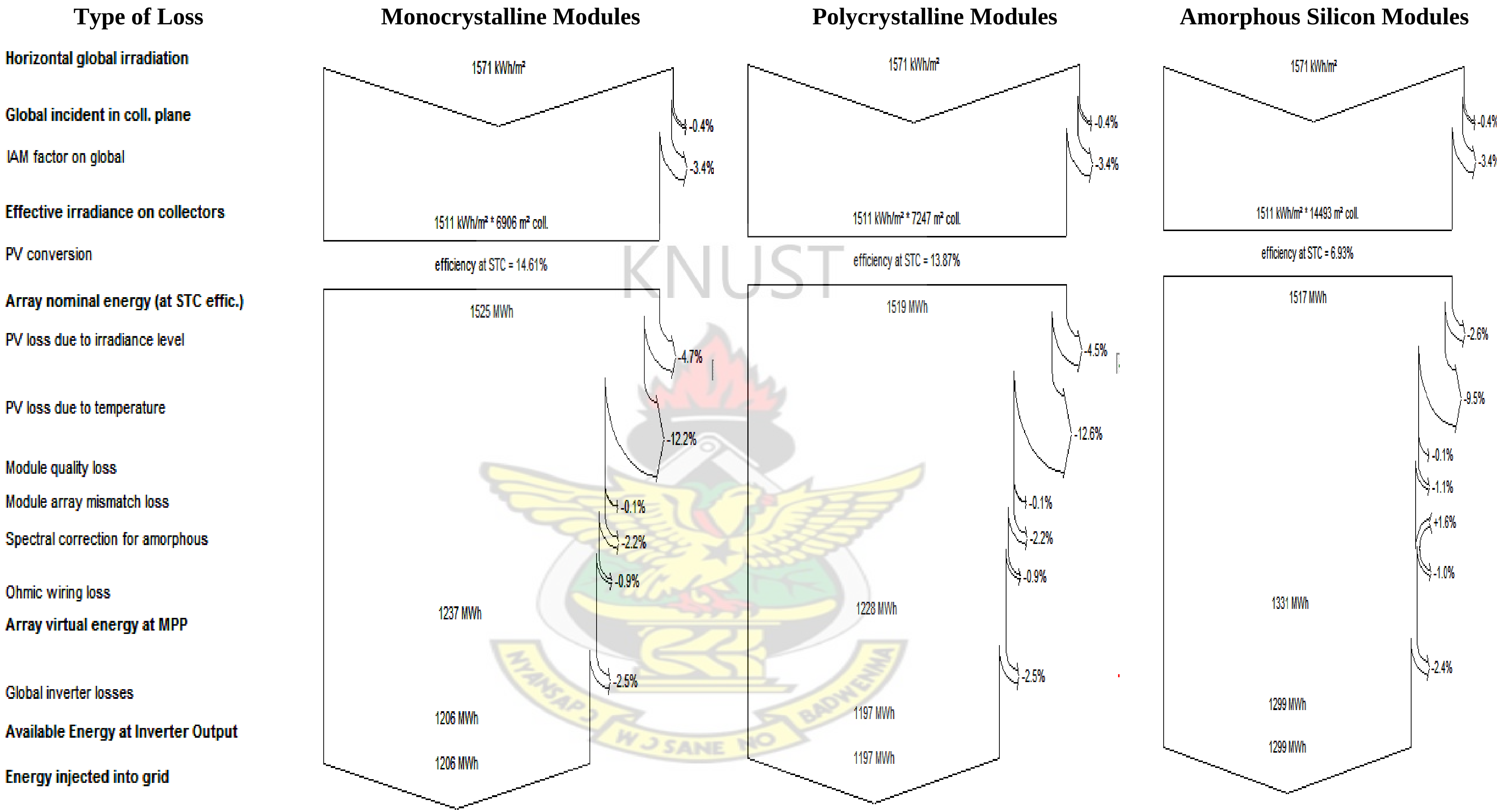

Figure 4.8: Loss flow Chart for 1MW grid-connected solar PV system

4.2 Economic Analysis

The economic analysis in this work was carried out to assess the cost and intended benefits of the project. It was carried out with the help of RETScreen software. The software has the capability of simulating some financial indicators such net present value and simple payback period over the life of the project. RETScreen also has the capability of simulating the technical performance as well as estimating the greenhouse gas saving potential of renewable energy projects over their entire operational life.

The analysis considers the total investment cost as well as the operation and maintenance cost of the system and matches it against the revenue generated from the sale of electricity to the utility grid. The main financial indicators used for this analysis are Net Present Value (NPV).

NPV is used in capital budgeting to analyze the profitability of an investment or a project. It is the difference between the present value of all revenues and the present value of all expenses, including savings, accrued during the life cycle of an investment. It is a standard method for long-term projects appraisal which takes into account the time value of money. It measures the excess or shortfall of cash flows, in present value terms, once financial charges are met. Net Present Value (NPV) is represented as

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t}$$

Where C_t = Net cash flow (revenue + savings – expenses)

r = Discount rate

t = Period

N = Total number of periods

Net Present Value is an indicator of how much value is added to an investment under the specified conditions of discount rate, d, and the economic life time of the investment, N; positive NPV indicates the economic viability of an investment: the greater the value of the NPV, the more profitable the investment.

4.2.1 Total Investment, Operation and Maintenance Costs

The total investment cost comprises the following components; module, inverter, mounting structures, and installation. The cost of solar PV systems has reduced significantly over the years due to the massive improvement in the technology and also the economies of scale. For the purpose of this study, the cost of the solar system was taken from one of the leading solar PV installers in the country (Energiebau Sunergy Ghana) and the breakdown is presented in Table 4.1. The module cost alone accounts for about 53% of the total investment of US$4,450,000.

Table 4.3: Cost breakdown for the Grid-Connected Solar PV system

Component	**Cost ($/Wp)**
Module	2.36
Inverter	0.51
Mounting Structures	0.42
Accessories	0.24
Installation	0.92
Total	**4.45**

Grid-connected solar PV systems are globally considered as 'maintenance free' systems, mainly because of the very low level of maintenance carried out on the systems during their operational life compared to other electricity generation systems. The major maintenance works, however carried out on PV systems are done on the inverters. For the purpose of this study, the operation and maintenance (O & M) costs for the systems is set at 5% of the capital cost as specified by the PURC draft feed-in-tariff policy and guidelines.

4.2.2 Financing Options and their Implications on Project Viability

The Parliament of Ghana recently passed a Renewable Energy Act which has a component for feed-in tariffs for electricity generated using renewable energy technologies (Ghana Parliament, 2011). This comes as a boost for investment in the renewable energy industry. The purpose of this section of the work is to look at the various financing options available to renewable energy investors and how they affect the viability of projects. This was done by first developing a business as usual (BAU) scenario with the parameters below in the RETScreen software package;

- Solar PV system cost = US$4.45/$W_p$
- Operating and Maintenance Cost =5% of capital cost
- Project Life =25years
- Discount Rate =10%
- Inflation Rate =0%
- Grant/Capital Subsidy =0%
- GHG Credit =US$0/tonne

Other scenarios were developed, by varying the BAU parameters, to analyse the impact feed-in tariffs (FiT), grants/subsidies, GHG income and reducing system cost would have on the viability of the project.

4.2.2.1 Feed-in tariffs

This scenario presents the implications of various levels of feed-in tariffs, as a means of financing grid-connected solar PV projects, on the net present value of the project. The results, presented in Figure 4.9, shows that with the BAU parameters, the project is not viable yielding an NPV of about US$-3,000,000 at a feed-in tariff of US$0.11/kWh. The project however breaks even at a feed-in tariff of US$0.43/kWh. The project only becomes viable at feed-in tariffs above US$0.43/kWh, yielding positive NPV.

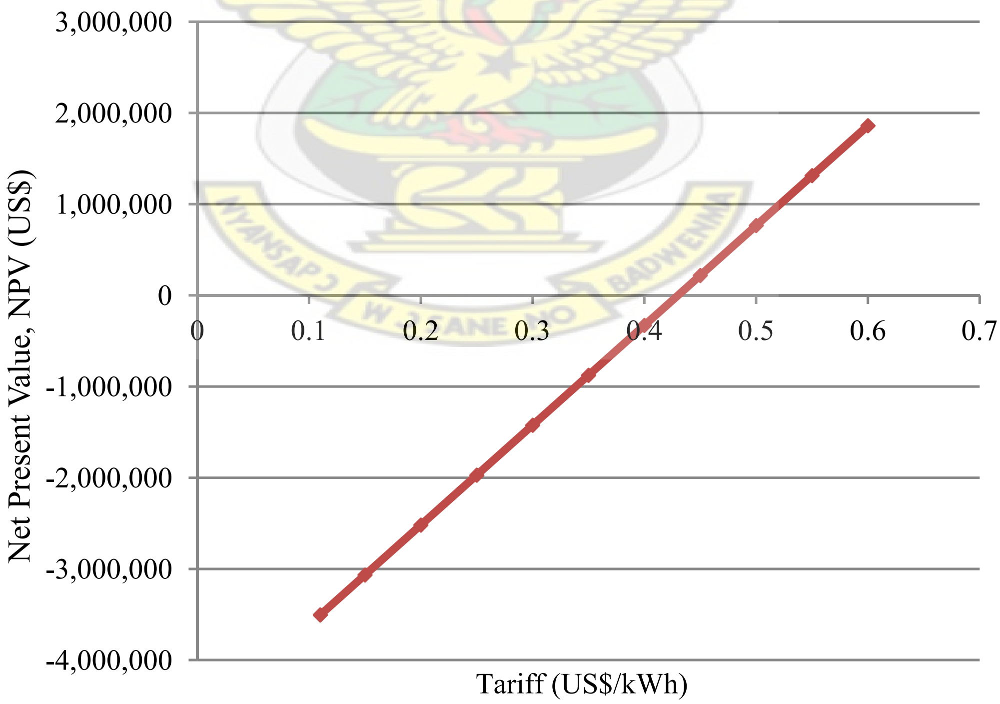

Figure 4.9: Impact of feed-in tariffs on the NPV

4.2.2.2 Grants and Capital Subsidies

Grants and capital subsidies unlike loans are not repayable and have served as good incentives for the development of various renewable energy projects in Ghana. Ghana, currently, has a policy which allows importers of solar PV panels to do so without paying any duties on their imports. In addition to this, different levels of grants/capital subsidies when provided will encourage the development of grid-connected PV systems in the country by reducing the total investment cost of the system.

This scenario presents different levels of grants/subsidies and their effects on the net present value of the project. The results presented in Figure 4.10 indicate that, when a grant of 50% of the total investment cost is provided for the project, the project becomes viable at feed-in tariffs greater than US$0.23/kWh. On the other hand, when a grant is provided to cover 80% of the total investment cost, it takes a feed-in tariff greater than US$0.11/kWh for the project to be viable.

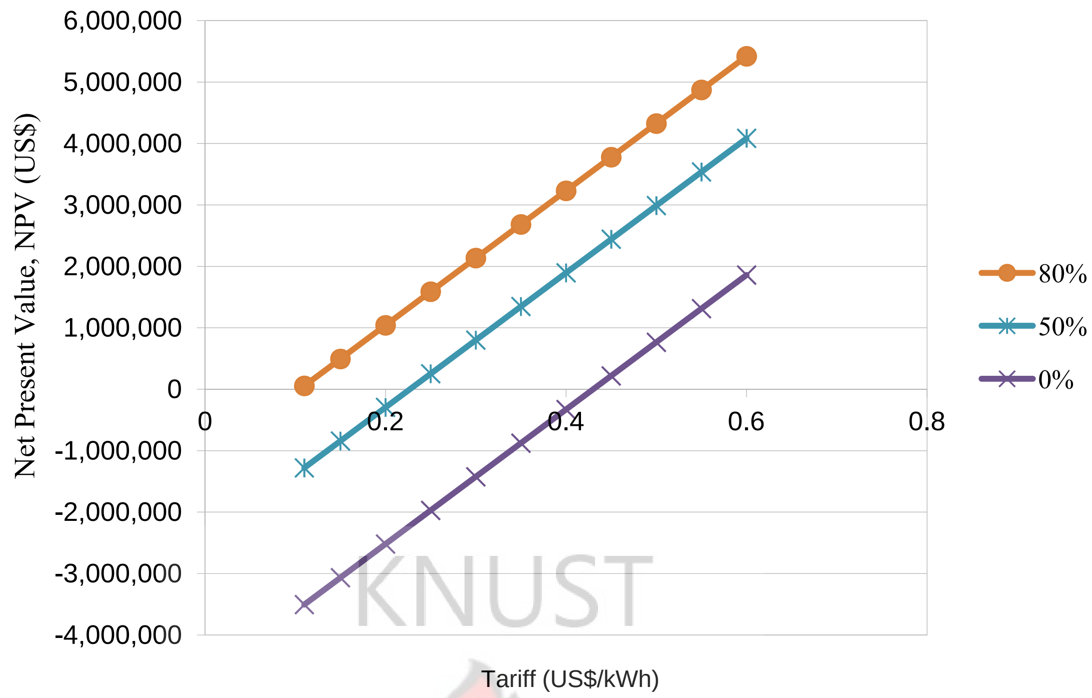

Figure 4.10: Effect of grants/subsidies on NPV

4.2.2.3 Carbon Credit Financing

Grid-connected solar PV systems are globally regarded as carbon free during their operational life and as such are a very effective tool to help mitigate the effects of climate change. The 1MW grid-connected solar PV system designed in this project will save about 824 tonnes of CO_2 annually when compared to a thermal power plant generating the same amount of electricity but running on crude oil, which can be traded as specified by the Kyoto Protocol to bring additional revenue to the project. Figure 4.11 shows the impact of GHG income on the NPV for the project. It is observed that GHG income doesn’t affect the financial indicators by much but then provides significant revenue to cater for the annual operation and maintenance cost of running the project.

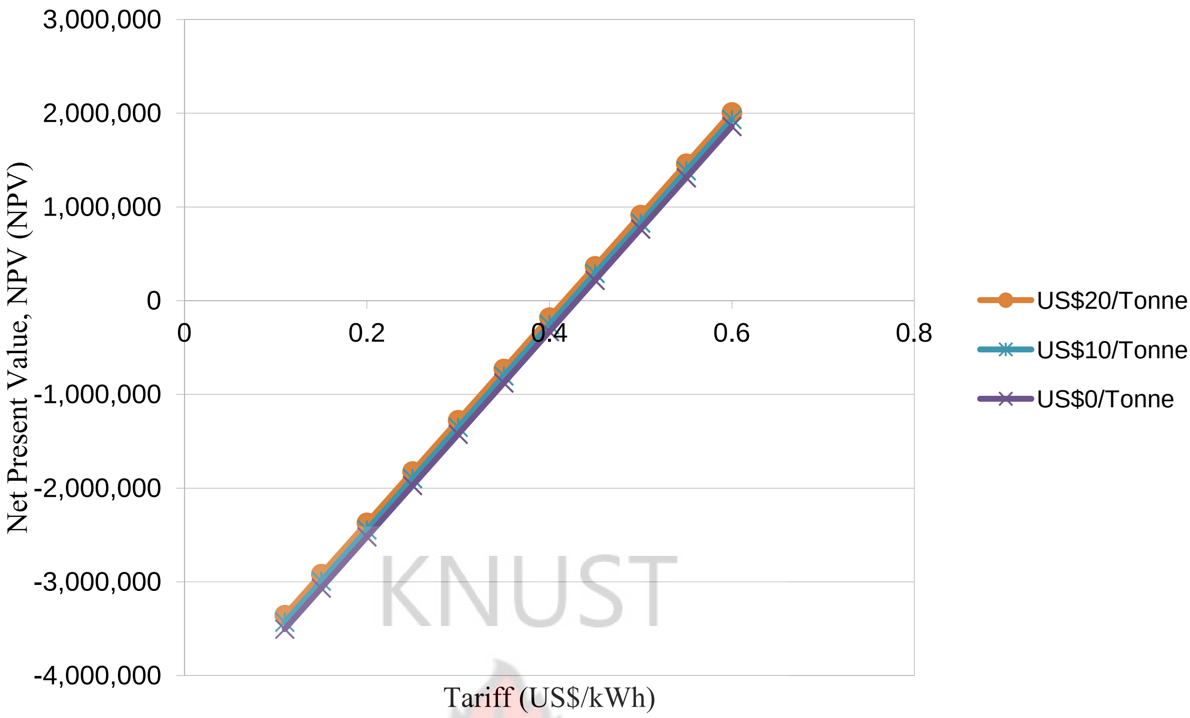

Figure 4.11: Impact of GHG income on NPV

4.2.2.4 Reducing PV System Cost

The cost of solar PV systems has taken a downward turn over the past few years. The European Photovoltaic Industry Association (EPIA) believes this is as a result of technological innovation, production optimisation, economies of scale, increasing the performance ratio of PV systems, extending the life of PV systems, development of standards and specifications as well as advancement in next generation technologies (EPIA, 2011).

The results of this scenario presented graphically in Figure 4.12 show that, a reduction in the cost of PV systems has a similar effect as grants/capital subsidies on the financial indicators; it improves the viability of the project by yielding more positive NPV. This suggests that grid-connected solar PV systems will be more viable in Ghana when there is reduction in the cost of the PV systems. This cost reduction like that of the world market will be due to an improvement in solar PV technology and maturity in market the Ghanaian solar PV market.

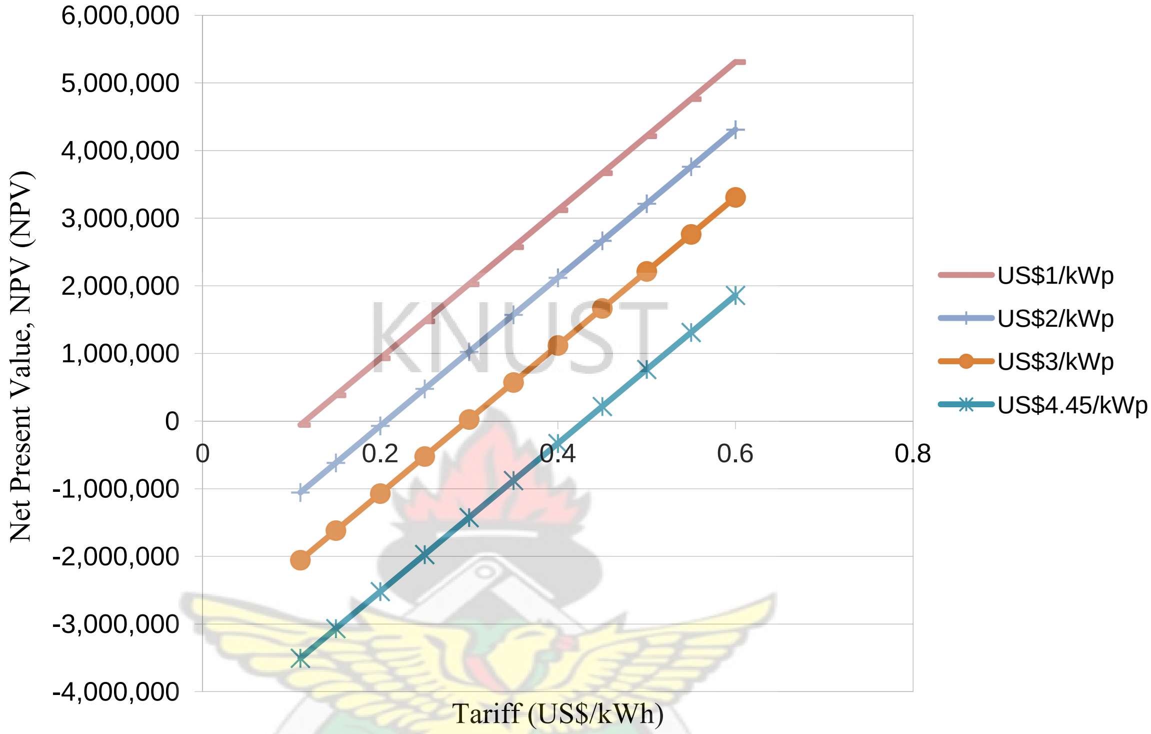

Figure 4.12: Effect of reducing PV system cost on NPV

CHAPTER FIVE – CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Africa, in spite of its huge potential for solar energy applications, has not seen much investment in the area mainly due to the very high investment cost associated with the technology. However, technological innovations leading to improvements in efficiency as well as the economies of scale stemming from mass production have and are still helping to bring down the cost of PV systems.

It is expected that the framework developed in this study will make it easy for institutions to plan and analyse their own grid-connected solar PV system. The solar resource assessment carried out as part of the site assessment showed that, KNUST-Kumasi receives about 4.30kWh/m^2 of global horizontal solar radiation per day. The institution also consumes an average of about 12,397 MWh of electricity annually which is taken from the national grid.

In all, about one hundred and four (104) buildings were considered out of which 74% had gable roofs, 15% had flat roof, 6% had arch-shaped roofs and 5% were hipped roofs. About 48% of the roofs had north-south orientation, 27% had east-west orientation and 24% were flat roofs. The total roof area available is about 62,554m2; 16,372m^2 facing north, 16,372m^2 facing south, 10,990m^2 facing east, 10,990m^2 facing west and 7,830 m^2 flat and arch-shaped roofs. The selection of suitable roofs for grid-connected solar PV installations was done based on the following criteria; size of roof (roof area), roof orientation, roof strength and the possibility of shading from neighbouring buildings, vegetation or other obstacles. Thirteen (13) buildings with roof area of 9,434 m^2 facing south were selected for the 1MWp installation.

Three solar PV module technologies were selected and their performance compared. These are monocrystalline silicon, polycrystalline silicon and amorphous silicon modules.

The technical analysis showed that, amorphous silicon modules, in spite of their low efficiencies, generate more electricity per rated output than monocrystalline silicon and polycrystalline silicon modules. This is because amorphous silicon modules have a lower temperature coefficient than monocrystalline and polycrystalline modules. The 1MWp amorphous silicon system generated about 1,299MWh of electricity annually with a performance ratio of 83.1% as compared to 1,206MWh and 77.2% by the 1MWp monocrystalline system and 1,197MWh and 76.6% by the 1MWp polycrystalline system. The 1MWp amorphous silicon system also operated with a capacity factor of 14.8%, higher than the 1MWp monocrystalline and 1MWp polycrystalline systems which had capacity factors of 13.8% and 13.7% respectively.

At prevailing solar PV system cost, and bulk generation charge, a capital intensive project of this kind is not feasible except at feed-in tariffs greater than US$0.43/kWh. However, when grants/capital subsidies are provided to cater for about 50% of the total investment cost, the project becomes viable at a feed-in tariff of US$0.23/kWh. GHG income, on the other hand does not affect the viability of the project much since a 1MWp solar PV system saves only about 842tonnes of CO_2 per annum.

5.2 RECOMMENDATIONS

The recommendations from this study are that;

1. A study should therefore be carried out to examine the capacity of the utility grid in terms of how much electricity can be injected. This is because knowing the capacity of the utility grid will provide useful information about how much electricity from solar PV systems can be injected into the grid.

2. It will be necessary to know the impact a 1MWp or higher capacity grid-connected solar PV system will have on the utility grid. It is therefore recommended that a study be carried out to address this issue.

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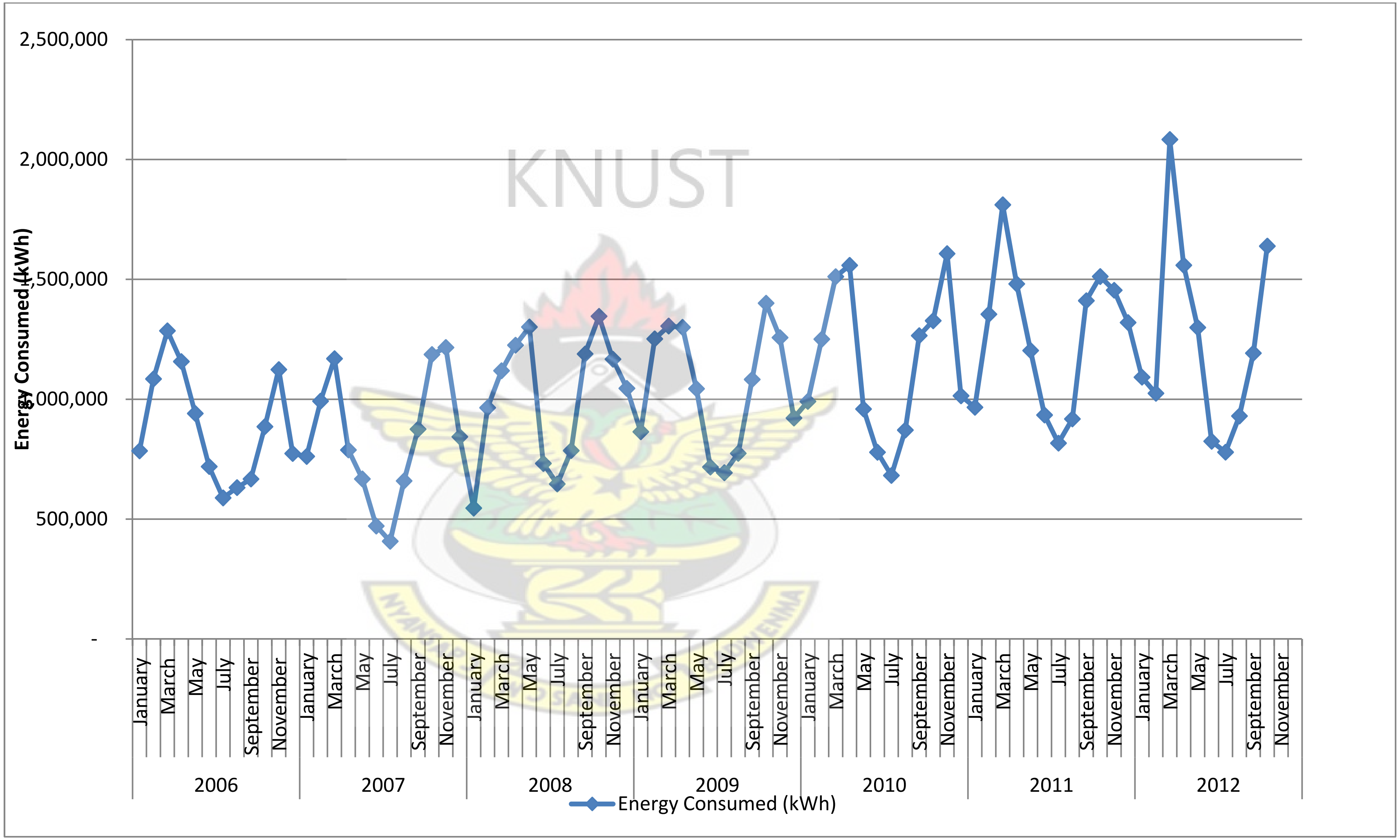
APPENDICES

A. Zero-order draft procedure

1. Determine the total capacity of the system to be designed.
2. Conduct a simple prefeasibility study (using RETScreen or other suitable software) to
    a. obtain an idea of the amount of energy that will be generated
    b. Estimate the total space (area) required for the project and
    c. Estimate economics of the whole project.
3. Obtain a land use map of the location showing the various sites that can be used for the project.
4. Confirm the various locations on the land use map and update where necessary.
5. Identify various building roofs and car parks that can be used for the project based on a minimum roof area.
6. Obtain the dimensions of the roofs of the selected buildings and car parks to be used.
7. Assess the suitability of the various roofs. This can be in terms of;
    a. Roof type
    b. Roof orientation
    c. Roof pitch
    d. Effect of shading on the roof
    e. Structural strength of the roof
    f. Building electrical system and options for grid connection
8. Select suitable roofs and collate the total area available for the project based on the results of Step 7 above.
9. Obtain solar PV information from various solar dealers both locally and internationally. This information should include; type, cost, size, weight, etc
10. Repeat Steps 7 and 8 using actual data obtained from solar PV dealers.
11. Design the layout of the system for each of the selected roofs/buildings.
12. Simulate technical performance (use PVsyst or other suitable software) and determine financial viability of the project (using RETScreen or other suitable software).

B. Electricity consumption from the year 2006 to 2012



Source: ECG (2012)

C. Properties of roofs on KNUST campus

College/Faculty/Department	Name of Building	Roof Type	Estimated Roof Area Facing (Square metre)						No of Stories	Roofing Material	Roof Frame	Possibility of Shading
			South	North	East	West	Flat Roofs	Total Roof				
College of Agricultural Science and Natural Rources	Horticulture Block 7	Gable	70	70				140	1	Aluminium	Wood	No
College of Agricultural Science and Natural Rources	Horticulture Block 4	Gable	75	75				150	1	Aluminium	Wood	No
College of Agricultural Science and Natural Rources	Horticulture Block 2	Gable	85	85				170	1	Aluminium	Wood	No
College of Science	Chemistry Block 1	Gable	140	140				280	4	Aluminium	Wood	No
Administration	Finance Office	Gable	150	150				300	3	Aluminium	Wood	No
College of Science	Biological Science Block 1	Gable	156	156				312	2	Aluminium	Wood	No
College of Science	Biological Science Block 2	Gable	175	175				350	3	Aluminium	Wood	No
College of Engineering	Provost office Block	Gable	178	178				355	4	Aluminium	Wood	No
College of Architecture and Planning	New Block 1	Gable	185	185				370	5	Aluminium	Wood	No

										m		
College of Engineering	Professorial Block	Gable	190	190				380	2	Aluminium	Wood	No
College of Agricultural Science and Natural Rources	Natural Resources Block 4	Gable	195	195				390	3	Aluminium	Wood	No
College of Agricultural Science and Natural Rources	Natural Resources Block 5	Gable	195	195				390	3	Aluminium	Wood	No
College of Architecture and Planning	Drawing Building 1	Gable	195	195				390	4	Aluminium	Steel/Wood	No
College of Science	Biological Science Block 3	Gable	200	200				400	3	Aluminium	Wood	No
College of Agricultural Science and Natural Rources	Natural Resources Block 2	Gable	230	230				460	3	Aluminium	Wood	No
College of Arts and Social Sciences	Law Classroom Block	Gable	265	265				530	3	Aluminium	Wood	No
College of Architecture and Planning	Planning Dept Office block	Flat	290					290	3	Aluminium	Wood	No
College of Health Sciences	SMS Block 1	Gable	400	400				800	1	Aluminium	Wood	No
College of Engineering	New Block	Gable	415	415				830	4	Aluminium	Wood	No
College of Arts and Social Sciences	Mathematics and Social	Gable	425	425				850	4	Aluminiu	Wood	No

	Science office Block									m		
College of Engineering	Agric Engineering Dept	Gable	450	450				900	1	Aluminium	Wood	No
College of Health Sciences	SMS Block 2	Gable	470	470				940	1	Aluminium	Wood	No
College of Health Sciences	SMS Block 3	Gable	640	640				1,280	1	Aluminium	Wood	No
College of Health Sciences	SMS Block 4	Gable	665	665				1,330	1	Aluminium	Wood	No
College of Health Sciences	Herbal Medicine	Gable	690	690				1,380	2	Aluminium	Wood	No
College of Arts and Social Sciences	Social Science New Auditorium	Gable	715	715				1,430	2	Aluminium	Steel	No
College of Health Sciences	SMS Block 5	Gable	790	790				1,580	1	Aluminium	Wood	No
Administration	Great Hall	Hipped	800	800	150	150		1,900	2	Aluminium	Steel	No
College of Science	Science Complex Block	Gable	857	857	942	942		3,598	5	Aluminium	Wood	No
College of Arts and Social Sciences	Central Classroom Block	Arch-Shaped					1,600	1,600	4	Aluminium	Wood	No
Administration	Main Administrati	Flat					360	360	4	Aluminiu	Wood	No

	on Block 1									m		
Administration	Main Administrati on Block 2	Flat					360	360	3	Aluminiu m	Wood	No
College of Agricultural Science and Natural Rources	Agric Science Block 1	Flat					380	380	2	Aluminiu m	Wood	No
College of Agricultural Science and Natural Rources	Agric Science Block 2	Flat					380	380	2	Aluminiu m	Wood	No
College of Architecture and Planning	Provost office Block	Flat		300				300	3	Aluminiu m	Wood	No
College of Health Sciences	Pharmacy Block 1	Flat					690	690	4	Aluminiu m	Wood	No
College of Health Sciences	Pharmacy Block 2	Flat					470	470	4	Aluminiu m	Wood	No
Administration	Main Library (New)	Gable			500	500		1,000	5	Aluminiu m	Wood	No
Administration	Examination Hall	Gable							4	Aluminiu m	Wood	No
College of Agricultural Science and Natural Rources	Horticulture Block 1	Gable			135	135		270	1	Aluminiu m	Wood	No
College of Agricultural Science and Natural Rources	Horticulture Block 3	Gable			115	115		230	1	Aluminiu m	Wood	No
College of Agricultural Science and Natural	Horticulture Block 5	Gable			55	55		110	1	Aluminiu	Wood	No

Rources										m		
College of Agricultural Science and Natural Rources	Horticulture Block 6	Gable			55	55		110	1	Aluminium	Wood	No
College of Agricultural Science and Natural Rources	Natural Resources Block 1	Gable			175	175		350	2	Aluminium	Wood	No
College of Agricultural Science and Natural Rources	Natural Resources Block 3	Gable			210	210		420	3	Aluminium	Wood	No
College of Architecture and Planning	New Block 2	Gable			185	185		370	5	Aluminium	Wood	No
College of Arts and Social Sciences	Law Auditorium	Gable			285	285		570	2	Aluminium	Wood	No
College of Engineering	New Auditorium	Gable			750	750		1,500	2	Aluminium	Metal	No
College of Science	Biological Science Block 4	Gable			210	210		420	2	Aluminium	Wood	No
College of Science	Chemistry Block 2	Gable			305	305		610	4	Aluminium	Wood	No
College of Arts and Social Sciences	Law Library	Hipped			285	285		570	2	Aluminium	Wood	No
College of Science	Graduate School	Gable	165	165				330	2	Aluminium	Wood	Yes
College of Architecture and Planning	Lecture Theatre	Gable	169	169				338	1	Aluminiu	Wood	Yes

										m		
College of Engineering	Lecture Theatre Block	Gable	215	215				430	2	Asbestos	Wood	Yes
College of Science	Physics Block	Gable	273	273				545	3	Aluminium	Wood	Yes
Administration	Main Library (Old)	Arch-Shaped					630	630	4	Aluminium	Wood	Yes
College of Architecture and Planning	Drawing Building 2	Gable			127	127		254	1	Aluminium	Wood	Yes
College of Engineering	Agric Engineering Workshop	Gable			240	240		480	1	Aluminium	Steel	Yes
College of Arts and Social Sciences	School of Business	Gable	560	560				1,120				
			11,672	**11,682**	**4,724**	**4,724**	**4,870**	**37,672**				
Independence Hall	Annex	Flat					260	260	9	Concrete	Concrete	No
Queen Elizabeth Hall	Annex	Flat					260	260	9	Concrete	Concrete	No
Republic Hall	Annex	Flat					260	260	9	Concrete	Concrete	No
University Hall	Annex	Flat					260	260	9	Concrete	Concrete	No
Africa Hall	Block A	Flat					260	260	9	Concrete	Concrete	No
Unity Hall	Block A	Flat					700	700	9	Concrete	Concrete	No
Africa Hall	Block B	Flat					260	260	9	Concrete	Concrete	No
Unity Hall	Block B	Flat					700	700	9	Concrete	Concrete	No
Independence Hall	Main Block 1	Gable	155	155				310	3	Asbestos	Wood	No
Queen Elizabeth Hall	Main Block 1	Gable	155	155				310	3	Asbestos	Wood	No

Republic Hall	Main Block 1	Gable	390	390				780	3	Asbestos	Wood	No
University Hall	Main Block 1	Gable	155	155				310	3	Asbestos	Wood	No
Independence Hall	Main Block 2	Gable			600	600		1,200	3	Asbestos	Wood	No
Queen Elizabeth Hall	Main Block 2	Gable			600	600		1,200	3	Asbestos	Wood	No
Republic Hall	Main Block 2	Gable	470	470				940	3	Asbestos	Wood	No
University Hall	Main Block 2	Gable			600	600		1,200	3	Asbestos	Wood	No
Independence Hall	Main Block 3	Gable			600	600		1,200	3	Asbestos	Wood	No
Queen Elizabeth Hall	Main Block 3	Gable			600	600		1,200	3	Asbestos	Wood	No
Republic Hall	Main Block 3	Gable	225	225				450	3	Asbestos	Wood	No
University Hall	Main Block 3	Gable			600	600		1,200	3	Asbestos	Wood	No
Republic Hall	Main Block 4	Gable			235	235		470	3	Asbestos	Wood	No
Republic Hall	Main Block 5	Gable			265	265		530	3	Asbestos	Wood	No
			1,550	**1,550**	**4,100**	**4,100**	**2,960**	**14,260**				
Guss House (Brunei)	Baby Block 1	Gable	395	395				790	**4**	Aluminium	Wood	No
Guss House (Brunei)	Baby Block 2	Gable			395	395		790	**4**	Aluminium	Wood	No

Guss House (Brunei)	Baby Block 3	Gable	395	395				790	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	Baby Block 4	Gable			395	395		790	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	New Block 1	Gable	260	260				520	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	New Block 2	Gable			260	260		520	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	New Block 3	Gable	260	260				520	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	New Block 4	Gable			260	260		520	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	Old Block 1	Gable	335	335				670	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	Old Block 2	Gable			335	335		670	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	Old Block 3	Gable	335	335				670	**4**	Aluminiu m	Wood	No
Guss House (Brunei)	Old Block 4	Gable			335	335		670	**4**	Aluminiu m	Wood	No
Hall Seven	Block 1	Gable	585	585				1,170	**4**	Aluminiu m	Wood	No
Hall Seven	Block 4	Gable	585	585				1,170	**4**	Aluminiu	Wood	No

										m		
Hall Seven	Block 2	Gable			93	93		186	**4**	Aluminium	Wood	No
Hall Seven	Block 3	Gable			93	93		186	**4**	Aluminium	Wood	No
Sub-Total			**3,150**	**3,150**	**2,166**	**2,166**	**0**	**10,632**				
Grand Total			**16,372**	**16,382**	**10,990**	**10,990**	**7,830**	**62,564**				

D. Matlab code for Sunny Tripower inverter selection

```
B=[17, 15, 12,10,8];


A(1)=input ('input nimber = ');
for i=1:10
if A(i)~=0
C(i)=(A(i)-mod(A(i),B(i)))/B(i);
A(i+1)=mod(A(i),B(i));
else
break
end
end
disp = horzcat((B(1,1:size(C,2)))',C')
```

E. Prefeasibility Study for 1MWp Grid-Connected Solar PV system

Prefeasibility Study for 1MWP Grid-Connected Solar PV System

Ebenezer Nyarko Kumi
The Energy Center
Kwame Nkrumah University of Science and Technology- Ghana

March 2011

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EXECUTIVE SUMMARY

This study is conducted as part of a bigger project to design and analyse a 1MW grid-connected solar PV system for KNUST with the aim of helping replicate such institutional large-scale grid-connected solar PV systems in other institutions in the country.

The study was conducted using RETScreen software, designed by the Natural Resources Canada, used for prefeasibility study of most renewable energy projects including grid-connected solar PV systems. The software has a broad database of meteorological data such as global daily horizontal solar irradiance and also a database of various renewable energy systems from different manufacturers.

The results of the study show that the project is socially beneficial to the community since it replaces about 12.5% of KNUST's electricity consumption saving about 850 tonnes of CO_2 in the process. However, under the prevailing tariff conditions in the country, the project is not financially viable without grants or capital subsidies since it has a very large negative NPV and a simple payback period of about 50years. When feed-in tariffs are introduced, it will serve as an incentive since it improves the financial viability of the project.

ACKNOWLEDGEMENT

First and foremost acknowledgement goes to the Almighty God for making it possible for me to live to undertake this study.

This study is part of a bigger project to design and analyse a 1MW grid-connected solar PV system in KNUST and is conducted as part of the implementation of the ATPS Phase VI Strategic Plan, 2008-2012 funded by ATPS Donors including the Ministerie van Buitenlandse Zaken (DGIS) the Netherlands, amongst others. I hereby thank ATPS for the financial and technical support during the implementation of the programme.

I also appreciate Prof. Abeeku Brew-Hammond for his immense contribution to this project.

LIST OF ACCRONYMNS AND ABBREVIATIONS

CO_2	Carbon dioxide
KNUST	Kwame Nkrumah University of Science and Technology
kW	Kilowatt
kWp	Kilowatt peak
kWh	Kilowatt hour
$kWh/m^2/day$	Kilowatt hour per metre squared per day
MWh	Megawatt hour
MWh/year	Megawatt hour per year
m^2	Metre squared
NPV	Net Present Value
PV	Photovoltaic
Sq	Square
SWERA	Solar and Wind Resource Assessment
UNEP	United Nations Environment Programme
US$	United States Dollar
Wp	Watt peak

INTRODUCTION

This study is conducted as part of a project to design and analyse 1MW grid-connected solar PV system for KNUST; a thesis to be submitted to the school of Graduate Studies of KNUST in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

The 1MW grid-connected solar PV system will be decentralised and mounted on the rooftops of the various faculty and residential buildings on the campus. The implementation of the project will enhance further research into large-scale institutional grid-connected solar PV system, making it possible for it to be replicated in other institutions eventually helping to mitigate the effects of the climate change problem.

PROJECT SITE

The project site, Kwame Nkrumah University of Science and Technology campus in Kumasi, was chosen because it is the only science and technology university in Ghana. An installation of that capacity will help enhance further research and study into grid-connected solar PV systems.

KNUST is located on latitude 6.67^o north and longitude 1.57^o east. It covers a total land area of 7sq miles and is located about 8miles to the east of Kumasi, the capital city of the Ashanti region of Ghana. There are six colleges in the university with a total student population of about 22000 with six halls of residence, each housing an average of about 960 students in each hall.

The campus is connected to the national electricity grid through an 11kV distribution network with its own distribution transformers. There is also a bulk supply point that is currently under construction to help supply power efficiently to KNUST and other parts of the Kumasi Metropolis.

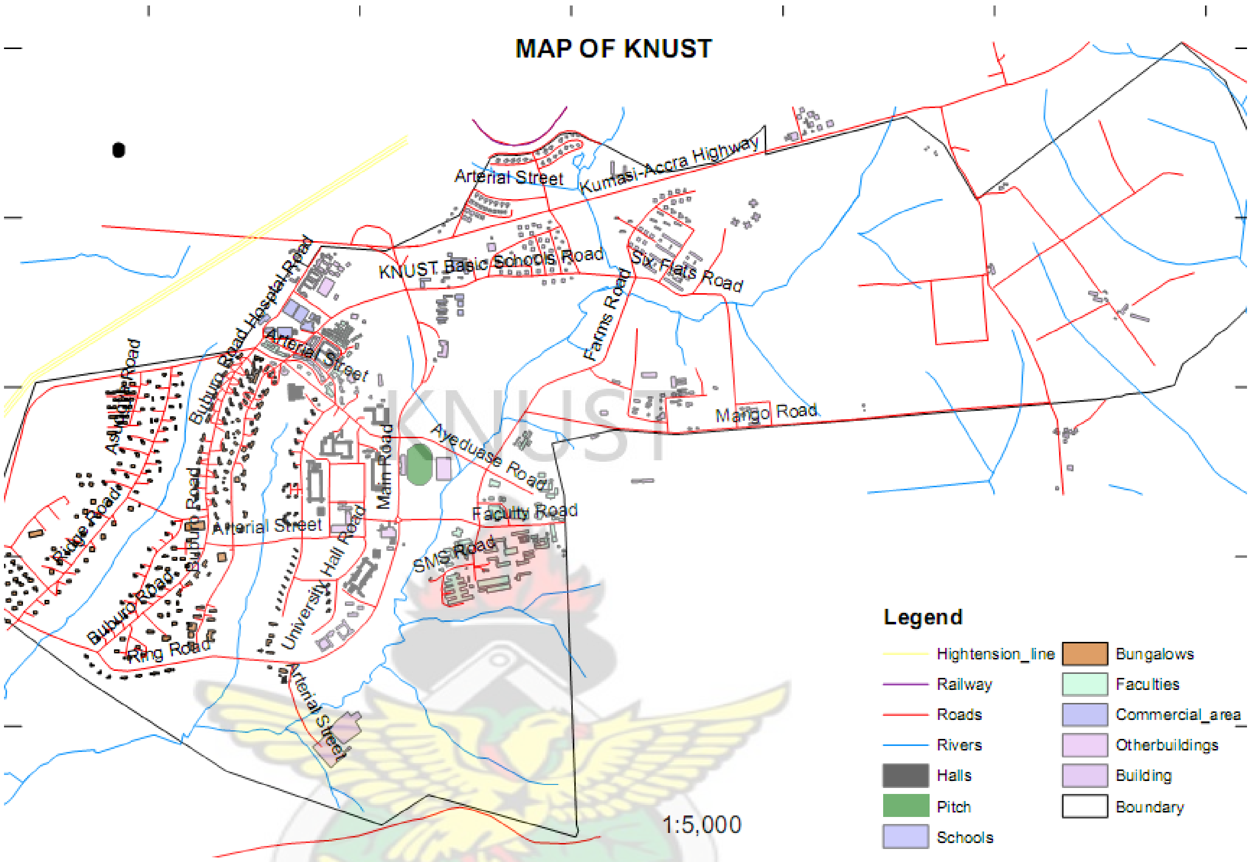

Figure 1: Map of KNUST

SOLAR RESOURCE

The daily horizontal solar irradiation for Kumasi (KNUST) used for this study is 4.34kWh/m^2/day based on radiation data in the RETScreen software. This value is lower than that in the SWERA database by UNEP, which is 4.633kWh/m^2/day. Figure 1 shows a comparison of the horizontal solar radiation in both the RETScreen and SWERA databases.

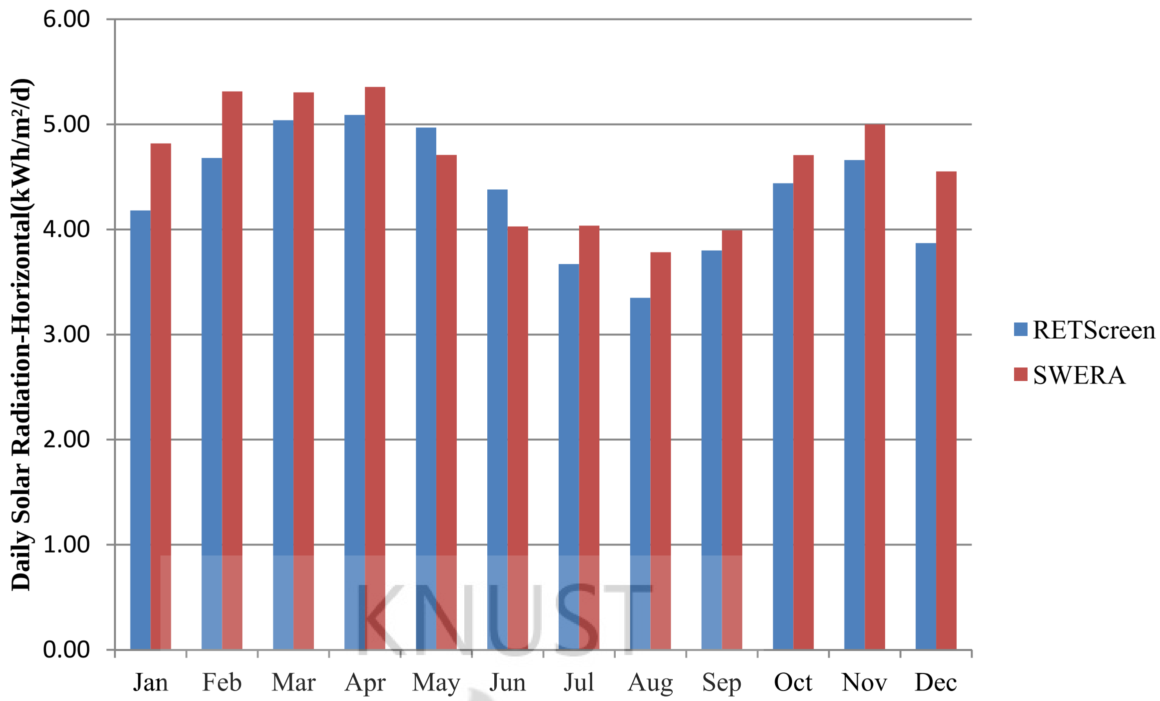

Figure 2: Daily horizontal solar radiations comparison

CONCEPTUAL DESIGN

The proposed 1MWp grid-connected solar PV system will be installed on rooftops of existing buildings including faculty building as well as residential buildings on the campus. There are about 20 major building on the campus with most of the roofs having slopes ranging between 15° and 30° with only a few of them being flat.

The proposed PV system for this study is the Poly-Si-DC Power Wall from BP Solar with a module capacity of 240Wp and efficiency of 11.3%. In all, a total of about 4,167 modules will be installed covering a total area of about 8,819m^2. A string concept will be used with a number of modules connected to a string and a number of strings to an inverter before discharge to the grid. A summary of the plant layout and module configuration is given in table 1 below.

Table 1: Plant layout and module configuration

Meteo Data	
Daily horizontal irradiation	4.34kWh/m^2/day
Daily tilted irradiation on module	4.33kWh/m^2/day
Module Orientation	
Module Inclination	15^o
Module Azimuth	0^o
Module-Inverter Details	
Module Type	Polycrystalline (Poly-Si-DC Power wall for BP Solar)
Module capacity	240Wp
Module Efficiency	11.3%
Total Installed Module capacity	1000.80kWp
Inverter Capacity	1000kW l
Inverter Efficiency	95%

YIELD ASSESSMENT AND DESIGN OPTIMISATION

RETScreen software was used in the plant energy yield. Photovoltaic Power Model can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for central-grid, isolated-grid and off-grid photovoltaic (solar electric) projects. The software can model a wide variety of projects ranging from large scale multi-array central power plants, to distributed power systems located on commercial buildings and houses, to industrial remote wind-PV-genset hybrid power supplies, to stand-alone battery storage systems for lighting.

The PV system performance indicators assessed in the study are the following; energy yield, yield factor and performance ratio.

Yield factor (YF) refers to the plant's specific performance in net kWh delivered to the grid per kW of installed nominal PV module power. This is also equivalent to the number of full load hours for the plant.

Performance ratio (PR) is defined as the actual amount of PV energy delivered to the grid in a given period, divided by the theoretical amount according to STC data of the modules. Table 2 gives a summary of the key results.

Table 2: Key Results of PV system

Performance at the inverter output		
Output	**Unit**	**Total**
Energy Yield	MWh/year	1250.46
Yield Factor	kWh/Kwp/year	1250.36
Performance Ratio	%	79.20

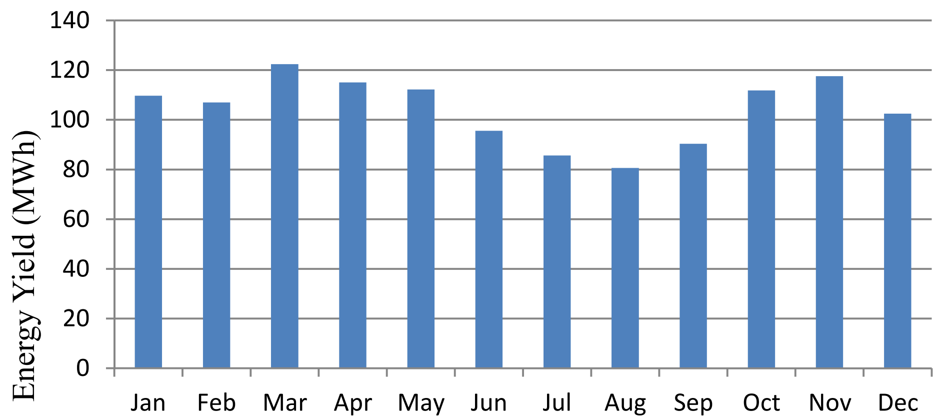

Figure 3: Monthly Output of System

INVESTMENT COST

The investment cost used in the study is US$5/kWp, which is the typical cost of roof-mounted grid-connected solar PV installations in Ghana. This cost includes that of the modules, inverters, electrical cablings, mountings, grid connections and labour. This brings the total investment cost to US$ 5,000,400.

ECONOMIC BENEFITS

An economic analysis was carried out to evaluate whether the project lead to an efficient allocation of national resources and to assess the net macroeconomic benefits of the project. The annual energy yield of 1,250MWh/year covers about 12.5% of KNUST's annual electricity consumption, saving about 850tonnesCO^2/year which can be traded on the carbon market for extra income to the project.

Using the financial parameters in table 3, the project makes a return of about US$100,037 per annum and an NPV of –US$4million with a simple payback of about 50 years. Figures 4 and 5 show variations of the NPV and simple payback period with increasing feed-in tariff.

Table 3: Financial Parameters used for economic analysis

Parameter	**Value**
Project Life	25 years
Bulk Generation Charge	US$0.08/kWh
Inflation Rate	9.16%
Discount Rate	10%

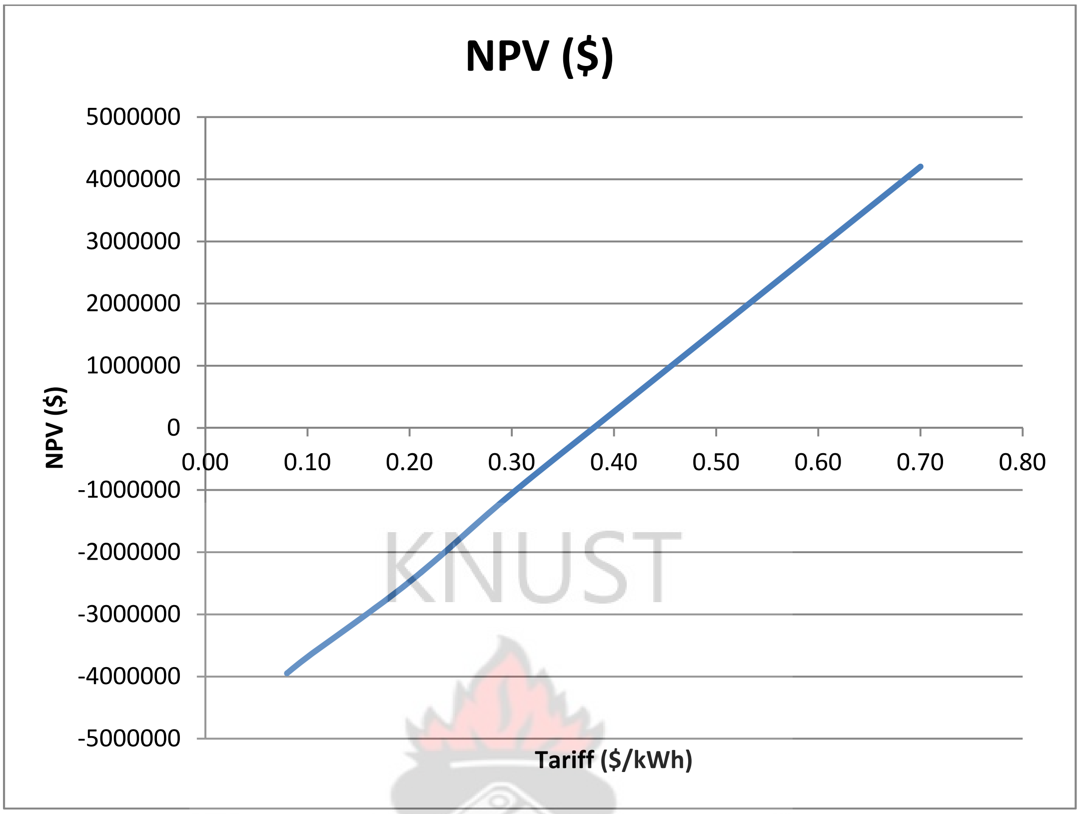

Figure 4: Net Present Value of the Project

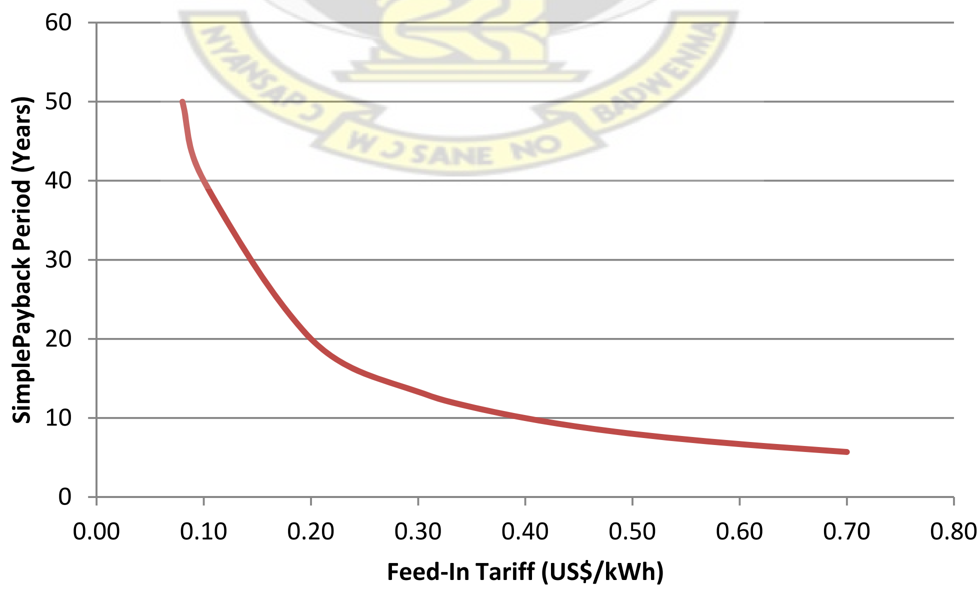

Figure 5: Simple Payback Period for the Project

CONCLUSION

Results of the analysis indicate that, the project when implemented will supply about 12.5% of KNUST's electricity consumption needs. The project also stands the chance of saving about 850 tonnes of CO2 which would have been emitted by a crude oil fired thermal power plant generating the same amount of electricity.

With the prevailing tariff conditions in the country, this project can be considered is not financially viable except with grants and capital subsidies. However, the other non-financial benefits like the greenhouse gas emissions savings can in the long run help mitigate the adverse effects of the climate change problem plaguing the entire earth.

Ghana currently doesn't have a feed-in tariff policy making it difficult for renewable energy projects to be implemented. However, there is a Renewable Energy Bill (which has a section on feed-in tariffs) currently in parliament waiting to be passed into a law. The scenario shown in figure 4 indicates that for the project to break even, a tariff of about US$0.38/kWh must be provided for a period of 10 years. The simple payback scenario in figure 5 also helps in determining a favourable feed-in tariff for the project and this show that for the 25years of the project, a feed-in tariff of about $0.20/kWh will be needed.

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F. Datasheets and technical simulation results

PVSYST V5.56		03/06/12 19h57

Characteristics of a PV module

Manufacturer, model : **Schott Solar AG, Schott PERFORM MONO 190**

Availability : Prod. from2011

Data source : Manufacturer 2011

STC power (manufacturer)	**Pnom**	**190**	**Wp**	**Technology**		**Si-mono**	
Module size (W x L)		0.810 x 1.620	m²	Rough module area	Amodule	1.31	m²
Number of cells		1 x 72		Sensitive area (cells)	Acells	1.10	m²

Specifications for the model (manufacturer or measurement data)

Reference temperature	TRef	25	°C	Reference irradiance	GRef	1000	W/m²
Open circuit voltage	Voc	45.2	V	Short-circuit current	Isc	5.46	A
Max. power point voltage	Vmpp	37.6	V	Max. power point current	Impp	5.10	A
=> maximum power	Pmpp	191.8	W	Isc temperature coefficient	muIsc	1.6	mA/°C

One-diode model parameters

Shunt resistance	Rshunt	750	ohm	Diode saturation current	IoRef	37	nA
Serie resistance	Rserie	0.14	ohm	Voc temp. coefficient	MuVoc	-142	mV/°C
				Diode quality factor	Gamma	1.30	
Specified Pmax temper. coeff.	muPMaxR	-0.44	%/°C	Diode factor temper. coeff.	muGamma	-0.000	1/°C

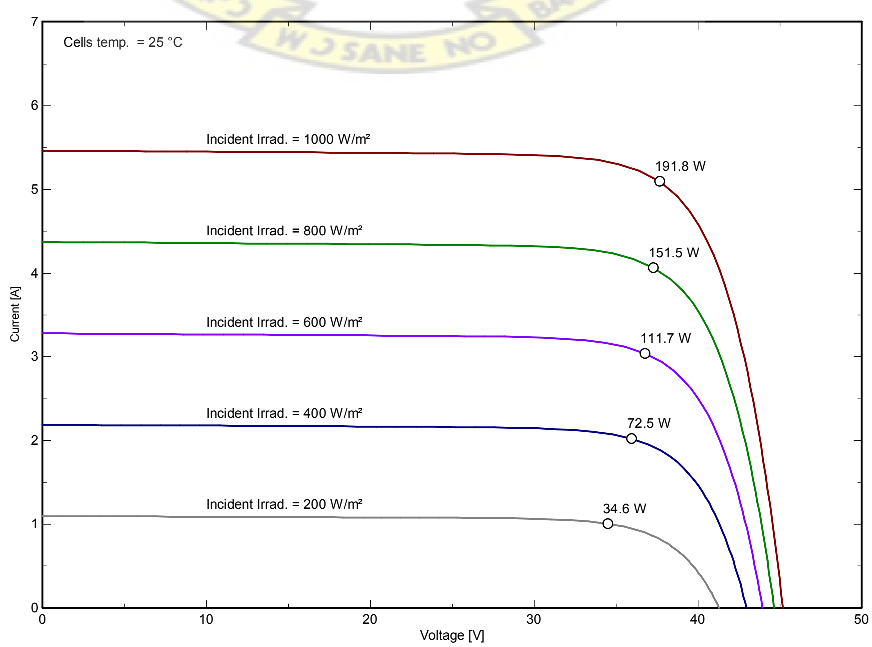
Reverse Bias Parameters, for use in behaviour of PV arrays under partial shadings or mismatch

Reverse characteristics (dark)	BRev	3.20	mA/V²	(quadratic factor (per cell))		
Number of by-pass diodes per module		3		Direct voltage of by-pass diodes	-0.7	V

Model results for standard conditions (STC: T=25°C, G=1000 W/m², AM=1.5)

Max. power point voltage	Vmpp	37.7	V	Max. power point current	Impp	5.09	A
Maximum power	Pmpp	191.8	Wc	Power temper. coefficient	muPmpp	-0.44	%/°C
Efficiency(/ Module area)	Eff_mod	14.6	%	Fill factor	FF	0.777	
Efficiency(/ Cells area)	Eff_cells	17.5	%				

PV module: Schott Solar AG, Schott PERFORM MONO 190



Grid-Connected System: Simulation parameters

Project :	**1MW Grid-Connected Solar PV**			
Geographical Site	**KNUST, Kumasi**		**Country**	**Ghana**
Situation	Latitude	6.7°N	Longitude	1.6°W
Time defined as	Legal Time	Time zone UT+1	Altitude	287 m
	Albedo	0.20		
Meteo data :	KNUST, Kumasi, Synthetic Hourly data			

Simulation variant :	**1MW Grid-Connected Solar PV for KNUST**			
	Simulation date	20/05/12 20h17		

Simulation parameters

Collector Plane Orientation	Tilt	15°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module Si-mono	Model	**Schott PERFORM MONO 190**		
	Manufacturer	Schott Solar AG		
Number of PV modules	In series	19 modules	In parallel	277 strings
Total number of PV modules	Nb. modules	5263	Unit Nom. Power	190 Wp
Array global power	Nominal (STC)	**1000 kWp**	At operating cond.	897 kWp (50°C)
Array operating characteristics (50°C)	U mpp	639 V	I mpp	1404 A
Total area	Module area	**6906 m²**	Cell area	5769 m²

Inverter	Model	**Sunny Tripower10000 TL**		
	Manufacturer	SMA		
Characteristics	Operating Voltage	150-800 V	Unit Nom. Power	10.0 kW AC
Inverter pack	Number of Inverter	100 units	Total Power	1000.0 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	7.6 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	0.1 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

Grid-Connected System: Main results

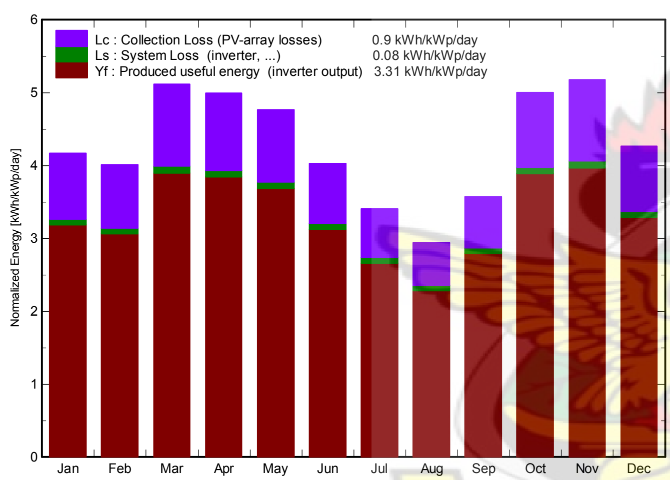
Project : **1MW Grid-Connected Solar PV**

Simulation variant : **1MW Grid-Connected Solar PV for KNUST**

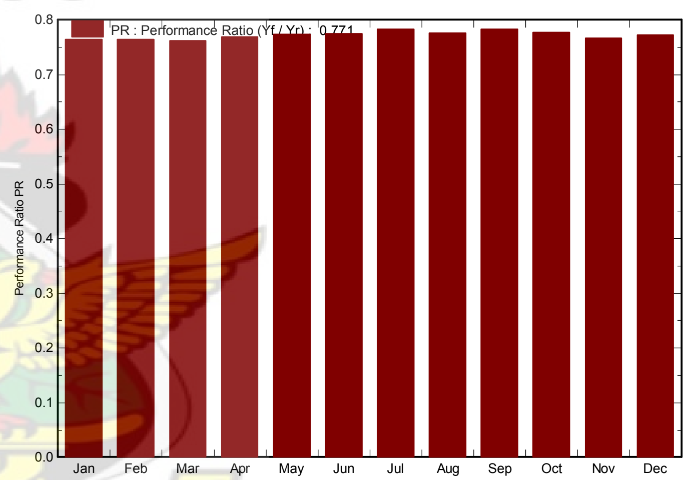
Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	Schott PERFORM MONO 190	Pnom	190 Wp
PV Array	Nb. of modules	5263	Pnom total	**1000 kWp**
Inverter	Model	Sunny Tripower10000 TL	Pnom	10.00 kW ac
Inverter pack	Nb. of units	100.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**1206 MWh/year**	Specific prod.	1206 kWh/kWp/year
	Performance Ratio PR	77.1 %		

Normalized productions (per installed kWp): Nominal power 1000 kWp



Performance Ratio PR



1MW Grid-Connected Solar PV for KNUST

Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	%	%
January	121.2	26.10	129.3	125.3	101.2	98.7	11.33	11.06
February	109.6	27.20	112.2	108.4	87.9	85.7	11.34	11.06
March	158.4	27.80	158.6	153.6	123.7	120.8	11.29	11.03
April	156.0	27.20	149.9	144.8	117.9	115.2	11.39	11.13
May	160.3	26.70	147.6	142.2	116.9	114.1	11.46	11.20
June	132.0	26.10	120.9	116.1	96.0	93.6	11.50	11.21
July	111.9	24.40	105.5	101.2	84.8	82.5	11.64	11.33
August	94.5	24.40	91.0	87.5	72.9	70.6	11.59	11.23
September	108.9	24.40	107.2	103.2	86.2	83.8	11.64	11.32
October	150.7	25.60	155.0	150.2	123.2	120.3	11.51	11.24
November	144.9	26.10	155.3	150.6	121.8	119.0	11.35	11.09
December	123.1	25.60	132.1	127.8	104.5	101.9	11.45	11.17
Year	1571.5	25.96	1564.7	1511.0	1236.9	1206.4	11.45	11.16

Legends:				
GlobHor	Horizontal global irradiation		EArray	Effective energy at the output of the array
T Amb	Ambient Temperature		E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane		EffArrR	Effic. Eout array / rough area
GlobEff	Effective Global, corr. for IAM and shadings		EffSysR	Effic. Eout system / rough area

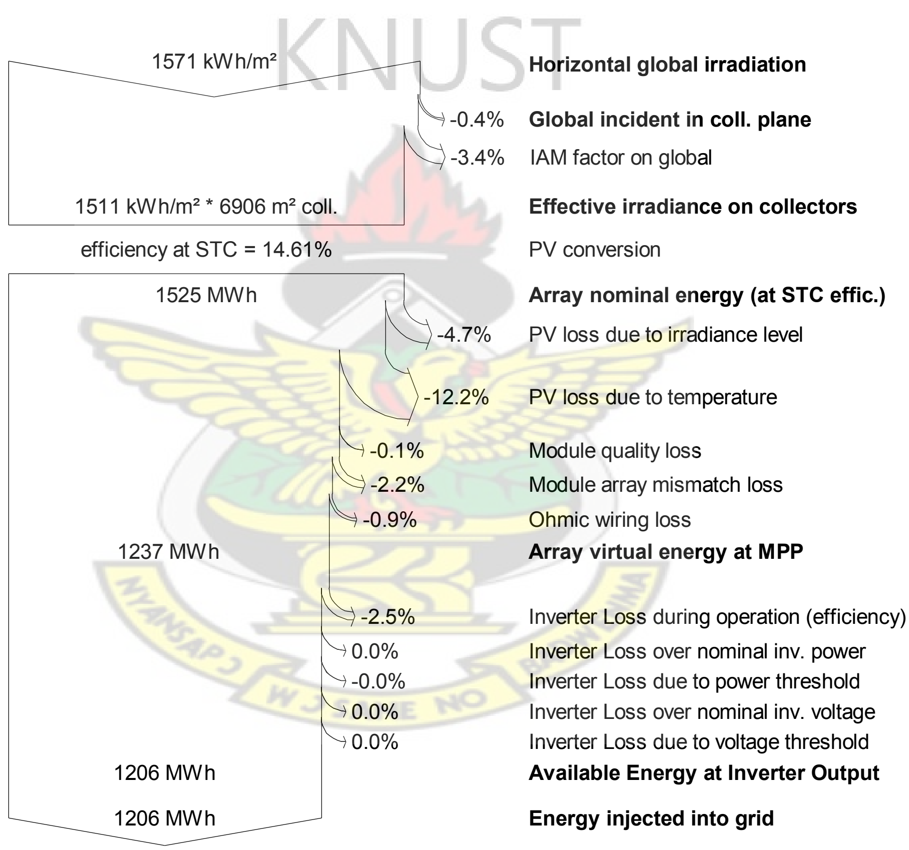
Grid-Connected System: Loss diagram

Project : **1MW Grid-Connected Solar PV**

Simulation variant : **1MW Grid-Connected Solar PV for KNUST**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	Schott PERFORM MONO 190	Pnom	190 Wp
PV Array	Nb. of modules	5263	Pnom total	**1000 kWp**
Inverter	Model	Sunny Tripower10000 TL	Pnom	10.00 kW ac
Inverter pack	Nb. of units	100.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



PVSYST V5.56		03/06/12 14h33

Characteristics of a PV module

Manufacturer, model :	**Schott Solar AG, Schott PROTECT POLY 185**
Availability :	Prod. from2011
Data source :	Manufacturer 2011

STC power (manufacturer)	**Pnom**	**185**	**Wp**	**Technology**		**Si-poly**	
Module size (W x L)		0.993 x 1.351	m²	Rough module area	Amodule	1.34	m²
Number of cells		1 x 48		Sensitive area (cells)	Acells	1.17	m²

Specifications for the model (manufacturer or measurement data)

Reference temperature	TRef	25	°C	Reference irradiance	GRef	1000	W/m²
Open circuit voltage	Voc	29.2	V	Short-circuit current	Isc	8.45	A
Max. power point voltage	Vmpp	23.5	V	Max. power point current	Impp	7.90	A
=> maximum power	Pmpp	185.7	W	Isc temperature coefficient	muIsc	4.2	mA/°C

One-diode model parameters

Shunt resistance	Rshunt	230	ohm	Diode saturation current	IoRef	196	nA
Serie resistance	Rserie	0.11	ohm	Voc temp. coefficient	MuVoc	-98	mV/°C
				Diode quality factor	Gamma	1.35	
Specified Pmax temper. coeff.	muPMaxR	-0.45	%/°C	Diode factor temper. coeff.	muGamma	-0.000	1/°C

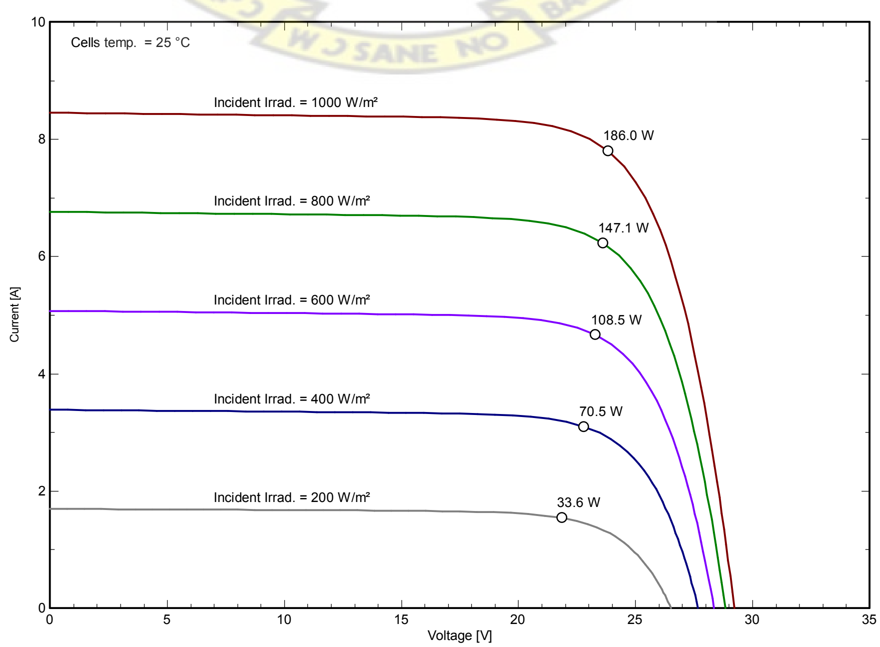
Reverse Bias Parameters, for use in behaviour of PV arrays under partial shadings or mismatch

Reverse characteristics (dark)	BRev	3.20	mA/V²	(quadratic factor (per cell))		
Number of by-pass diodes per module		3		Direct voltage of by-pass diodes	-0.7	V

Model results for standard conditions (STC: T=25°C, G=1000 W/m², AM=1.5)

Max. power point voltage	Vmpp	23.8	V	Max. power point current	Impp	7.80	A
Maximum power	Pmpp	186.0	Wc	Power temper. coefficient	muPmpp	-0.45	%/°C
Efficiency(/ Module area)	Eff_mod	13.9	%	Fill factor	FF	0.753	
Efficiency(/ Cells area)	Eff_cells	15.9	%				

PV module: Schott Solar AG, Schott PROTECT POLY 185



Grid-Connected System: Simulation parameters

Project : **1MW Grid-Connected Solar PV**

Geographical Site		**KNUST, Kumasi**	**Country**	**Ghana**
Situation	Latitude	6.7°N	Longitude	1.6°W
Time defined as	Legal Time	Time zone UT+1	Altitude	287 m
	Albedo	0.20		

Meteo data : KNUST, Kumasi, Synthetic Hourly data

Simulation variant : **1MW Grid-Connected Solar PV for KNUST-poly**

Simulation date 03/06/12 14h36

Simulation parameters

Collector Plane Orientation	Tilt	15°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module Si-poly	Model	**Schott PROTECT POLY 185**		
	Manufacturer	Schott Solar AG		
Number of PV modules	In series	28 modules	In parallel	193 strings
Total number of PV modules	Nb. modules	5404	Unit Nom. Power	185 Wp
Array global power	Nominal (STC)	**1000 kWp**	At operating cond.	890 kWp (50°C)
Array operating characteristics (50°C)	U mpp	591 V	I mpp	1505 A
Total area	Module area	**7247 m²**	Cell area	6313 m²

Inverter	Model	**Sunny Tripower10000 TL**		
	Manufacturer	SMA		
Characteristics	Operating Voltage	150-800 V	Unit Nom. Power	10.0 kW AC
Inverter pack	Number of Inverter	100 units	Total Power	1000.0 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	6.7 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	0.1 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

Grid-Connected System: Main results

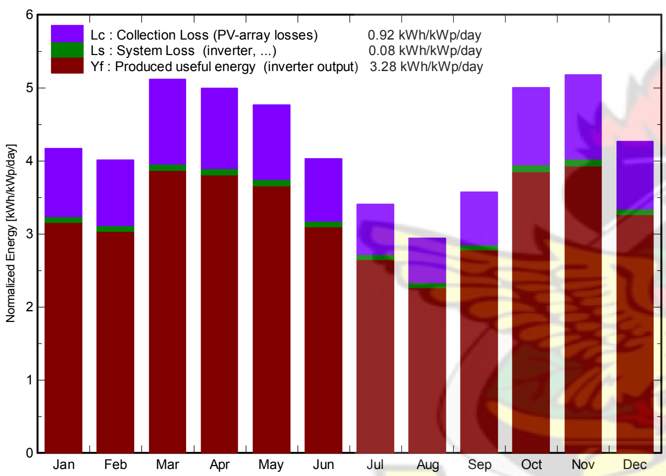
Project : **1MW Grid-Connected Solar PV**

Simulation variant : **1MW Grid-Connected Solar PV for KNUST-poly**

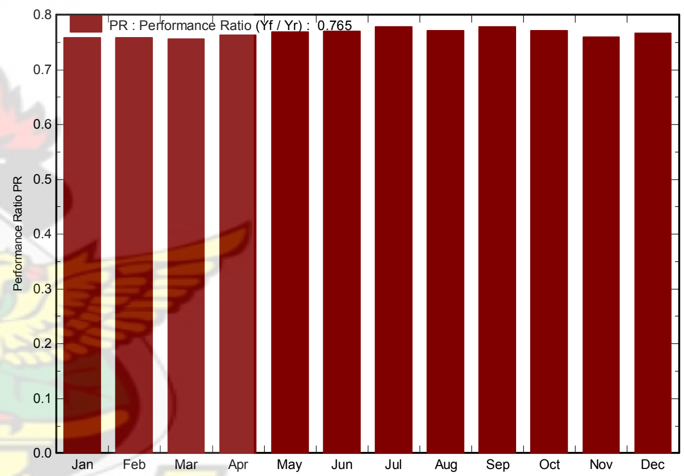
Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	Schott PROTECT POLY 185	Pnom	185 Wp
PV Array	Nb. of modules	5404	Pnom total	**1000 kWp**
Inverter	Model	Sunny Tripower10000 TL	Pnom	10.00 kW ac
Inverter pack	Nb. of units	100.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**1197 MWh/year**	Specific prod.	1198 kWh/kWp/year
	Performance Ratio PR	76.5 %		

Normalized productions (per installed kWp): Nominal power 1000 kWp



Performance Ratio PR



1MW Grid-Connected Solar PV for KNUST-poly

Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	%	%
January	121.2	26.10	129.3	125.3	100.4	97.9	10.71	10.45
February	109.6	27.20	112.2	108.4	87.2	85.1	10.72	10.46
March	158.4	27.80	158.6	153.6	122.7	119.8	10.67	10.42
April	156.0	27.20	149.9	144.8	116.9	114.3	10.77	10.52
May	160.3	26.70	147.6	142.2	116.0	113.3	10.85	10.59
June	132.0	26.10	120.9	116.1	95.4	93.0	10.89	10.61
July	111.9	24.40	105.5	101.2	84.3	82.0	11.03	10.73
August	94.5	24.40	91.0	87.5	72.4	70.2	10.97	10.63
September	108.9	24.40	107.2	103.2	85.6	83.3	11.02	10.73
October	150.7	25.60	155.0	150.2	122.2	119.4	10.88	10.63
November	144.9	26.10	155.3	150.6	120.7	117.9	10.73	10.48
December	123.1	25.60	132.1	127.8	103.7	101.1	10.83	10.57
Year	1571.5	25.96	1564.7	1511.0	1227.6	1197.3	10.83	10.56

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

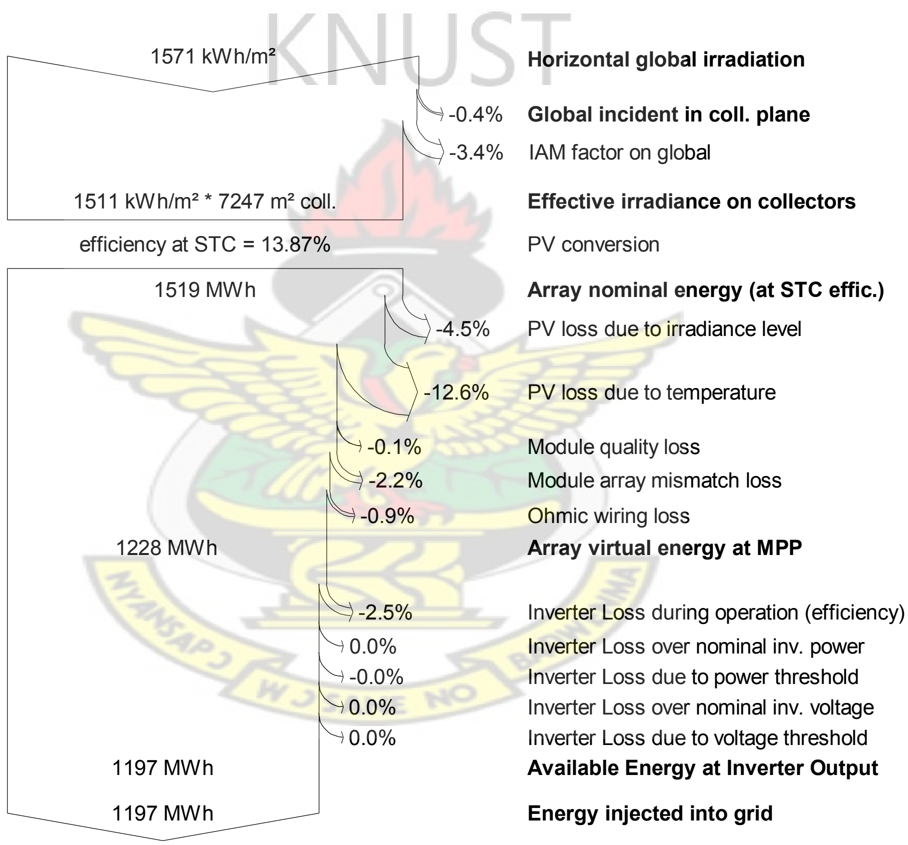
Grid-Connected System: Loss diagram

Project : **1MW Grid-Connected Solar PV**

Simulation variant : **1MW Grid-Connected Solar PV for KNUST-poly**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	Schott PROTECT POLY 185	Pnom	185 Wp
PV Array	Nb. of modules	5404	Pnom total	**1000 kWp**
Inverter	Model	Sunny Tripower10000 TL	Pnom	10.00 kW ac
Inverter pack	Nb. of units	100.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



PVSYST V5.56		03/06/12 19h58

Characteristics of a PV module

Manufacturer, model : **Schott Solar AG, ASI 100**

Availability : Prod. from2010 to 2011

Data source : Manufacturer 2010

STC power (manufacturer)	**Pnom**	**100**	**Wp**	**Technology**	**a-Si:H tandem**		
Module size (W x L)		1.108 x 1.308	m²	Rough module area	Amodule	1.45	m²
Number of cells		3 x 24		Sensitive area (cells)	Acells	N/A	m²

Specifications for the model (manufacturer or measurement data)

Reference temperature	TRef	25	°C	Reference irradiance	GRef	1000	W/m²
Open circuit voltage	Voc	40.9	V	Short-circuit current	Isc	3.85	A
Max. power point voltage	Vmpp	30.7	V	Max. power point current	Impp	3.25	A
=> maximum power	Pmpp	99.8	W	Isc temperature coefficient	muIsc	3.1	mA/°C

One-diode model parameters

Shunt resistance	Rshunt	150	ohm	Diode saturation current	IoRef	1130	nA
Serie resistance	Rserie	0.54	ohm	Voc temp. coefficient	MuVoc	-156	mV/°C
				Diode quality factor	Gamma	4.65	
Specified Pmax temper. coeff.	muPMaxR	-0.20	%/°C	Diode factor temper. coeff.	muGamma	-0.000	1/°C

Special parameter for amorphous modules

Rshunt exponential	Rsh(G=0)	1800	ohm	Exponential parameter	Rsh exp	5.5	
Recombination parameter	di² / mu tau	1.11	1/V	Spectral correction enabled		Yes	

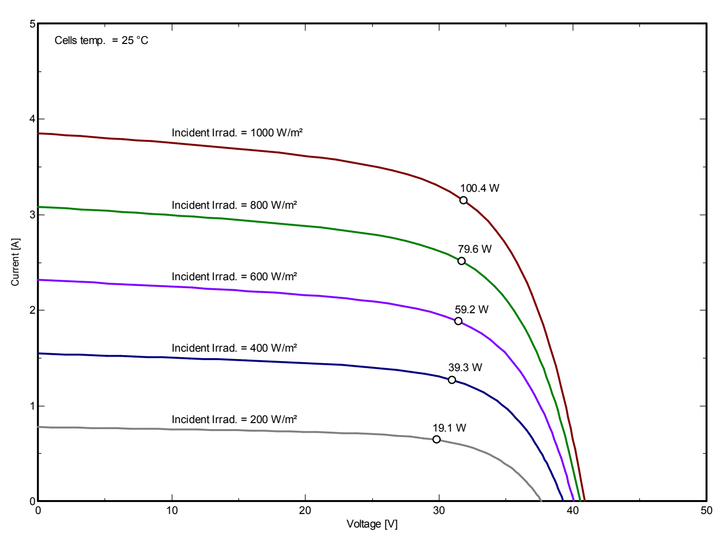
Reverse Bias Parameters, for use in behaviour of PV arrays under partial shadings or mismatch

Reverse characteristics (dark)	BRev	3.20	mA/V²	(quadratic factor (per cell))		
Number of by-pass diodes per module		1		Direct voltage of by-pass diodes	-0.7	V

Model results for standard conditions (STC: T=25°C, G=1000 W/m², AM=1.5)

Max. power point voltage	Vmpp	31.9	V	Max. power point current	Impp	3.15	A
Maximum power	Pmpp	100.4	Wc	Power temper. coefficient	muPmpp	-0.20	%/°C
Efficiency(/ Module area)	Eff_mod	6.9	%	Fill factor	FF	0.638	
Efficiency(/ Cells area)	Eff_cells	N/A	%				

PV module: Schott Solar AG, ASI 100



Grid-Connected System: Simulation parameters

Project :	**1MW Grid-Connected Solar PV**			
Geographical Site	**KNUST, Kumasi**		**Country**	**Ghana**
Situation	Latitude	6.7°N	Longitude	1.6°W
Time defined as	Legal Time	Time zone UT+1	Altitude	287 m
	Albedo	0.20		
Meteo data :	KNUST, Kumasi, Synthetic Hourly data			

Simulation variant :	**1MW Grid-Connected Solar PV for KNUST-Asi**			
	Simulation date	03/06/12 14h19		

Simulation parameters

Collector Plane Orientation	Tilt	15°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module a-Si:H tandem	Model	**ASI 100**		
	Manufacturer	Schott Solar AG		
Number of PV modules	In series	20 modules	In parallel	500 strings
Total number of PV modules	Nb. modules	10000	Unit Nom. Power	100 Wp
Array global power	Nominal (STC)	**1000 kWp**	At operating cond.	934 kWp (50°C)
Array operating characteristics (50°C)	U mpp	579 V	I mpp	1614 A
Total area	Module area	**14493 m²**		

Inverter	Model	**Sunny Tripower10000 TL**		
	Manufacturer	SMA		
Characteristics	Operating Voltage	150-800 V	Unit Nom. Power	10.0 kW AC
Inverter pack	Number of Inverter	100 units	Total Power	1000.0 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	6.1 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	0.1 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

Grid-Connected System: Main results

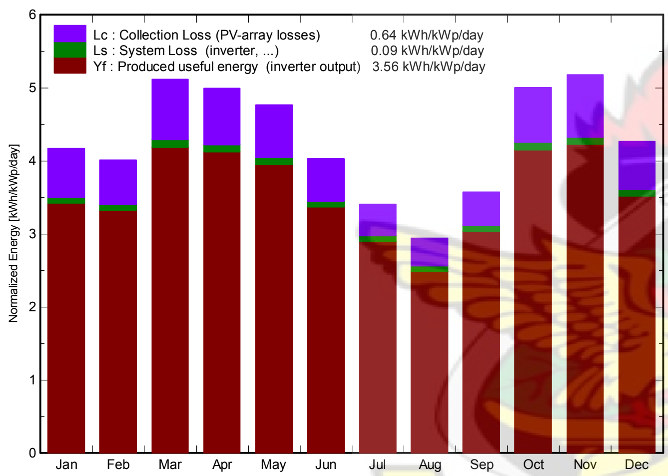
Project : **1MW Grid-Connected Solar PV**

Simulation variant : **1MW Grid-Connected Solar PV for KNUST-Asi**

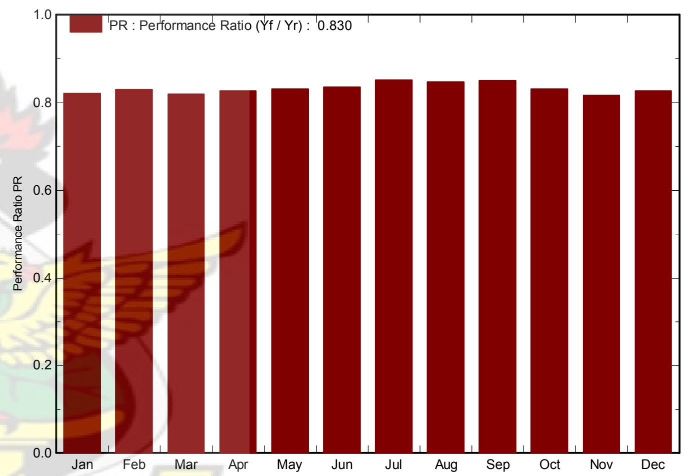
Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	ASI 100	Pnom	100 Wp
PV Array	Nb. of modules	10000	Pnom total	**1000 kWp**
Inverter	Model	Sunny Tripower10000 TL	Pnom	10.00 kW ac
Inverter pack	Nb. of units	100.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**1299 MWh/year**	Specific prod.	1299 kWh/kWp/year
	Performance Ratio PR	83.0 %		

Normalized productions (per installed kWp): Nominal power 1000 kWp



Performance Ratio PR



1MW Grid-Connected Solar PV for KNUST-Asi

Balances and main results

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	121.2	26.10	129.3	125.3	108.6	106.1	5.80	5.66
February	109.6	27.20	112.2	108.4	95.2	93.0	5.86	5.72
March	158.4	27.80	158.6	153.6	132.9	129.8	5.78	5.64
April	156.0	27.20	149.9	144.8	126.6	123.8	5.83	5.70
May	160.3	26.70	147.6	142.2	125.4	122.5	5.86	5.73
June	132.0	26.10	120.9	116.1	103.5	101.0	5.91	5.76
July	111.9	24.40	105.5	101.2	92.1	89.7	6.03	5.87
August	94.5	24.40	91.0	87.5	79.4	77.1	6.02	5.84
September	108.9	24.40	107.2	103.2	93.5	91.1	6.02	5.86
October	150.7	25.60	155.0	150.2	131.8	128.8	5.87	5.73
November	144.9	26.10	155.3	150.6	129.7	126.7	5.76	5.63
December	123.1	25.60	132.1	127.8	111.8	109.2	5.84	5.70
Year	1571.5	25.96	1564.7	1511.0	1330.7	1298.6	5.87	5.73

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

Grid-Connected System: Loss diagram

Project : **1MW Grid-Connected Solar PV**

Simulation variant : **1MW Grid-Connected Solar PV for KNUST-Asi**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	15°	azimuth	0°
PV modules	Model	ASI 100	Pnom	100 Wp
PV Array	Nb. of modules	10000	Pnom total	**1000 kWp**
Inverter	Model	Sunny Tripower10000 TL	Pnom	10.00 kW ac
Inverter pack	Nb. of units	100.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year