UNIVERSITY OF MINES AND TECHNOLOGY, TARKWA

FACULTY OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

A THESIS REPORT ENTITLED

# PERFORMANCE ANALYSIS OF THE NAVRONGO VRA SOLAR PLANT FOR IMPROVED EFFICIENCY - A CASE STUDY

BY

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SUBMITTED IN FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF MASTER OF PHILOSOPHY IN MECHANICAL ENGINEERING

THESIS SUPERVISOR

………………………………………..

ASSOC PROF ANTHONY SIMONS

TARKWA, GHANA

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# DECLARATION

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# ABSTRACT

The aim of this research is to investigate the power output performance of the Navrongo VRA Solar Plant for improved efficiency. Primary data about the performance of the plant was obtained using the master wiring picture: 18 Edition software program. General review of the design criteria of the plant was considered and this assisted in determining the characteristics of the variables that affect the output of the power plant. Physical site analysis of the plant was carried out to assess some physical constraints affecting power generation of the plant. The power output of the solar plant was evaluated and a microgrid technology was proposed to eliminate generation down time and power transmission losses. Photovoltaic Power Optimization Module for energy generation and delivery was developed for the solar plant to optimize energy generation. The PV optimization model was simulated using Microsoft excel and Rstudio which was 29.8% and 30.4% increase in power output respectively. The difference of 0.6% between the two methods show convergence in the methods used. Results from the PV optimization model shows that, if dust effect is controlled and an optimum cell temperature of 50.0 °C is maintained, then energy generation will boost by an average of 30.1% translating into 1,285,191.4 kWh and a monetary gain of GH¢ 912,071.30 per year.

# DEDICATION

This work is dedicated to my wife Diyouh Charity and my children Malti Angela, Berkumwin Rachel, Maayele Emmanuel and other children who may be borne by my wife Charity and I.

# ACKNOWLEDGMENT

I owe a particular gratitude to Assoc Prof Anthony Simons, Assoc Prof S. M Sckey and Assoc Prof C. K Amuzuvi who guided me, spent time and energy to supervise this work.

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# CHAPTER ONE

## INTRODUCTION

### 1.1 General Overview

In the midst of the energy crisis in Ghana, the attention has been drawn to renewable energy as an alternative source of energy. The Volta River Authority was established April 26, 1961 under the Volta River Development Act, 1971 (Act 46) of the Republic of Ghana to produce and transmit reliable electric energy for industrial and domestic use in Ghana. This initially, involved the development of the hydroelectric potentials of the Volta River and the construction and maintenance of a nation-wide transmission system. As the country's electricity demand increased, it was realised that additional generating capacity was required by 1997 (Anon, 1971).

Studies carried out showed that the most viable manner of developing and generating this power was from a Combined Cycle Thermal Power Plant. However, these thermal plants depend heavily on fossil fuels for their operation. Reducing fossil fuel dependency is a central energy policy at a global level for reasons of climate change, security of supply and future cost-competitiveness (Anon, 1971).

According to Electricity Company of Ghana (ECG, 2005), electricity consumption has been growing at 10 to 15 percent per annum for the last two decades. It is projected that the average demand growth over the next decade will be about six percent per year. As a result, consumption of electricity will reach 9,300 GWh by the year 2020. The projected electricity growth assumption has profound economic, financial, social and environmental implications for the country.

The aspirations of a developing country like Ghana for higher living standards can only be satisfied through sustained development of electric power markets as part of basic infra-structural needs. Electricity demand will grow much faster than overall economic growth or than population growth because continuing urbanization will allow newly urbanized segments of the population to expand their electricity consumption manifold (Ghana Energy Commission, 2005).

Urbanization in Ghana is expected to increase from around 40 percent in 2010 to about 55 percent in 2020 and eventually to 60 percent by 2030. A little more than a third of the urban population live in Greater Accra and is expected to reach around 40 percent by 2020. A considerable percentage of household expenditure goes into energy or electricity tariffs (Ghana Energy Commission, 2015).

Ghana has an installed power capacity of 1982.60 MW which is made up of 79.7 % hydro, 0.1 % solar and 20.2 % thermal sources. The future of Ghana in terms of renewable energy depends much on hydro and solar source. Solar energy in Ghana until recent times seems to be receiving the least attention for which the reasons are not fully established (Ghana Energy Commission, 2015).

Electricity demand which is currently 1400 MW is growing at about 10 % per year. Ghana requires additional power capacity of about 200 MW to catch up with the increasing demand in the medium to long term. The existing power plants in Ghana are unable to attain full generation capacity as a result of limitations in fuel supply due to the rising cost of fuel, obsolesce and the intermittent supply patterns of rain water feeding the hydropower dams.

We have enough literature on photovoltaic configuration, models design, power tracking, area analyses, solar efficiency and other general information. However, there is no specific information or performance data for improving the efficiency of the Navrogo VRA plant as it is new and unique in Ghana.

The only installed solar plant in Ghana is the Navrongo VRA Solar Plant, which is operating under its installed capacity and needs attention for increased efficiency. Solar energy is clean and is abundantly available. Solar technologies use the sun to provide heat, light and electricity for domestic and industrial applications. With the alarming rate of depletion of the major conventional energy resources such as Coal, Petroleum and Natural gas, coupled with the environmental degradation caused by the process of harnessing these energy sources, it has become an urgent necessity to invest in renewable energy resources that would power the future sufficiently without degrading the environment through greenhouse gas emission.

The energy potential of the sun is immense, but despite this unlimited solar energy resource, harvesting it is a challenge mainly because of the limited efficiency of the array cells. The best conversion efficiency of most commercially available solar cells is in the range 10 to 2% (IEA, 2011).

Although recent breakthrough in the technology of solar cells shows significant improvement but the fact that the maximum solar cell efficiency still falls less than 20 % means much still needs to be done for improvement.

## 1.2 Background to the Research

In the present civilization, the use of energy resources has increased tremendously. Fast depleting fossil fuel reserves have inevitably gathered the attention of all energy experts to think and devise means for optimum energy utilization. In order to optimally use energy, the world's energy experts are much concerned with identifying and eliminating sources of waste in energy generation, transmission and usage. This obviously requires an in depth research study and analysis of renewable energy systems.

Renewable energy systems for producing electric power have been given much attention in Ghana in the twenty first century due to increase in fossil fuel prices. Also, the nation is concerned with mitigating the over increasing levels of greenhouse gas emissions resulting from thermal power stations in Ghana and the global climate change.

Photovoltaic electricity is widely considered as one of the more promising renewable energy technologies which produces electricity without mechanical processes (Hoffmann, 2013). This has led to growing support from governments for photovoltaic research, development programs and market introduction schemes (Alsema and Nieuwlaar, 2011).

There is an urgent need to develop and optimize the use of our renewable energy resources that can make substantial contributions towards curtailing the impact of increasing energy demand. Energy crisis is a contemporary issue in the world. The European Commission (EC, 2014) has identified photovoltaic (PV) as one of such a technology that will solve the world's energy crisis.

Indeed, the startup cost of PV electricity remains higher than electricity generated using fossil fuels. On the contrary, the conventional economic comparison is distorted by unseen environmental and health costs associated with fossil fuels which are not generally included in energy prices together with the fact that many conventional energy carriers are subsidized (Bakos and Soursos, 2012).

Environmental concerns are increasing and the attention on environmental issues is growing, and the idea of generating electricity without pollution is becoming a desperate target of the world. Unlike conventional generation systems, the sun's energy for PV systems is readily available "at no cost". PV systems generate electricity with no pollution and can easily be installed on the roof of residential buildings as well as on the walls of commercial buildings for grid-connected application (Zahedi, 2013).

Generally, we have enough information on PV systems and the type of grid connections. However, inadequate information on practical measures is given to PV power system in case of low performance or decline, and the effects of PV systems operating outside the Standard Test Conditions. A more widespread use of domestic rooftops and grid-connected PV systems in Ghana are hindered by low power output or system decline and this necessitated the research work.

Since mid-1980s, PV technology has developed and become acceptable worldwide. As a promising renewable energy resource, PV technology receives substantial government support in research and application in several major industrial countries such as Germany, Italy, Spain, Bolivia and many others. International competition, along with years of experience in manufacturing, research and development, has resulted in improved PV module efficiency, cost reduction and productivity increases (Gong and Kulkarni, 2012).

Continuous increase of conventional fuel costs as well as growing pressure to turn towards renewable energy resources have been identified as the main drivers behind this rapidly expanding industry which, since 2000 has achieved consistent annual growth rates of around 25%. At a global energy output level, the PV industry is still lagging behind other renewable energy technologies, such as, hydropower and wind energy (Poullikkas, 2012).

## 1.3 Problem Definition

For Ghana to reduce her over dependence on fossil fuels for electric power generation, it needs to devise means of boosting the energy output of locally installed solar plants.

The Navrongo VRA Solar Plant has an installed capacity of 2.6 MW. However, the actual output value is averaged to be 1.5 MW. Currently the plant has an output power deficit of This deficit of 1.1 MW of power is significant enough in terms of power supply to the people of Navrongo, and when translated into money is about GH₵ 9,367.74 worth loss of power per day. To reduce this loss, it is therefore imperative to investigate the power generation process, performance analysis and ways of improving the power output efficiency of the solar plant at Navrongo.

## 1.4 Purpose of the Research

The purpose of the study is to analyse the performance characteristics of the Navrongo Volta River Authority (VRA) Solar Plant for improved efficiency.

## 1.5 Research Objectives

The study is guided by the following research objectives: to

i. analyse and identify the factors affecting the performance of the Navrongo VRA solar plant;

ii. review the design criteria for better performance of the solar power plants; and

iii. come out with photovoltaic power optimizations model for the plant.

## 1.6 Research Questions

The government of Ghana through VRA intends to invest more resources in solar energy but the first solar plant at Navrongo seems not to be satisfying the purpose for which it was acquired (Anon, 1971).

The research is necessitated and guided by the research questions below to critically analyse the solar plant for increased efficiency.

i. What are the factors that influence the performance of the Navrongo VRA Solar power plant?
ii. What are the possible reviews to be carried out for better performance of the solar power plant?
iii. How can the power output of the solar plant be optimised?

## 1.7 Research Methodology

The methods used for this research study include:

i. Review of relevant literature on the performance analysis of photovoltaic cells, modules, arrays and solar power plants;
ii. Attachment to the Navrongo VRA Solar Plant for field experience, data collection, analysis and evaluation;

iii. Interviews and administration of questionnaires on soiling losses, mismatch losses, sun tracking losses, cell temperature, inverter efficiency, panel mounting and module cracking;
iv. Review of Plant layout, power production and transmission lines; and
v. Assessment of plant's major components such as PV modules, type of module mount, inverters and effect of temperature on cells.

## 1.8 Facilities Used

The facilities used include:

i. The Navrongo VRA Solar Power Plant;
ii. Solar radiation intensity meter (radiometer);
iii. Scada Graph: master wiring picture software programme;
iv. Multifunction energy meters;
v. Laptop computer and internet;
vi. Digital camera and mobile phone; and
vii. Stationed weather equipment.

## 1.9 Definition of Terms and Key Concepts

*Power crises:* it is a term used to describe an unreliable and erratic power supply system.

*Photovoltaic cells*: it is the most elementary photovoltaic device and is either connected electrically in series and/or parallel circuits to produce higher voltages and/or currents.

*Photovoltaic module*: it consists of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building block of the complete photovoltaic generating unit.

*Photovoltaic panel*: it refers to more than one PV module assembled as a pre-wired, field-installable unit.

*A photovoltaic array*: it is the complete power-generating unit, consisting of any number of PV modules and panels.

*Solar radiation*: it is the amount of incident Sun rays falling on the Earth's surface.

*Solar insolation*: it is the amount of solar energy received on a surface commonly expressed in units of kilowatt-hours per square meter ($kWh/m^2$).

*Photoelectric effect:* it is the emission of electrons from a metal surface when light radiation of appropriate frequency falls on it.

*Grid***:** it is a common reference made to electricity distribution and transmission system.

*Micro grid*: it is a grid that is isolated from other grids and that is intended to serve only for the distribution of electricity.

*Grid connected photovoltaic system:* it is a PV system that functions only in the grid connected mode of operation.

*Solar cell efficiency*: refers to the portion of energy in the form of sunlight that can be converted via photovoltaic into electricity.

*Total module area*: it is the front surface of a photovoltaic module as defined by its outer edges.

*Down time*: it refers to the periods in a sun light day when the solar plant is not generating power as a result of a fault or challenge.

### 1.10 Scope of the Research

The study is centrally focused on performance analysis of the Navrongo VRA Solar plant for increased energy efficiency. The work covers analysis and evaluation of production output characteristics, maximum sun tracking analysis, review of production and transmission lines and assessment of system components of the solar power plant.

### 1.11 Thesis Structure

The thesis is organized into six chapters. Chapter one introduces the entire research work; problem definition, purpose of research, research objectives, research questions methodology, facilities used, definition of terms and key concepts, scope of the research, and thesis structure. Chapter Two presents a literature review of the performance of photovoltaic systems. Chapter Three has general information about the VRA Solar Power Plant at Navrongo. Chapter Four discusses the research methodology, tools and strategies employed. Chapter Five focuses on results and discussion and Chapter Six has the conclusion and recommendations.

# CHAPTER TWO

## LITERATRURE REVIEW

### 2.1 Introduction

A review of literature on the analysis of photovoltaic power systems for improved efficiency, effects of ambient temperature, temperature coefficient of PV cells and current state of the art of photovoltaic (PV) systems and the associated weaknesses pertaining to the literature is presented in this chapter. Attention was focused on how other researchers and authors have expressed their views on the topic and other related issues.The review was carried out under the conceptual and empirical reviews.

### 2.2 Conceptual Review

The conceptual review is organized under the following subheadings:

i. The Concept of Solar Energy Electrification;

ii. History and Development of Photovoltaic (PV) Cells;
iii. Performance Evaluation and Assessments of PV Cells; and
iv. Factors affecting Solar Power Delivery.

#### 2.2.1 The Concept of Solar Energy Electrification

Solar power is the conversion of sunlight into electricity, either directly using Photovoltaic (PV) system as in Figure 2.1 or indirectly using Concentrated Solar Power (CSP). Concentrated solar power systems uses lens or mirrors and tracking systems to focus a large area of sunlight into a small beam (Liebreich, 2011). PV system converts light into electric current using the photoelectric effect.

The photoelectric effect is the name given to the observation that when light is shone onto a piece of metal, a small current flows through the metal. The light gives its energy to the electrons in the atoms of the metal allowing them to move around, producing the current.

However, not all colours of light affect metals in this way. No matter how bright a red light you have, it will not produce a current in a metal, but even a very dim blue light will result in a current flowing. Einstein (a physicist), explained that, light was actually made up of lots of small packets of energy called photons that behaved like particles (Schnoor, 2011).

Einstein showed that red light can't dislodge electrons because its individual photons don't have enough energy; the impacts are just not large enough to shift the electrons.

However, blue light can dislodge electrons; each individual photon has more energy than the red photon. And photons of ultraviolet light, which have yet more energy, will give electrons enough energy to whizz away from the metal altogether (Schnoor, 2011).

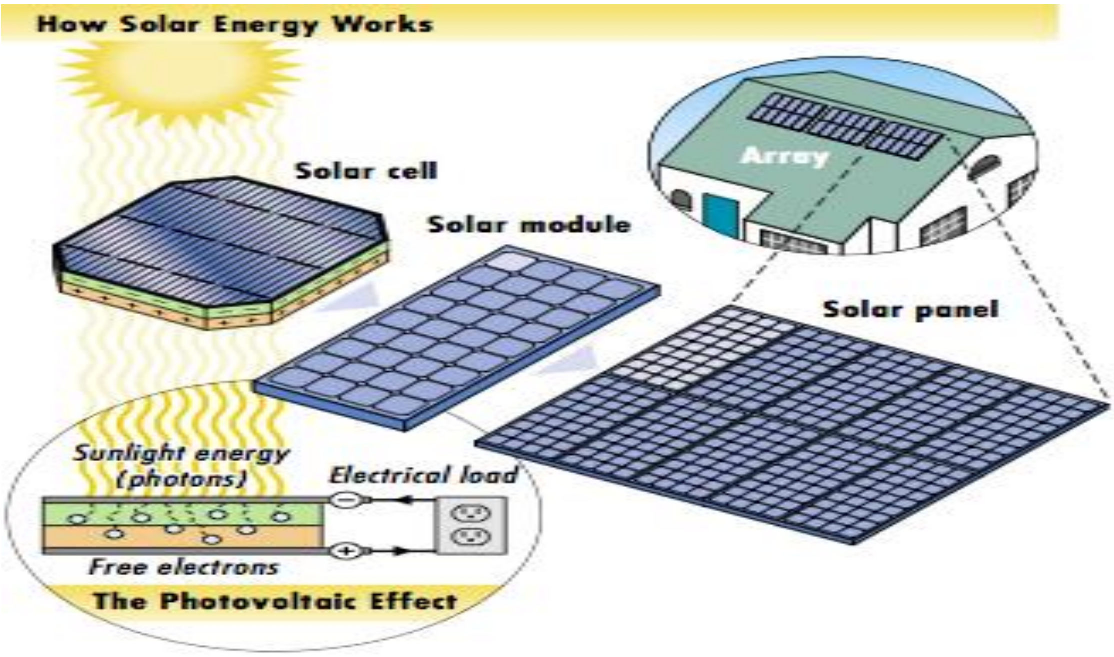


**Figure 2.1 How Solar Energy Works**

**(Schnoor, 2011)**

Solar power technology attempts to capture some solar energy and convert it to electricity to power a portion of our lifestyle. Some solar energy can also be captured as heat energy and used to heat our houses, buildings and produce hot water (Poullikkas, 2012). Capturing the vast energy of the sun has been the dream of scientists for millennia.

Unfortunately, it is not an easy thing to do economically. Part of the reason for this is that solar energy is very diffuse and it costs a lot to concentrate it into usable forms. There are two main methods of directly capturing sunlight to be used as an energy source for electricity generation (Cha, 2008).

The first is through the use of semiconductors to convert sunlight directly into electricity. This method is known as Photovoltaic (PV) solar energy.

The second method involves using mirrors to concentrate sunlight onto pipes or towers containing liquid material that is used to heat steam to drive a turbine to make electricity. This method goes by the name of Concentrated Solar Power (CSP). Photovoltaic (PV) modules are solid-state devices that convert sunlight, the most abundant energy source on the planet, directly into electricity without an intervening heat engine or rotating equipment (Cha, 2008).

PV equipment has no moving parts and, as a result, requires minimal maintenance and has a long life. It generates electricity without producing emissions of greenhouse or any other gases and its operation is virtually silent. Photovoltaic systems can be built in virtually any size, ranging from milliwatt to megawatt, and the systems are modular, thus, more panels can be easily added to increase output. Photovoltaic systems are highly reliable and require little maintenance (Poullikkas, 2012).

They can also be set up as stand-alone PV systems. A PV cell consists of two or more thin layers of semiconducting material, most commonly silicon. When the silicon is exposed to light, electrical charges are generated; and this can be conducted away by metal contacts as direct current. The electrical output from a single cell is small, so multiple cells are connected and encapsulated (usually glass covered) to form a module (also called a panel). The PV panel is the main building block of a PV system, and any number of panels can be connected together to give the desired electrical output. This modular structure is a considerable advantage of the PV system, where further panels can be added to an existing system as required (Diemuodeke *et al*, 2016).

Photovoltaic systems have developed into a mature technology that has been used for fifty years in specialized applications, and grid-connected systems have been operating for over twenty years (Liebreich, 2011). A roof-top system recoups the invested energy for its manufacturing and installation within 0.7 to 2 years and produces about 95 percent of net clean renewable energy over a 30-year service lifetime (Diemuodeke *et al*, 2016).

As new installations are growing exponentially, prices for PV systems have rapidly declined in recent years. However, they vary by markets and the system's size. In the United States, prices for utility-scale systems were around $1.77 – $3.09 equivalent to

GH¢ 9.60 – 16.70 per watt in 2015, while prices for smaller roof-top systems in the highly penetrated German market fell below €1.90 equivalent to GH¢ 7.60 per watt in 2015.

In the Germany market, solar panels make up for 40 to 50 percent of the overall cost, leaving the rest to installation labour and to the PV system's remaining components (Liebreich, 2011).

PV modules are designed for outdoor use under harsh conditions, such as marine, tropic, arctic, and desert environments. The PV array consists of a number of individual photovoltaic pannels connected together to give a suitable current and voltage output. Common power modules have a rated power output of around 50–180 W each. As an example, a small system of 1.5 – 2 kWp may therefore comprise some 10–30 modules covering an area of around 15 – 25 $m^2$, depending on the technology used and the orientation of the array with respect to the sun (Poullikkas, 2012).

Most power modules deliver direct current electricity at 12 V, whereas most common household appliances and industrial processes operate with alternating current at 240 or 415 V (Xiong *et al*., 2007). Therefore, an inverter is used to convert the low-voltage DC to higher-voltage AC. Other components in a typical PV system are the array mounting structure and various cables and switches needed to ensure that the PV generator can be isolated. The basic principle of a PV system is shown in Figure 2.2. The PV array produces electricity, which can be directed from the controller to either battery storage or a load. Whenever there is no sunshine, the battery can supply power to the load if it has satisfactory capacity.

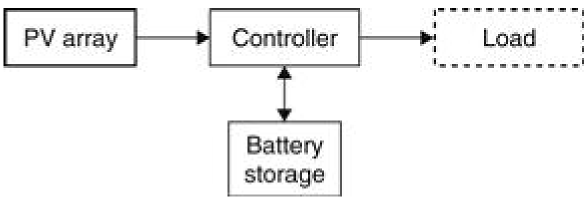


**Figure 2.2 Basic Principle of PV Solar Energy System**
**(Modified After Shnoor, 2011)**

*Categories of PV Systems*

*Direct-coupled PV system / Off-grid without Battery:* In a direct-coupled PV system, the PV array is connected directly to the load. Therefore, the load can operate only whenever there is solar radiation, so such a system has very limited applications. The schematic diagram of such a system is shown in Figure 2.3. A typical application of this type of system is for water pumping, i.e., the system operates as long as sunshine is available, and instead of storing electrical energy, water is usually stored.

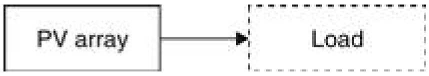


**Figure 2.3 Schematic Diagram of a Direct-Coupled PV System (Modified After Shnoor, 2011)**

*Stand-alone applications / Off-grid with battery storage*: Stand-alone PV systems are used in areas that are not easily accessible or have no access to an electric grid. A stand-alone system is independent of the electricity grid, with the energy produced normally being stored in batteries. A typical stand-alone system would consist of a PV module or modules, batteries, and a charge controller. An inverter may also be included in the system to convert the direct current generated by the PV modules to the alternating current form required by normal appliances.

A charge controller may be incorporated in the system to: a) avoid battery damage by excessive charging or discharging and, b) optimizing the production of the cells or modules by Maximum Power Point Tracking (MPPT). However, in simple PV systems where the PV module voltage is matched to the battery voltage, the use of MPPT electronics is generally considered unnecessary, since the battery voltage is stable enough to provide near-maximum power collection from the PV module (Xiong *et al*., 2007).

In small devices (e.g. calculators, parking meters) only Direct Current (DC) is consumed. In larger systems (e.g. buildings, remote water pumps) AC is usually required. To convert the DC from the modules or batteries into AC, an inverter is used. A schematic diagram of a stand-alone system is shown in Figure 2.4. As it can be seen, the system can satisfy both DC and AC loads simultaneously.

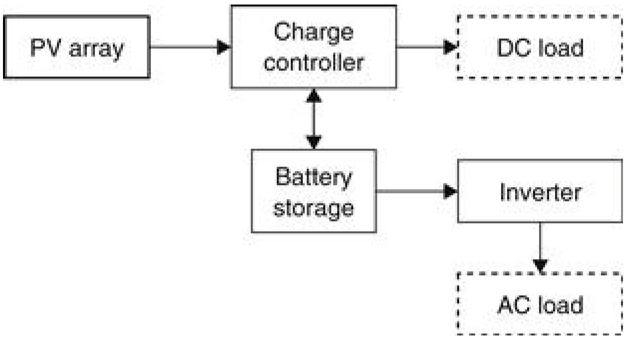


**Figure 2.4 Schematic Diagram of a Stand-Alone PV Application (Modified After Shnoor, 2011)**

*Grid-connection*

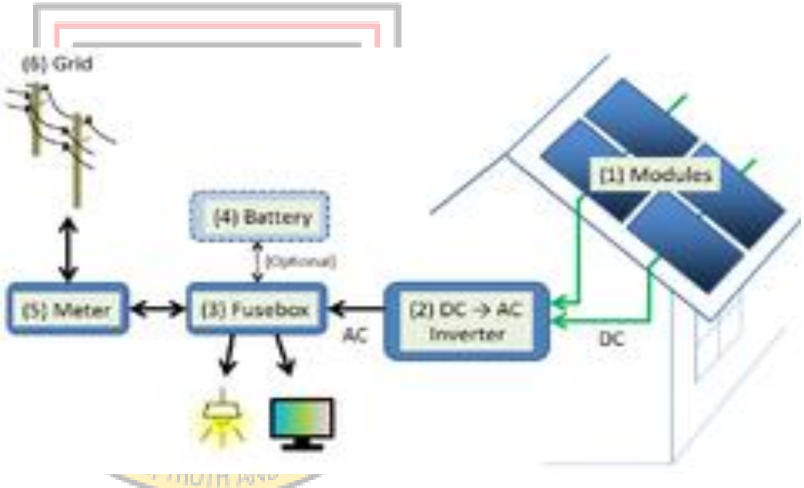


**Figure 2.5 Schematics of a Typical Residential PV System (Anon, 2014)**

A grid-connected PV system is a type of installation where three major components are used. Thus, the PV generator (comprising a number of PV modules connected in series or parallel), the inverter, DC and AC cabling and a conventional power line (Spooner and Harbidge, 2015). The inverter plays a key role in energy efficiency and reliability since it operates the PV array at the Maximum Power Point (MPP).

Moreover, inverters convert the DC power generated by PV modules into AC of the desired voltage and frequency (e.g. 230 V/50 Hz). Grid-connected PV systems do not include batteries (Cramer *et al*, 2013). Since the public electricity network serves as storage for grid-connected PV system.

The metered output of the PV system should be capable of measuring in both directions (i.e. import and export), and where this is not the case, an incoming meter should be included between the outgoing meter and the mains circuit breaker. The electrical energy invoiced to the utility (where this occurs) will be the difference between the metered output and input energy taking into consideration the applicable Feed-in Tariffs (FITs).

The figure below shows the classification of photovoltaic systems according to their applications. Most modules (72 crystalline silicon cells) generate 160 W to 300 W at 36 volts (Xiong *et al*., 2007). It is sometimes necessary or desirable to connect the modules partially in parallel rather than all in series. One set of modules connected in series is known as a ‘string’.

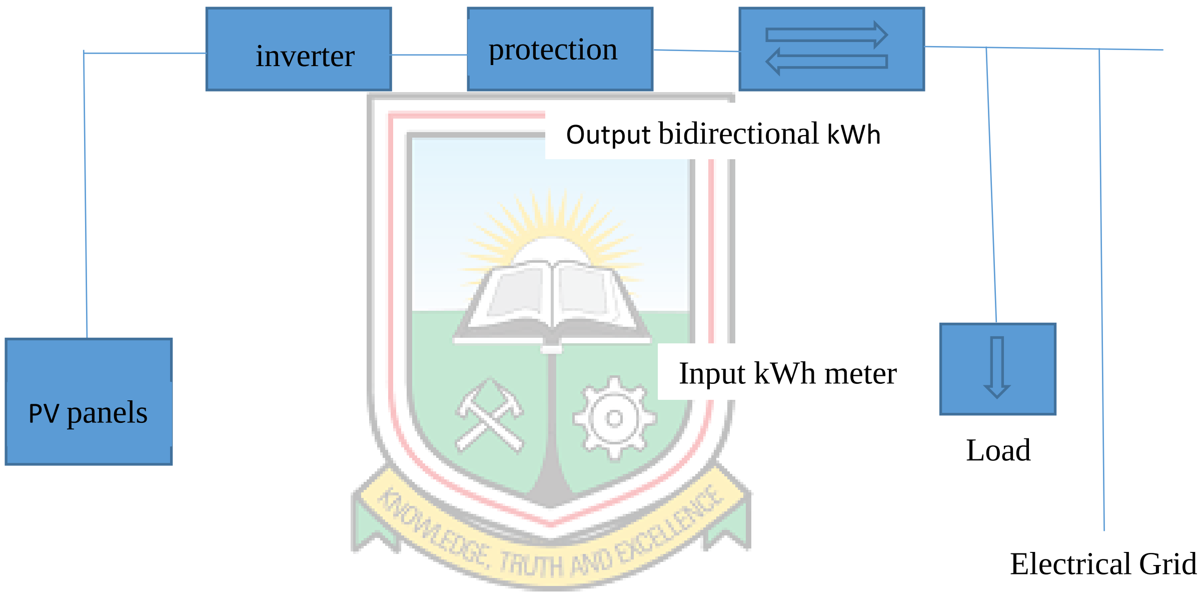


**Figure 2.6 Grid-Connected Photovoltaic System**

**(Modified After Bernal Et Al, 2010)**

Grid-connected PV systems have a variety of manifestations including: large centralized power stations; and building mounted or integrated on commercial buildings and individual houses. Worldwide, the application of grid connected PV power systems is expanding rapidly. Prices of both PV modules and Balance of System (BOS) components are decreasing following a trend of increased production and improved technology which will lead to further increase in use. Grid-connected solar photovoltaic electricity has not reached competitiveness yet, but it has considerable long term potential.

Grid-connected distributed PV systems are installed to provide power to a grid-connected customer or directly to the electricity network. Such systems may be on or integrated into the customer's premises, often on the demand side of the electricity meter, on public and commercial buildings (IEA, 2010).

A grid-connected photovoltaic system eliminates the need for battery storage bank resulting in a considerable reduction in the initial and maintenance costs. The photovoltaic system instead uses the grid as a storage bank where the excess electrical power can be deposited to, and when necessary withdrawn from. When the photovoltaic system is applied in buildings, the PV modules are mounted either on rooftops or facades, which can reduce the size and cost of mounting structures and land requirements (Gong and Kulkarni, 2015).

Since PV is dependent on intermittent solar irradiation, during daytime only and centered around noon, it is generally not fit for base or intermittent load electricity production (van der Zwaan and Rabl, 2013). Building of smart grid PV systems has been promoted by the Government of Ghana through the Volta River authority as part of the efforts to power the nation.

*Hybrid-connected system*

In the hybrid-connected system, more than one type of electricity generator is employed. The second type of electricity generator can be renewable, such as a wind turbine, or conventional, such as a diesel engine generator or the utility grid. The diesel engine generator can also be a renewable source of electricity when the diesel engine is fed with biofuels. A schematic diagram of a hybrid-connected system is shown in Figure 2.7. Again, in this system, both DC and AC loads can be satisfied simultaneously.

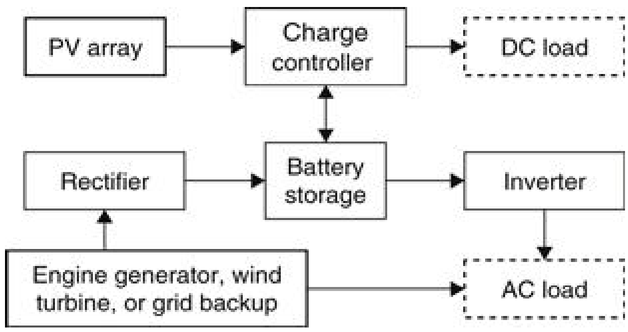


**Figure 2.7 Schematic Diagram of a Hybrid Connected System (Modified After Bernal Et Al, 2010)**

*Basic PV System Components*

A basic household solar PV system consists of the following:

i. Solar photovoltaic modules;

ii. Proper electrical disconnects and overcurrent protection systems; and

iii. A string inverter or micro inverters that change the DC generated electricity to alternating Current (AC) used in most residences.

*Solar Photovoltaic Modules*

Conventional solar cells, normally wired in series, are encapsulated in a solar module to protect them from the harsh weather. The module consists of a tempered glass as cover, a soft and flexible encapsulated, a rear back sheet made of a weathering and fire-resistant material and an aluminum frame around the outer edge. Electrically connected and mounted on a supporting structure, solar modules build a string of modules, often called solar panel. A solar array consists of one or many such panels. A photovoltaic array (or solar array) is a linked collection of solar panels. The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an array (Martinot *et. al*., 2002).

The most common semiconductor material used in PV cells is silicon, an element most commonly found in sand. There is no limitation to its availability as a raw material and it is the second most abundant material in the Earth's mass. The nucleus of a PV system is the cell which consists of PV modules interconnected to form a DC power generating unit. A physical assembly of modules and their support forms an array as shown in Figure 2.8.

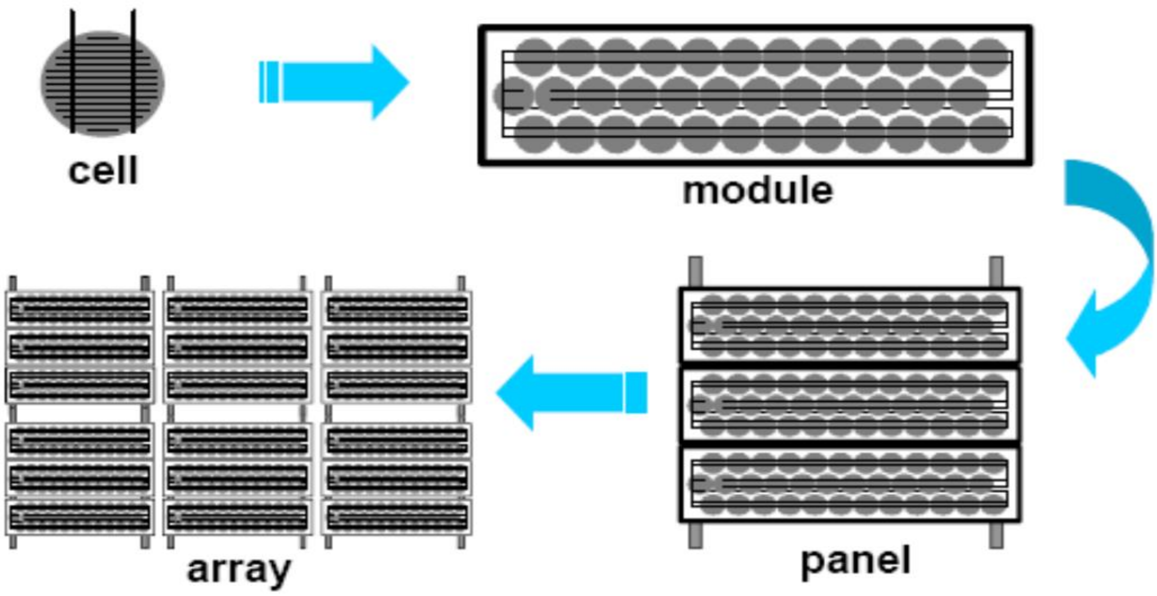


**Figure 2.8 Relationship between PV Cell, module and Array (Markvart, 2014)**

A PV array is the complete power generating unit consisting of any number of PV modules. It consists of a number of individualized PV modules or panels wired together in series and/or parallel to deliver the voltage and amperage required. An array can be as small as a single pair of modules, or large enough to cover wide areas.

*Electrical Safety Disconnects*

Electrical disconnects consist of additional switching that shuts off the AC power between the inverter and the grid, as well as a DC disconnect to safely interrupt the flow of electricity from the PV array to the inverter for system maintenance and troubleshooting possible system problems. These disconnects add costs and complexity to the photovoltaic system but ensure a redundancy to safety and overcurrent protection.

*DC to AC inverters*

A solar electric inverter is a component that converts DC electricity from the output of the PV array into grid-compliant AC electricity that is used in most homes. An inverter takes the DC power from the PV module array and causes it to oscillate until it matches the frequency of the power grid at 60 Hz (cycles per second). An inverter with ground fault protection also constantly checks for DC wiring shorts and bad connections, shutting the system down if problems are detected. If there is a power outage, the inverter will discontinue supplying electricity to the grid preventing electrical feedback to the power lines and personal injury to repair personnel. Most inverters have an efficiency of 85–96% depending on make and model. The power losses in the conversion of DC to AC as well as wire and switch-gear losses should be accounted for when determining the number of PV modules required (Cha, 2008).

**Figure 2.9 Inverter for Grid Connected PV**

**(Cha, 2008)**

*Charge Controller*

PV systems with integrated battery solutions also need a charge controller, as the varying voltage and current from the solar array requires constant adjustment to prevent damage from overcharging. Basic charge controllers may simply turn the PV panels on and off, or may meter out pulses of energy as needed, a strategy called PWM or pulse-width modulation. More advanced charge controllers will incorporate MPPT logic into their battery charging algorithms. Charge controllers may also divert energy to some purpose other than battery charging. Rather than simply shut off the free PV energy when not needed, a user may choose to heat air or water once the battery is full (IEA 2011).

*Battery*

Although still expensive, PV systems increasingly use rechargeable batteries to store a surplus to be later used at night. Batteries used for grid-storage also stabilize the electrical grid by leveling out peak loads, and play an important role in a smart grid, as they can charge during periods of low demand and feed their stored energy into the grid when demand is high (Cha, 2008). Other rechargeable batteries that are considered for distributed PV systems include sodium sulphur and vanadium redox batteries, two prominent types of a molten salt and a flow battery, respectively.

*Monitoring and Metering*

The metering must be able to accumulate energy units in both directions and two meters must be used. Many meters accumulate bidirectional, some systems use two meters, but a unidirectional meter (with detent) will not accumulate energy from any resultant feed into the grid.

**Figure 2.10 Canadian Electricity Meter**

**(Anon, 2014)**

In some countries, for installations over 30 kWp a frequency and a voltage monitor with disconnection of all phases is required. This is done where more solar power is being generated than can be accommodated by the utility, and the excess cannot either be exported or stored. Grid operators historically have needed to provide transmission lines and generation capacity. Now they need to also provide storage. This is normally hydro-storage, but other means of storage are used. Initially storage was used so that base load generators could operate at full output.

With variable renewable energy, storage is needed to allow power generation whenever it is available and consumption whenever it is needed. The two variables grid operators have are storing electricity for when it is needed, or transmitting it to where it is needed. If both of those fail, installations over 30 kWp can automatically shut down, although in practice all inverters maintain voltage regulation and stop supplying power if the load is inadequate (Schnoor, 2011).

Grid operators have the option of curtailing excess generation from large systems, although this is more commonly done with wind power than solar power, and results in a substantial loss of revenue. Three-phase inverters have the unique option of supplying reactive power which can be advantageous in matching load requirements.

Photovoltaic systems need to be monitored to detect breakdown and optimize their operation. Several photovoltaic monitoring system strategies are available, depending on the output of the installation and its nature. Monitoring can be performed on site or remotely.

### 2.3 History and Development of photovoltaic (PV) cells

The word 'photovoltaic' is a combination of two Greek words 'photo' and 'volt'. 'Photo' in Greek means 'light' and volt is a measure of electric potential or voltage at a point.

The photovoltaic effect is the process by which a PV cell converts sunlight into electricity when sunlight falls on a photovoltaic cell. The sunlight may be reflected, absorbed, or pass through it. The absorbed sunlight is what generates electricity.

Edmund Becquerel in 1839 was the first scientist to discover this photovoltaic phenomenon. However, the concept of this effect was made clear around the early part of the 1950's when it was used as a source of power for space applications. PV has its origins in the US space programme and were first utilised in the 1960s to power satellites (Owens, 2013).

Global concerns over the effects of the 1973 oil crisis triggered funding for research and development programmes which led to a rapid development of PV for energy conversion. Since then until the early 1990s research in the area has focused on improving the efficiency of light conversion into electricity. Conversion efficiencies are typically in the 12-20% range without concentrators, and 22-28% with concentrators (Owens, 2013). PV systems have progressively come down in price making them increasingly affordable to power homes and businesses.

Photovoltaic is emerging as a major power resource, increasingly becoming more affordable and proving to be more reliable than conventional power utilities in some areas. The Ideal weather conditions for generating electricity using photovoltaic cells are long, clear, cold, sunny days.

In the early 1990s, the concept of integrating PV arrays into a building's fabric and connecting the system to the grid so that the cost of power generation and demand can be negotiated between the PV owner and the electrical supplier was introduced. This concept has provided a major boost for the technology resulting in an annual growth of 15-30% during the 1990s worldwide (Bahaj, 2015).

The early driver of market expansion was niche applications for very small amounts of power such as calculators, and remote small-scale applications such as telecommunications. However, supportive policies in several countries have played an important role in expanding markets for PV for both grid and off-grid electricity supply in recent years (Gross et al, 2003).

In 2009 global installed PV power was in excess of 7.2 GWp and by the end of 2009 the global cumulative capacity exceeded 22.8 GWp. The EU contributed around 70% of the global cumulative capacity (IEA, 2010).

The PV industry is experiencing rapid growth as concerns over security of fuel supplies and carbon emissions mean that governments and individuals are increasingly prepared to ignore its current high costs. It is envisaged that PV will become a mainstream electricity generation technology when its costs are comparable to other energy sources (Bhandari and Stadler, 2009).

At the moment, it is still more expensive than grid supplied electricity in most parts of the world. Growing recognition of the environmental impact of non-renewable energy sources and the economic volatility that comes from the reliance on oil and gas has contributed to current expansion of the PV industry (Bagnall and Boreland, 2008).

Most of the growth in the late 1990s in Japan and Germany was triggered by subsidy-based market strategies. At country level, many governments (Austria, Germany, Greece, Italy, France, Czech Republic, Spain, and Portugal) have already included different PV promotion programmes (e.g. subsidies, feed-in tariff, etc.) in their national electrification plans.

At industrial level, efforts aimed at promoting PV systems worldwide have focused on increasing the technical and economic performances of PV modules and systems, developing new technologies, and enacting effective government regulations and policies (IEA, 2009).

### 2.3.1 State of Art of Solar Photovoltaic Technology

Solar electricity is more expensive than those produced by the traditional sources. However, over the past two decades, the cost gape has been closing. Solar photovoltaic technology has emerged as a useful power source of application such as lightning, meeting the electricity needs of villages, hospitals, telecommunications and houses (Hand book for Solar PV systems).

The long and increasing dominance of crystalline silicon in the photovoltaic market is perhaps more popular, giving the wide materials capable of producing photovoltaic effect. Photovoltaic based silicon wafers has captured more than 90% market shares because it is more reliable and generally more efficient than competing technologies. The crystalline silicon is more durable in real practice but it is not economically viable due to the high cost of silicon as a starting material (Hand book for Solar PV systems).

But still, research is on-going on developing diverse set of alternative photovoltaic technology. Currently, photovoltaic technology is increasingly recognized as a part of the solution to the growing energy demand, challenges and an essential component of future global energy production (Mott, 2011).

The current PV market consists of a range of technologies including wafer-based silicon and a variety of thin-film technologies. There are four major types of PV modules commercially available namely: monocrystalline, polycrystalline, amorphous and thin film. Monocrystalline cells are the oldest and most expensive production technique but they are the most efficient conversion technology available (Green, 2006).

Polycrystalline cells are less efficient than monocrystalline cells but their manufacturing costs are lower. Amorphous and thin film cells have the lowest cost but their efficiencies are lower than those for single and polycrystalline cells. Table 2.1 shows different PV modules and their associated efficiencies.

**Table 2.1 Solar PV Module Type and Efficiency**

| Cell type | Efficiency (%) |
|---|---|
| Monocrystalline | 17 |
| Polycrystalline | 15 |
| Amorphous | 10 |
| Thin film | 9 – 12 |

**Source (Green, 2006)**

2.3.2 Performance Studies

This section reviews different research works carried by many researchers on grid-connected PV system performance as stated in literature. It is put into sub headings for convenience and easy perusals.

## 2.4 Performance Evaluation and Assessment of PV cells

Evaluation and assessment of photovoltaic cell performance requires the measurement of current as a function of:

i. Voltage;
ii. Temperature;
iii. Intensity of solar radiation;
iv. Wind speed;
v. Radiation spectrum;
vi. Photovoltaic conversion; and
vii. Conversion efficiency.

The most influential of these parameters is the PV conversion efficiency, which is measured under standard test condition (Malik and Damit, 2003).

Monitoring PV performance provides data to demonstrate the performance of system components, energy production and loss mechanisms associated with system operation, reliability and causes of system failures, validity of theoretical models using measured data, and long term system performance (Tripathy and Saxena 2014).

Although PV cell temperature affects module performance, there exists other mechanisms such as spectral effects and low-light level behavior that are also significant to consider. Crystalline silicon modules perform better in winter (wet season) than summer (dry season) while the reverse is true for amorphous because crystalline has larger negative temperature coefficients (Notton *et al*, 2010).

The hourly energy generation by a grid-connected PV system depends on many parameters such as:

i. PV array peak power;
ii. In-Plane Solar Radiation;
iii. PV Cell Temperature;
iv. Inverter Efficiency and Size; and
v. Maximum power point tracking losses.

Mondol et al. 2006, carried out long-term performance analysis of a 13 kWp roof mounted grid-connected PV system in Northern Ireland over a period of three years. They analyzed the measured data on hourly, daily and monthly bases and evaluated the performance parameters which include:

i. Reference Yield;
ii. Array Yield;
iii. Final Yield;
iv. Array Capture Losses;
v. System losses, PV and inverter efficiencies; and
vi. Performance ratio.

They investigated the effects of insolation and inverter operation on system performance.

Their results showed that the monthly average of inverter efficiencies varied from 4.5% to 9.2%, 3.6% to 7.8% and 50% to 87% respectively, while the annual average PV module, system and inverter efficiencies were 7.6%, 6.4% and 75%, respectively. The monthly average daily PV array and system performance ratios ranged from 35% to 74% and 29% to 66%, respectively, while the annual average monthly PV system performance ratios were 60%, 61% and 62%, respectively during the monitoring period.

Kymakis *et al*. (2009) also monitored the performance of a 171.4 kWp photovoltaic park in the island of Crete, Greece over a year using data collected at 10 minutes intervals. They evaluated the performance ratio and computed different power losses (temperature, soiling, internal, network, power electronics, grid availability and interconnection). The Park supplied 229 MWh of electricity to the grid in 2007, with daily output ranging from 335.5 to 869.7 kWh. The average annual energy output in the same year was 1,336.4 kWh/kWp. The final yield ranged from 1.96 to 5.07 h/d, the performance ratio ranged from 58 to 73%, with an annual average of 67.4% while the average annual capacity factor was 15.2%.

Decker and Jahn (2006) analysed the performance of 170 kWp grid-connected PV plants in Northern Germany. The annual final yields of the PV plants ranged between 430 and 875 kWh/kWp with a mean value of 680 kWh/kWp. The annual performance ratios - determined using annual in-plane irradiation - ranged between 47.5 - 81% with a mean of 66.5%.

Cardona and López (2007) analysed the performance of a 2.0 kWp grid-connected photovoltaic system installed in Málaga (Spain) between January and December 1997. The total energy output from their PV system was 2,678 kWh with mean daily output of 7.4 kWh/d. The annual performance ratio was 64.5% while the monthly average daily system efficiency varied between 6.1 and 8.0%.

Benatiallah *et a*l. (2007) presented performance evaluation results of a 1.5 kWp photovoltaic system with nominal PV module efficiency of 12% installed in southern Algeria. Between January and December 2001, the average solar insolation was 7.2 kWh/m$^2$/d. The DC power output varied from 3,512 kWh in December to 7,983 kWh in August.

The annual average daily PV module and inverter efficiencies were 10.1% and 80.7% respectively during the same period. They reported that low insolation led to a decrease in PV module efficiency. The efficiency decreased at low incident solar radiation and was higher in summer than winter because of longer days. The system generated 2.5 kWh during the period January 2000 to August 2000.

Chokmaviroj *et a*l. (2006), Presented results for the first eight months of monitoring a 500 kWp photovoltaic pilot plant in Mae Hong Son province, Thailand. Their PV system consisted of a PV array of 1680 modules (140 strings, 12 modules/string; 300 Wp), power conditioning units and battery converter system.

During the first eight months of operation, the PV system generated about 383,274 kWh. The average daily electricity generation was 1,695 kWh ranging from 1,452 to 2,042 kWh. The system efficiency ranged from 9 to 12% while the inverter efficiency ranged from 92

to 98%. The final yield ranged from 2.91 to 3.98 h/d and the performance ratio ranged from 0.7 to 0.9.

### 2.4.1 PV Performance Prediction

Alamsyah et al. (2010) presented a simplified method for predicting long-term average conventional energy conversion or performance of a PV system in Malaysia. They reported that their approach was suitable for hand calculations using only one day for each month. The method is however, limited to initial evaluation of the average performance of PV systems with a more rigorous techno-economic analysis being required for more accurate predictions.

Again, Alamsyah et al. (2014) presented a methodology for modeling the photovoltaic potential of a site. They modeled the energy produced by a PV system using its nominal power, incoming irradiance and major energy loss mechanisms.

They found that energy loss mechanisms involve:

i. The temperature of the pv cells;
ii. The response of pv cells to low intensity light;
iii. The spectrum and polarization of light;
iv. The deviation from maximum power point tracking;
v. Module mismatch; and
vi. Ohmic losses.

The model proposed by Alamsyah *et a*l. (2006) is based on the nominal power of the PV array, the temperature coefficient of the modules, in-plane solar irradiance, the air temperature and wind speed. Measured field performance data is required to analytically calculate the factors that cause reduction in power output from standard test conditions (STC). Their model can however, be improved if empirical formulae based on PV array specific data are used.

Their proposed model is given as: $p_m = \frac{p_p.\eta_t.G_m}{G_{STC}}$

where:

$P_m$ = maximum power (W);

$P_p$ = nominal power (W).

$\eta_t$ = coefficient that includes all factors that lead to the actual energy produced by a module/array with respect to the energy that would be produced if it were operating at standard test condition (dimensionless).

$G_m$ = in-plane solar radiation ($W/m^2$) and

$G_{STC}$ = solar radiation under standard test conditions ($W/m^2$)

## 2.5 Factors that Affect Solar Power Production

There is no such thing as a perfect technology. Research reveals the different factors that can affect the efficiency of solar panel mounting systems. Some of these factors have been studied to either increase or decrease the power production from the three types of mountings such as sun intensity, cloud cover, relative humidity, and heat buildup.

When the sun is in its peak (intense), during midday, the most solar energy is collected; therefore, there is an increase in the power output. Cloudy days contribute to the decrease in sunlight collection effectiveness since clouds reflect some of the sun's rays and limit the amount of sun absorption by the panels (Anon, 2010).

During summer days when the temperature is at its highest and heat is built up quickly, the solar power output is reduced by 10% to 25% for the reason that too much heat increases the conductivity of semiconductor making the charges balance and reducing the magnitude of the electric field. In addition, if humidity penetrates into the solar panel frame, this can reduce the panel's performance producing less amount of power and can permanently deteriorate the performance of the modules (Anon, 2010).

### 2.5.1 Types of Solar Panel Mountings

Research shows that there are three types of solar panel mountings. These are fixed, adjustable, and tracking.

*Fixed Mount*

Figure 2.12 shows a fixed type of mount which is completely stationary. This is the simplest and cheapest type of solar panel. The solar panels are installed in such a way that they are always facing the equator (due south in the northern hemisphere). The angle of inclination favors the winter sun and favors the summer sun slightly less (Anon, 2010)

*Merits of fixed PV Systems*

i. Fixed-mount systems typically cost less initially, when using the traditional measure of dollar per watt.

ii. Fixed-mount solar may also be a good option due to geographic and siting constraints, such as topography and system location.

*Demerits of fixed PV systems*

i. For many other locations, however, this isn't the case, and clients with fixed systems will not be able to maximize their energy production as effectively.

ii. Many customers do not make as much return on fixed systems over time, as they tend to produce less energy than tracking systems.

**Figure 2.11 Fixed Solar Panel Mount**

**(courtesy of Navrongo VRA solar plant)**

*Adjustable Mount*

Figure 2.13 shows the adjustable type of mount. The adjustable solar panel mounting system includes adjusting the angle of inclination of the solar panel mount two or more times a year to account for the lower angle of the sun in the seasons. This system is more expensive than the fixed mount but it increases the solar panel power output by approximately 25%, thus making it more efficient (Anon, 2010).

**Figure 2.12 Adjustable Solar Panel Mount (Anon, 2010)**

*Trucking mount*

Figure 2.14 shows the trucking type of mount. The tracking solar panel mounting system is the most expensive of the three types of mounting. It tracks and follows the path of the sun (east to west) during the day as well as the seasonal declination movement of the sun. The tracking solar panel output increases by approximately 25% - 30%. It cannot be denied that this type of mounting is the most efficient in producing the greatest amount of solar power (Lux Research, 2010).

**Figure 2.13 Tracking Solar Panel Mount (Anon, 2010)**

*Merits of the tracking solar panel*

i. Trackers generate more electricity than their stationary counterparts due to increased direct exposure to solar rays. This increase can be as much as 10 to 25% depending on the geographic location of the tracking system.

ii. There are many different kinds of solar trackers, such as single-axis and dual-axis trackers, all of which can be the perfect fit for a unique jobsite. Installation size, local weather, degree of latitude and electrical requirements are all important considerations that can influence the type of solar tracker best suited for a specific solar installation.

iii. Solar trackers generate more electricity in roughly the same amount of space needed for fixed tilt systems, making them ideal for optimizing land usage.

iv. In certain states some utilities offer Time of Use (TOU) rate plans for solar power, which means the utility will purchase the power generated during the peak time of the day at a higher rate. In this case, it is beneficial to generate a greater amount of electricity during these peak times of day. Using a tracking system helps maximize the energy gains during these peak time periods.

v. Advancements in technology and reliability in electronics and mechanics have drastically reduced long-term maintenance concerns for tracking systems.

*Demerits of tracking solar panel*

i. Solar trackers are slightly more expensive than their stationary counterparts, due to the more complex technology and moving parts necessary for their operation.

ii. Even with the advancements in reliability there is generally more maintenance required than a traditional fixed rack, though the quality of the solar tracker can play a role in how much and how often this maintenance is needed.

iii. Trackers are a more complex system than fixed racking. This means that typically more site preparation is needed, including additional trenching for wiring and some additional grading.

iv. Single-axis tracker projects also require an additional focus on company stability and bankability. When it comes to getting projects financed, these systems are more complex and thus are seen as a higher risk from a financier's viewpoint.

v. Solar trackers are generally designed for climates with little to no snow making them a more viable solution in warmer climates. Fixed racking accommodates harsher environmental conditions more easily than tracking systems.

vi. Fixed racking systems offer more field adjustability than single-axis tracking systems. Fixed systems can generally accommodate up to 20% slopes in the E/W direction while tracking systems typically offer less of a slope accommodation usually around 10% in the N/S direction.

### 2.5.2 Module Mismatch

Due to slight differences in modules' IV curves, the one in which is MPP used for an entire array or series string will not be a perfect fit for each individual module. If there are different makes and models of modules in the array, the power loss will be even greater. If individual series strings of modules have their own MPPT, the loss will be less. Most PV arrays with one kind of module and a single MPPT for the entire array will experience a 2% loss due to module mismatch, so we will use a 0.98 mismatch factor (IEA, 2011).

### 2.5.3 Inverter

We also need to account for the power it takes to convert the DC electricity from the PV array to AC, and we can do so by factoring in the inverter efficiency. While inverter specification sheets will list "maximum efficiency," a more useful value is the "weighted efficiency," which accounts for the percentage of time the inverter commonly spends at various power levels. This gives a better indication of the inverter's real-world efficiency. Most grid-direct inverters have weighted efficiencies greater than 90%. (IEA, 2011).

### 2.5.4 Shading

This is a no-brainer factor; shaded solar panels produce less electricity. One thing to consider is that shading varies seasonally. As the angle of the sun changes through the year, trees and other barriers may pose shading issues in different seasons. It all depends on the size, height, and proximity of surrounding barriers. Properly designed solar systems minimize or eliminate shading.

Under some circumstances, it is not possible to avoid all shading, so proper design will minimize it during peak mid-day production periods. Besides the mass grid production system, attention should also be given to the effects of adding on roof-top PVs, stand alone and others (Poullikkas, 2012).

## 2.6 Empirical Review

Xiong *et al*, (2007) looked at the dire situation of Africa with regards to access to electricity calls for urgent measures if the continent is to develop and lift its citizens out of poverty. They advocated that the traditional grid extension approach needs to be complemented by decentralized solutions as well, particularly where these turn out to be more cost-effective. With the decreasing cost of Solar Photovoltaic (PV) technology globally, PV based mini-grid is one of the options that are available to governments and other stakeholders for accelerating access to electricity for many communities across the continent.

This becomes an even more interesting proposition when viewed in the light of Africa's significant solar resources. The study came out with a technical manual intended to provide a step-by-step practical guide on how to plan, design, install, operate and maintain a solar PV-Based mini-grid that supplies electricity to an Africa village (or group of villages).

The manual considers two options. The first option is solar PV with battery only mini-grid and the second option is hybrid PV-diesel with battery storage. It considers systems of sizes up to 100 kW.

Sukhatme (2008) empirically analysed those benefits of solar energy by applying a conceptual and methodological framework previously developed by the authors to three renewable energy technologies in three different places in Spain. With the help of case studies, their paper shows that the contribution of renewable energy resources to the economic and social dimensions of sustainable development might be significant. Particularly important is employment creation in these areas.

Although, in absolute terms, the number of jobs created may not be high, their study indicated that it may be so with respect to the existing jobs in the areas considered.

The study outlined that the specific socioeconomic features of the territories, including the productive structure of the area, the relationships between the stakeholders and the involvement of the local actors in the renewable energy project may play a relevant role in this regard. Furthermore, other local (socioeconomic) sustainability aspects beyond employment creation should be considered.

According to Bahaj (2015) ventured into maximum capture of irradiation using a satellite and suggested that, Satellite Solar Power (SSP) is an alternative to terrestrial energy resources for electricity generation. The study considers the market for electricity from the present day to the year 2020, roughly the year when many experts expect SSP to be technically achievable.

It is found that several trends from the present to 2020 should influence decisions about the design, development, financing and operation of SSP. Second set of observations pertains specifically to challenges facing SSP. They stated that the festive immaturity of the technologies required for SSP makes it difficult to assess the validity of estimated costs and the likely competitiveness of SSP.

Additionally, they added that national security and national economic considerations may discourage some countries from participating in an SSP system operated by another country or group of countries. Countries with these concerns may require equity participation in SSP, limit their reliance on SSP to only a small share of their energy portfolio, or decline use of the technology altogether.

They recommended that the energy industry should be invited to be at the table in technical and economic analysis of SSP, that is, to both participate in conducting the analysis and learn about the results.

Finally, the authors identified specific topics for future research to focus on the use of SSP in terrestrial markets. SSP capabilities may be applicable to non-terrestrial systems, such as the international space station, other large orbiting platforms, lunar bases, and other activities that are used to explore and develop space.

According to Markvart *et al*, (2000) in their study explored the complexities associated with diffusion of small-scale photovoltaic systems in rural areas of developing countries, with the experience of Global Environment Facility (GEF) project of Zimbabwe. GEF has founded 41 renewable energy projects in 26 developing countries to the tune of US $ 480 million by 2000.

They were of the opinion that GEF program is quite successful in achieving the targets and in creating the awareness and benefits of PV systems. It was able to take good use of subsidy and has created a good number of stakeholders. The paper also throws light on the macroeconomic problems like inflation and explains how depression will curse success of the PV industry. As a policy matter the authors stress upon the need of sustainable energy policy, political stability and more demand pull approach than technology push (Bahaj, 2015).

Newman (2011) opined that technological change was the driving force for development, thus policy makers have a need to understand the techno-economic dynamics. The authors gave a model, in that they said the present dynamics of solar cells was the technology and market, specifically for the long run. They also wrote that real beginning of PV technology was in 1960's, especially in US, when oil crisis occurred and due to the progress in PV technology the annual sales of PV systems have increased by 33 percent in the last decade.

They also found that the target set by different countries like Europe aims 3 GWp electricity production, Japan 4.6 GWp and US 7 GWp production by 2010 (Newman, 2011). It is Japan and USA who play very important role in the PV technology and usage; thus, the patents taken by these countries are highest in the world. Particularly CIEA and Sanya companies of Japan and, Solaex and ECD companies of USA will be key actors in the world of PV market. As policy issues, authors have suggested that measures should be taken towards the diffusion of solar cells in terms of procurement of cells, new competing design and, at last, policy should ensure careful material and environmental management (Newman, 2011).

Alsema and Nieuwlaar (2000) in their paper analyze the Energy Payback Time (EPBT) of PV systems by assuming 25 percent energy loss in the production. They have mentioned that EPBT is only 2 to 6 years, whereas life of the PV system is 25 to 30 years. In the paper given availability of future technology of PV systems and further they have mentioned that future technology will reduce EPBT to 1.5 to 2 years.

In the paper it is also found that $CO_2$ emission from conventional electricity is 0.57 kg/kWh, but by PV systems emission is only 50 to 60 g/kWh, they have also written that $CO_2$ emission is even less in biomass and wind energy. In the policy implications the authors suggest that cost effective technology should be developed and still life of system should be increased. Finally, the paper concludes that PV system will play an important role in the future in sustainable energy supply, especially after 2010 (Alsema and Nieuwlaar, 2000).

Marafia (2001) explored the possibility of attaining sustainable rural development in Bangladesh through fostering decentralized rural companies based on photovoltaic (PV) technologies, because authors opines that the solar electricity could be a promising business and able to generate employment opportunities to landless and marginal farmers as it is not a much seasonal business like agriculture.

The paper begins with the discussion on the scope of PV technologies in Bangladesh, and then tries to apply different models for sustainable rural development. In different models, the authors explain the role of the government, rebate strategy, consumers, local industries, price of solar electricity, NGO's etc. Further they explain the role of stake holders namely NGO's, training institutes and marginal agriculturist (Marafia, 2001).

Lastly, they conclude that PV technologies used appropriately may improve the quality of life of rural people and provide income generating opportunities and also stresses on the requirement of the new model that specifically address social, economic and environmental issues.

Joshi et al (2009) analyze the potential economic impact of a demand of Photovoltaic (PV) devices in terms of induced production and job creation, directly and indirectly. The authors say that implementation of PV manufacturing facilities may stimulate several economic activities helping to set up local industries and inducing more environmental development. Presently, USA and Japan are the leading countries in production of electricity from PV systems and total world electricity production through this means is about 400 MW in 2001, in business value it is 2.5 billion euro dollars.

Finally, the analysis concludes that PV installation has not only created direct and indirect employment but also has made an impact on the GDP growth of the country.

Hoffmann (2013) in his paper says that solar photovoltaic (PV) technology plays an important role in the sustainable development of civilization in the 21st century and he further mentions that the development of clean energy technology is most important task of modem science. By the mass consumption of fossil fuels, pollutants like $CO_2$, $NO_2$, CO etc. will be omitted which leads to global warming.

The author built a model called the '3E-Trilemma. The model illustrates cyclical correlation of the Economy, Energy and Environment. The writer also mentions that, Asia by 2010 will import 69.2 percent fuel to meet its total demand.

Then, the paper deals with the key issues of PV technology and its bright future in different stages. Finally, he concludes that with PV technology, a new kind of energy revolution will take place, within next 25 years.

Cramer et al, (2013) opine that solar photovoltaic systems are prohibitively expensive in terms of installation costs. Power from them is also available intermittently only when energy from the sun is available. On the other hand, the PV systems are free of the ever-rising costs of input fuel. They also incur much less operation and maintenance costs and are supposed to have a longer lifetime than, for example, a fossil fuel power plant.

Thus using solar PV power looks uneconomical in the short term, but may be profitable in the long term. It is, therefore, interesting to identify the factors that can make investment in solar PV power generation acceptable. The paper also carries out a financial analysis of installing a 10 MW solar photovoltaic power generation plant for sale of electricity to a grid. It compares the level of cost of this mode of energy generation as compared to a fossil fuel plant. It also calculates the cost of electricity generation and tariff for power from this plant. It then identifies the factors that can make the investment in a grid-scale solar PV plant more favorable than investment in other conventional and non-renewable sources.

Notton *et al*, (2010) in their paper have demonstrated the implications of introducing PV systems and compact florescent lamps in rural Tanzania. The study is based on the cost-sensitivity analysis of PV systems with traditional diesel systems with certain assumptions. The analysis says that the PV options are most expensive for the low load case, whereas traditional system is most expensive for the high load case. The papers throw the light on the environmental aspects like stoppage of some percentage of $CO_2$ emissions by using PV systems.

Lastly, as a policy matter, the author suggests that from a national policy point of view, introduction of renewable technologies such as PV power kits for household use, should consider that other development goals might be over seen if infrastructure planning focuses on individual and short term needs.

### 2.7 Summary

A review of literature on grid-connected Photovoltaic systems confirmed a continuous increase in global dependence on renewable solar energy with growth sustained by the states and the private sector supports in some countries. The trends of Technology in 2015 showed that PV modules with crystalline silicon cells had over 80% dominance of the world market share with thin film cells covering 20%. However, monocrystalline photovoltaic cells have superior qualities and efficiency than the other PV technologies. Literature also revealed that energy output prediction of PV cells is dependent on accurate determination of their efficiency. However, PV cell efficiencies quoted by manufacturers are measured under standard test conditions which are different from the practical field operating weather conditions over the world and hence, West Africa

# CHAPTER THREE

## GENERAL INFORMATION, DESCRIPTION AND PLANT LAYOUT AT NAVRONGO

### 3.1 General information, Location and Accessibility

The Navrongo VRA Solar Plant is sited at Pungu, Upper East Region Ghana. Navrongo is about 32 km away from the regional capital, Bolgatanga, 490.34 km from Kumasi and about 811 km away from the national capital, Accra Ghana.

The Upper East Region of Ghana is located in the northeastern corner of the country between longitude 00 and 10 West and latitudes 100 30"N and 110N and bordered by Burkina Faso to the north and Togo to the east, the west by Sissala in Upper West and the south by West Mamprusi in Northern Region.

The capital is Bolgatanga, sometimes shortened to Bolga. Other cities include Bawku and Navrongo. In terms of land mass, the Upper East Region is 8842 square kilometers and has a population over 1,046,545 by the records of the 2010 population and housing census. Table 3.1 and Figure 3.1 below show the location of the solar plant in the geographical map of the Upper East region of Ghana respectively.

**Table 3.1 Location of the Solar Plant**

| Administrative Region | Administrative District | Administrative Town | Site address | GPS coordinates |
|---|---|---|---|---|
| Upper East | Kassena Nankana East | Navrongo | Pungu Telania (4.77 ha size of land) | 10°55'28.10"N 01°03'24.90"W<br>10°55' 36.50 N 01°03'16.80"W<br>10° 55' 28.50" N 01° 03'10.60" W |

**Source (Anon, 2012)**

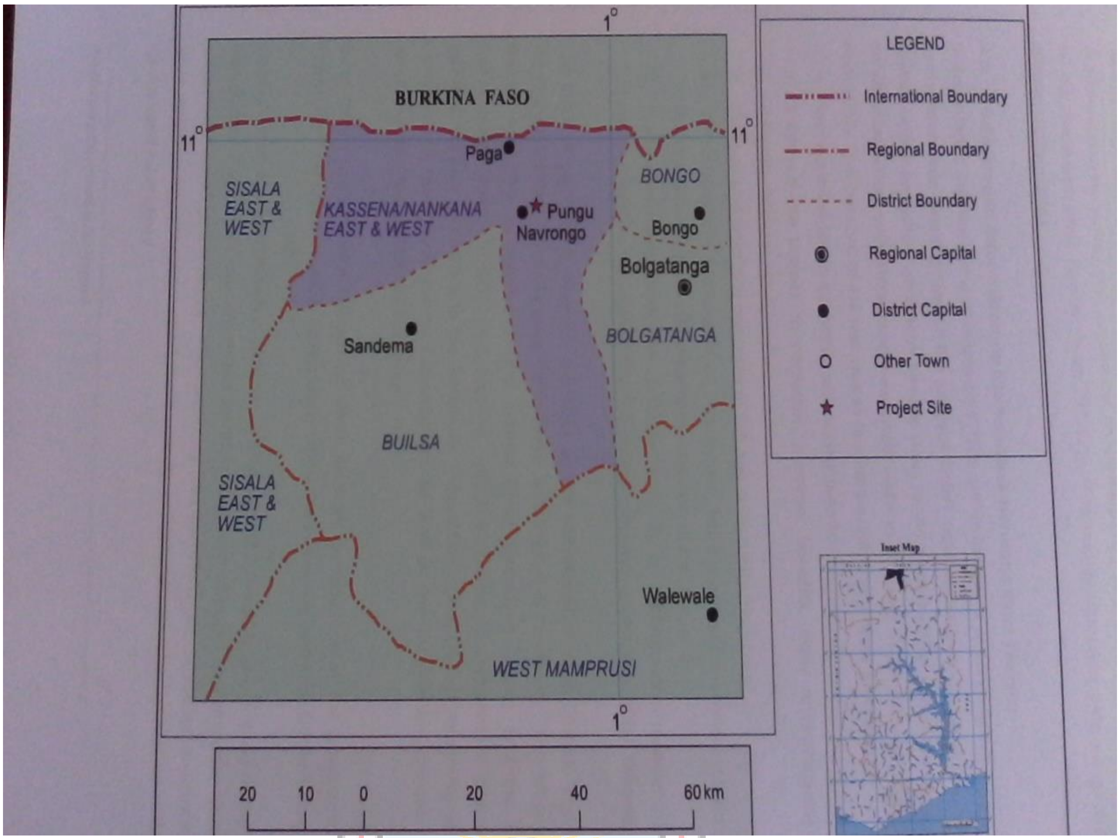


**Figure 3.1 Map of Upper East Region**

**(Courtesy of Navrongo VRA Solar Plant, 2016)**

## 3.2 Climate

The climate is characterized by one rainy season from May/June to September/October. The mean annual rainfall during this period is between 800 mm and 1100 mm. The rainfall is erratic spatially and in duration. There is a long spell of dry season from November to mid-February, characterized by cold, dry and dusty harmattan winds. Temperatures during this period can be as low as 14 degrees Celsius at night, but can go to more than 35 degrees Celsius during the daytime. However, humidity is very low making the daytime temperature very high and uncomfortable.

## 3.3 Plant description

The electrical design of the Navrongo Solar power plant consists of the Direct Current (DC) and Alternating Current (AC) components

### 3.3.1 The Direct Current (DC) System

The DC system is made up of the following components:

i. Photovoltaic Modules or panels (generators);
ii. Combiner/Junction/Collector Boxes;
iii. Inverters;
iv. DC Cabling;
v. DC Connectors (plug and sockets);
vi. DC Disconnects or Switches; and
vii. Protection Device and Earthling.

### 3.3.2 The Alternating Current (AC)

The AC system is made up of the following components:

i. AC Cabling;
ii. Switchgear;
iii. 34.5 kV Transformer;
iv. Substation ;
v. Earthing and Surge Protection;
vi. AC Disconnects; and
vii. Protective Device.

## 3.4 Photovoltaic Modules (AC generators)

Figure 3.2 shows a crossectional view of some of the photovoltaic modules. The modules as alluded in literature converts the sun light into electrical energy and are usually referred to as generators on the field. The main components of the plant are the power arrays which are composed of several photovoltaic panels which convert solar energy (radiation from the sun) into electricity.

There are one hundred and twenty (120) power arrays and each array has 72 PV modules. A total of 8622 photovoltaic modules have been installed which generate energy between 700 – 900 volts daily. The plant structures are arranged in a manner to avoid over shading of the modules on one another and also allow easy access to the modules for maintenance.

Based on NASA radiation data and calculation for maximum amount of solar radiation, the power arrays are fixed mounted with angles of tilt between 12°-15° towards the

Northern Hemisphere depending on the position of the array. The area of a module is 1956 mm x 992 mm, and the effective area covered by the 8622 modules is about 16729.71 $m^2$. The wiring of the photovoltaic modules also includes underground wiring which connects the power arrays to the collector station. The entire ground is tidy and covered with quarried gravels to control weeds.

The photovoltaic cell technology used is the polycrystalline silicon type manufactured by Suntect and Jinko industries and has a lifetime between 20 – 25 years.

The photovoltaic cell characteristics are as follows:

| | |
|---|---|
| Rated Maximum Power (Pmax) | 295 W; |
| Output Tolerance | 0/+5 %; |
| Current at Pmax (Imp) | 8.27 A; |
| Voltage at Pmax (Vmp) | 35.7 V; |
| Short Circuit current (Isc) | 8.57 A; |
| Open Circuit Voltage (Voc) | 45.1 V; |
| Normal operating cell Temperature | 45 °C +2 °C; and |
| Module Weight | 27 kg. |

**Figure 3.2 PV Modules at Pungu**

**(Courtesy Navrongo VRA Solar Plant, 2013)**

### 3.4.1 The combiner Box

Figure 3.3 shows a combiner box which is also known as the junction box or the collector box, it sums up the composite voltages of 4 photovoltaic arrays (288 modules) for transmission in the inverter. In all, the plant has 32 combiner boxes which transmit energy into the inverters.


**Figure 3.3 Array Combiner Box at Navrongo VRA Solar Plant**

### 3.4.2 The Inverters

The inverter is a major component of photovoltaic (PV) systems either autonomous or grid connected. It affects efficiency of the overall performance of the PV system. Any problems or issues with an inverter are difficult to notice unless the inverter totally shuts down

Figure 3.4 is a DC inverter. An inverter is a power conversion device that converts DC electricity generated by the PV modules into AC electricity suitable for grid supply. The main functions of the inverter are: transformation of DC into AC, wave shaping of the AC output and regulation of the effective value of the output voltage.

The plant has five (5) inverters which are fed with DC by 32 combiner boxes. Inverters 1, 2, 3 and 4 take six combiner boxes each, and inverter 5 takes eight combiner boxes. The inverters receive between 700 – 900 volts of DC energy from the 32 combiner boxes and transform it into 415 volts of AC for onwards transmission into the AC transformer.

The inverters (Fig. 3.4) are direct current sensitive and switches on or off in the presence or absence of AC, whichever the case may be as the day and night rotates.


**Figure 3.4 DC Inverter at Navrongo VRA Solar Plant**

## 3.5 The AC Transformer Substation

The transformer in used is a dual type transformer. Figure 3.5 shows the dual transformer in application. It steps up the 415 volts received from the inverters to 34500 volts (34.5 kV) for transmission from the transformer substation to the Pungu line into the national grid. On the other hand, when the solar plant is down and not generating power, the same transformer takes power from the national grid from the Navrongo Substation, and processes it to the power requirements for the Navrongo VRA Solar Plant department for administrative use.

**Figure 3.5 Dual Transformers at Navrongo VRA Solar Plant**

## 3.6 Circuit Diagram of Plant Layout and Description

The line diagram in Figure 3.6 illustrates the layout of the plant. The power plant is made up of the photovoltaic modules arranged into arrays and linked together by wiring into 16 combiner boxes.

However, the constituent elements of the plant from input to output are listed below in a chronological order. The combiner boxes deliver the DC voltage from the array to the DC inverters for translation into AC. Through a bus bar, the inverters deliver into a circuit breaker about 700 Volts to 900 Volts for passage into the AC transformer. The transformer steps the voltage up to about 34500 Volts AC, which passes through another circuit breaker before it is delivered into the national grid for distribution.

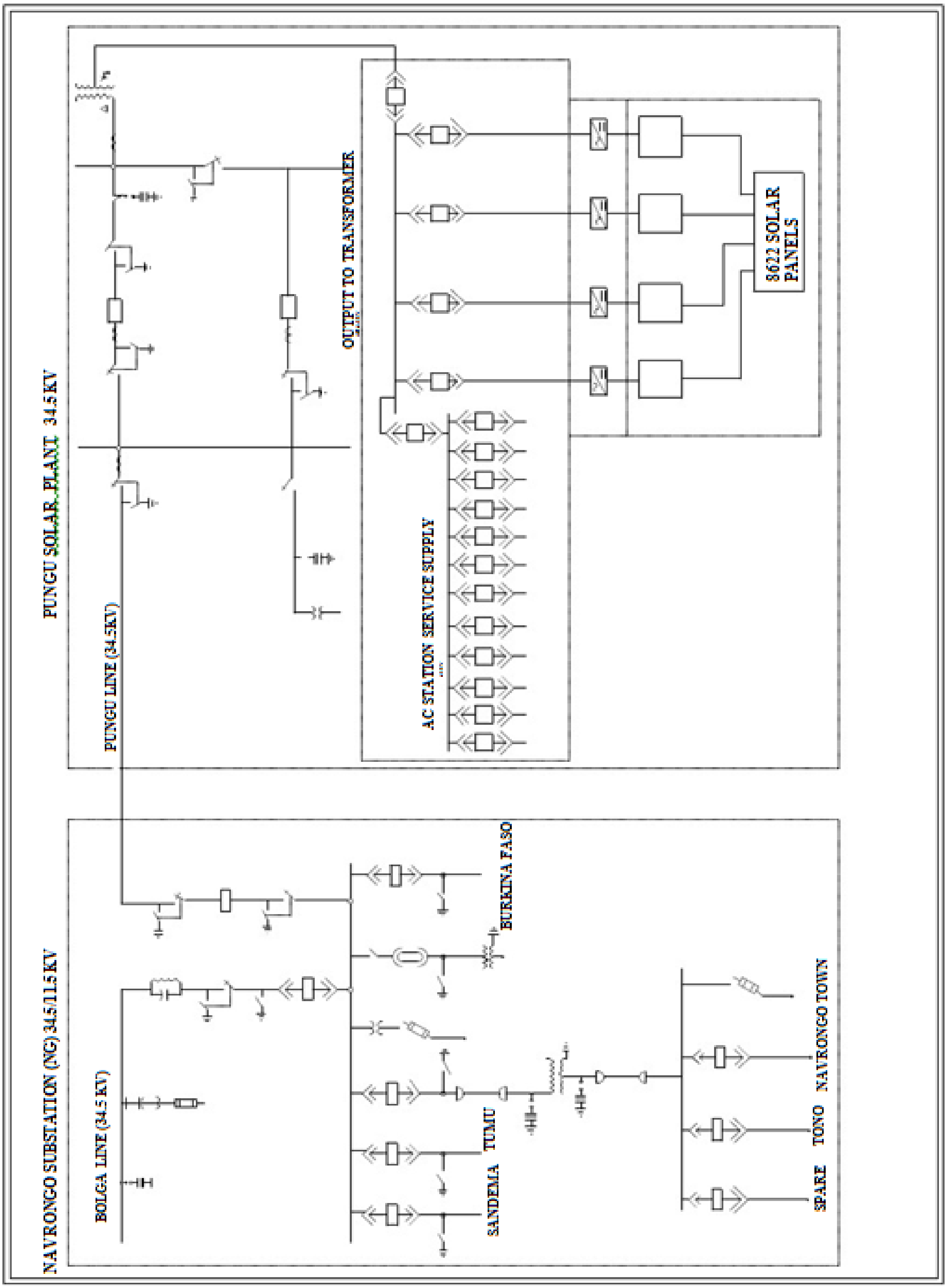


**Figure 3.6 Circuit Diagram of Navrongo VRA Solar Plant Layout at Pungu**

### 3.6.1 Description layout

The circuit diagram as seen in Figure 3.6 consists of the PV power generators which deliver power to the transformer substation on site for processing. Power from the transformer unit is delivered into the Pungu line for transmission into the Navrogo Substation which also receives power from Bolgatanga. The Navrongo Substation then supplies energy to the township, Burkina Faso, Tumu, Sandema Tono and Spare for consumptions.

## 3.7 Summary

The Navrongo VRA Solar Power Plant is made up of solar cells, modules, panels and arrays. Each module is made up of 288 cells (12 × 24) and an array has 72 modules. There are 8622 pieces of PV panes translate into 120 arrays. The energies generated by the individual modules of every 4 arrays are linked together by series and parallel wirings and converged into one combiner box. The 120 arrays are therefore connected into 32 combiner boxes.

The combiner boxes transfer a composite voltage of about 700 to 900 volts to the inverters which transform it into 415 volts of alternating current. The AC transformer receives the 415 volts from the inverters and steps it up to 34500 volts (34.5 KV) for transmission onto the national grid.

The multifunctional energy meters and the power distribution meters are integrated into the plant layout to measure accurately the amount of energy generated, the energy consumed, the amount transmitted to the grid daily, monthly and yearly basis.

There is the battery bank system which takes over in the case of downtime and supplies power to the system control panels, communication systems and the computers for administrative duties. The communication system has the software component installed on computer monitors which draws a line diagram of the solar plant layout and displays it visually on the screen and also displays all the performance variable characteristics which are read and recorded hourly in monitoring.

# CHAPTER FOUR

## METHODOLOGY

### 4.1 Introduction

This chapter outlines the research methodology employed in achieving the aims, objectives and goals of the study. It involves the type of study, population, sample, sampling design, research design, data collection instrument and sources of data. The mode of establishing method of data analysis and ethical consideration are also described in this chapter.

### 4.2 Research Design

The research design guides the Planning and organization of the study in a way that is most helps to attain the projected goal. In deciding on the research design, numerous research methods were examined.

The research adopted the mixed method approach. Creswell (2005), states that you conduct a mixed method study when you have both quantitative and qualitative data and both types of data together provide a better understanding of your research problem than either type by itself. The study is organized into two parts namely:

i. Data collection; and
ii. Interview.

In the first part, a prefeasibility study was undertaken using Master-wiring picture: 18th edition to obtain an idea of the power production variables.

Additionally, a period of two months attachment to the Navrongo VRA Solar Power Plant build up the researcher's field experience, observation, data collection, analysis, evaluation and conclusion. This was carried out through the following methods:

i. Collection of secondary data from site which covers the average power generated in kWh, the average power delivered in kWh, the average power lost in kWh and the average site power consumed in kWh. Other data collected include average irradiance of the site in $Wh/m^2$ and the average temperature of the environment in degree Celsius.

ii. Obtain a layout of the solar plant. This assisted in determining the characteristics of the variables that affect the output of the plant. Additionally, it assisted in the review of the design criteria of the plant for better performance. Through this review, a recommendation for future work was proposed.

iii. A physical site analysis was carried out to get an overview of what goes on at the site, ascertain some physical factors affecting the operation of the plant as well as verify the authenticity of some of the responses received from sit workers interviewed.

In the second part of the study, a comprehensive interview was performed on the factors affecting the performance of the plant as well as make inputs to addressing the problems of the solar plant for maximum power delivery. Personal observations of the various facilities available were made in the site to assess the problems emanating from the plant for better performance.

Basically, quantitative research design was employed to systematically investigate and explain the survey design to elicit data on the performance, analyse data on factors affecting the performance of the plant and address problems affecting power generation from the plant. The methods and strategies used in the performance analysis of the Solar Power Plant for increased efficiency included a thorough review of existing literature dedicated to:

i. The Analysis of The Solar Plant Layout;

ii. The Analysis of PV Modules;

iii. PV Module Losses;

iv. Temperature and Solar Radiation; and

v. Inverter Efficiencies.

### 4.3 Population

According to Ary *et al* (2002) “population” refers to the entire group of individuals to whom the findings of a study apply. The population for the research involved workers at Navrongo VRA Solar plant of Upper East Region, Ghana. The total number of workers on site is nine (9).

### 4.4 Sample and Sampling Techniques

The sample for the study was chosen using the purposive and convenience sampling technique. The purposive sampling technique used ensured that participants for the study have knowledge on the subject matter under discussion. The convenience sampling technique employed was based on the criterion that participants were accessible throughout the period of study and thus could be easily recruited.

On the other Hand, Lartey (2009) acknowledges that every member of the population has equal chance of being selected in a simple random technique.

### 4.5 Data Collection Instruments

Data collection instruments for this study were of three types. First was the secondary data obtained from the site. This data consisted of monthly average power generated, monthly average power delivered, monthly average power lost and monthly average site power consumed. Other secondary data collected were the monthly average irradiance and the monthly average temperature as seen in Tables 4.1, 4.2, 4.3 and 4.4 for 2013, 2014 2015 and 2016 respectively.

**Table 4.1 Average Monthly Performance Characteristics for the Year 2013**

| Month | Ave. Energy Generated (kWh) | Ave. Energy Delivered (kWh) | Ave. Energy Lost (kWh) | Ave. Site Energy Consumed (kWh) | Ave. Irradiance (Wh/m$^2$) | Ave. Envir. Temp. ($^o$C) |
|---|---|---|---|---|---|---|
| Jan. | 7824.38 | 5711.55 | 135.20 | 53.45 | 954.5 | 35.0 |
| Feb. | 8598.93 | 8370.38 | 165.83 | 62.72 | 1030.0 | 36.0 |
| Mar. | 9669.09 | 9423.30 | 162.61 | 62.72 | 1005.5 | 36.5 |
| Apr. | 9293.30 | 9021.82 | 185.32 | 86.45 | 1130.4 | 37.0 |
| May | 9443.27 | 9173.33 | 172.04 | 97.89 | 999.5 | 34.5 |
| Jun. | 8474.00 | 8115.00 | 120.16 | 68.30 | 598.3 | 28.1 |
| Jul. | 6558.86 | 6405.00 | 97.97 | 55.89 | 693.0 | 34.3 |
| Aug. | 3743.78 | 5880.00 | 75.40 | 49.41 | 468.0 | 25.8 |
| Sep. | 8983.59 | 8895.00 | 56.21 | 48.18 | 561.5 | 28.9 |
| Oct. | 10578.12 | 7970.00 | 85.44 | 47.79 | 840.0 | 30.9 |
| Nov. | 10724.94 | 10575.00 | 150.10 | 54.81 | 8118.0 | 35.2 |
| Dec. | 8715.20 | 8535.00 | 180.20 | 46.98 | 855.8 | 32.3 |
| TOTAL | 102607.46 | 98075.38 | 3251.48 | 734.59 | 17254.5 | |

**Table 4.2 Average Monthly Performance Characteristics for the Year 2014**

| Month | Ave. Energy Generated (kWh) | Ave. Energy Delivered (kWh) | Ave. Energy Lost (kWh) | Ave. Site Energy Consumed (kWh) | Ave. Irradiance (Wh/m$^2$) | Ave. Envir. Temp. ($^o$C) |
|---|---|---|---|---|---|---|
| Jan. | 9451.66 | 9138.0 | 313.75 | 57.46 | 952.2 | 35.4 |
| Feb. | 7659.09 | 9515.0 | 144.09 | 51.84 | 1035.0 | 35.5 |
| Mar. | 12744.01 | 12615.0 | 80.14 | 84.51 | 1002.0 | 36.0 |
| Apr. | 12010.26 | 11890.0 | 62.18 | 73.08 | 1124.3 | 36.5 |
| May | 11209.97 | 11032.5 | 111.32 | 66.05 | 997.5 | 34.0 |
| Jun. | 11814.69 | 11625.0 | 119.81 | 71.82 | 1115.5 | 33.6 |
| Jul. | 11075.47 | 10882.5 | 131.41 | 61.56 | 918.8 | 33.4 |
| Aug. | 8946.23 | 8775.0 | 116.96 | 54.23 | 651.5 | 31.5 |
| Sep. | 10941.25 | 11047.5 | 67.44 | 51.30 | 897.0 | 30.3 |
| Oct. | 12339.96 | 12180.0 | 89.75 | 70.20 | 1056.3 | 34.9 |
| Nov. | 10661.19 | 10492.5 | 138.88 | 68.04 | 945.0 | 35.4 |
| Dec. | 111992.5 | 11820.0 | 120.66 | 190.08 | 932.3 | 32.0 |
| TOTAL | 230846.29 | 131013.0 | 1496.39 | 900.16 | 11327.4 | |

**Table 4.3 Average Monthly Performance Characteristics for the Year 2015**

| Month | Ave. Energy Generated (kWh) | Ave. Energy Delivered (kWh) | Ave. Energy Lost (kWh) | Ave. Site Energy Consumed (kWh) | Ave. Irradiance (Wh/m$^2$) | Ave. Envir. Temp. ($^o$C) |
|---|---|---|---|---|---|---|
| Jan. | 11895.64 | 11690 | 156.32 | 49.32 | 923.7 | 35.0 |
| Feb. | 10019.29 | 9878 | 72.86 | 68.76 | 750.0 | 36.0 |
| Mar. | 10892.95 | 10650 | 166.63 | 76.32 | 997.7 | 36.6 |
| Apr. | 11246.96 | 7037 | 112.69 | 73.92 | 1021.3 | 37.9 |
| May | 11031.20 | 6840 | 590.98 | 70.20 | 551.3 | 36.6 |
| Jun. | 8135.90 | 6840 | 1233.97 | 61.92 | 6426.0 | 33.1 |
| Jul. | 7610.00 | 7199 | 236.78 | 52.92 | 699.0 | 34.5 |
| Aug. | 8528.10 | 8350 | 137.78 | 40.32 | 472.7 | 26.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Sep. | 8054.13 | 7870 | 136.60 | 46.85 | 555.9 | 29.0 |
| Oct. | 8979.96 | 8760 | 151.21 | 68.64 | 848.4 | 31.0 |
| Nov. | 9446.66 | 9190 | 173.50 | 8316 | 819.9 | 35.5 |
| Dec. | 8113.41 | 7910 | 144.73 | 58.68 | 864.3 | 33.0 |
| TOTAL | 113543.90 | 102625 | 3214.05 | 751.01 | 14930.2 | |

**Table 4.4 Average Performance Characteristics for the Year 2016**

| **Month** | **Ave. Energy Generated (kWh)** | **Ave. Energy Delivered (kWh)** | **Ave. Energy Lost (kWh)** | **Ave. site Energy Consumed (kWh)** | **Ave. Irradiance (Wh/m²)** | **Ave. Envir. Temp. (°C)** |
|---|---|---|---|---|---|---|
| Jan. | 7746.91 | 5655.0 | 133.86 | 52.92 | 956 | 35.0 |
| Feb. | 8513.79 | 8287.5 | 164.19 | 62.10 | 1031 | 36.0 |
| Mar. | 9573.36 | 9330.0 | 161.00 | 82.35 | 1006 | 36.5 |
| Apr. | 9201.29 | 8932.5 | 183.20 | 85.59 | 1130 | 37.0 |
| May | 9349.77 | 9082.5 | 170.34 | 96.93 | 910 | 34.5 |
| Jun. | 8832.57 | 8590.0 | 157.61 | 84.96 | 916 | 34.0 |
| Jul. | 5640.84 | 5500.0 | 91.16 | 49.68 | 921 | 33.5 |
| Aug. | 8856.76 | 8687.3 | 115.79 | 53.68 | 662 | 34.5 |
| Sep. | 10831.83 | 10937.0 | 66.76 | 50.78 | 894 | 32.0 |
| Oct. | 12216.56 | 12058.2 | 88.85 | 69.50 | 1046 | 35.0 |
| Nov. | 10554.58 | 10387.6 | 137.50 | 67.36 | 936 | 36.0 |
| Dec. | 11872.57 | 11701.8 | 119.45 | 188.18 | 923 | 33.0 |
| TOTAL | 113190.83 | 109149.55 | 1589.70 | 944.03 | 19521 | |

Secondly, primary data was collected from interviews. An interview was designed for workers at the solar plant. Questions were formulated to get views of respondents on the performance of the solar plant, the factors that adversely affect maximum power delivery of the solar plant, suggestions on how to minimize power losses as well as future work recommendations for solar power plan improvement. A sample of the questionnaire is seen in appendix A.

This interview approach allowed the respondents to freely express their opinion. In all cases, prior notice was given to interviewees about the intention to have the interview with them. During the interview, the researcher recorded field notes to aid in the data analysis. Clarifications of questionnaires were provided where possible to avoid misunderstanding of informants.

Thirdly, data on current and voltage was taken through direct measurement of some selected panels with a voltmeter and an ammeter.

### 4.6 Pre-testing

To ascertain the reliability and validity of the instrument, a pilot study was conducted to help decide whether the study was feasible and worthwhile to continue. It also provided an opportunity to assess the appropriateness and practicality of the data collection instrument. The wisdom in doing a pre-test was also to help revise questions in the guide that were apparently unclear or produced negative reactions in the subjects.

The questions for the interview were pre-tested on five (5) respondents. The responses obtained were used to eliminate ambiguous, non-specific items and made some modifications.

### 4.7 Data Collection Procedure and Ethical Considerations

In the context of research, ethics refers to the appropriateness of one's behavior or conduct in relation to the right of those who become the subject of one's work, or may be affected by it. The research process considered ethical issues throughout the period of the research and remained sensitive to the impact of work on those whose consent were sought and the participants.

For participants to do their best to give realistic response to each question, they were assured of confidentiality as the purpose of the research is for purely academic exercise. This is in Accordance with Kelley *et al* (2003) as the most important ethical consideration to adhere to when conducting a survey. Furthermore, assurance was given that information obtained would be used solely for the intended purpose.

### 4.8 Data Analysis

Raw data collected was edited to correct errors and omissions to ensure consistency and validity. Subsequently, the data was tallied item by item and input into a computer. For the purpose of data analysis, Statistical Program for Social Science software version 20 was used. Descriptive statistics, as well as frequency tables were used to aid easy understanding. The interview data were analysed using content analysis which according to Krueger (1998) compares the words used in the answers of the respondents. The researcher looked for themes and similar ideas or responses to the questions posed to the respondents of which the respondent's information or speeches were translated into specific categories for the purposes of analysis.

# CHAPTER FIVE

## PRESENTATION AND DISCUSSION OF RESULTS

### 5.1 Introduction

This chapter focuses on the quantitative and qualitative description of the sample and how it relates to the population under study. The chapter presents the results generated from the data collected. The data was presented with the help of tables. Through qualitative, quantitative and site analyses, the researcher tested and validated the preset objectives and answered the study questions.

### 5.2 Factors Affecting Maximum Power Delivery of the Solar Plant

The responses collected from the interview were put into themes, analysed and presented using a simple statistical tool called the Simple Percentage Method. It is a method used to summarize the percentage of respondents who agreed or disagreed to a particular factor. This method calculates the frequency of occurrence of a particular factor in a set of variables expressed as a percentage. The results are displayed in Figure 5.1.

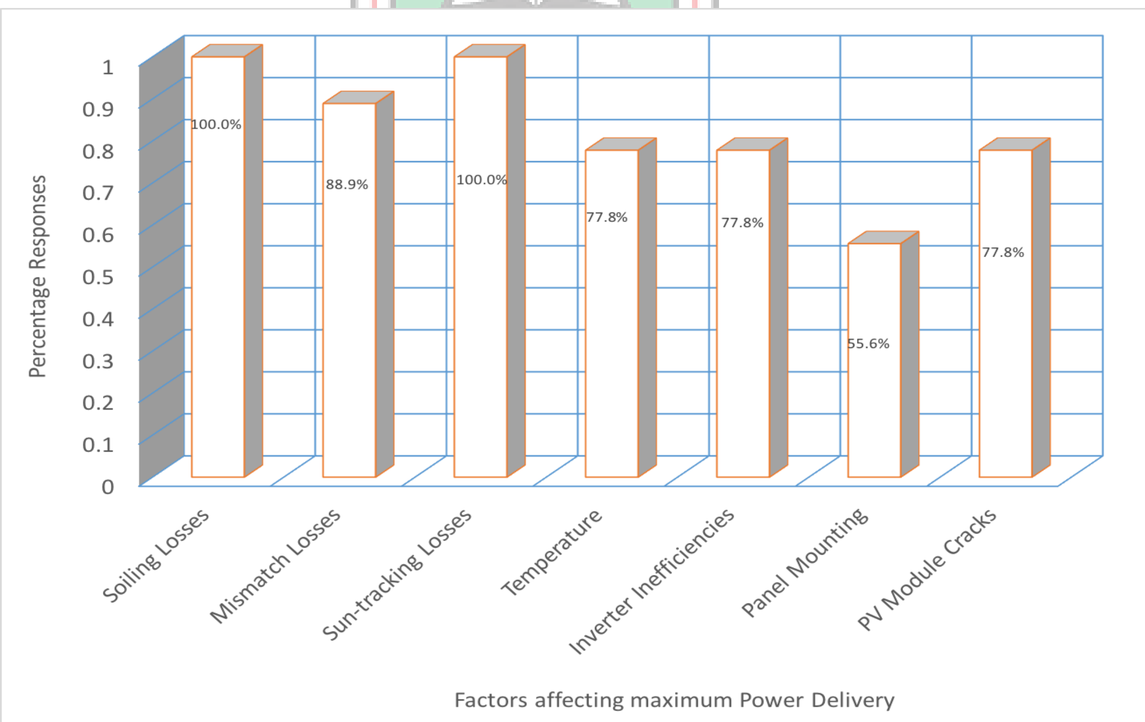


**Figure 5.1 Factors Affecting Maximum Power Delivery**

### 5.2.1 Soiling Losses

Soiling losses refer to loss in power resulting from snow, dirt, dust and other particles that cover the surface of the PV module. The study had 100 % of the respondents indicating that soiling losses affects maximum power delivery at the site. The researcher on examining the area realized that dust was generated from many sources such as farms, cattle rearing, pollution by wind, and vehicular movements among many others.

These accumulated dusts, over time aggravate the soiling effect. In fact, the amount of accumulated dust on the surface of the PV module affects the overall energy delivered from the PV module on a daily, monthly, seasonal and annual basis. The findings are in agreement with Sanaz (2014) who investigated the pattern of dust distribution in different parts of the world came out that the Middle East and Africa have the worst dust accumulation zones in the world. He posited that losses due to dust is a challenge which need to be addressed if maximum power is to be generated and energy losses portion of total output reduced.

### 5.2.2 Mismatch losses

When PV modules with different characteristics (current and Voltage) are connected together they provide a total output power less than the power achieved by summing the output power provided by each of the modules when not connected together. PV modules with same ratings coming out of one production line in a factory do not possess identical current–voltage characteristics for reasons such as temperature, chemical concentration and variations in the Silicon concentration of cells in the module.

The researcher realized that photovoltaic cell technologies used at the station are the multi-silicon and polycrystalline silicon type manufactured by Suntect and Jinko industries respectively. The modules, because they do not have identical physical and chemical properties, they experience different conditions from one another.

This inequality causes PV modules to compromise on common voltage and current when they are connected in series or parallel in an array. This compromise results in a type of power losses known as mismatch losses.

From the interview with the respondents, 88.9% confirmed the existence of this loss on site. This finding is in conformity with earlier studies by Samad et al (2014) who examined mismatch loss minimisation in photovoltaic arrays and suggested a solution based on arranging PV modules in arrays by genetic similarities.

As established from literature, when modules are wired in parallel and in series finally the combined into the collector boxes, they are usually associated losses. Again, losses exist if the modules in use are not of the same kind and have different physical and chemical properties. These factors were investigated.

Mismatch losses are caused by the interconnection of solar modules in both series and parallel. Therefore the selection of modules becomes quite important in overall performance of the plant. Mismatch losses is estimated to be approximately 0.98 % of the gross annual power output of the plant.

### 5.2.3 Sun-tracking losses

The study had all respondents (100 %) confirming the assertion that among the major factors affecting power losses are factors which result into sun tracking losses. These factors are the ambient temperature, the irradiance, humidity and tilt angle or orientation of the PV panel.

The more sunlight (irradiance) hitting the modules, the more current they will produce. Irradiance is measured with the site meteorological equipment integrated into the power plant system. It needs to be placed at the exact same tilt angle and orientation as the PV array, ideally lined up adjacent to a module.

### 5.2.4 Temperature

Seventy-seven percent (77.8%) of the respondents indicated temperature as a factor affecting power delivery of the panels. Solar cells perform better in cold rather than in hot climate and as things stand, panels are rated at 25 ˚C which can be significantly different from the real outdoor situation. For each degree rise in temperature above 25 ˚C the panel output decays by about 0.25% for amorphous cells and about 0.4 to 0.5 % for crystalline cells.

The effects of PV cell operating temperature on the electrical performance of silicon based photovoltaic installations has attracted much attention from the scientific community and led to the development of special models which can be used for its estimation.

With an increase in ambient temperature, there is a deficiency in the electrical energy that the PV cells can supply. This situation is especially important in hot climates.

Outdoor exposure tests of PV cells carried out by Malik et al (2013) showed that the efficiency of single crystal silicon PV cells strongly depends on its operating temperature. They observed that at an operating temperature of 64 °C, there was a decrease of 69 % in the efficiency of the PV cell compared to that measured under standard test conditions.

### 5.2.5 Inverter Efficiency

Moreover, 77.8% respondents were of the opinion that inefficiencies of inverters as factors affecting maximum power delivery of the solar plant. When the solar PV system is catering to the needs of the AC loads an inverter is needed. As things stand, in real world nothing is 100 % efficient. Although inverters come with wide ranging efficiencies between 80% to 90% efficient (Anon, 2015).

### 5.2.6 Panel Mounting.

In addition to the above, 55.6% of the respondents agreed that the type of panel mounting also affects solar power delivery. Research shows that there are three types of solar panel mountings. These are fixed, adjustable, and tracking. The type of mount in application at the site is the fixed mount. The fixed solar panel mounting system is completely stationary with an angle of inclination of $15^{o}$ to the horizontal floor. This is the simplest and cheapest type of solar panel. The solar panels are installed in such a way that they are always facing the equator (due south in the northern hemisphere). The angle of inclination favors both the harmattan sun and the wet season sun slightly less Peaked.

### 5.2.7 PV Module Cracks

In the course of the PV analysis, it was also discovered that 62 of the module were ineffective in generating power due to serious cracks sustained as a result of thermal expansion and contraction (Figure 5.2). The cracks could also be attributed to defective product on mass production. It was therefore not surprising to the researcher that 77.8% of the respondents indicated PV module cracks as among the major factors affecting power delivery.

It was observed that the individual PV modules are not calibrated into the Master Wiring Picture software program to monitor the output characteristic of each module. As it stands now, if a module is cracked or damaged by any means, the system cannot report it to management for remedy.

### 5.3 Observations

The following observations were made on site:

i. It was observed that much DC power was generated between the hours of 11 am and 12 pm because the sun light appears to be perpendicular at this period. Comparatively, less energy is generated for the rest of the hours of the day due to low solar insolation striking the PV cell surfaces. The PV module mount is fixed and does not track the Sun as it moves across the sky;

ii. Modules are washed quarterly to undo the dust deposition as it tends to insulate the cell surface against solar insolation;

iii. PV arrays assembled with two different brands mixed together (Jinko and Suntech) tend to deliver less energy as compared to an array assembled with one kind of module owing to the factor of module mismatch losses; and

iv. Some PV modules were found with cracks due to overheating. Cell temperatures were monitored and measured to be ranging between 35.0 °C to 67.3 °C and 30.1 to 53.0 before cooling and after cooling respectively in each hour of the solar day. The current (ampere) and the voltage (volts) of the cells were also measured in relation to before cooling and after cooling for the selected modules. The output of the selected modules current (I), voltage (V) and power were found to be higher after cooling each time in the hours as seen in Table 5.1.

**Table 5.1 before Cooling and After Cooling of Selected PV Modules**

| Time/Hours | Before Cooling Modules | | | | After Cooling Modules | | | |
|---|---|---|---|---|---|---|---|---|
| | Ave. Current/A | Ave. Voltage/V | Ave. Cell Temp./°C | Ave. Power/W | Ave. Current/A | Ave. Voltage/V | Ave.Cell Temp./°C | Ave. Power/W |
| 7 am | 0.85 | 10.6 | 35.0 | 9.01 | 1.94 | 11.6 | 32.6 | 22.50 |
| 8 am | 2.26 | 16.1 | 42.0 | 36.39 | 2.33 | 17.1 | 36.0 | 39.84 |
| 9 am | 2.38 | 17.6 | 49.2 | 41.89 | 2.47 | 18.5 | 38.6 | 45.70 |
| 10 am | 2.44 | 17.4 | 58.5 | 42.46 | 2.53 | 18.5 | 46.0 | 46.81 |
| 11 am | 2.45 | 17.5 | 58.9 | 42.88 | 2.54 | 18.7 | 43.7 | 47.50 |
| 12 am | 2.48 | 17.4 | 67.3.7 | 43.15 | 2.55 | 18.5 | 53.1 | 47.18 |
| 1 pm | 2.50 | 17.3 | 66.3 | 43.25 | 2.59 | 18.6 | 49.9 | 48.17 |
| 2 pm | 2.44 | 16.9 | 64.6 | 41.24 | 2.53 | 18.2 | 43.8 | 46.05 |
| 3 pm | 2.42 | 17.9 | 57.1 | 43.32 | 2.19 | 17.4 | 42.8 | 38.11 |
| 4 pm | 2.20 | 13.4 | 53.4 | 29.48 | 2.24 | 13.9 | 43.4 | 31.4 |

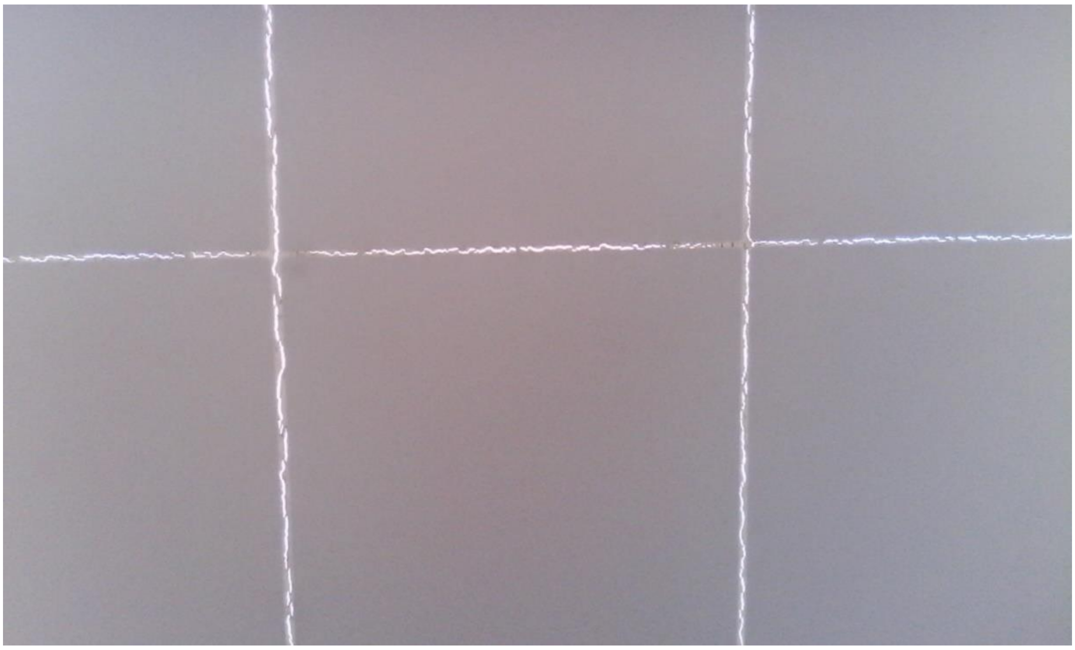

**Figure 5.2 Cracks on PV module at Navrongo VRA Solar Power Plant**

## 5.4 Performance Analysis of the Solar Plant

The first research objective of the study was to ascertain the performance of the solar plant at the site. In order to achieve this objective, a period of two months attachment to the Navrongo VRA Solar Power Plant was undertaken. The layout of solar power plant has software by name Masterwiring Picture: 18th Edition, integrated into the system which monitors, records and displays the characteristics of the variables that affect the output of the plant. The variables monitored, measured and recorded on daily basis include the following: Ambient temperature (°C), Irradiation ($kW/m^2$), Voltage output (V), Current output (A), Power output (kWh), Daily power generation (kWh), Daily power consumed (kWh) and Daily power loss (kWh).

Tables 4.1, 4.2, 4.3 and 4.4 show the summary of the performance data of the plant for the years 2013, 2014, 2015 and 2016 respectively.

### 5.4.1 Power Generated and Delivered by the Solar Plant

From the performance analysis data, graphs of the average power generated and power delivered are plotted against successive months in the in Figures 5.3 to 5.6.

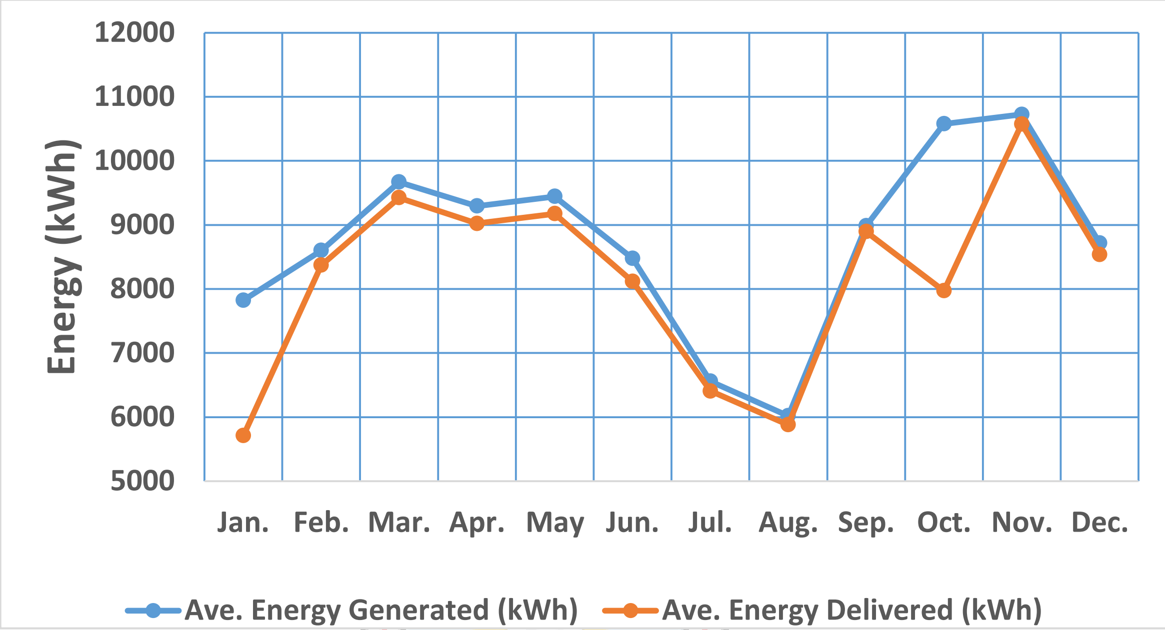


**Figure 5.3 Graph of Power Generated and Delivered by the Plant for the Year 2013**

From the graph, power delivered increased from January to February due to start up challenges faced by the plant at the beginning of the year such as DC inverter failure, frequent breakdown of fuses in combiner boxes and improper coordination in the power control units.

Power generated and power delivered stalled until a decline in July to August due to high humidity and poor solar irradiance. Power delivery dropped from September to November and November to December due to power consumed in installing administrative equipment. There was a sharp drop in power generation from November to December because breakdown of two DC inverters.

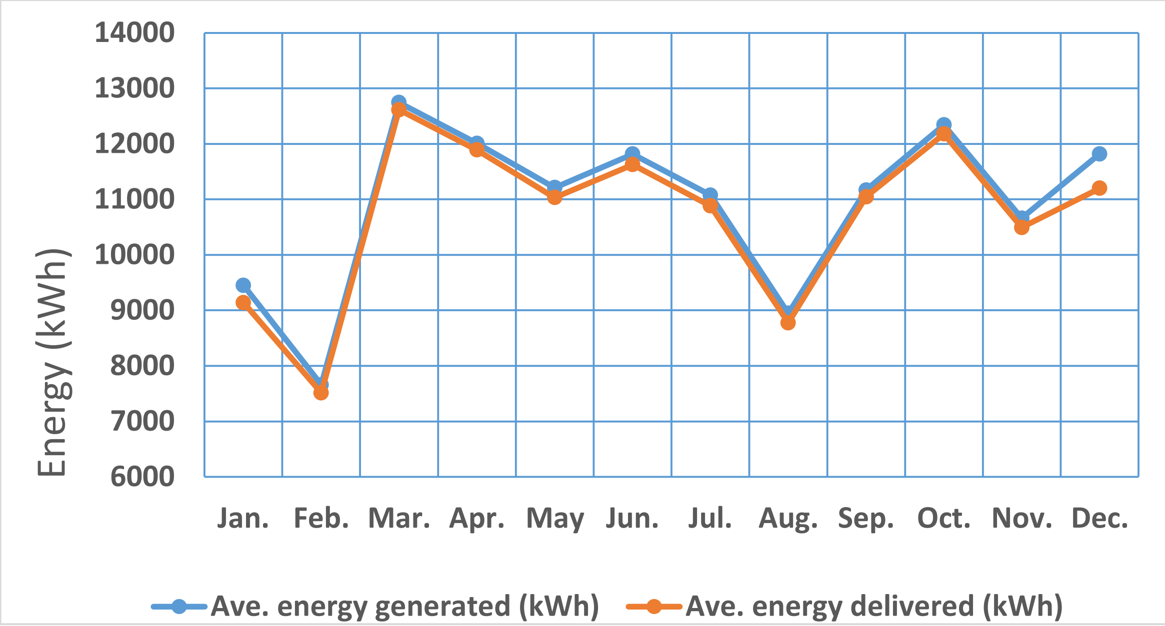


**Figure 5.4 Graph of Power Generated and Delivered by the Plant for the Year 2014**

From figure 5.4 it could be seen that dust accumulation increased in November 2013 to February 2014 due to the harmattan. Generation and delivery after January increased from February to March for good peak radiations. It was relatively steady From March to early May. After the effect of rain clouds on May, June and July it dropped again in August due to rain clouds coupled with downtime.

Again, power generation appreciated from November to December but the power delivered dropped markedly due to frequent grid power cuts that came with increased in energy consumed on site.

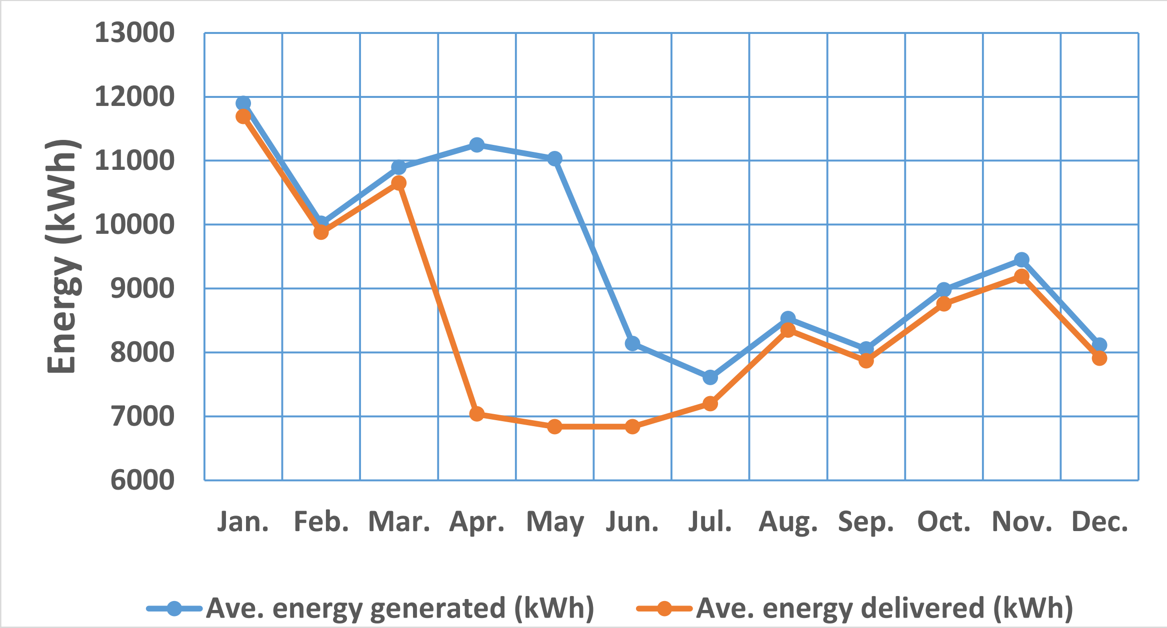


**Figure 5.5 Graph of Power Generated and Delivered by the Plant for the Year 2015**

Power generation in the year 2015 was adversely hindered by profound down time from March to July. About 2340.45 kW of power was lost equivalent to 72.8 % of the total energy lost in the 2015 production year. Power generated was recorded but delivery was interrupted by frequent grid power outages in the periods indicated.

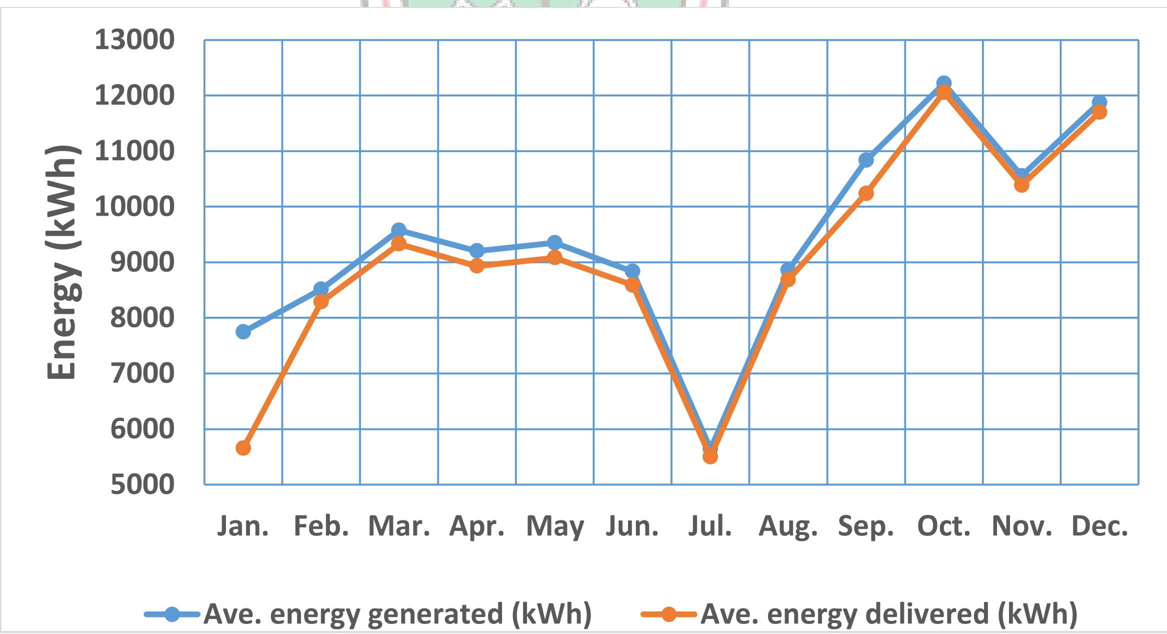


**Figure 5.6 Graph of Power Generated and Delivered by the Solar Plant for the Year 2016**

It was observed from the 2016 data that less power was consumed on site on January and the effect is increased in power delivered in the same period. Again, power cut was regular in this year especially from June to July and there was a sharp decline in generation and delivery. Power generation improved from August to October when dust accumulation caused it to decline to November.

5.4.2 Comparative analysis of power generated and delivered in the four years period under review. The details are seen in figure 5.7 and 5.8 respectively

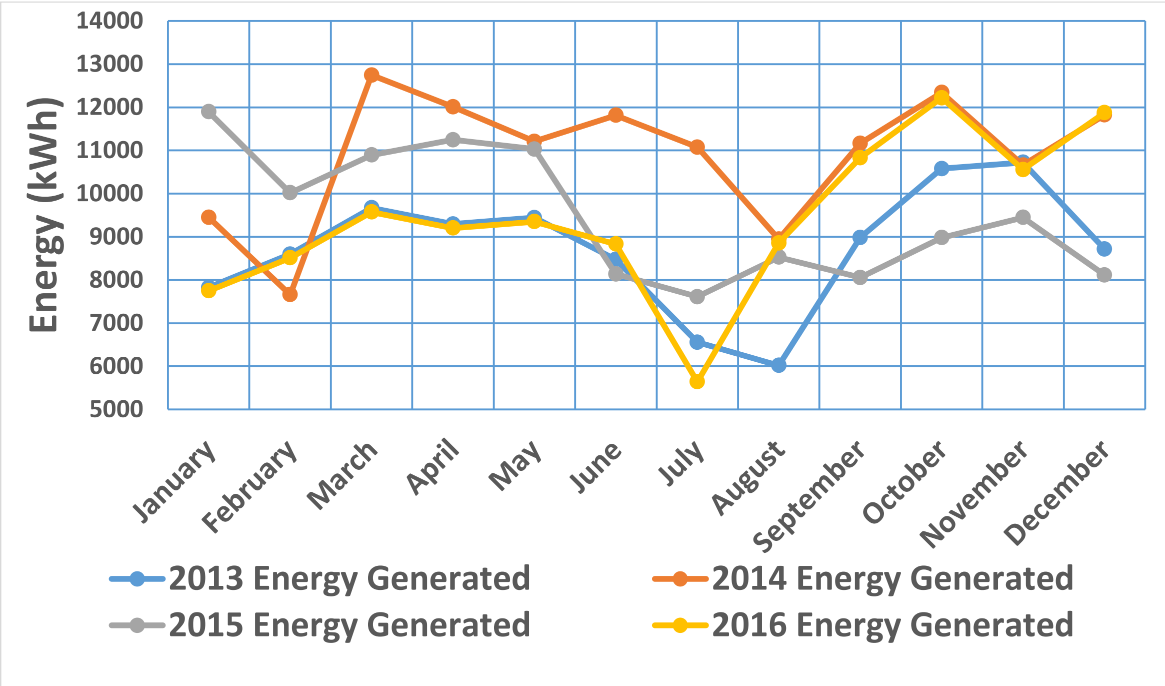


**Figure 5.7 Composite Graph of Power Generated by the Plant from 2013 to 2016**

Figure 5.7 represents a summary of the power generated curves for the four years period under review as discussed above. From Tables 4.1 to 4.4 the average power generated per the years under review are as follows:

i. In the year 2013, 10 260.46 kWh of power;
ii. In the year 2014, 230 846.29 kWh of power;
iii. In the year 2015, 113 543.90 kWh of power; and
iv. In the year 2016, 113 190.83 kWh of power.

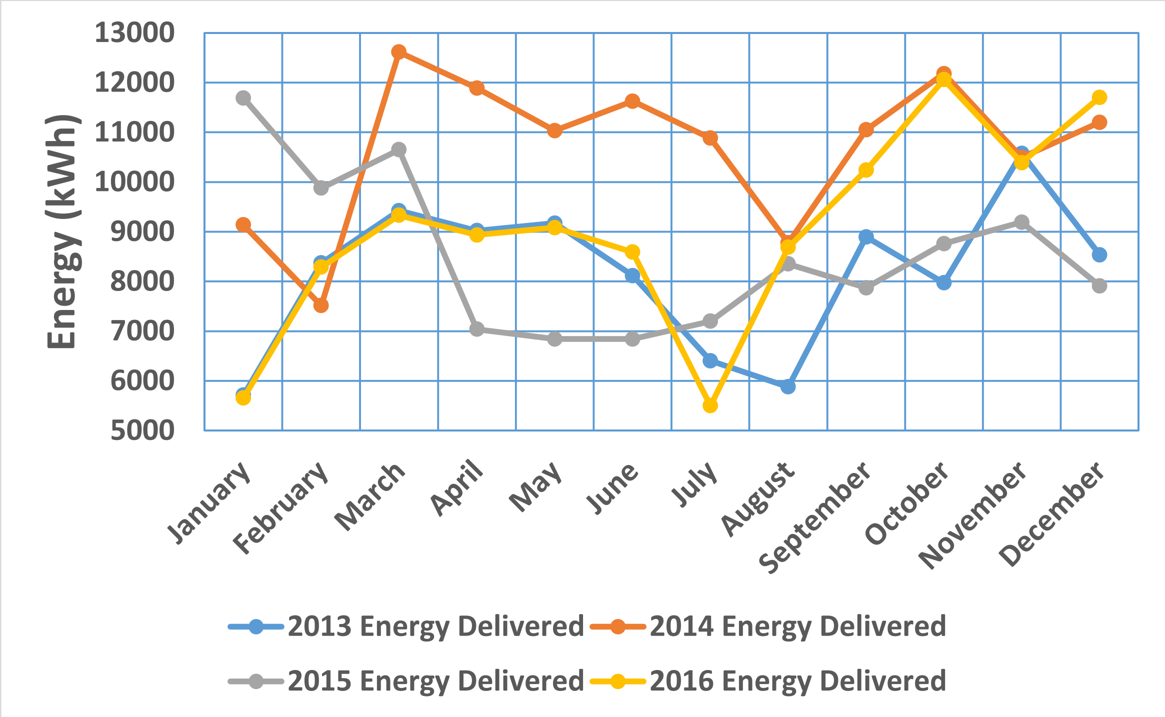


**Figure 5.8 Composite Graph of Power Delivered by the Plant from 2013 to 2016**

Figure 5.8 represents a summary of the energy delivered curves for the period under review as discussed above. From Tables 4.1 to 4.4 the average power delivered per the years under review are as follows:

i. In the year 2013, 98 075.38 kWh of power;

ii. In the year 2014, 131 013.00 kWh of power;

iii. In the year 2015, 102 625.00 kWh of power; and

iv. In the year 2016, 109 149.55 kWh of power.

5.4.3 Power Lost by the plant

Figures 5.9 to 5.12 depict the energy lost characteristics for the four years period of energy production. The causes of the losses within the years include: grid power outage, dust accumulation, low irradiance, transmission losses, PV module cracking and high cell temperatures. The effects of these factors vary with time as displayed by the graphs.

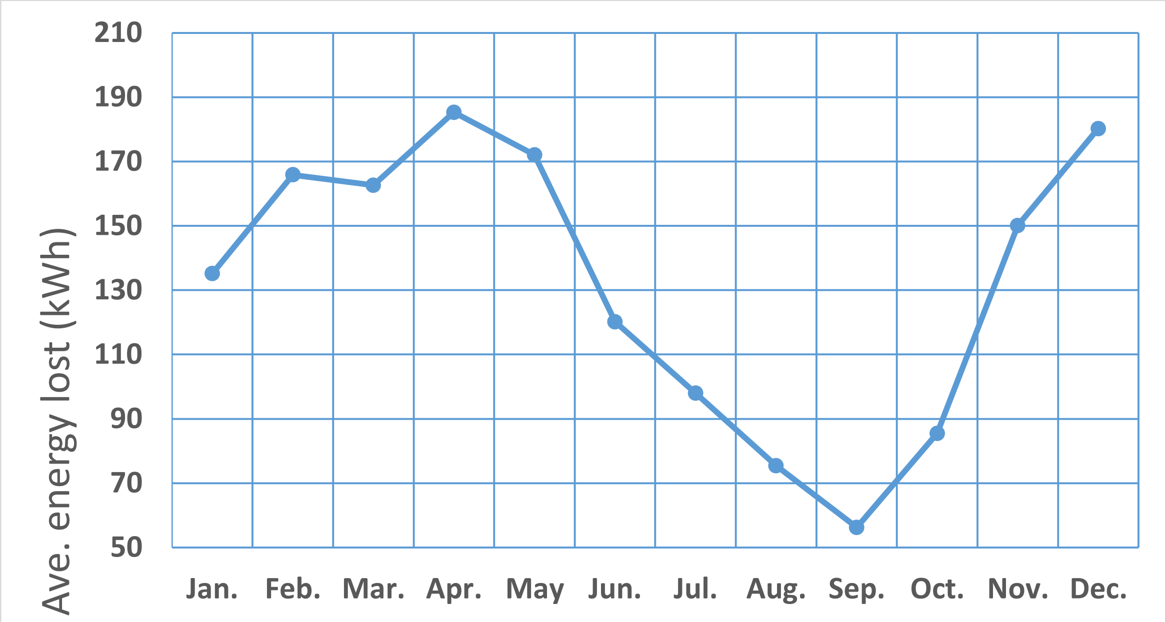


**Figure 5.9 Power Losses in the Year 2013**

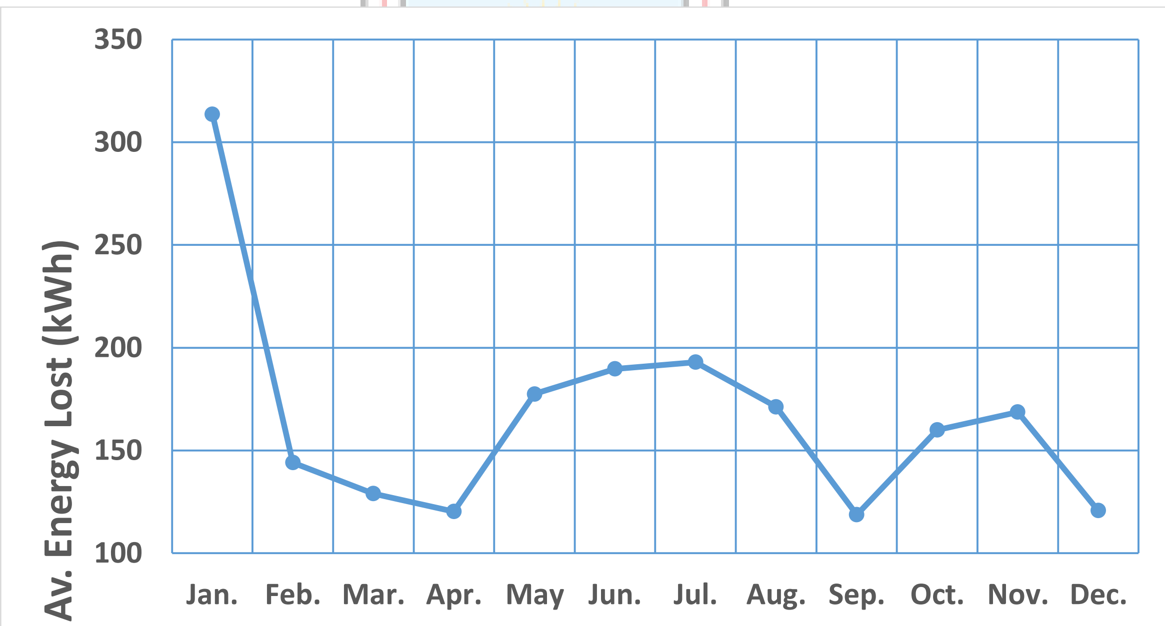


**Figure 5.10 Power Losses in the Year 2014**

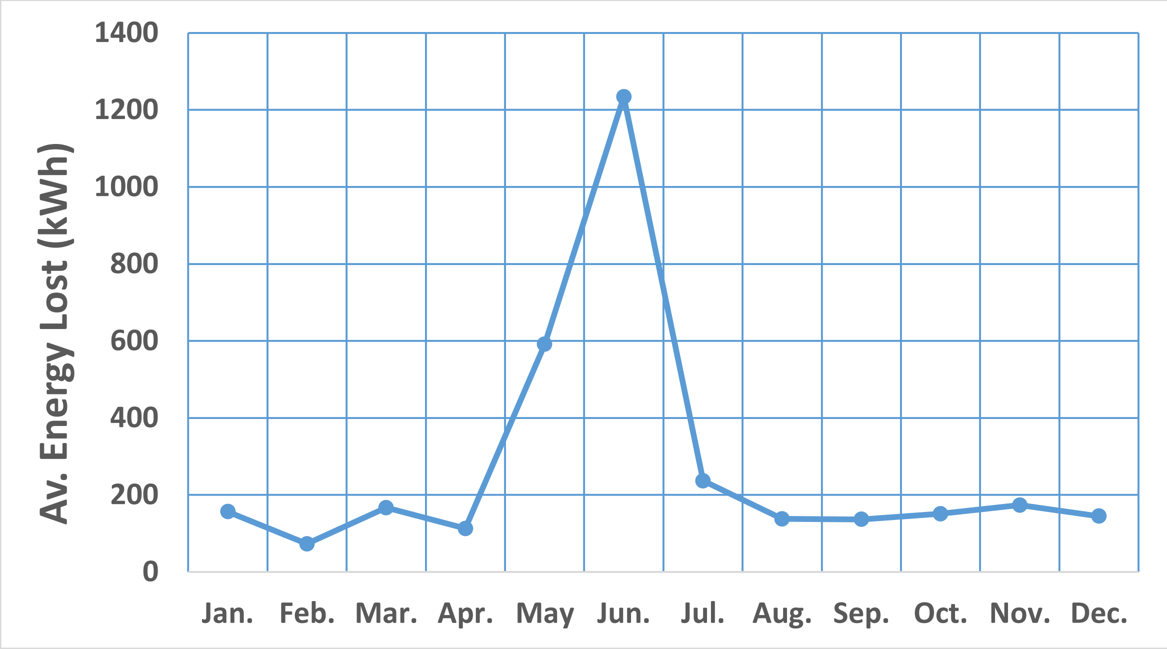


**Figure 5.11 Power Losses in the Year 2015**

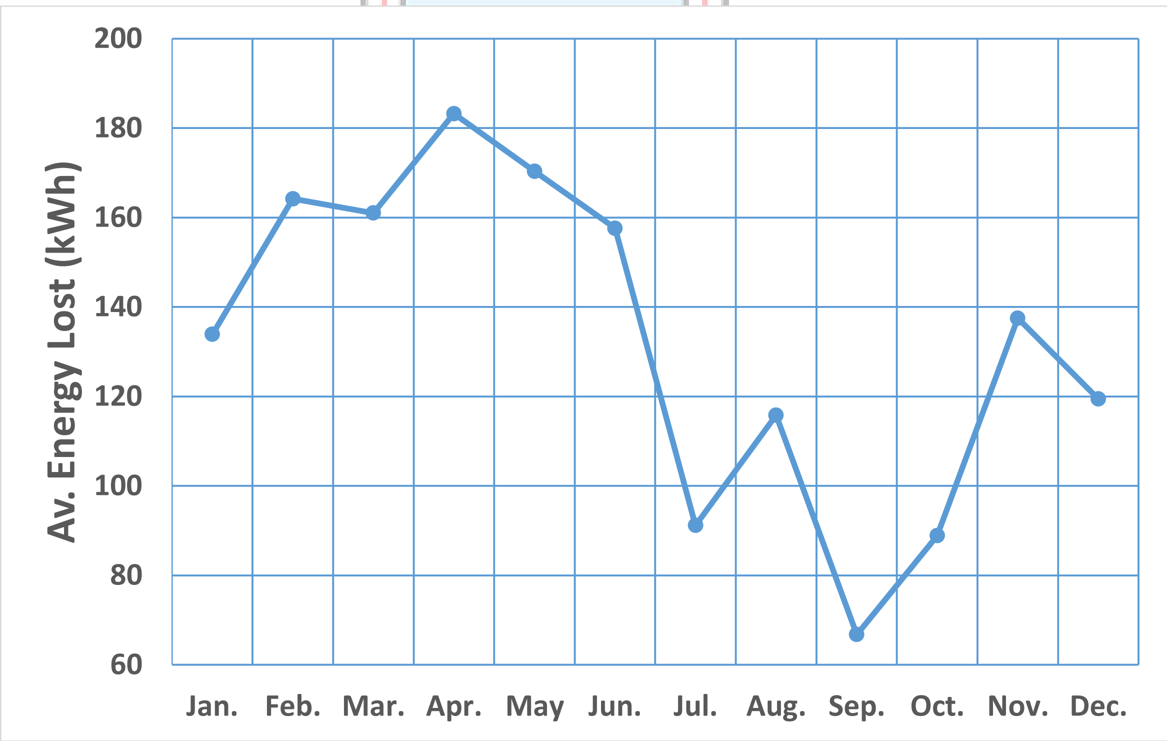


**Figure 5.12 Power Losses in the Year 2016**

5.4.4 Comparative analysis of power losses in the four years period of generation.

Figure 5.13 represents a summary of the loss curves for the periods under review.

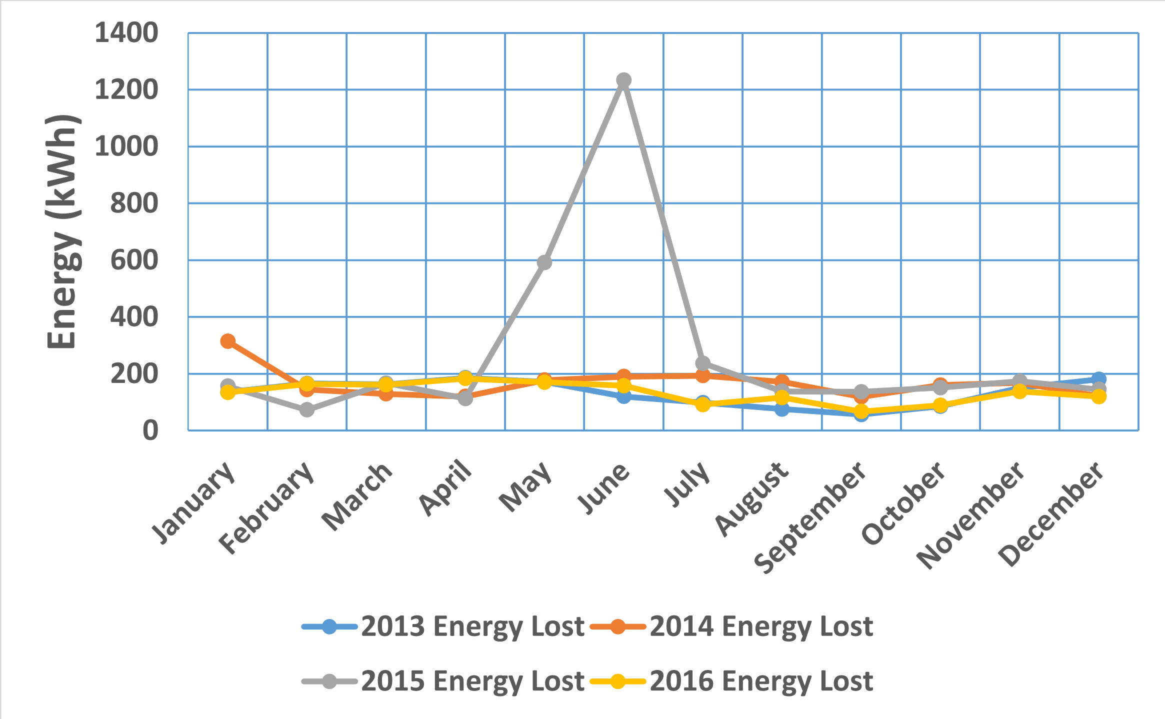


**Figure 5.13 Composite Graph of Power losses by the Plant from 2013 to 2016**

From Figure 5.13, there was a huge power loss due to PV module cracking in November, 2014. Again, much power was also lost between April and June, then, declined to July in 2015 due to serious power interruptions. From Tables 4.1 to 4.4, the average power losses per the years under review are as follows:

i. In the year 2013, 3 251.48 kWh of power;
ii. In the year 2014, 1 496.39 kWh of power;
iii. In the year 2015, 3 214.05 kWh of power; and
iv. In the year 2016, 1 589.70 kWh of power.

5.4.5 Power Lost and Site Power Consumed by the plant from 2013 to 2016.

Figure 5.14 is a composite graph of power losses and site power consumed for the four years under study.

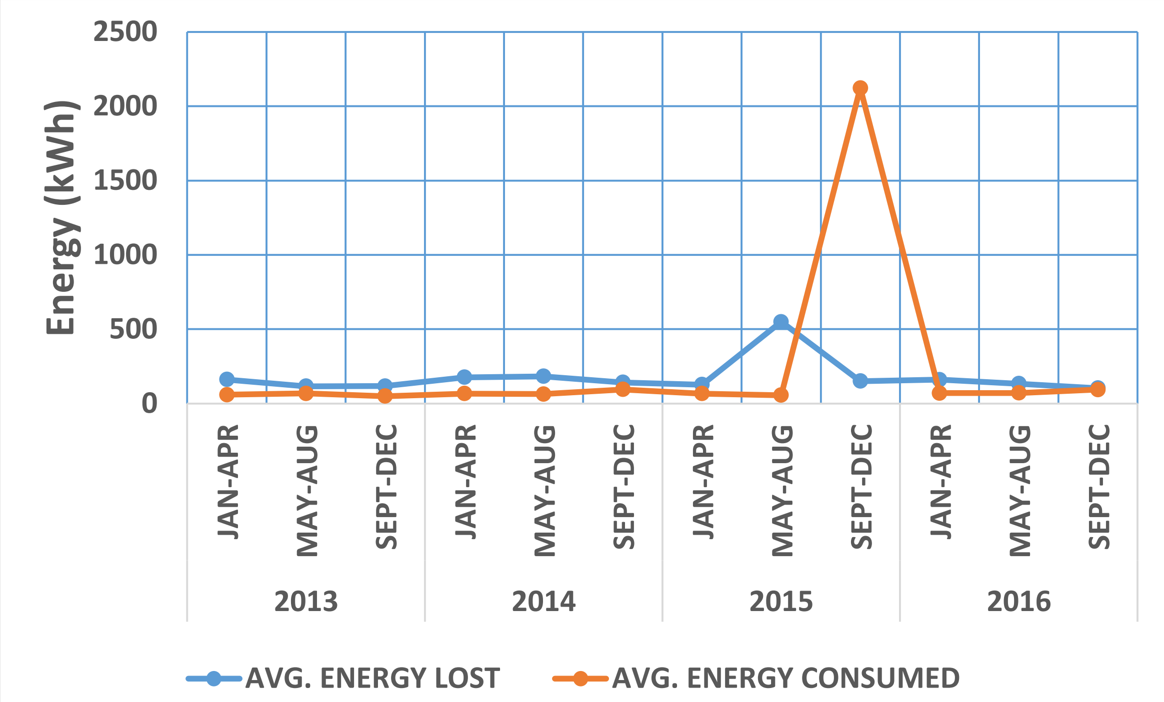


**Figure 5.14 Graph of Power Loss and Consumed**

From graph 5.14 at any point in time, power consumed at site is less than power loss. The implication is that the station loses more power than it is consumed.

The graph indicates that in 2013 a significant amount of energy was lost due to start up challenges with the power plant such as such as DC inverter failure, frequent breakdown of fuses in combiner boxes and improper coordination in the power control units.

The highest lost was recorded in the year 2015 as the period was associated with peaked power crisis and generation down time. However, losses in 2014 and 2016 were minimal.

One of the key factors amounting to energy losses includes transmission losses. The transmission losses are due to the internal resistance within the transmission process. From the study, the power is generated at Pungu and transmitted to Navrongo Substation and retransmitted back for use at Pungu. This process results in huge losses within the system. These losses would be minimized if household panel mounting are adopted. Furthermore, this will also result in elimination of down time whenever power goes off as a result of faults on the transmission lines. In this instance, power is generated but consumers stay out of power till the problem is mitigated.

### 5.4.6 Generation Down Time

The DC inverters are grid-sensitive, in that they only start processing energy when there is power in the Navrongo-Pungu transmission lines, and shut down immediately when power goes off. This shut down in power production and transmission is termed as Generation Down Time (GDT). When generation down time occurs the PV arrays continue to generate between 700 to 900 volts of Direct Current (DC), but it is usually wasted at the cell because the inverters stop processing for lack of power in the grid transmission lines.

### 5.4.7 Power Transmission Losses

Transmission losses as deduced from literature are said to be a factor in electric conductors that tends to oppose the flow of energy through it and increases with area and length. Electrical resistance is indispensable in conductors but can be minimized by keeping the transmission distance as short as possible with a reduced area of conduction. The transmission losses of the plant are estimated to be about 26 % (Anon, 2016). This loss, when translated into money is about GH₵ 29 227.34

## 5.5 Review of the Design Criteria for Better Performance of the Solar Plant

The design of the production and transmission lines of the solar plant was reviewed and modified for improved power output.

### 5.5.1 Existing Plant Design

The plant is made up of 8622 PV modules connected to 32 combiner boxes which deliver about 700 Volts to 900 Volts (DC) to the five (5) DC inverters for processing. The inverters give out 415 Volts (AC) to the multipurpose power transformer which steps it up to 34.5 kV (AC) to be transmitted to the Navrongo Substation for distribution. The production flow diagram is represented in Figure 5.15.

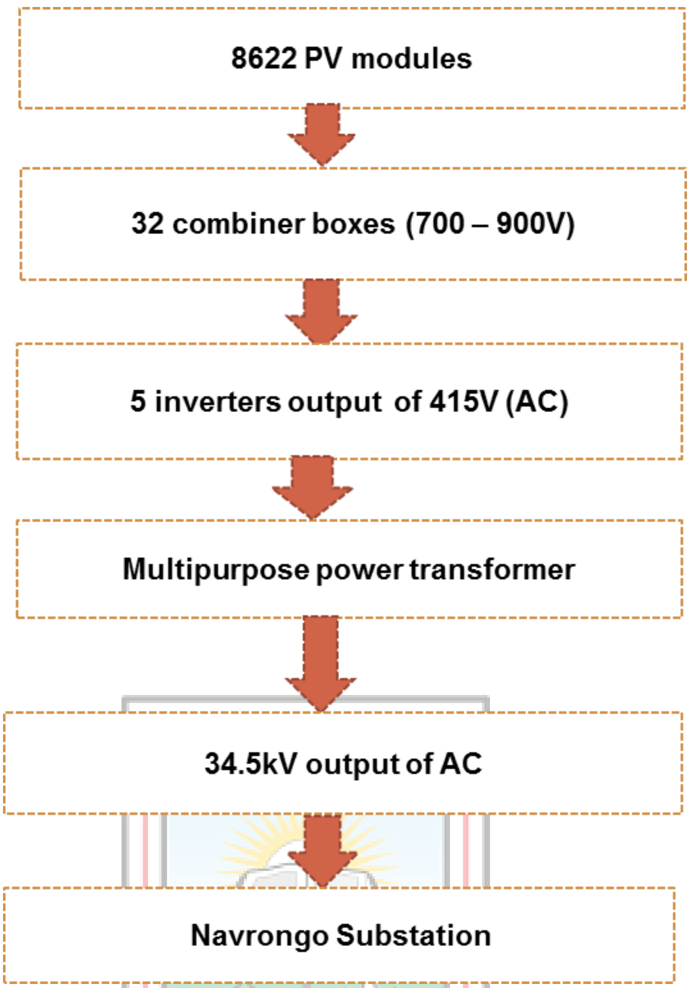


**Figure 5.15 Flow Chart for the Existing Design and Production**

As illustrated in the above diagram, power production starts from the 8622 mounted PV modules wired together through 32 combiner boxes. The PV modules by means of photoelctric effect generates between 700 to 900 Volts DC fed into the five inverters. the inverters give an output voltage of 415 Volts AC which is conducted into the multi-purpose tranformer to be stepped up to 34500 Volts (34.5 kV) of Alternating Current (AC). This Voltage is then transmitted through the Pungu grid line into the Navrongo Substation for distribution and cosumption.

### 5.5.2 Proposed Microgrid Design

The power consumpnsion of the Pungu community is measured to 2.8 MWh. However, the plant generate 2.6 MW which is 0.2 MW less than the power requirements of the community. Taking cognisance the losses due to transmission and down time, it is imperative to look at other alternatives to improve power supply to the Pungu community. Two opinions were propossed:

i. Segregate and give consumers with low consumption solar pannels for household usage; and
ii. Design a mircogrid for the community to ensure that whatever amount of power generated is not sent to Navrongo and the back to Pungu.

The micro-grid design came about as a result of careful observation, analysis and study of the power production and transmission lines of the Solar power plant and the associated losses. Figures 5.16 and 5.17 depict the console and the circuit diagrame respectively for the proposed Micro-Grid design.

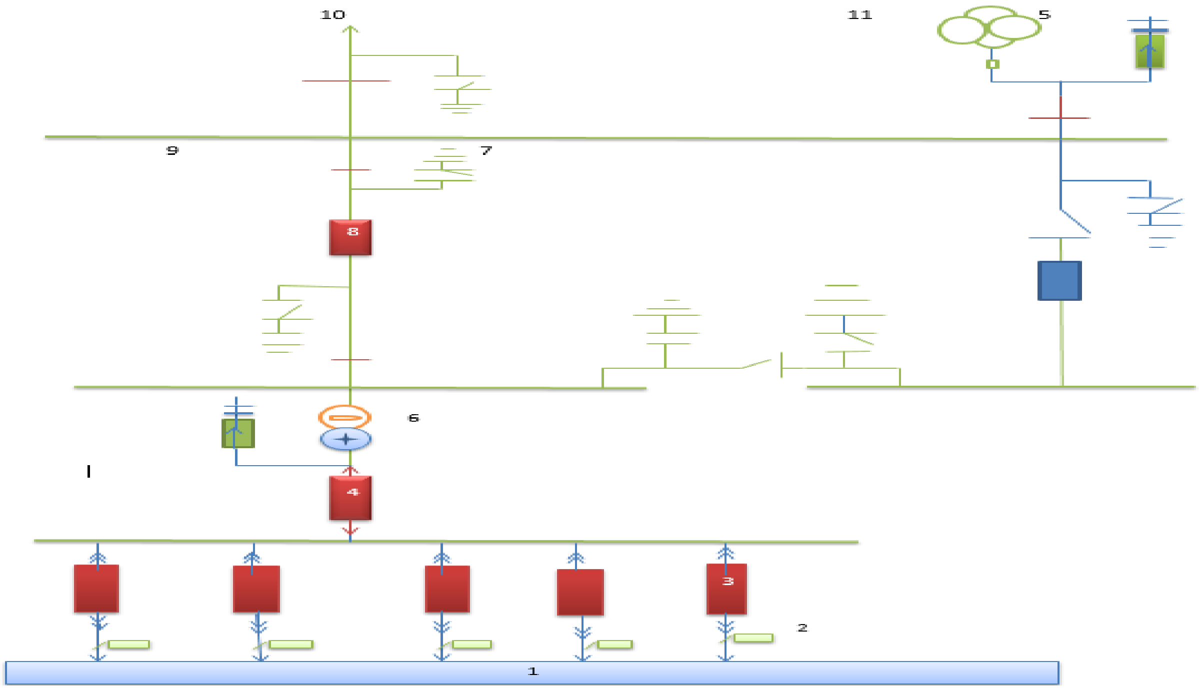


**Figure 5.16 Proposed Microgrid Design for Pungu community**

***Legend***

1 Photovoltaic Array, 2 - DC Combiner Box, 3 - DC Inverters, 4 - AC Circuit Breaker (1), 5 - Lightning Arrester, 6 - AC Transformer, 7 - Disconnect Switch, 8 - AC Circuit Breaker (2) 9 - Buss Bar, 10 -Pungu Service Line and 11 -Potential transformer

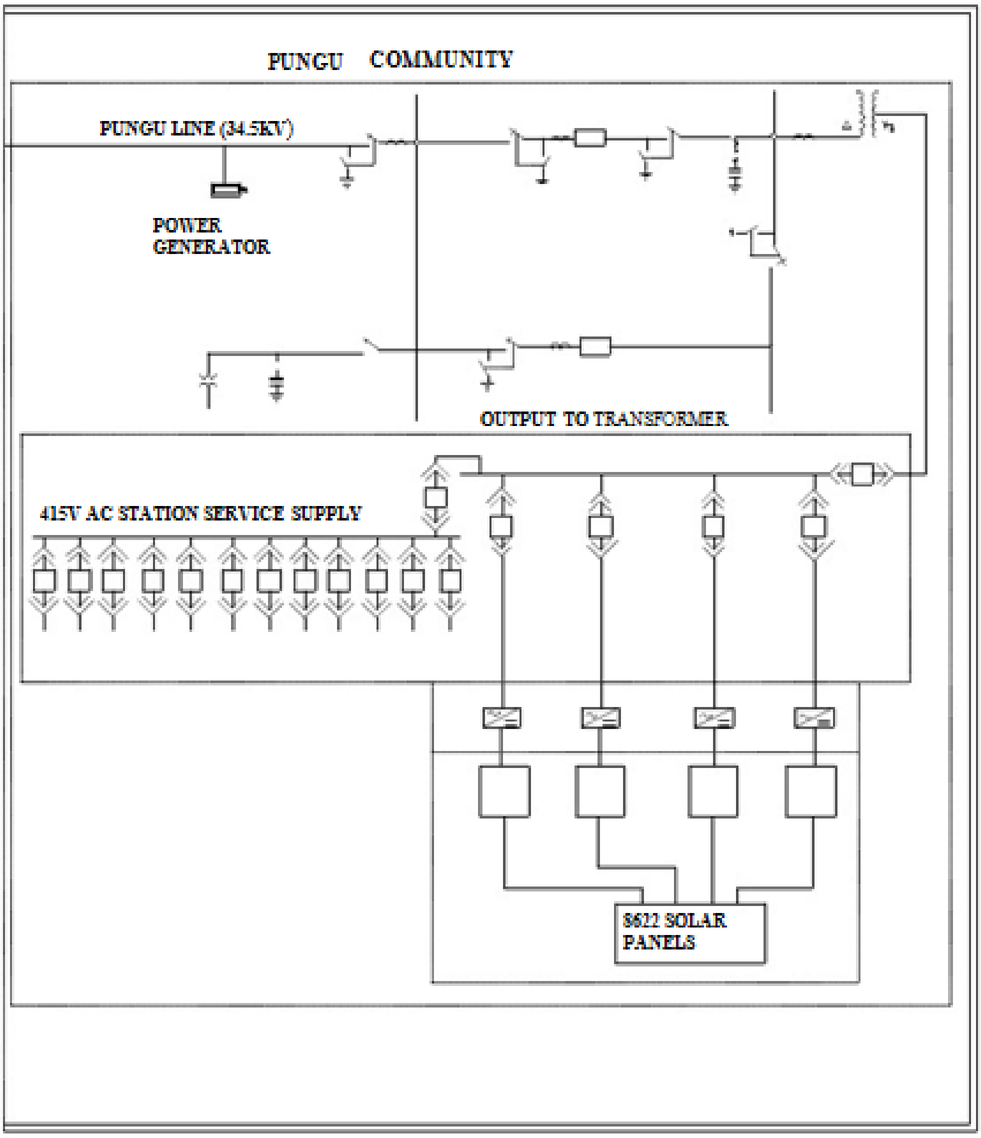


**Figure 5.17 Circuit Diagram of Proposed Micrgrid for Pungu Community**

### 5.5.3 Circuit Description

The circuit diagrm consists of the PV power generators wired into combiner boxes which deliver a DC voltage into the DC inverters. An AC circuit breaker is stationed between the DC inverter and the multi-purpose transformer. There are two lightning arresters connected at the output of the inverters by a circuit breaker and also at the output of the transformer. Two eathing wires are each fixed at the two output paths. The potential transformer maintains the value of the power to be transmitted into the community.

A start-up power generator is incorporated to initiate the inverters into action again after a shut down. The change over switch makes it possible for the pungu community to still draw power from the national grid when the solar plant is not generating power.

From the results, the percentage gain of energy due to the microgrid is calculated.

Thus, Perentage Gain in Energy = $\frac{Microgrid\ Output - Grid\ Output}{Grid\ Output}\ x\ 100\%$

**Table 5.2 Microgrid Average Monthly Performance Characteristics for the Year 2013**

| **Month** | **Ave. Energy Generated (kWh)** | **Grid Output (kWh)** | **Microgrid Output (kWh)** | **Ave. Site Energy Consumed (kWh)** | **Ave. Irradiance ($Wh/m^2$)** | **Ave. Envir. Temp. ($^oC$)** |
|---|---|---|---|---|---|---|
| Jan. | 7824.38 | 5711.55 | 5846.75 | 53.45 | 954.5 | 35.0 |
| Feb. | 8598.93 | 8370.38 | 8536.21 | 62.72 | 1030.0 | 36.0 |
| Mar. | 9669.09 | 9423.30 | 9585.91 | 62.72 | 1005.5 | 36.5 |
| Apr. | 9293.30 | 9021.82 | 10872.14 | 86.45 | 1130.4 | 37.0 |
| May | 9443.27 | 9173.33 | 9345.37 | 97.89 | 999.5 | 34.5 |
| Jun. | 8474.00 | 8115.00 | 8235.16 | 68.30 | 598.3 | 28.1 |
| Jul. | 6558.86 | 6405.00 | 6502.97 | 55.89 | 693.0 | 34.3 |
| Aug. | 3743.78 | 5880.00 | 5955.4 | 49.41 | 468.0 | 25.8 |
| Sep. | 8983.59 | 8895.00 | 8951.21 | 48.18 | 561.5 | 28.9 |
| Oct. | 10578.12 | 7970.00 | 8055.44 | 47.79 | 840.0 | 30.9 |
| Nov. | 10724.94 | 10575.00 | 10725.1 | 54.81 | 8118.0 | 35.2 |
| Dec. | 8715.20 | 8535.00 | 8715.2 | 46.98 | 855.8 | 32.3 |
| TOTAL | 102607.46 | 98075.38 | 101326.9 | 734.59 | 17254.5 | |

**Source: Navrongo VRA Solar Plant, 2016**

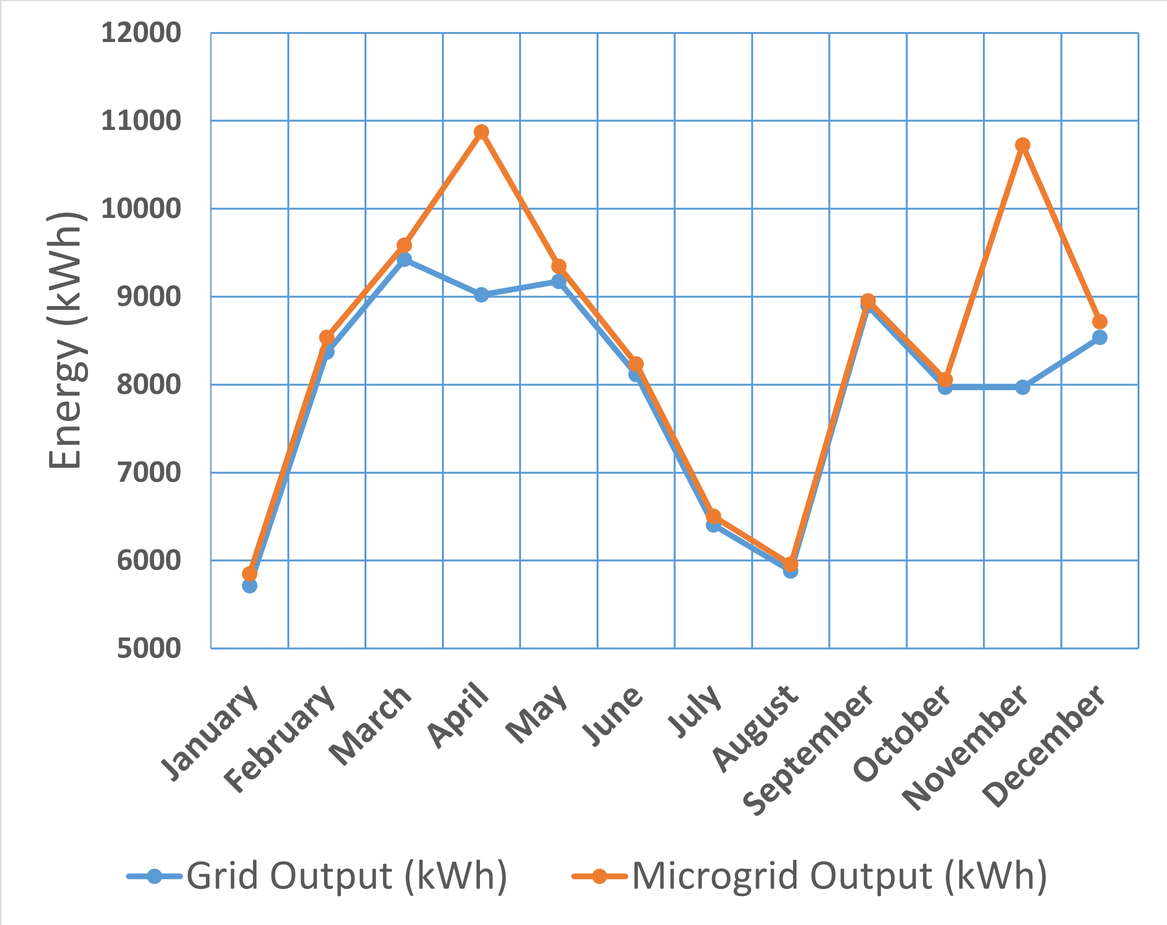


**Figure 5.18 Graphs of Existing Grid Output ant Microgrid Output for the Year 2013**

**Table 5.3 Microgrid Average Monthly Performance Characteristics for the Year 2014**

| Month | Ave. Energy Generated (kWh) | Grid Output (kWh) | Microgrid Output (kWh) | Ave. site Energy Consumed (kWh) | Ave. Irradiance ($Wh/m^2$) | Ave. Envir. Temp. ($^oC$) |
|---|---|---|---|---|---|---|
| Jan. | 9451.66 | 9138.0 | 9451.75 | 57.46 | 952.2 | 35.4 |
| Feb. | 7659.09 | 9515.0 | 9659.09 | 51.84 | 1035.0 | 35.5 |
| Mar. | 12744.01 | 12615.0 | 12695.14 | 84.51 | 1002.0 | 36.0 |
| Apr. | 12010.26 | 11890.0 | 11952.18 | 73.08 | 1124.3 | 36.5 |
| May | 11209.97 | 11032.5 | 11143.82 | 66.05 | 997.5 | 34.0 |
| Jun. | 11814.69 | 11625.0 | 11744.81 | 71.82 | 1115.5 | 33.6 |
| Jul. | 11075.47 | 10882.5 | 11013.91 | 61.56 | 918.8 | 33.4 |
| Aug. | 8946.23 | 8775.0 | 8891.96 | 54.23 | 651.5 | 31.5 |
| Sep. | 10941.25 | 11047.5 | 11114.94 | 51.30 | 897.0 | 30.3 |
| Oct. | 12339.96 | 12180.0 | 12269.75 | 70.20 | 1056.3 | 34.9 |
| Nov. | 10661.19 | 10492.5 | 10631.38 | 68.04 | 945.0 | 35.4 |
| Dec. | 111992.5 | 11820.0 | 11940.66 | 190.08 | 932.3 | 32.0 |
| TOTAL | 230846.29 | 131013.0 | 132509.4 | 900.16 | 11327.4 | |

**Source: Navrongo VRA Solar Plant, 2016**

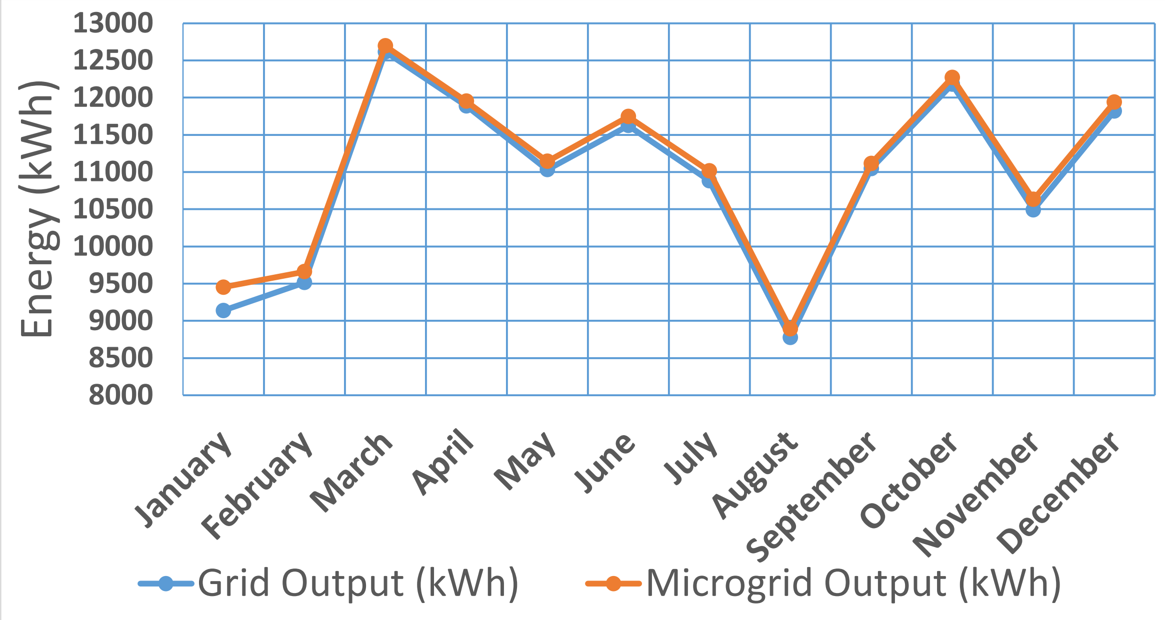


**Figure 5.19 Graphs of Existing Grid Output and Microgrid Output for the Year 2014**

**Table 5.4 Microgrid Average Monthly Performance Characteristics for the Year 2015**

| **Month** | **Ave. Energy Generated (kWh)** | **Grid Output (kWh)** | **Microgrid (kWh)** | **Ave. Site Energy Consumed (kWh)** | **Ave. Irradiance ($Wh/m^2$)** | **Ave. Envir. Temp. ($^oC$)** |
|---|---|---|---|---|---|---|
| Jan. | 11895.64 | 11690 | 11846.32 | 49.32 | 923.7 | 35.0 |
| Feb. | 10019.29 | 9878 | 9950.86 | 68.76 | 750.0 | 36.0 |
| Mar. | 10892.95 | 10650 | 10816.63 | 76.32 | 997.7 | 36.6 |
| Apr. | 11246.96 | 7037 | 7149.69 | 73.92 | 1021.3 | 37.9 |
| May | 11031.20 | 6840 | 7430.98 | 70.20 | 551.3 | 36.6 |
| Jun. | 8135.90 | 6840 | 8073.97 | 61.92 | 6426.0 | 33.1 |
| Jul. | 7199.70 | 7610 | 7846.78 | 52.92 | 699.0 | 34.5 |
| Aug. | 8528.10 | 8350 | 8487.78 | 40.32 | 472.7 | 26.0 |
| Sep. | 8054.13 | 7870 | 8006.6 | 46.85 | 555.9 | 29.0 |
| Oct. | 8979.96 | 8760 | 8911.21 | 68.64 | 848.4 | 31.0 |
| Nov. | 9446.66 | 9190 | 9363.5 | 8316 | 819.9 | 35.5 |
| Dec. | 8113.41 | 7910 | 8054.73 | 58.68 | 864.3 | 33.0 |
| TOTAL | 113543.90 | 102625 | 105939.05 | 751.01 | 14930.2 | |

**Source: Navrongo VRA Solar Plant, 2016**

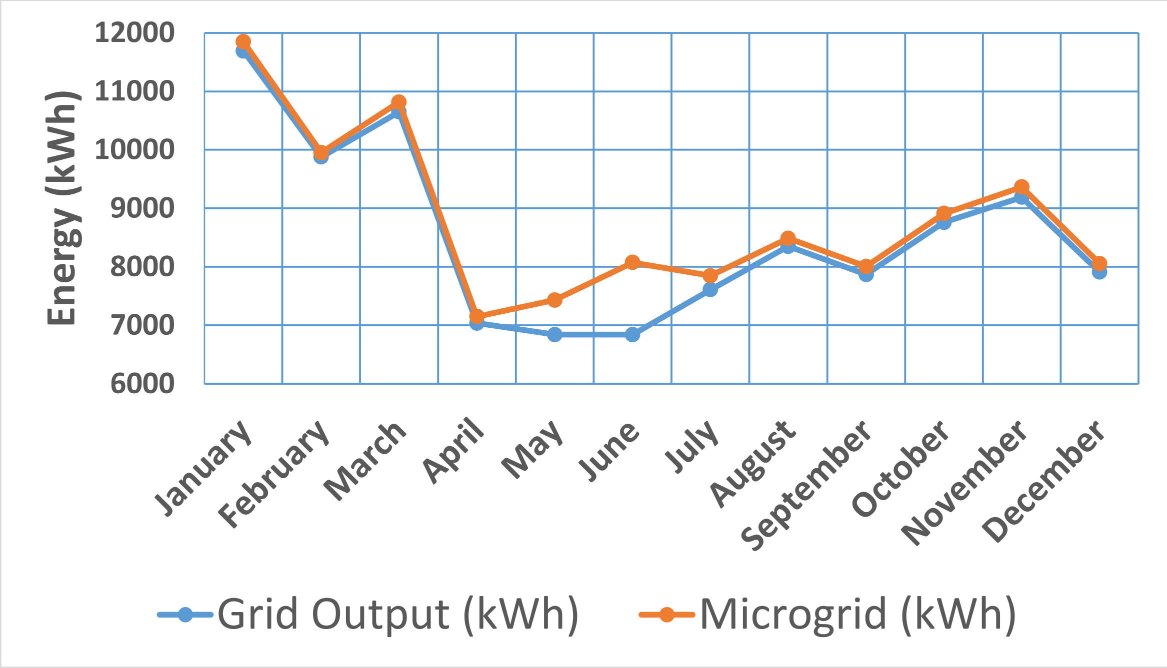


**Figure 5.20 Graphs of Existing Grid Output and Microgrid Output for the Year 2015**

**Table 5.5 Microgrid Average Monthly Performance Characteristics for the Year 2016**

| Month | Ave. Energy Generated (kWh) | Grid Output (kWh) | Microgrid Output (kWh) | Ave. Site Energy Consumed (kWh) | Ave. Irradiance ($Wh/m^2$) | Ave. Envir. Temp. ($^oC$) |
|---|---|---|---|---|---|---|
| Jan. | 7746.91 | 5655.0 | 5788.86 | 52.92 | 956 | 35.0 |
| Feb. | 8513.79 | 8287.5 | 8451.69 | 62.10 | 1031 | 36.0 |
| Mar. | 9573.36 | 9330.0 | 9491 | 82.35 | 1006 | 36.5 |
| Apr. | 9201.29 | 8932.5 | 9115.7 | 85.59 | 1130 | 37.0 |
| May | 9349.77 | 9082.5 | 9252.84 | 96.93 | 910 | 34.5 |
| Jun. | 8832.57 | 8590.0 | 8747.61 | 84.96 | 916 | 34.0 |
| Jul. | 5640.84 | 5500.0 | 5591.16 | 49.68 | 921 | 33.5 |
| Aug. | 8856.76 | 8687.3 | 8803.09 | 53.68 | 662 | 34.5 |
| Sep. | 10831.83 | 10937.0 | 11003.76 | 50.78 | 894 | 32.0 |
| Oct. | 12216.56 | 12058.2 | 12147.05 | 69.50 | 1046 | 35.0 |
| Nov. | 10554.58 | 10387.6 | 10525.1 | 67.36 | 936 | 36.0 |
| Dec. | 11872.57 | 11701.8 | 11821.25 | 188.18 | 923 | 33.0 |
| TOTAL | 113190.83 | 109149.55 | 110739.11 | 944.03 | 19521 | |

**Source: Navrongo VRA Solar Plant, 2016**

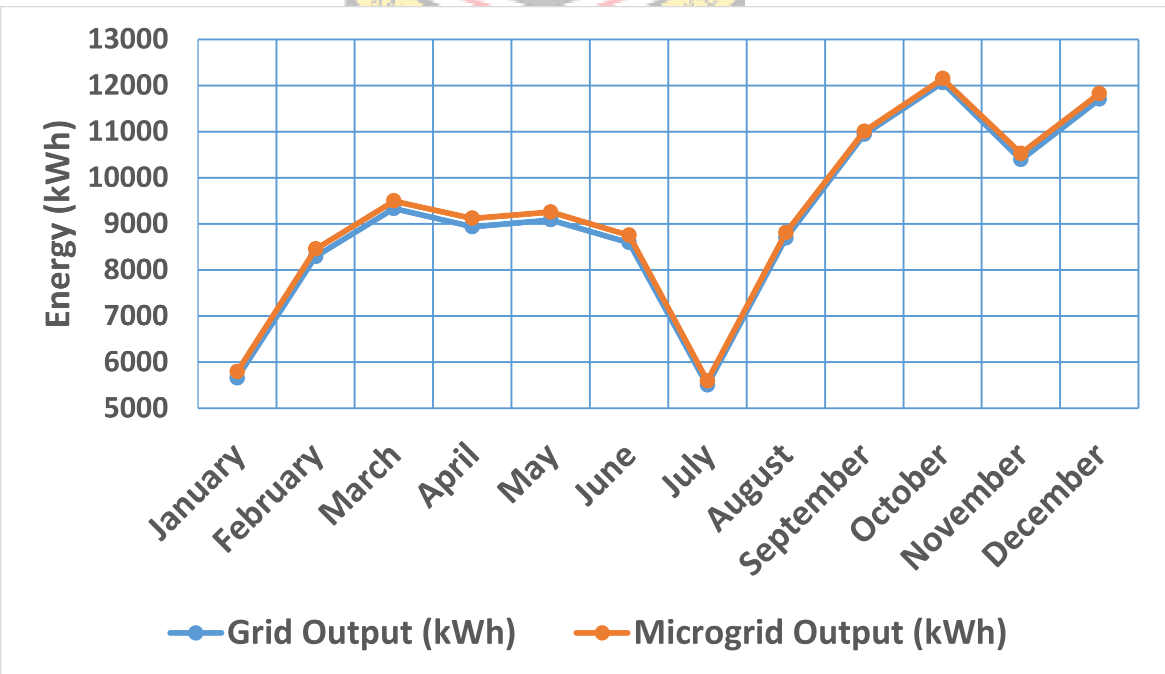


**Figure 5.21 Graphs of Existing Grid Output and Microgrid Output for the Year 2016**

In Figure 5.18 there was a rise in the power delivered by the microgrid system from March to April as seen between October and September, due to the elimination of down time and transmission losses those periods. The microgrid system converts the power lost by the existing grid system into useful energy. These peaks are not the same as seen seen in Figure 5.19 since down time was satisfactory except for transmission losses in the year 2014.

Down time became profound between April and July of  the year 2015 as seen in Figure 5.20. However, the trend in Figure 5.21 of 2016 shows general drop in both grid output micrograrid output due to persistent down times in the year.

It was determined that about 26 % of the energy lost by the plant is attributable to production down time and the 21 % by transmission losses.  From Figure 5.18 to 5.21 , it is observed that the proposed microgrid translates about 47 % of the energy lost into energy delivered and hence, increase power output of the solar plant by 2.3 % equivalent to an average power of 2412.88 kWh per year.

### 5.6 Optimization Model for Power Generation and Delivery

Numerical optimization plays a key role in almost every aspect of the operation and planning of electric power networks. Its applications cover time frames ranging from seconds to years. In this scenario, optimal power problems are modeled and solved in order to determine how to adjust the system to minimize cost while maintaining maximum power delivery. The system is modeled taking into consideration the following factors: dust deposition, ambient temperature, cell temperature, irradiance, normal operating cell temperature, peak sun hours, area of PV modules, cell efficiency, cell temperature coefficient and temperature at STC.

Dust depositing on the solar panels is a function of ambient temperature and the cell temperature. Dust on the solar panels is controlled by the temperature difference between the cell and the ambient temperature.

According to the Kinetic theory of matter, the behavior of dust particles on the submicron particles of dust can be modeled to be gas molecules in constant motion, their internal kinetic energy provided by the solar irradiance (Wh/m$^2$). An increase in irradiance results in an increase in the velocities of the gas molecules with rise in temperature of dust particles.

This temperature difference creates what is known as thermophoreses which either draws dust away or towards the panel surface which is synonymous with Charles law. It states that the volume of a fixed mass of gas at constant pressure is directly proportional to its absolute or thermodynamic temperature. When the temperature of the cell becomes greater than the ambient temperature, the system experiences a state where dust is blown away from the surface. Therefore, the rising temperature difference may reduce dust accumulation density and increase power output of PV modules due to the direction of thermophoresis force.

In fact, dust deposition, irradiance and temperature effects on solar PV modules are quite interrelated and can be influenced by many factors, such as wind velocity, the inclination of PV modules, thermophoresis induced by the temperature difference during the day and night (Wang Y. et al, 2016).

Table 5.5 indicates the effect of temperature difference and average dust deposition density ($g/m^2$).

**Table 5.6 Average Dust Deposition Density per Day-Night Ambient and Cell Temperature Difference**

| Day-Night Temperature Difference (°C) | Average Dust Deposition Density ($g/m^2$) |
|---|---|
| 0 | 0.85 |
| 10 | 0.80 |
| 20 | 0.73 |
| 30 | 0.65 |
| 40 | 0.58 |
| 50 | 0.54 |

**Source (Anon, 2013)**

### 5.6.1 Peak Sun Hours

While the amount of sunlight the panels receive is important, a more accurate representation of the amount of energy the panels can produce is termed as peak sun hours whenever the irradiation 1000 $Wh/m^2$ and above. It is important to note that "peak sun hours" are not the same as "hours of daylight." which refers to how much solar energy is available in an area during a typical day. A peak sun hour, specifically, is an hour during which the intensity of sunlight is 1,000 watts per square meter (1 $kW/m^2$).

The daily amount of solar radiation striking any location on earth varies from sunrise to sunset due to clouds, the sun's position in the sky, and what is mixed into the atmosphere. Maximum solar radiation occurs at solar noon, the time when the sun is highest in the sky, compared to the rest of the day.

Sunlight in the morning and evening does not deliver as much energy to the earth's surface as it does at midday because at low angles (less than perpendicular), the atmosphere filter the sunlight the more. Beside the day to day differences, there are also seasonal effects. In the dry season, due to the dryness and clarity of weather, an hour of sunshine packs more energy than the same hour of sunshine in the wet season.

The amount of solar radiation, or insolation, delivered by the sun varies throughout the day, based on the sun's position in the sky, clouds, and other atmospheric conditions such as:

i. Time of Day: Peak solar radiation occurs at solar noon, when the sun is highest in the sky. The low angle of the sun at sunrise and sunset means that the atmosphere filters the sunlight more and resulting in less energy being delivered to the earth's surface;

ii. Season: Sun-hours increase during the dry season due to the sun's higher position in the sky; and

iii. Geography: Solar energy increases near the equator, as it is closer to the sun.

### 5.6.2 Determination of Peak Sun Hours of the Plant

A peak sun hour is roughly the amount of solar energy striking a 1-square-meter area perpendicular to the sun's location over a 1-hour period. The amount of power is standardized at 1,000 $Wh/m^2$ (1 $kWh/m^2$).

By adding up the various amounts of solar irradiation over the course of a day, and counting them as units equivalent to 1 solar noon hour (1,000 watts per square meter for 1 hour), we get a useful comparison number, the peak sun hours.

In Navrongo, the PV modules on site receive an average 11 hours of sunlight per day. Power generation begins at 6 am and ends at 5 pm daily. Though some amount of energy is generated between 5 pm and 6 pm, it is usually not recorded until the plant shuts down since the solar irradiance falls below the threshold frequency.

The average peak sun hours is actually five (5) and lies between 11 am to 3 pm daily. However, many areas in Ghana may experience less during the wet season and more during the dry season. Knowing the yearly and seasonal average peak sun hours in your locality is a helpful tool for deciding whether or not solar panels are a worthwhile investment for your home or business.

In calculating the peak sun hours, the results of the station weather equipment presented in appendix $C_1$ and $C_3$ were very useful in determining the number of peak sun hours. It was established that:

i. The average daily solar radiation from 6 am to 10 am was 427.2 $Wh/m^2$;

ii. The average daily solar radiation from 11 am to 3 pm was 1036.1 $Wh/m^2$; and

iii. The average daily solar radiation from 4 pm to 5pm was 290.7 $Wh/m^2$.

Tables 5.7 and 5.8 are samples of hourly readings of solar radiations taken on site at the Navrongo solar plant on August 3, 2016 and April 5, 2014 for 11 hours in typical solar days.

**Table 5.7: Hourly Readings of Solar Irradiance, August 3, 2016**

| **Time (hours)** | 6am | 7am | 8am | 9am | 10am | 11am | 12am | 1pm | 2pm | 3pm | 4pm | 5pm | 6pm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Irrad. ($Wh/m^2$)** | 0 | 166 | 478 | 624 | 931 | 1079 | 1170 | 1092 | 1046 | 1002 | 602 | 296 | 0 |

A graph of Time in hours versus irradiance in $Wh/m^2$ was also plotted. Figure 5.13 indicate clearly peak sun hours per day.

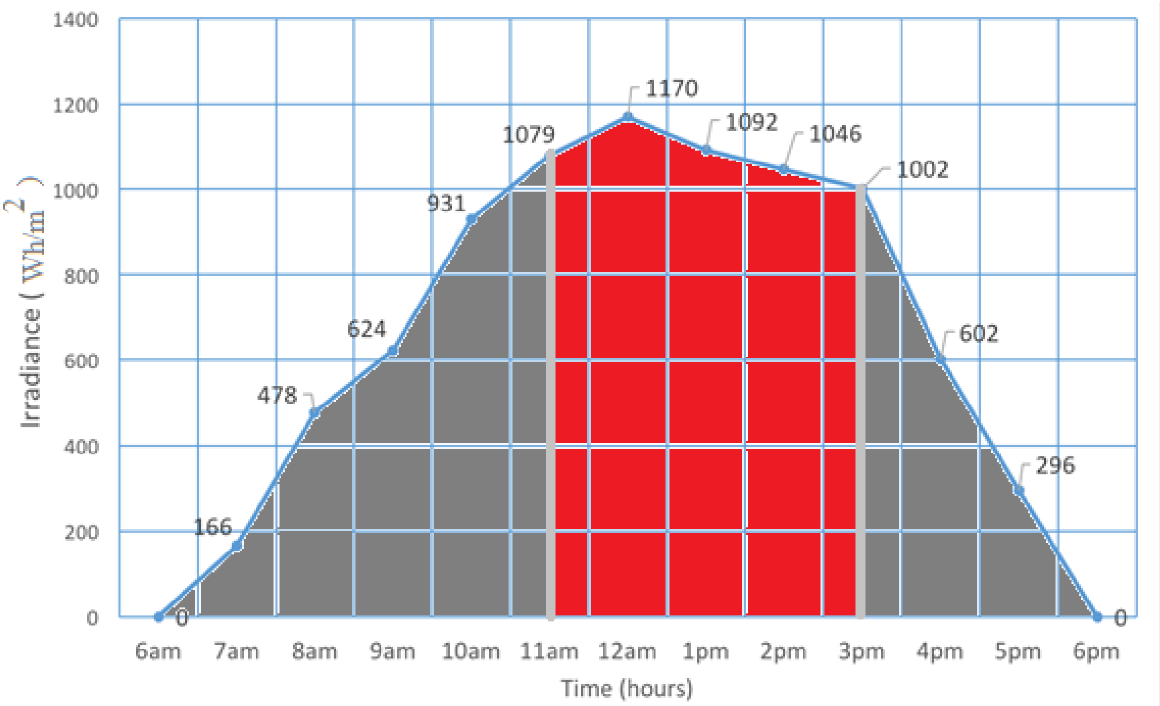


**Figure 5.22 Hourly Readings of Solar Irradiance and Peak Sun Hours**

It can be deduced from Figure 5.21 that, the peak hours are between the hours of 11 am and 3 pm. At 6 am, the irradiance is zero and it comes back to zero at 6 pm. There is an upward trend of irradiance from 6 am 11 am and a downward trend from 3 pm to 6 pm. The peak hour registered was at 12 pm. Numerically, the peak irradiance is from 1002 $Wh/m^2$ to 1170 $Wh/m^2$

**Table 5.8 Hourly Readings of Solar Irradiance, April 5, 2014**

| **Time (hours)** | 6am | 7am | 8am | 9am | 10am | 11am | 12am | 1pm | 2pm | 3pm | 4pm | 5pm | 6pm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Irrad. ($Wh/m^2$)** | 2 | 148 | 412 | 697 | 859 | 1040 | 1115 | 1056 | 1023 | 992 | 50 | 38 | 0 |

## 5.7 PV Optimisation Model Equation

The equation is modeled to determine the relationship between the operating cost and power delivery and how to adjust the power system to minimise power generation cost losses, but increase power delivery by the plant. The general efficiency, cell efficiency, dust deposition, cell and ambient temperatures, peak sun hours, irradiance and total PV Module area, were the constraints of the power system and were taken into consideration. From the theories of mathematical optimization, the objective function equation is obtained as:

$$Optimum\ Power\ (P) = \left(1 - \left[(0.00845)\times(X_2 - 25)\times(0.93)\times(0.15)\times X_3 \times 150 \times (16729.71)\right]\right)$$

*Constraints*

$C_1 : 31 \le X_1 \le 36 \text{ OR } a_1 \le X_1 \le a_2$

$C_2 : X_2 \le 67 \text{ OR } X_2 \le b$

$C_3 : 0.84 \le X_3 \le 0.992 \text{ OR } C_1 \le X_3 \le C_2$

$C_4 : X_2 = X_1 + \left(\frac{NOCT - 20}{0.8}\right) \times X_3 \le b$

*where,*

$a_1$ = *minimum ambient temperature (°C)*

$a_2$ = *maximum ambient temperature (°C)*

*b = maximum cell temperature (°C)*

$C_1$ = *minimum irradiance* ($kWh/m^2$)

$C_2$ = *maximum irradiance* ($kWh/m^2$)

$X_1$ = *ambient temperature (°C)*

$X_2$ = *cell temperature (°C)*

$X_3$ = *irradiance* ($kWh/m^2$)

*NOCT = normal operating cell temperature*

*Alternatively,*

$$Optimum\ Power\ (P) = (1 - (d \times (X_2 - e) \times f \times g \times X_3 \times h \times i \qquad 1$$

*where,*

*d = temperature coefficient (0.00845/°C)*

*e = temperature at STC (25°C)*

*f = dirt rating (0.93)*

*g = cell efficiency (0.15)*

*h = peak sun hours by average number days per month (5 x 30)*

*I = total surface area of PV modules (16729.71 $m^2$)*

Using equation 1, with the various constraints stated, Microsoft excel was used to compute the optimised values. The optimised energy values are indicated in Tables 5.9, 5.10, 5.11 and 5.12 respectively for the years 2013, 2014, 2015, 2016 data records. These tables are graphed in Figures 5.20 to 5.23 respectively as indicated below.

**Table 5.9 Optimised Average Monthly Power Characteristics for 2013**

| **Month** | **Energy Gen. (kWh)** | **Optimised Energy (kWh)** | **Max. Irrad ($Wh/m^2$)** | **Min. Irrad. ($Wh/m^2$)** | **Max. Envir. Temp. (°C)** | **Min. Envir. Temp.(°C)** | **Cell Temp. (°C)** |
|---|---|---|---|---|---|---|---|
| Jan. | 242555.8 | 340350.9 | 1002 | 932 | 36.2 | 35.0 | 50.7 |
| Feb. | 240770.0 | 445690.0 | 1072 | 930 | 36.0 | 34.5 | 42.5 |
| Mar. | 299741.8 | 417874.3 | 1002 | 879 | 36.0 | 34.0 | 54.4 |
| Apr. | 278799.0 | 386742.8 | 1107 | 723 | 37.0 | 35.0 | 60.0 |
| May | 292741.4 | 389473.7 | 1086 | 779 | 36.9 | 30.9 | 58.4 |
| Jun. | 254220.0 | 105788.0 | 872 | 78 | 32.0 | 22.8 | 54.8 |
| Jul. | 203324.7 | 292993.6 | 1004 | 144 | 34.0 | 27.5 | 52.7 |
| Aug. | 116057.2 | 186552.6 | 873 | 332 | 29.5 | 21.8 | 42.6 |
| Sept. | 269507.7 | 375693.2 | 979 | 375 | 33.0 | 21 | 52.4 |
| Oct. | 327921.7 | 339998.0 | 1150 | 384 | 34.0 | 30.9.0 | 55.3 |
| Nov. | 321748.2 | 436281.8 | 946 | 890 | 36.0 | 33.8 | 56.4 |
| Dec. | 270171.2 | 373489.4 | 1056 | 640 | 35.2 | 28.6 | 55.8 |
| Total | 3117558.7 | 4090928.3 | | | | | |

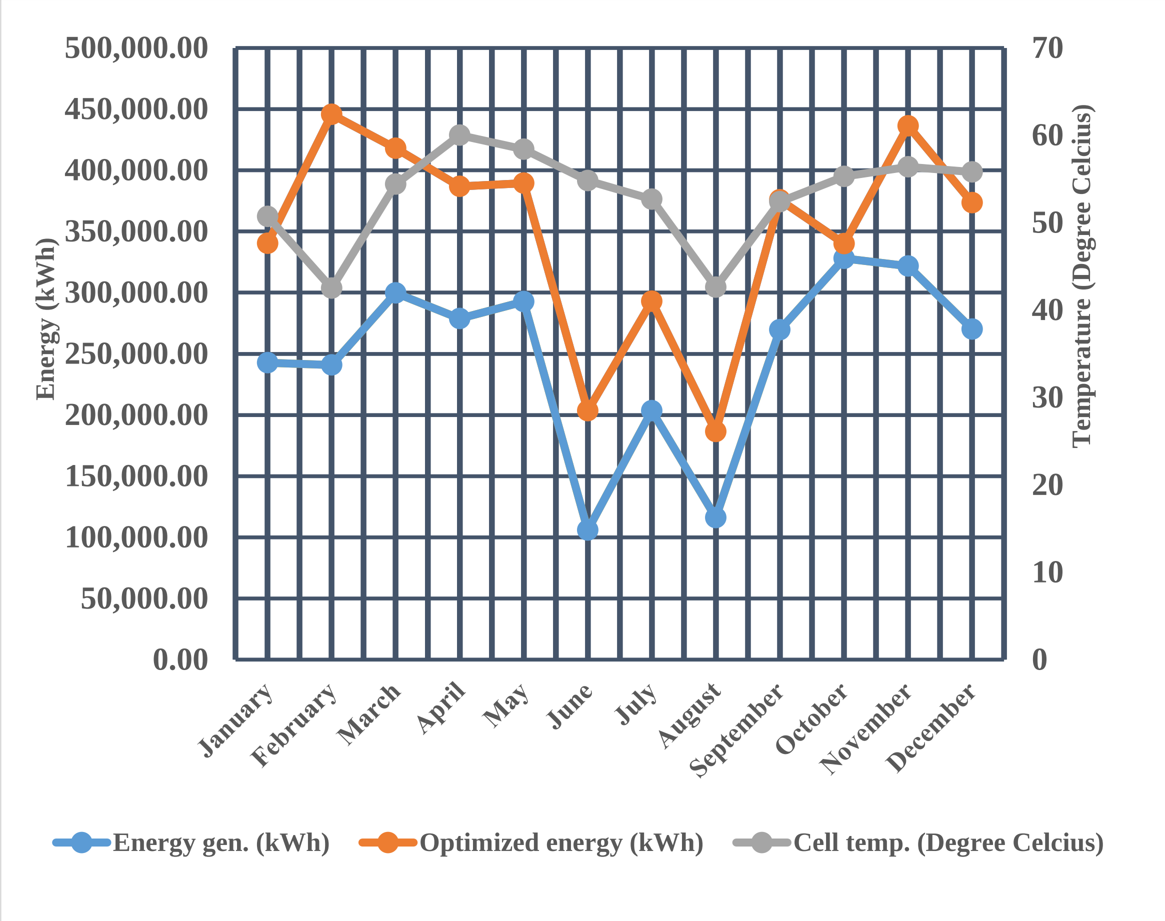


**Figure 5.23 Graphs of Nominal Power Generated and Optimised Power over Months of the Year 2013 at Cell Temperatures**

**Table 5.10 Optimised Average Monthly Power Characteristics for 2014**

| Month | Energy Gen. (kwh) | Optimised Energy (kwh) | Max. Irradiance (wh/m$^2$) | Min. Irradiance (wh/m$^2$) | Max. Evir. Temp. ($^O$C) | Min. Evir. Temp. ($^o$C) | Cell Temp ($^o$C) |
|---|---|---|---|---|---|---|---|
| Jan | 293001.4 | 351601.7 | 1006 | 910 | 37.0 | 29.8 | 55.0 |
| Feb | 214454.5 | 257345.4 | 1078 | 983 | 36.5 | 30.5 | 55.0 |
| Mar | 395064.3 | 474077.2 | 1002 | 925 | 36.0 | 31.0 | 44.2 |
| Apr | 360307.8 | 432369.4 | 1139 | 952 | 35.6 | 29.8 | 57.5 |
| May | 347509.1 | 417010.9 | 1097 | 723 | 36.9 | 30.0 | 58.0 |
| Jun | 354440.7 | 487328.8 | 1175 | 943 | 35.8 | 30.4 | 41.0 |
| Jul | 343339.6 | 512890.5 | 1127 | 571 | 35.0 | 32.0 | 50.3 |
| Aug | 277333.1 | 332799.7 | 834 | 519 | 33.2 | 30.2 | 54.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sept | 328237.5 | 393885 | 1224 | 975 | 33.2 | 22.4 | 57.0 |
| Oct | 382538.8 | 459046.6 | 1101 | 930 | 35.7 | 30.4 | 56.0 |
| Nov | 319835.7 | 383802.8 | 992 | 925 | 35.9 | 30.9 | 55.7 |
| Dec | 3471767.5 | 4766121 | 962 | 905 | 33.8 | 30.0 | 41.5 |
| Total | 7087830 | 9268279 | | | | | |

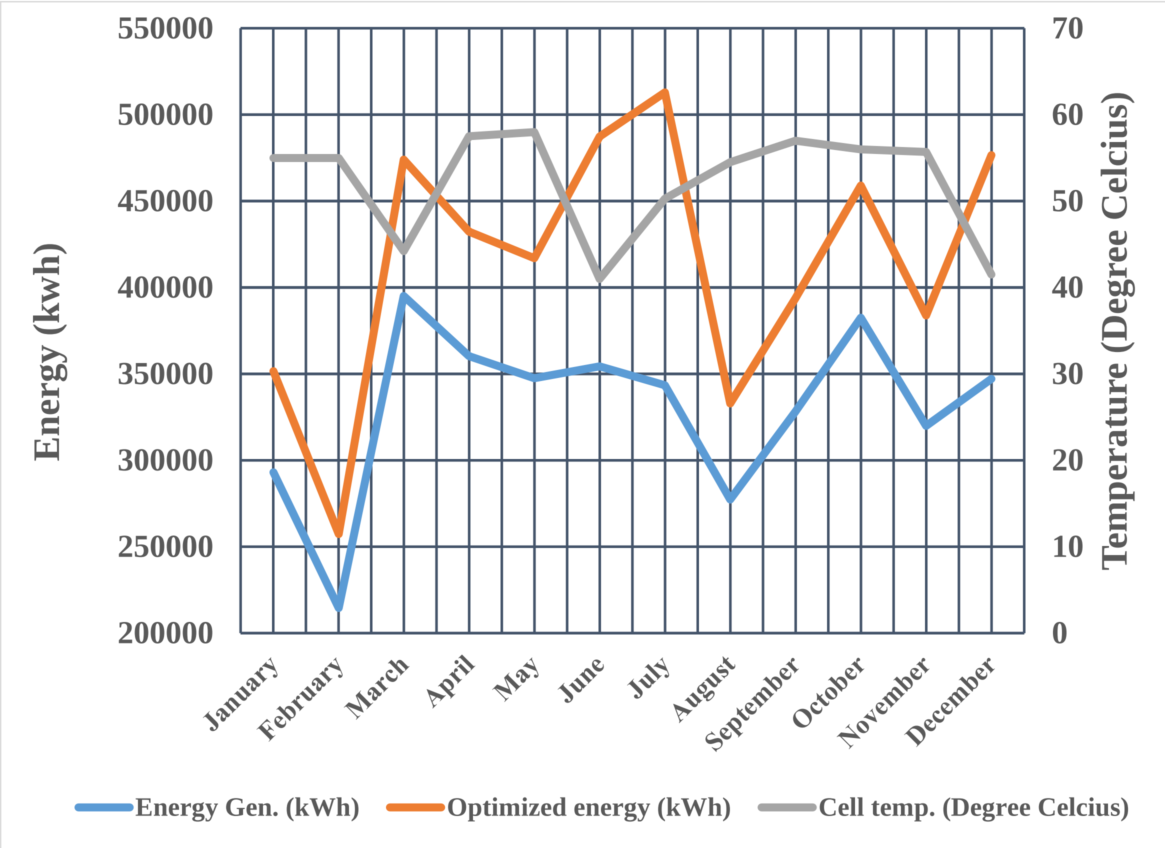


**Figure 5.24 Graph of Nominal Power Generated and Optimised Power over Months of the Year 2014 at Cell Temperatures**

**Table 5.11 Optimised Average Monthly Power Characteristics for 2015**

| Month | Energy gen. (kWh) | Optimised Energy (kWh) | Max. Irrad ($Wh/m^2$) | Min. Irrad. ($Wh/m^2$) | Max. Invir. Temp. ($^oC$) | Min. Envir. Temp.($^oC$) | Cell Temp. ($^oC$) |
|---|---|---|---|---|---|---|---|
| Jan. | 368764.8 | 472517.8 | 956 | 898 | 35.1 | 33.1 | 53.0 |
| Feb. | 280540.1 | 366648.1 | 889 | 504 | 36.0 | 34.6 | 58.7 |
| Mar. | 337681.4 | 435217.7 | 1124 | 811 | 36.2 | 34.5 | 58.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Apr. | 337408.8 | 434890.6 | 1055 | 986 | 36.4 | 35.2 | 53.1 |
| May | 341967.2 | 440360.6 | 1079 | 469 | 37.4 | 35 | 55.9 |
| Jun. | 244077.0 | 322892.2 | 1069 | 640 | 33.5 | 32 | 62.1 |
| Jul. | 223190.7 | 297828.8 | 1025 | 699 | 35.0 | 33.1 | 57.3 |
| Aug. | 264371.1 | 347245.3 | 992 | 742 | 35.0 | 34.1 | 55.8 |
| Sept. | 241623.9 | 319948.7 | 1015 | 897 | 36.1 | 34.5 | 56.8 |
| Oct. | 278378.8 | 364054.6 | 1047 | 992 | 36.8 | 35.5 | 56.5 |
| Nov. | 283399.8 | 370079.8 | 1056 | 864 | 35.4 | 34.6 | 57.2 |
| Dec. | 251515.7 | 321818.8 | 1048 | 984 | 35.1 | 33.3 | 56.6 |
| Total | 3452919.3 | 4493503 | | | | | |

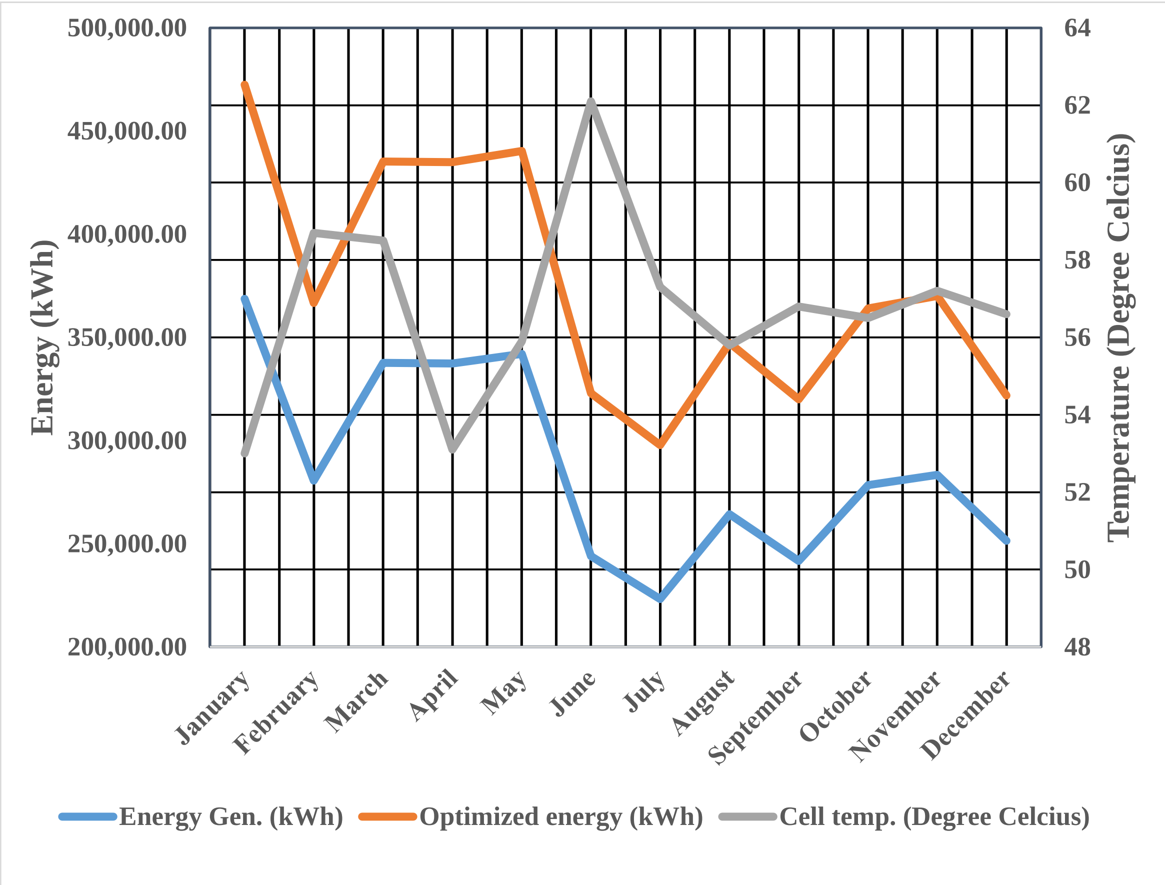


**Figure 5.25 Graph of Nominal Power Generated and Optimised Power over Months of the Year 2015 at Cell Temperatures**

**Table 5.12 Optimised Average Monthly Power Characteristics For 2016**

| Month | Energy Gen. (kWh) | Optimised Energy (kWh) | Max. Irrad ($Wh/m^2$) | Min. Irrad. ($Wh/m^2$) | Max. Envir. Temp. (°C) | Min. Envir. Temp.(°C) | Cell Temp. (°C) |
|---|---|---|---|---|---|---|---|
| Jan. | 240154.2 | 307685.0 | 1006 | 368 | 35.5 | 33.6 | 50.7 |
| Feb. | 246899.9 | 325279.9 | 1041 | 631 | 36.7 | 35.6 | 57..5 |
| Mar. | 296774.2 | 385729.0 | 1016 | 642 | 37.5 | 36.1 | 58.4 |
| Apr. | 276038.7 | 360646.4 | 1130 | 455 | 37.0 | 35.1 | 60.2 |
| May | 289842.8 | 376811.4 | 1090 | 658 | 35.6 | 33.1 | 59.2 |
| Jun. | 264977.1 | 346972.5 | 1056 | 916 | 34.0 | 30.9 | 58.3 |
| Jul. | 174866.0 | 238839 | 1028 | 921 | 31.8 | 29.6 | 58.7 |
| Aug. | 274559.6 | 358471.5 | 1092 | 662 | 31.6 | 29.4 | 56.7 |
| Sept. | 324954.9 | 418945.9 | 1038 | 894 | 32.5 | 30.4 | 55.4 |
| Oct. | 38713.40 | 59456.1 | 1024 | 846 | 34.8 | 32.7 | 48.9 |
| Nov. | 316637.4 | 409964.9 | 1033 | 936 | 37.2 | 35 | 51.2 |
| Dec. | 368049.7 | 470659.6 | 1065 | 923 | 34.6 | 32.6 | 49.9 |
| Total | 3112467.9 | 4059461.2 | | | | | |

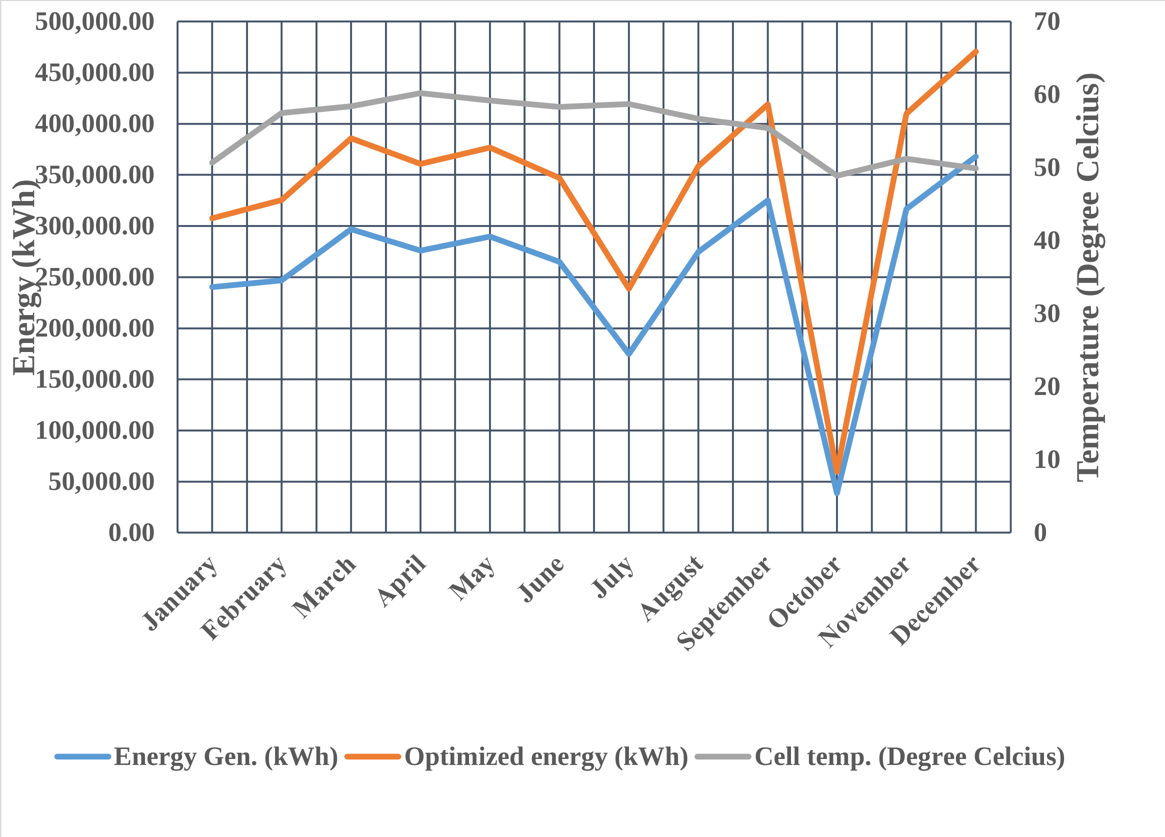


**Figure 5.26 Graph of Nominal Power Generated and Optimised Power over Months of the Year 2016 at Cell Temperatures**

From Tables 5.9 to 5.12, the optimised Power values for each month exceeds the nominal Power generated which depicts a shortfall in the existing power generation system. Inferring from these Tables, it is known that the lower the cell temperature the higher the power output by the module.

From the model, it is observed that in Fig.2.25, the highest power was obtained in January 2015 with a cell temperature of 53 $^{o}$C and a steady irradiance of 956 Wh/m$^2$.

Similarly, in Figure 5.24, at a cell temperature of 50.3 $^{o}$C and a minimum ambient temperature of 32.0 $^{o}$C, an optimised energy of 512,890.5 kWh is estimated. Thus, maximum power is produced in July under these temperatures with peak irradiance of 1127 wh/m$^2$.

Again, in Figure 5.26 optimised energy is 470,659.6 kWh in December which is the highest, with cell temperature of 49.9 and ambient temperature of 32.6 $^{o}$C.

The implication is that, the plant produces maximum power at peak sun hours with average cell temperature of 50.1 $^oC$, approximated to 50 $^oC$.

The study could therefore conclude that there is a particular combination of threshold cell temperature and ambient temperature for which maximum power is delivered. Hence as the cell temperature decreases, power generated increases until a minimum temperature is reached within which power generation starts decreasing.
The following mathematical deductions can be made from Tables 5.9 to 5.12 respectively.

***For Table 5.9***

*Optimised Value Difference = 4090298.3 - 3117558.7*

*= 972739.6*

$\%\ increment = \frac{Optimal\ Value\ Difference}{Nominal\ Value}\ x\ 100$

$= \frac{972739.6}{3117558.7}\ x\ 100$

*= 31.2%*

***For Table 5.10***

*Optimised Value Difference = 9268279 - 7087830*

*= 2180449*

$\%\ increment = \frac{Optimal\ Value\ Difference}{Nominal\ Value}\ x\ 100$

$= \frac{2180449}{7087830}\ x\ 100$

*= 30.8%*

***For Table 5.11***

*Optimised Value Difference = 4493503 - 3452919.3*

*= 1040583.7*

$\%\ increment = \frac{Optimal\ Value\ Difference}{Nominal\ Value}\ x\ 100$

$= \frac{1040583.7}{3452919.3} \; x \; 100$

*= 30.1%*

***For Table 5.12***

*Optimised Value Difference = 4059461.2 - 3112467.9*

*= 946993.3*

*% increment* $= \frac{Optimal\ Value\ Difference}{Nominal\ Value} \; x \; 100\ \%$

$= \frac{946993.3}{3112467.9} \times 100\ \%$

*= 30.4 %*

**5.8 Rstudio**

The strength of the PV optimization module equation was tested further using Rstudio as an alternative method of simulation besides Microsoft excel. The system produced an average boost of 29.8% of power output of the solar plant at peak sun hours as compared to 30.4% boost by the Microsoft excel simulation of the module.

There is convergence in terms percentage power gained, using the two statistical tools in in the module simulation. Results and codes of the Rstudio simulated values are displayed in appendix C and D respectively.

**5.9 Summary**

It is observed from optimisation that if the issues of dust effect, temperature and irradiance are compensated for, the energy generated would appreciate by an average value of 30.4 %, translating to 1,285,191.4 kWh of energy per year. Hence, there is a loss of 30.4 % of energy produced in the current project.

Solar irradiance increases with increasing ambient temperature and PV module surface temperature. The difference in temperature (temperature gradient) between the PV module surface and the ambient temperature creates a force called thermophoresis.

This force may either blow dust towards or away from the PV cell surfaces. If the ambient temperature is higher than the PV panel surface temperature, then dust will flow to settle on the PV panel surface. The reverse is true when the PV cell temperature is higher than the ambient.

It is known from Figures 5.24 and 5.26 that, the threshold temperature for optimum power production at peak sun hours is 50 $^{o}$C.

# CHAPTER SIX

## CONCLUSION AND RECOMMENDATIONS

### 6.1 Conclusion

Results of the Performance Analysis of the Navrongo VRA solar Plant shows that the main losses associated with the plant are generation downtime, transmission inefficiencies, module cracking and high cell temperatures (above 67 °C).

A new microgrid service system has been designed and when integrated into the national grid will eliminate down time and power transmission losses and increase efficiency of the existing system by 2.3 % which translates into 2412.88 kWh of energy.

It was determined from Microsoft Excel and Rstudio that maintaining an optimum cell temperature of 50.0 °C will boost power output by an average of 30.1 % at peak sun hours and also prevent PV module cracking. From the optimisation, power output will increase on the average by 1,285,191.4 kWh per year which translates to GH₵ 912,071.30 per anum.

It is established from the research that, if the proposed power changes of the microgrid system and the PV optimisation model are implemented there will be an average increase in efficiency of the Navrongo VRA Solar Power plant of 32.7% which corresponds to an increase in power of 1,287,604.28 kWh, and a financial gain of GH₵ 913,783.68 per year.

### 6.2 Recommendations

In order to help Ghana meet her commitments to providing stable and reliable energy, improve efficiency of renewable energy supply and reduce cost through energy losses, the following recommendations are outlined to ensure energy security and economic competitiveness:

a. Micro-grid design technology should be used in place of the grid transmission system in future new investments in solar energy in order to prevent transmission losses and production down time;

b. Automatic mist blower systems should be integrated into the solar power plant to maintain the threshold cell temperature of 50 °C for optimum cell delivery;

c. Solar trackers are recommended for receiving maximum radiation at any point in time for optimum power delivery of the plant;
d. The government of Ghana should adopt household panel mounting as a state renewable energy policy for communities with low population and energy consumption rates; and

e. Further studies should be carried out on how to improve cooling of photovoltaic cells and the rate of dust deposition on the PV modules.

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## APPENDIX A

STRUCTURED INTERVIEW FOR WORKERS

Introduction

Dear Sir/Madam,

I am a student of the *University of Mines and Technology, Tarkwa (UMaT).* I am conducting a research on the topic *Performance Analysis of the Navrongo VRA Solar Plant for Improved Efficiency*. This interview questions are designed to gather information to assist in carrying out this research which is part of our academic requirements for the completion of MSc/MPhil degrees in UMaT. Kindly respond honestly by answering the questions appropriately. Your responses and information will be confidential and IEAymous.

Thank you very much.

1. Are you satisfied with the performance of this Solar Plant?

Yes [ ] No [ ]

2. In your view, what factors adversely affect maximum power delivery of the plant?

a. …………………………………………………………………………………

b. …………………………………………………………………………………

c. …………………………………………………………………………………

d. …………………………………………………………………………………

e. ………………………………………………………………………………..

f. …………………………………………………………………………………

3. What suggestions do you think if implemented could help minimize power losses at the site?

a. ………………………………………………………………………………..

b. ……………………………………………………………………………………..

c. ……………………………………………………………………………………..

d. …………………………………………………………………………………….

e. ……………………………………………………………………………………..

4. What recommendations do you have on future work in the field of solar power plant development?

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………………………………………………………………………………………………

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Thank You!!!

# APPENDIX B

Appendix $B_1$: Hourly Readings of Plant Performance Variables for 03/08/2016

| | | | | | | | | | | | | | | | | Date: | 8/3/2016 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | 34.5kV Bus Voltage | | | | | | Outgoing | | | the Main Circuit | | | Branches | | | LV side of the M Trfm | | | M Trfm | M Trfm | Envir. | Global |
| | A | B | C | AB | AC | BC | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Oil T | Coil T | Temp. | Radiat |
| | kV | kV | kV | kV | kV | kV | A | kW | kVar | A | kW | kVar | A | kW | kVar | A | kW | kVar | ℃ | ℃ | ℃ | wh/m2 |
| 6am | 19.63 | 19.36 | 19.13 | 33.94 | 33.29 | 33.44 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 31.8 | 33.81 | 22 | 0 |
| 7am | 19.85 | 19.57 | 19.44 | 34.28 | 33.76 | 33.9 | 2.29 | 152.23 | -16.74 | 2.29 | 152.23 | -16.7 | | | | 239.06 | 160.02 | -9.5 | 31.75 | 33.86 | 24.5 | 166 |
| 8am | 19.42 | 19.12 | 18.98 | 33.53 | 32.94 | 33.15 | 12.11 | 723.08 | -38.06 | 12.11 | 723.08 | -38.1 | | | | 1071.1 | 735.78 | -16.07 | 32.81 | 33.6 | 29.4 | 478 |
| 9am | 19.1 | 18.82 | 18.69 | 32.98 | 32.46 | 32.61 | 18.82 | 1099.1 | -47.95 | 18.82 | 1099.1 | -48 | | | | 1643 | 1119.4 | 0 | 36.55 | 35.5 | 31.9 | 624 |
| 10am | 19.53 | 19.23 | 19.11 | 33.7 | 33.19 | 33.34 | 26.41 | 1570.2 | -61.65 | 26.41 | 1570.2 | -61.7 | | | | 2292.2 | 1596.5 | 16.07 | 43.3 | 39.03 | 34.4 | 931 |
| 11am | 19.69 | 19.35 | 19.24 | 33.95 | 33.39 | 33.61 | 29.71 | 1775.7 | -68.5 | 29.71 | 1775.7 | -68.5 | | | | 2566.4 | 1794.5 | 18.27 | 47.04 | 44.67 | 36.3 | 1079 |
| 12pm | 18.73 | 19.4 | 19.27 | 34.03 | 33.47 | 33.66 | 31.16 | 1862.5 | -72.31 | 31.16 | 1862.5 | -72.3 | | | | 2698.8 | 1882.2 | 18.27 | 52.79 | 51.47 | 38.1 | 1170 |
| 13pm | 19.77 | 19.47 | 19.34 | 34.11 | 33.59 | 33.74 | 27.76 | 1665.4 | -69.26 | 27.76 | 1665.4 | -69.3 | | | | 2400 | 1688.6 | 5.85 | 57.01 | 54.74 | 38.9 | 1092 |
| 14pm | 19.46 | 19.2 | 19.06 | 33.61 | 33.14 | 33.22 | 28.77 | 1698.9 | -92.1 | 28.77 | 1698.6 | -92.1 | | | | 2483.2 | 1720.7 | 0 | 59.7 | 56.38 | 39.3 | 1046 |
| 15pm | 19.28 | 19.03 | 18.85 | 33.33 | 32.8 | 32.87 | 23.86 | 1402.8 | -61.65 | 23.86 | 1402.8 | -61.7 | | | | 2073.1 | 1429.9 | 10.23 | 58.96 | 56.43 | 40.3 | 1002 |
| 16pm | 19.39 | 19.08 | 18.95 | 33.47 | 32.9 | 33.07 | 16.67 | 990.23 | -41.86 | 16.67 | 990.23 | -41.9 | | | | 1460.2 | 1004.7 | 0 | 56.27 | 56.17 | 39.8 | 602 |
| 17pm | 18.84 | 18.55 | 18.4 | 32.54 | 31.97 | 32.13 | 7.27 | 423.19 | -44.15 | 7.27 | 423.19 | -44.2 | | | | 659.77 | 430.36 | -36.53 | 53.85 | 54.06 | 39.1 | 296 |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |
| Time | #1 Inverter | | | | #2 Inverter | | | | #3 Inverter | | | | #4 Inverter | | | | #5 Inverter | | | | | |
| | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | | |
| 6am | 0 | 0 | 0 | 33.09 | 0 | 0 | 0 | 32.49 | 0 | 0 | 0 | 32.49 | 0 | 0 | 0 | 33.09 | 0 | 0 | 0 | 33.09 | daily operational hrs | Total monthiy operational hrs |
| 7am | 398.8 | 28.99 | 27.99 | 32.49 | 397.8 | 27.99 | 27.99 | 31.89 | 399.84 | 30.99 | 27.99 | 32.49 | 397.8 | 44.98 | 37.99 | 33.09 | 401.84 | 71.97 | 45.98 | 32.49 | | |
| 8am | 400.8 | 193.9 | 145.9 | 33.69 | 397.8 | 196.9 | 146.9 | 31.89 | 400.84 | 199.8 | 145.94 | 33.09 | 398.8 | 203.9 | 150.9 | 32.49 | 405.84 | 268.89 | 181.9 | 31.89 | | |
| 9am | 398.8 | 438.8 | 314.9 | 37.79 | 396.8 | 437.8 | 314.9 | 36.59 | 398.84 | 437.8 | 312.88 | 37.79 | 396.8 | 443.8 | 317.9 | 37.79 | 416.84 | 548.79 | 385.9 | 34.29 | | |
| 10am | 398.8 | 463.8 | 331.9 | 40.18 | 397.8 | 447.8 | 324.9 | 38.98 | 399.84 | 445.8 | 314.88 | 40.18 | 397.8 | 462.8 | 332.9 | 40.78 | 417.84 | 575.78 | 405.8 | 35.49 | | |
| 11am | 399.8 | 524.8 | 370.9 | 42.58 | 398.8 | 505.8 | 364.9 | 40.78 | 400.84 | 511.8 | 364.86 | 41.98 | 398.8 | 506.8 | 365.9 | 42.58 | 421.84 | 633.75 | 450.8 | 37.19 | | |
| 12pm | 399.8 | 530.9 | 372.3 | 42.58 | 396.8 | 512.8 | 372.9 | 41.38 | 399.84 | 512.8 | 369.86 | 41.98 | 398.8 | 533.8 | 368.9 | 42.58 | 421.84 | 618.76 | 440.8 | 37.29 | 11hrs | 88hrs |
| 13pm | 399.8 | 474.8 | 342.9 | 43.78 | 397.8 | 465.8 | 335.9 | 41.98 | 400.84 | 474.8 | 339.87 | 43.18 | 397.8 | 464.8 | 334.9 | 43.78 | 421.84 | 576.78 | 401.8 | 37.79 | | |
| 14pm | 398.8 | 447.8 | 321.9 | 45.48 | 396.8 | 448.8 | 325.9 | 43.78 | 398.84 | 450.8 | 321.87 | 43.78 | 397.8 | 457.8 | 328.9 | 44.38 | 414.84 | 567.78 | 397.8 | 38.39 | | |
| 15pm | 398.8 | 388.9 | 279.9 | 45.48 | 396.8 | 387.9 | 284.9 | 43.78 | 398.84 | 384.9 | 274.89 | 43.78 | 396.8 | 393.9 | 284.9 | 44.38 | 413.84 | 491.81 | 342.9 | 38.98 | | |
| 16pm | 398.8 | 257.9 | 188.9 | 45.48 | 395.9 | 257.9 | 192.9 | 43.78 | 398.84 | 254.9 | 184.93 | 43.18 | 396.8 | 262.9 | 192.9 | 44.38 | 408.84 | 334.87 | 228.9 | 38.98 | | |
| 17pm | 395.9 | 77.97 | 61.98 | 44.38 | 393.9 | 77.97 | 61.98 | 43.18 | 395.85 | 73.97 | 57.98 | 42.58 | 393.9 | 76.97 | 60.98 | 43.18 | 381.85 | 115.95 | 72.97 | 38.98 | | |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | Daily Delieved Energy | | | 13440.00Kwh | | | |
| | | | | | | | | | | | | | | | | Daily Generated Energy | | | 13546.01kwh | | | |
| Outgoing | | | LV Side | | | Site Consumed | | | Current | | -0.81 | F6S Pressure | | | 0.55 | Mntly Accm Gen Energy | | | 103714.61Kwh | | | |
| 6am | 18pm | Qty. | 6am | 18pm | Qty. | 6am | 18pm | Qty. | Battery Voltage | | 132.87 | 415V Voltage | | | 410.8 | Accum. Delivered Energy | | | 701820.00kwh | | | |

Appendix $B_2$: Hourly Readings of Plant Performance Variables for 02/04/2016

Date: 4/2/2016

| Time | 34.5kV Bus Voltage A | B | C | AB | AC | BC | Outgoing Current | Active | Idle | the Main Circuit Current | Active | Idle | Branches Current | Active | Idle | LV side of the M Trfm Current | Active | Idle | M Trfm Oil T | M Trfm Coil T | Envir. Temp. | Global Radiat |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | kV | kV | kV | kV | kV | kV | A | kW | kVar | A | kW | kVar | A | kW | kVar | A | kW | kVar | ℃ | ℃ | ℃ | wh/m2 |
| 6am | 18.34 | 18.27 | 17.81 | 31.46 | 30.89 | 30.8 | 0.91 | -11.42 | 36.53 | 0.91 | -11.42 | 36.53 | | | | 53.91 | -11.69 | 35.8 | 32.6 | 35.07 | 26.2 | 0 |
| 7am | 18.11 | 18.02 | 17.9 | 31.55 | 30.98 | 31.03 | 2.86 | 177.34 | -17.51 | 2.86 | 177.34 | -17.51 | | | | 281.25 | 181.94 | -13.88 | 33.02 | 35.29 | 26.7 | 102 |
| 8am | 18.09 | 17.92 | 17.85 | 31.46 | 30.82 | 31 | 9.38 | 534.32 | -42.62 | 9.38 | 534.32 | -42.62 | | | | 840.23 | 544.34 | -29.23 | 34.6 | 36.23 | 28.4 | 296 |
| 9am | 17.69 | 17.91 | 17.82 | 31.25 | 30.71 | 30.55 | 18.35 | 1018.4 | -39.58 | 18.35 | 1018.4 | -39.58 | | | | 1599.6 | 1048.5 | 0 | 38.87 | 37.18 | 32.2 | 585 |
| 10am | 17.96 | 18.17 | 18.04 | 31.73 | 31.12 | 30.96 | 18.16 | 1023.72 | -37.3 | 18.16 | 1023.7 | -37.3 | | | | 1571.5 | 1041.9 | 14.61 | 42.98 | 40.03 | 34.4 | 547 |
| 11am | 18.97 | 18.86 | 18.77 | 32.89 | 32.55 | 32.59 | 31.29 | 1798.56 | -85.25 | 31.29 | 1798.6 | -85.25 | | | | 2682.4 | 1819.4 | 13.15 | 50.26 | 47.57 | 36.7 | 1068 |
| 12pm | 18.85 | 18.7 | 18.55 | 32.63 | 32.21 | 32.34 | 27.79 | 1591.53 | -82.2 | 27.79 | 1591.5 | -82.2 | | | | 2398.8 | 1617.7 | 5.85 | 51.58 | 48.84 | 37.8 | 965 |
| 13pm | 18.47 | 18.38 | 18.18 | 32.04 | 31.63 | 31.62 | 29.55 | 1662.31 | -80.68 | 29.55 | 1662.3 | -80.68 | | | | 2540.6 | 1687.8 | 9.5 | 53.95 | 51.95 | 38 | 1002 |
| 14pm | 18.58 | 18.4 | 18.23 | 32.17 | 31.64 | 31.8 | 27.73 | 1567.17 | -86.01 | 27.73 | 1567 | -86 | | | | 2401.1 | 1589.9 | 0 | 56.48 | 54.38 | 38.7 | 883 |
| 15pm | 18.28 | 18.13 | 17.91 | 31.68 | 31.15 | 31.23 | 10.77 | 609.67 | -44.91 | 10.77 | 609.7 | -44.9 | | | | 956.25 | 621.8 | -29.23 | 55.27 | 54.58 | 38.8 | 1013 |
| 16pm | 18.32 | 18.32 | 18.11 | 32.01 | 31.41 | 31.4 | 11.4 | 652.29 | -41.34 | 11.4 | 652.29 | -41.34 | | | | 1039.5 | 691.25 | -20.46 | 53.85 | 54.43 | 38.4 | 281 |
| 17pm | 18.2 | 18.25 | 18.08 | 31.92 | 31.37 | 31.3 | 4.2 | 251.17 | -25.88 | 4.2 | 251.17 | -25.88 | | | | 411.33 | 272.84 | -28.5 | 51.9 | 53.16 | 38.2 | 165 |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |

| Time | #1 Inverter Voltage | Current | Active | Temp. | #2 Inverter Voltage | Current | Active | Temp. | #3 Inverter Voltage | Current | Active | Temp. | #4 Inverter Voltage | Current | Active | Temp. | #5 Inverter Voltage | Current | Active | Temp. | Daily operational hours | Total monthly operational hrs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6am | 392.9 | 0 | 0 | 35.49 | 390.85 | 0 | 0 | 33.69 | 392.85 | 0 | 0 | 34.89 | 390.9 | 0 | 0 | 28.89 | 372.85 | 0 | 0 | 36.59 | | |
| 7am | 392.9 | 42.98 | 33.99 | 35.49 | 389.85 | 38.98 | 33.99 | 33.69 | 392.85 | 38.98 | 33.99 | 34.29 | 390.9 | 38.98 | 34.99 | 28.89 | 367.86 | 75.97 | 44.98 | 34.89 | | |
| 8am | 392 | 128 | 97 | 35.5 | 389.9 | 150 | 111.96 | 33.09 | 391.85 | 143.94 | 108.96 | 34.29 | 390.9 | 156.9 | 116 | 28.89 | 367.86 | 192.92 | 118 | 34.89 | | |
| 9am | 392.9 | 312.9 | 224.9 | 36.59 | 389.85 | 311.9 | 224.91 | 35.49 | 392.85 | 312.88 | 221.91 | 36.59 | 390.9 | 317.9 | 266.9 | 31.89 | 378.85 | 379.85 | 240.9 | 34.29 | | |
| 10am | 392.9 | 352.9 | 249.9 | 38.98 | 390.85 | 347.9 | 245.9 | 37.19 | 393.85 | 338.87 | 236.91 | 38.39 | 392.9 | 331.9 | 237.9 | 33.69 | 381.85 | 386.85 | 247.9 | 35.49 | | |
| 11am | 396.8 | 502.8 | 349.9 | 41.38 | 394.85 | 501.8 | 360.86 | 39.58 | 397.84 | 496.81 | 352.86 | 40.78 | 395.9 | 504.8 | 355.9 | 35.49 | 409.84 | 637.75 | 438.8 | 36.59 | | |
| 12pm | 395.9 | 471.8 | 333.9 | 42.58 | 393.85 | 482.8 | 342.87 | 40.78 | 396.84 | 479.81 | 334.87 | 41.38 | 393.9 | 483.8 | 342.9 | 36.59 | 403.84 | 553.78 | 376.9 | 37.19 | | |
| 13pm | 394.9 | 466.8 | 326.9 | 43.18 | 392.85 | 459.8 | 326.87 | 41.38 | 395.85 | 454.82 | 320.87 | 42.58 | 393.9 | 451.8 | 320.9 | 37.19 | 396.84 | 604.76 | 404.8 | 38.38 | 11hrs | 22hrs |
| 14pm | 393.9 | 396.8 | 277.9 | 43.78 | 391.85 | 390.9 | 279.89 | 41.98 | 394.85 | 397.84 | 280.89 | 43.18 | 392.9 | 403.8 | 286.9 | 37.79 | 395.85 | 562.78 | 375.9 | 38.98 | | |
| 15pm | 392.9 | 252.9 | 181.9 | 43.78 | 390.85 | 217.9 | 166.93 | 41.98 | 393.85 | 253.9 | 181.93 | 42.58 | 391.9 | 252.9 | 183.9 | 37.19 | 388.85 | 346.86 | 227.9 | 39.58 | | |
| 16pm | 392.9 | 136 | 104 | 43.18 | 390.85 | 133 | 101.96 | 41.38 | 393.85 | 139.94 | 105.96 | 42.58 | 391.9 | 146.9 | 111 | 36.59 | 375.85 | 232.91 | 146.9 | 38.98 | | |
| 17pm | 392.9 | 51.98 | 43.98 | 43.98 | 390.85 | 51.98 | 43.98 | 41.38 | 393.85 | 51.98 | 43.98 | 41.98 | 391.9 | 53.98 | 44.98 | 36.59 | 371.85 | 95.96 | 55.98 | 38.98 | | |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |

| Outgoing | | | LV Side | | | Site Consumed | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | Daily Delieved Energy | 10680.00KWh |
| | | | | | | | | | | | | | Daily Generated Energy | 10855.7kWh |
| | | | | | | | | | | | | | Mntly Accu. Del. Energy | 21780.00kWh |
| | | | | | | | | | Current | -1.08 | Pressure | 0.55 | y Accm Gen Energy | 22108.31kWh |
| 6am | 18pm | Qty. | 6am | 18pm | Qty. | 6am | 18pm | Qty. | Battery Voltage | 132.98 | 415V Voltage | 401.8 | Accum Delivered Energy | 973026.00KWh |
| 2460.3 | 2463.9 | 10680 | 2584.9 | 2588.7 | 10797.4 | 407.94 | 408.48 | 58.32 | Bus Voltage | 124.53 | System Frequency | 50.08 | Accu. Generated Energy | 979509.94kWh |

Supervisor: A. A Fatawu

Operators: Raymond, Rashid

Appendix $B_3$: Hourly Readings of Plant Performance Variables for 05/04/2014

| | | | | | | | | | | | | | | | | Date: | 4/5/2014 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | 34.5kV Bus Voltage | | | | | | Outgoing | | | the Main Circuit | | | Branches | | | LV side of the M Trfm | | | M Trfm | M Trfm | Envir. | Global |
| | A | B | C | AB | AC | BC | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Oil T | Coil T | Temp. | Radiat |
| | kV | kV | kV | kV | kV | kV | A | kW | kVar | A | kW | kVar | A | kW | kVar | A | kW | kVar | ℃ | ℃ | ℃ | wh/m2 |
| 6am | 19.7 | 19.4 | 19.3 | 34.1 | 33.49 | 33.66 | 0.67 | -12.94 | 36.53 | 0.67 | -12.9 | 36.53 | | | | 43.36 | -10.96 | 37.3 | 36.18 | 37.7 | 30.1 | 2 |
| 7am | 19.8 | 19.6 | 19.4 | 34.3 | 33.74 | 33.86 | 3.11 | 203.98 | -18.3 | 3.11 | 204 | -18.3 | | | | 302.3 | 207.51 | -10 | 35.97 | 37.9 | 30.8 | 148 |
| 8am | 19 | 18.8 | 18.6 | 32.9 | 32.38 | 32.48 | 12.33 | 722.32 | -41.1 | 12.33 | 722.3 | -41.1 | | | | 1100 | 741.62 | -22 | 36.71 | 37.6 | 32.7 | 412 |
| 9am | 19.2 | 19 | 18.9 | 33.2 | 32.77 | 32.92 | 21.05 | 1233.8 | -54 | 21.05 | 1234 | -54 | | | | 1838 | 1258.9 | 0 | 38.77 | 38.2 | 33.7 | 697 |
| 10am | 19.2 | 19 | 18.9 | 33.2 | 32.77 | 32.92 | 26.07 | 1521.5 | -81.4 | 26.07 | 1522 | -81.4 | | | | 2257 | 1545.4 | 0 | 43.72 | 41.7 | 35.2 | 859 |
| 11am | 19.3 | 19.1 | 19 | 33.4 | 32.94 | 33.07 | 29.68 | 1739.2 | -91.3 | 29.68 | 1739 | -91.3 | | | | 2564 | 1763.1 | 0 | 47.41 | 45.6 | 36.8 | 1040 |
| 12pm | 19.4 | 19.2 | 19 | 33.5 | 33.06 | 33.16 | 30.82 | 1813 | -74.6 | 30.82 | 1813 | -74.6 | | | | 2664 | 1834 | 0 | 51 | 50.2 | 38 | 1115 |
| 13pm | 19.5 | 19.3 | 19.1 | 33.6 | 33.2 | 33.29 | 29.05 | 1718.6 | -86 | 29.05 | 1719 | -86 | | | | 2505 | 1739.7 | 0 | 52.16 | 51.5 | 40 | 1056 |
| 14pm | 19.4 | 19.1 | 19 | 33.2 | 32.62 | 32.82 | 27.19 | 1605.2 | -83 | 27.19 | 1605 | -83 | | | | 2393 | 1636 | 0 | 53.37 | 52.5 | 40 | 1023 |
| 15pm | 19.7 | 19.4 | 19.3 | 34 | 33.53 | 33.77 | 22.09 | 1320.6 | -48 | 22.09 | 1321 | -48 | | | | 1934 | 1351.7 | 18.3 | 51.9 | 52.6 | 39.9 | 992 |
| 16pm | 19.6 | 19.3 | 19.1 | 33.8 | 33.3 | 33.39 | 1.22 | 78.4 | 0 | 1.22 | 78.4 | 0 | | | | 130.1 | 82.57 | 13.9 | 48.94 | 50.8 | 37.2 | 50 |
| 17pm | 20.4 | 20.1 | 20 | 35.2 | 34.68 | 34.93 | 0.88 | 57.08 | 7.61 | 0.88 | 57.08 | 7.61 | | | | 102 | 59.91 | 17.5 | 45.46 | 46.4 | 34.7 | 38 |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |
| Time | #1 Inverter | | | | #2 Inverter | | | | #3 Inverter | | | | #4 Inverter | | | | #5 Inverter | | | | | |
| | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | | |
| 6am | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 35.49 | 0 | 0 | 0 | 24.99 | 0 | 0 | 0 | 30.09 | 399.84 | 0 | 0 | 36 | daily operational hrs | Total monthiy operational hrs |
| 7am | 402 | 37 | 33 | 36.6 | 399.8 | 47.98 | 40.98 | 34.49 | 401.8 | 46.98 | 39.98 | 37.19 | 399.84 | 38.98 | 34 | 30.99 | 403.84 | 74 | 46.98 | 35.5 | | |
| 8am | 398 | 185 | 136 | 37.2 | 396.8 | 182.9 | 138 | 35.99 | 398.8 | 186.9 | 136 | 37.79 | 396.84 | 186.9 | 138 | 32.49 | 388.85 | 265 | 171.9 | 34.9 | | |
| 9am | 399 | 328 | 236 | 37.8 | 397.8 | 327.9 | 238.9 | 37.19 | 399.8 | 329.9 | 235.9 | 39.58 | 397.84 | 331.9 | 240 | 34.29 | 406.84 | 431 | 293.9 | 35.5 | | |
| 10am | 400 | 415 | 297 | 39.6 | 397.8 | 411.8 | 296.9 | 38.98 | 400.8 | 419.8 | 300.9 | 41.38 | 398.84 | 428.8 | 310 | 35.99 | 413.84 | 534 | 370.9 | 36.6 | | |
| 11am | 401 | 482 | 345 | 40.8 | 397.8 | 490.8 | 352.9 | 40.18 | 400.8 | 484.8 | 342.9 | 40.78 | 398.84 | 484.8 | 344 | 34.29 | 413.82 | 602 | 419.8 | 37.8 | | |
| 12pm | 400 | 503 | 359 | 42.6 | 398.8 | 502.8 | 362.9 | 41.98 | 400.8 | 499.8 | 354.9 | 41.98 | 399.84 | 509.8 | 363 | 34.89 | 418.84 | 623 | 439.8 | 38.4 | 11hrs | 55hrs |
| 13pm | 400 | 478 | 341 | 43.8 | 398.8 | 480.8 | 348.9 | 43.18 | 400.8 | 477.8 | 340.9 | 43.18 | 398.84 | 486.8 | 2351 | 36.59 | 417.84 | 591 | 414.8 | 39 | | |
| 14pm | 400 | 439 | 318 | 44.4 | 398.8 | 438.8 | 316.9 | 43.78 | 401.8 | 438.8 | 313.9 | 43.78 | 399.84 | 440.8 | 317 | 36.59 | 421.84 | 539 | 383.9 | 40.2 | | |
| 15pm | 404 | 323 | 283 | 44.8 | 402.8 | 300.9 | 231.9 | 43.78 | 403.8 | 353.6 | 261.9 | 358.9 | 401.84 | 342.9 | 244 | 37.19 | 421.84 | 396 | 274.9 | 40.2 | | |
| 16pm | 399 | 13 | 1399 | 43.8 | 395.9 | 13.99 | 14.99 | 41.98 | 398.8 | 13.99 | 13.99 | 43.18 | 397.84 | 12.99 | 13 | 35.99 | 400.84 | 32 | 18.99 | 39 | | |
| 17pm | 406 | 5 | 6 | 40.8 | 403.8 | 7 | 5 | 39.58 | 402 | 5 | 5 | 41.38 | 401.84 | 4 | 5 | 33.69 | 418.84 | 14 | 8 | 39 | | |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | Daily Delieved Energy | | | 11700.00kwh | | | |
| | | | | | | | | | | | | | | | | Daily Generated Energy | | | 11818.13kwh | | | |
| | | | | | | | | | | | | | | | | Mntly Accu. Del. Energy | | | 63480.00kwh | | | |

Appendix $B_4$: Hourly Readings of Plant Performance Variables for 01/03/2014

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | Date: | 3/10/2014 | | | | | |
| Time | 34.5kV Bus Voltage | | | | | | Outgoing | | | the Main Circuit | | | Branches | | | LV side of the M Trfm | | | M Trfm | M Trfm | Envir. | Global |
| | A | B | C | AB | AC | BC | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Oil T | Coil T | Temp. | Radiat |
| | kV | kV | kV | kV | kV | kV | A | kW | kVar | A | kW | kVar | A | kW | kVar | A | kW | kVar | ℃ | ℃ | ℃ | wh/m2 |
| 6am | 19.04 | 18.79 | 18.56 | 32.93 | 32.31 | 32.42 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 31.22 | 33.81 | 21.7 | 0 |
| 7am | 19.49 | 19.24 | 19.05 | 33.7 | 33.14 | 33.25 | 2.2 | 150.7 | -6.85 | 2.2 | 150.7 | -6.85 | | | | 233.2 | 157.09 | 0 | 31.28 | 33.23 | 21.9 | 134 |
| 8am | 19.32 | 19.02 | 18.96 | 33.31 | 32.86 | 33.07 | 12.69 | 749.72 | -44.91 | 12.69 | 749.72 | -44.9 | | | | 1118 | 762.81 | -19 | 32.7 | 33.39 | 29.8 | 439 |
| 9am | 18.79 | 18.49 | 18.41 | 32.41 | 31.92 | 32.14 | 21.61 | 1236.8 | -65.46 | 21.61 | 1236.8 | -65.5 | | | | 1873.8 | 1256 | 0 | 36.18 | 35.13 | 31.7 | 714 |
| 10am | 18.54 | 18.24 | 18.2 | 31.94 | 31.53 | 31.75 | 28.51 | 1599.9 | -88.29 | 28.51 | 1599.9 | -88.3 | | | | 2465.6 | 1630.1 | -10.23 | 42.3 | 38.61 | 33.8 | 956 |
| 11am | 19.2 | 18.86 | 18.77 | 33.07 | 32.55 | 32.79 | 31.17 | 1810.7 | -83.72 | 31.17 | 1810.7 | -83.7 | | | | 2694.1 | 1834.7 | 11.69 | 47.73 | 45.94 | 35.8 | 1119 |
| 12pm | 19.52 | 19.77 | 19.61 | 34.37 | 34.2 | 33.94 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 52.58 | 51.84 | 36.9 | 1186 |
| 13pm | 19.27 | 18.96 | 18.83 | 33.24 | 32.69 | 32.91 | 25.75 | 1494.9 | -79.16 | 25.75 | 1494.9 | -79.2 | | | | 2239.5 | 1519.8 | 0 | 53.58 | 51.79 | 38.6 | 1167 |
| 14pm | 19.27 | 18.93 | 18.85 | 33.21 | 32.69 | 32.91 | 22.94 | 1335 | -60.89 | 22.94 | 1335 | -60.9 | | | | 2001.6 | 1362.7 | 0 | 55.96 | 53.96 | 39.5 | 1048 |
| 15pm | 18.98 | 18.66 | 18.53 | 32.73 | 32.16 | 32.4 | 19.31 | 1110 | -51.76 | 19.31 | 1110 | -51.8 | | | | 1689.8 | 1131.8 | 0 | 55.59 | 53.74 | 39.8 | 1005 |
| 16pm | 19.46 | 19.12 | 18.98 | 33.55 | 32.95 | 33.2 | 13.37 | 788.53 | -33.49 | 13.37 | 788.53 | -33.5 | | | | 1173.1 | 796.42 | -13.15 | 54.01 | 53.9 | 39.6 | 607 |
| 17pm | 18.69 | 18.38 | 18.24 | 32.25 | 31.64 | 31.88 | 5.49 | 316.63 | -38.06 | 5.49 | 316.63 | -38.1 | | | | 513.28 | 330.26 | -31.42 | 51.58 | 52.32 | 39 | 275 |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |
| Time | #1 Inverter | | | | #2 Inverter | | | | #3 Inverter | | | | #4 Inverter | | | | #5 Inverter | | | | | |
| | Voltag | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | | |
| 6am | 0 | 0 | 0 | 34.29 | 0 | 0 | 0 | 33.69 | 0 | 0 | 0 | 33.09 | 0 | 0 | 0 | 32.489 | 0 | 0 | 0 | 32.49 | daily operational hrs | Total monthiy operational hrs |
| 7am | 398.8 | 32.99 | 29.99 | 32.49 | 396.8 | 33.99 | 30.99 | 31.29 | 398.84 | 34.99 | 31.99 | 31.89 | 396.8 | 38.99 | 33.99 | 31.29 | 393.85 | 71.97 | 44.98 | 31.29 | | |
| 8am | 398.8 | 203.9 | 148.9 | 34.89 | 396.8 | 202.9 | 150.9 | 33.69 | 398.84 | 203.9 | 147.94 | 33.69 | 397.8 | 212.9 | 154.9 | 34.29 | 397.84 | 285.89 | 189.9 | 31.89 | | |
| 9am | 396.8 | 331.9 | 237.9 | 36.59 | 394.9 | 329.9 | 237.9 | 35.49 | 397.84 | 329.9 | 235.91 | 36.59 | 395.9 | 335.9 | 241.9 | 36.59 | 399.84 | 438.83 | 396.9 | 32.49 | | |
| 10am | 395.9 | 448.8 | 316.9 | 38.39 | 393.9 | 447.8 | 318.9 | 37.19 | 396.84 | 446.8 | 314.88 | 37.79 | 394.9 | 453.8 | 322.9 | 38.39 | 396.84 | 580.77 | 389.9 | 33.09 | | |
| 11am | 398.8 | 507.8 | 361.9 | 40.78 | 396.8 | 512.8 | 369.9 | 39.58 | 399.84 | 504.8 | 358.86 | 40.18 | 397.8 | 516.8 | 370.9 | 40.78 | 412.84 | 636.75 | 440.8 | 34.89 | | |
| 12pm | 397.8 | 533.8 | 379.9 | 43.18 | 396.8 | 523.8 | 375.9 | 41.38 | 399.84 | 396.8 | 289.88 | 40.78 | 397.8 | 0 | 0 | 43.18 | 414.84 | 650.75 | 456.8 | 35.99 | 11hrs | 1110 |
| 13pm | 399.8 | 515.8 | 370.9 | 43.18 | 396.8 | 518.8 | 373.9 | 41.98 | 399.84 | 515.8 | 366.86 | 41.98 | 0 | 0 | 0 | 42.58 | 410.84 | 645.75 | 446.8 | 36.19 | | |
| 14pm | 398.8 | 452.8 | 322.9 | 43.78 | 396.8 | 460.8 | 331.9 | 42.58 | 398.84 | 449.8 | 321.87 | 42.58 | 0 | 0 | 0 | 42.58 | 410.84 | 574.78 | 398.8 | 37.79 | | |
| 15pm | 397.8 | 377.9 | 271.9 | 44.38 | 395.9 | 377.9 | 273.9 | 42.58 | 397.84 | 378.9 | 269.89 | 42.58 | 0 | 0 | 0 | 42.58 | 403.84 | 488.81 | 331.9 | 38.39 | | |
| 16pm | 398.8 | 260.9 | 191.9 | 44.38 | 396.8 | 260.9 | 192.9 | 43.18 | 399.84 | 257.9 | 188.93 | 41.98 | 0 | 0 | 0 | 40.18 | 409.84 | 337.87 | 230.9 | 38.39 | | |
| 17pm | 395.9 | 99.96 | 77.97 | 43.78 | 393.9 | 98.96 | 76.97 | 42.58 | 396.84 | 96.96 | 74.97 | 41.38 | 0 | 0 | 0 | 40.18 | 380.85 | 149.94 | 94.96 | 38.39 | | |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | Daily Delieved Energy | | | 11850.00Kwh | | | |
| | | | | | | | | | | | | | | | | aily Generated Energy | | | 11996.75kwh | | | |
| Outgoing | | | LV Side | | | Site Consumed | | | Current | | -0.81 | F68 Pressure | | | 0.55 | Mntly Accm Gen Energy | | | 128625.47Kwh | | | |
| 6am | 18pm | Qty. | 6am | 18pm | Qty. | 6am | 18pm | Qty. | attery Voltag | | 132.87 | 415V Voltage | | | 410.8 | ccum. Delivered Energy | | | 726480.00kwh | | | |
| 1118 | 1122.4 | 11850 | 1176 | 1180 | 11923 | 180.7 | 181.38 | 73.44 | Bus Voltage | | 124.58 | System Frequency | | | 50.06 | Accu. Generated Energy | | | 753738.57Kwh | | | |

Appendix $B_5$: Hourly Readings of Plant Performance Variables for 18/03/2014

| | | | | | | | | | | | | | | | | Date: | 3/18/2014 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | 34.5kV Bus Voltage | | | | | | Outgoing | | | the Main Circuit | | | Branches | | | LV side of the M Trfm | | | M Trfm | M Trfm | Envir. | Global |
| | A | B | C | AB | AC | BC | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Oil T | Coil T | Temp. | Radiat |
| | kV | kV | kV | kV | kV | kV | A | kW | kVar | A | kW | kVar | A | kW | kVar | A | kW | kVar | ℃ | ℃ | ℃ | wh/m2 |
| 6am | 19.3 | 19.1 | 18.8 | 33.4 | 32.74 | 32.9 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 33.5 | 35.5 | 25 | 0 |
| 7am | 19.6 | 19.3 | 19.2 | 33.8 | 33.3 | 33.4 | 2.26 | 150.7 | -8.37 | 2.26 | 150.7 | -8.37 | | | | 239.1 | 156.4 | -6.6 | 33.7 | 35.3 | 26 | 112 |
| 8am | 19.3 | 18.9 | 18.9 | 33.2 | 32.65 | 33 | 10.24 | 608.9 | -43.4 | 10.24 | 608.9 | -43.4 | | | | 931.6 | 624 | -21 | 35.1 | 35.5 | 30 | 388 |
| 9am | 18.8 | 18.5 | 18.5 | 32.4 | 31.9 | 32.2 | 19.73 | 1128 | -54.8 | 19.73 | 1128 | -54.8 | | | | 1725 | 1147 | 0 | 37.3 | 37.1 | 33 | 615 |
| 10am | 19 | 18.7 | 18.7 | 32.8 | 32.27 | 56 | 27.32 | 1575 | -76.1 | 27.32 | 1575 | -76.1 | | | | 2380 | 1600 | -17 | 42.6 | 39.5 | 35 | 891 |
| 11am | 19.3 | 19 | 19 | 33.3 | 32.83 | 33.1 | 29.75 | 1742 | -86 | 29.75 | 1742 | -86 | | | | 2583 | 1763 | 0 | 47.9 | 45.7 | 37 | 1023 |
| 12pm | 20.1 | 19.8 | 19.8 | 34.7 | 34.28 | 34.5 | 29.85 | 1823 | -71.6 | 29.85 | 1823 | -71.6 | | | | 2600 | 1851 | 13.2 | 53.9 | 51.8 | 38 | 756 |
| 13pm | 19.9 | 19.5 | 20.1 | 35.2 | 34.8 | 35 | 29.14 | 1803 | -61.7 | 29.14 | 1803 | -61.7 | | | | 2525 | 1825 | 16.1 | 57.2 | 54.8 | 39 | 1069 |
| 14pm | 19.8 | 19.5 | 19.4 | 34.1 | 33.62 | 33.9 | 23.31 | 1399 | -68.5 | 23.31 | 1399 | -68.5 | | | | 2016 | 1407 | 0 | 58.6 | 55.9 | 40 | 797 |
| 15pm | 19.8 | 19.4 | 19.4 | 34 | 33.59 | 33.8 | 21.45 | 1283 | -60.1 | 21.45 | 1283 | -60.1 | | | | 1874 | 1309 | 0 | 57.2 | 56 | 41 | 1093 |
| 16pm | 19.3 | 19 | 18.9 | 33.2 | 32.81 | 33 | 16.17 | 947.6 | -45.7 | 16.17 | 947.6 | -45.7 | | | | 1427 | 965.2 | -12 | 55.6 | 55.6 | 41 | 553 |
| 17pm | 19.1 | 18.8 | 18.7 | 32.9 | 32.43 | 32.6 | 6.91 | 404.2 | -44.2 | 6.91 | 404.2 | -44.2 | | | | 631.6 | 412.8 | -38 | 53.4 | 53.4 | 40 | 257 |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |
| Time | #1 Inverter | | | | #2 Inverter | | | | #3 Inverter | | | | #4 Inverter | | | | #5 Inverter | | | | | |
| | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Curren | Active | Temp. | | |
| 6am | 0 | 0 | 0 | 34.3 | 0 | 0 | 0 | 33.69 | 0 | 0 | 0 | 35.49 | 0 | 0 | 0 | 30.09 | 0 | 0 | 0 | 34.3 | | Total |
| 7am | 401 | 27 | 25 | 33.1 | 397.8 | 35 | 30.99 | 33.09 | 400.8 | 27.99 | 25.99 | 34.89 | 399 | 30 | 27 | 27.69 | 397.8 | 60 | 38 | 33.7 | daily | mont |
| 8am | 398 | 140 | 103 | 34.3 | 394.9 | 178 | 131 | 33.69 | 397.8 | 143.9 | 105 | 35.99 | 396 | 147 | 108 | 30.09 | 392.9 | 232 | 152 | 33.7 | oper | hiy |
| 9am | 398 | 316 | 227 | 36 | 395.9 | 289 | 211.9 | 35.49 | 398.8 | 293.9 | 211.9 | 37.19 | 396 | 305 | 220 | 31.29 | 399.8 | 399 | 268 | 33.7 | atio | oper |
| 10am | 399 | 436 | 311 | 37.8 | 396.8 | 435 | 311.9 | 37.19 | 399.8 | 436.8 | 309.9 | 38.98 | 398 | 439 | 314 | 32.49 | 406.8 | 559 | 384 | 34.9 | nal | ation |
| 11am | 400 | 480 | 343 | 39.6 | 397.8 | 485 | 346.9 | 38.98 | 400.8 | 482.8 | 342.9 | 40.78 | 400 | 484 | 354 | 34.89 | 414.8 | 604 | 423 | 36 | hrs | al hrs |
| 12pm | 402 | 499 | 370 | 42 | 399.8 | 487 | 352.9 | 41.38 | 402.8 | 501.8 | 353.9 | 42.58 | 401 | 495 | 356 | 36.59 | 433.8 | 603 | 442 | 37.2 | 11hrs | |
| 13pm | 401 | 490 | 350 | 43.8 | 399.8 | 479 | 346.9 | 42.58 | 401.8 | 507.8 | 353.9 | 43.78 | 401 | 486 | 344 | 38.39 | 439.8 | 589 | 437 | 38.4 | | |
| 14pm | 401 | 379 | 280 | 45 | 398.8 | 351 | 250.9 | 43.78 | 400.8 | 311.9 | 224.9 | 44.98 | 400 | 403 | 313 | 38.98 | 422.8 | 497 | 355 | 39 | | |
| 15pm | 400 | 348 | 251 | 45 | 398.8 | 349 | 254.9 | 43.38 | 400.8 | 353.9 | 249.9 | 44.98 | 399 | 358 | 255 | 38.98 | 421.8 | 438 | 311 | 39.6 | | |
| 16pm | 398 | 250 | 182 | 45 | 396.8 | 254 | 184.9 | 43.78 | 398.8 | 252.9 | 183.9 | 43.78 | 397 | 259 | 188 | 37.79 | 408.8 | 338 | 231 | 39.6 | | |
| 17pm | 397 | 109 | 81 | 43.8 | 394.9 | 106 | 80.97 | 42.58 | 397.8 | 108 | 78.97 | 43.78 | 396 | 108 | 81 | 37.79 | 391.9 | 152 | 97 | 39 | | |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | Daily Delieved Energy | | | 12720.00 Kwh | | | |
| | | | | | | | | | | | | | | | | Daily Generated Energy | | | 12869.33kwh | | | |
| | | | | | | | | | | | | | | | | Mntly Accu. Del. Energy | | | 213402.00kwh | | | |
| Outgoing | | | LV Side | | | Site Consumed | | | Current | | -0.81 | F6S Pressure | | | 0.55 | Mntly Accm Gen Energy | | | 215934.73Kwh | | | |
| 6am | 18pm | Qty. | 6am | 18pm | Qty. | 6am | 18pm | Qty. | Battery Voltage | | 132.87 | 415V Voltage | | | 411 | Accum.Delivered Energy | | | 812100.00kwh | | | |
| 1147 | 1151 | 12720 | 1206 | 1210 | 12789 | 186.6 | 187.3 | 79.92 | Bus Voltage | | 124.58 | System Frequency | | | 50.1 | Accu.Generated Energy | | | 841047.83Kwh | | | |

Appendix $B_6$: Hourly Readings of Plant Performance Variables for 25/04/2014

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | Date: | 4/25/2014 | | | | |
| Time | 34.5kV Bus Voltage | | | | | | Outgoing | | | the Main Circuit | | | Branches | | | LV side of the M Trfm | | | M Trfm | M Trfm | Envir. | Global |
| | A | B | C | AB | AC | BC | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Oil T | Coil T | Temp. | Radiat |
| | kV | kV | kV | kV | kV | kV | A | kW | kVar | A | kW | kVar | A | kW | kVar | A | kW | kVar | ℃ | ℃ | ℃ | wh/m2 |
| 6am | 19.53 | 19.2 | 19.05 | 33.7 | 32.7 | 33.3 | 0.44 | -12.94 | 36.53 | 0.44 | -12.94 | 36.53 | | | | 52.73 | -11.69 | 37.26 | 35.76 | 37.18 | 28.8 | 8 |
| 7am | 19.12 | 18.82 | 18.73 | 32.98 | 32.48 | 32.68 | 5.33 | 318.91 | -38.06 | 5.33 | 318.91 | -38.06 | | | | 499.22 | 327.34 | -32.2 | 35.87 | 37.13 | 30.1 | 227 |
| 8am | 18.55 | 18.29 | 18.18 | 32.03 | 31.56 | 31.72 | 14.27 | 809.85 | -38.82 | 14.27 | 809.85 | -38.82 | | | | 1260.9 | 830.03 | -13.2 | 36.71 | 37.03 | 31.6 | 470 |
| 9am | 18.62 | 18.34 | 18.18 | 32.18 | 31.57 | 31.75 | 23.76 | 1348.73 | -57.08 | 23.76 | 1348.7 | -57.08 | | | | 2067.2 | 1375.11 | 11.69 | 38.45 | 38.29 | 33.3 | 776 |
| 10am | 20.34 | 20.04 | 19.97 | 35.07 | 34.64 | 34.79 | 27.17 | 1677.54 | -72.31 | 27.17 | 1677.5 | -72.31 | | | | 2347.3 | 1697.33 | 10.23 | 43.35 | 40.66 | 35 | 983 |
| 11am | 20.01 | 19.65 | 19.6 | 34.45 | 33.96 | 34.22 | 27.6 | 1673.73 | -74.59 | 27.6 | 1673.7 | -74.59 | | | | 2403.5 | 1704.64 | 9.5 | 47.57 | 45.2 | 35.7 | 1025 |
| 12pm | 19.81 | 19.49 | 19.41 | 34.15 | 33.67 | 33.88 | 29.43 | 1768.87 | -81.44 | 29.43 | 1769 | -81.4 | | | | 2551.2 | 1794.51 | 8.04 | 50.95 | 49.52 | 37.8 | 1110 |
| 13pm | 20.31 | 20.02 | 19.93 | 35.04 | 34.6 | 34.74 | 27.1 | 1671.45 | -70.79 | 27.1 | 1671 | -70.8 | | | | 2350.8 | 1695.14 | 0 | 53.48 | 52.85 | 39 | 1070 |
| 14pm | 19.68 | 19.39 | 19.27 | 33.95 | 33.46 | 33.63 | 26.16 | 1561.84 | -67.74 | 26.16 | 1562 | -67.7 | | | | 2271.1 | 1592.12 | 14.61 | 54.06 | 53 | 39.7 | 1012 |
| 15pm | 19.91 | 19.63 | 19.51 | 34.37 | 33.88 | 34.01 | 19.83 | 1204.11 | -47.95 | 19.83 | 1204 | -48 | | | | 1725 | 1220.94 | 0 | 53.53 | 53 | 40.5 | 1002 |
| 16pm | 19.68 | 19.68 | 19.28 | 33.96 | 33.5 | 33.64 | ##### | 899.66 | -43.38 | 14.91 | 899.7 | -43.4 | | | | 1310.2 | 914.06 | -11 | 52.95 | 53.06 | 40.7 | 557 |
| 17pm | 19.47 | 19.47 | 19.08 | 33.62 | 33.13 | 33.28 | 2.58 | 160.6 | -11.42 | 2.58 | 160.6 | -11.42 | | | | 256.64 | 165.86 | -8.04 | 50.47 | 52.27 | 39.4 | 110 |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |

| Time | #1 Inverter | | | | #2 Inverter | | | | #3 Inverter | | | | #4 Inverter | | | | #5 Inverter | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | | |
| 6am | 398.8 | 0 | 0 | 37.19 | 396.84 | 0 | 0 | 36.59 | 399.84 | 0 | 0 | 37.79 | 397.84 | 0 | 0 | 37 | 395.85 | 0 | 0 | 37.19 | | Total monthiy operational hrs |
| 7am | 397.8 | 67.97 | 53.98 | 35.99 | 395.85 | 86.97 | 67.97 | 35.99 | 397.84 | 88.97 | 67.97 | 37.19 | 396.84 | 70.97 | 56.98 | 36.98 | 388.85 | 120 | 76.97 | 34.89 | | |
| 8am | 395 | 241 | 174 | 37.2 | 393.9 | 238.9 | 173.93 | 37.19 | 395.84 | 236.91 | 168.93 | 38.39 | 393.85 | 224.9 | 157.9 | 37.79 | 380.85 | 308.9 | 196.9 | 34.89 | daily operational hrs | |
| 9am | 395.9 | 334.9 | 240.9 | 37.79 | 393.85 | 333.87 | 240.91 | 37.79 | 396.84 | 334.87 | 242.91 | 38.98 | 393.85 | 338.9 | 244.9 | 38.98 | 389.85 | 457.8 | 303.9 | 34.89 | | |
| 10am | 403.8 | 430.8 | 311.9 | 39.58 | 400.84 | 402.84 | 294.88 | 39.58 | 403.84 | 430.83 | 308.88 | 40.78 | 401.84 | 434.8 | 311.9 | 40.18 | 437.83 | 528.8 | 389.9 | 35.99 | | |
| 11am | 401.8 | 473.8 | 339.9 | 40.78 | 399.84 | 455.82 | 333.87 | 40.78 | 401.84 | 469.81 | 339.87 | 42.58 | 400.84 | 477.8 | 346.9 | 41.38 | 426.83 | 550.8 | 396.8 | 36.59 | | |
| 12pm | 400.8 | 501.8 | 357.9 | 42.58 | 398.84 | 486.81 | 350.86 | 42.58 | 401.84 | 490.81 | 345.86 | 43.78 | 399.84 | 491.8 | 352.9 | 43.18 | 425.83 | 590.8 | 424.8 | 37.79 | 11hrs | 274hrs |
| 13pm | 402.8 | 464.8 | 335.9 | 44.38 | 400.84 | 446.83 | 325.87 | 43.78 | 402.84 | 457.82 | 328.87 | 45.48 | 401.84 | 456.8 | 331.9 | 44.98 | 433.83 | 564.8 | 413.8 | 38.98 | | |
| 14pm | 400.8 | 446.8 | 324.9 | 44.98 | 398.84 | 442.83 | 321.88 | 44.38 | 400.84 | 438.83 | 312.88 | 45.48 | 398.84 | 430.8 | 310.9 | 44.98 | 420.84 | 510.8 | 359.9 | 38.98 | | |
| 15pm | 400.8 | 316.9 | 230.9 | 45.48 | 398.84 | 313.88 | 228.91 | 44.98 | 400.84 | 315.88 | 226.91 | 46.08 | 398.84 | 321.9 | 234.9 | 45.48 | 422.83 | 409.8 | 289.9 | 39.58 | | |
| 16pm | 399.8 | 232.9 | 169.9 | 45.48 | 397.84 | 226.91 | 169.93 | 44.38 | 400.84 | 229.91 | 167.93 | 46.08 | 399.84 | 228.9 | 171.9 | 45.48 | 405.84 | 316.9 | 214.9 | 40.18 | | |
| 17pm | 398.8 | 32.99 | 27.99 | 44.98 | 396.84 | 31.99 | 27.99 | 43.78 | 398.84 | 31.99 | 27.99 | 44.98 | 397.84 | 33.99 | 29.99 | 44.38 | 396.84 | 60.98 | 37.99 | 40.18 | | |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | Daily Delieved Energy | 12630.00kwh |
| | | | | | | | | | | | | | aily Generated Energy | 12798.63kwh |
| | | | | | | | | | | | | | Mntly Accu. Del. Energy | 285270.00kwh |
| Outgoing | | | LV Side | | | Site Consumed | | | Current | -0.81 | FoS Pressure | 0.55 | Mntly Accm Gen Energy | 289286.17Kwh |
| 6am | 18pm | Qty. | 6am | 18pm | Qty. | 6am | 18pm | Qty. | Battery Voltage | 132.81 | 415V Voltage | 401.8 | ccum. Delivered Energy | 1247190.00kwh |
| 1292 | 1296 | 12630 | 1357 | 1362 | 12732 | 213.57 | 214.19 | 66.96 | Bus Voltage | 124.58 | System Frequency | 50.08 | Accu. Generated Energy | 1268443.97Kwh |

Appendix B$_7$: Hourly Readings of Plant Performance Variables for 20/04/2014

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | Date: | 4/20/2014 | | | | | |
| Time | 34.5kV Bus Voltage | | | | | | Outgoing | | | the Main Circuit | | | Branches | | | LV side of the M Trfm | | | M Trfm | M Trfm | Envir. | Global |
| | A | B | C | AB | AC | BC | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Current | Active | Idle | Oil T | Coil T | Temp. | Radiat |
| | kV | kV | kV | kV | kV | kV | A | kW | kVar | A | kW | kVar | A | kW | kVar | A | kW | kVar | ℃ | ℃ | ℃ | wh/m2 |
| 6am | 19.45 | 19.13 | 19.03 | 33.54 | 33 | 33.25 | 0.51 | 31.21 | 25.88 | 0.51 | 31.21 | 0.51 | | | | 62.11 | 33.61 | 27.03 | 35.25 | 36.7 | 298.6 | 9 |
| 7am | 19.2 | 19.91 | 18.79 | 33.13 | 32.62 | 32.8 | 3.72 | 228.34 | -25.55 | 3.72 | 228.21 | -25.55 | | | | 362.11 | 234.54 | -14.6 | 35.29 | 36.66 | 29.9 | 203 |
| 8am | 19.57 | 19.28 | 19.2 | 33.76 | 33.29 | 33.49 | 15.23 | 911.84 | -40.34 | 15.23 | 911.84 | -40.34 | | | | 1341.8 | 929.4 | -5.85 | 36.5 | 37.39 | 31.6 | 486 |
| 9am | 18.94 | 18.63 | 18.55 | 32.65 | 32.17 | 32.39 | 21.46 | 1235.32 | -51.76 | 21.46 | 1235.3 | -51.76 | | | | 1872.7 | 1261.13 | 10.23 | 39.29 | 38.34 | 33.4 | 740 |
| 10am | 19.28 | 19 | 18.91 | 33.27 | 32.82 | 32.99 | 27.2 | 1590.77 | -77.64 | 27.2 | 1590.8 | -77.64 | | | | 2363.7 | 1618.42 | 0 | 44.41 | 42.14 | 35.5 | 955 |
| 11am | 19.3 | 19.03 | 18.92 | 33.3 | 32.85 | 33.02 | 29.56 | 1732.34 | -84.49 | 29.56 | 1732.3 | -84.49 | | | | 2561.7 | 1755.06 | 29.23 | 48.73 | 46.41 | 36.8 | 1075 |
| 12pm | 19.29 | 18.98 | 18.89 | 33.25 | 32.77 | 32.99 | 30.35 | 1773.44 | -76.11 | 30.35 | 1773 | -76.1 | | | | 2621.5 | 1795.24 | 9.5 | 52.27 | 50.63 | 37.8 | 1125 |
| 13pm | 16.54 | 16.28 | 16.21 | 28.5 | 28.13 | 28.27 | 34.67 | 1723.97 | -149.2 | 34.67 | 1724 | -149 | | | | 2080.1 | 1192.44 | -47.5 | 50.16 | 49.47 | 38.7 | 1084 |
| 14pm | 19.58 | 19.39 | 19.26 | 33.86 | 33.49 | 33.5 | 0.28 | -13.7 | -6.09 | 0.28 | -13.7 | -6.09 | | | | 17.58 | -12.42 | 0 | 49.15 | 49.47 | 39.3 | 1009 |
| 15pm | 19.12 | 18.83 | 18.7 | 33 | 32.64 | 32.64 | 5.82 | 345.32 | -43.38 | 5.82 | 345.3 | -43.4 | | | | 539.06 | 356.56 | -36.5 | 44.2 | 45.88 | 38.1 | |
| 16pm | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | 0 | - | 0 | 0 | | | | 0 | 0 | 0 | 40.93 | 41.93 | 32.7 | 204 |
| 17pm | 19.65 | 19.55 | 19.44 | 34.05 | 33.77 | 33.87 | 0.37 | 25.45 | 20.22 | 0.32 | 25.45 | 20.22 | | | | 70.31 | 47.49 | 18.27 | 40.72 | 41.72 | 33.5 | 75 |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | | | | | | | |
| Time | #1 Inverter | | | | #2 Inverter | | | | #3 Inverter | | | | #4 Inverter | | | | #5 Inverter | | | | | |
| | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | Voltage | Current | Active | Temp. | | |
| 6am | 397.8 | 0 | 0 | 35.99 | 395.84 | 0 | 0 | 35.9 | 398.84 | 0 | 0 | 37.19 | 396.84 | 0 | 0 | 37.19 | 388.85 | 0 | 0 | 35.49 | daily operational hrs | Total monthiy operational hrs |
| 7am | 397.8 | 70.97 | 55.98 | 35.99 | 395.85 | 53.98 | 45.98 | 36.59 | 398.84 | 70.97 | 55.98 | 37.19 | 396.84 | 74.97 | 55.98 | 37.19 | 388.85 | 97.96 | 62.98 | 35.49 | | |
| 8am | 400 | 250 | 181 | 37.2 | 397.8 | 197.9 | 147.94 | 37.19 | 400.84 | 246.9 | 178.93 | 38.39 | 397.84 | 248.9 | 181.9 | 38.39 | 400.84 | 323.9 | 220.9 | 34.89 | | |
| 9am | 397.8 | 347.9 | 249.9 | 37.79 | 394.85 | 344.86 | 249.9 | 38.86 | 397.84 | 346.86 | 246.9 | 39.58 | 395.85 | 348.9 | 249.9 | 39.58 | 404.84 | 450.8 | 306.9 | 35.49 | | |
| 10am | 399.8 | 442.8 | 316.9 | 39.58 | 397.84 | 440.83 | 316.88 | 39.58 | 399.84 | 442.83 | 314.88 | 41.38 | 397.84 | 447.8 | 318.9 | 40.78 | 414.84 | 556.8 | 388.9 | 36.59 | | |
| 11am | 399.8 | 483.8 | 345.9 | 40.78 | 397.84 | 489.81 | 349.86 | 40.78 | 399.84 | 483.81 | 342.87 | 42.58 | 398.84 | 489.8 | 349.9 | 42.58 | 414.84 | 606.8 | 423.8 | 37.79 | | |
| 12pm | 399.8 | 496.8 | 352.9 | 42.58 | 397.84 | 487.81 | 349.86 | 42.58 | 400.84 | 490.81 | 347.86 | 44.38 | 398.84 | 494.8 | 351.9 | 44.38 | 417.84 | 608.8 | 428.8 | 38.39 | 11hrs | 219hrs |
| 13pm | 387.9 | 497.8 | 342.9 | 43.18 | 385.85 | 499.8 | 347.86 | 42.58 | 388.85 | 488.81 | 338.87 | 42.58 | 384.85 | 501.8 | 508.8 | 42.58 | 358.86 | 708.7 | 427.8 | 39.58 | | |
| 14pm | 398.8 | 327.9 | 233.9 | 44.98 | 398.84 | 357.85 | 270.89 | 43.18 | 400.84 | 389.85 | 276.89 | 42.58 | 398.84 | 404.8 | 296.9 | 43.18 | 410.84 | 325.8 | 366.9 | 39.58 | | |
| 15pm | 402.8 | 96.96 | 74.97 | 42.58 | 400.84 | 91.96 | 72.97 | 40.78 | 402.81 | 93.96 | 71.97 | 40.78 | 400.84 | 95.96 | 73.97 | 40.78 | 409.84 | 135 | 90.96 | 38.39 | | |
| 16pm | 0 | 0 | 0 | 38.98 | 0 | 0 | 0 | 38.98 | 0 | 0 | 0 | 37.79 | 0 | 0 | 0 | 35.99 | 0 | 0 | 0 | 38.39 | | |
| 17pm | 398.8 | 20.99 | 18.9 | 39.58 | 397.84 | 16.99 | 16.99 | 38.98 | 398.84 | 18.99 | 16.99 | 37.79 | 397.84 | 18.99 | 17.99 | 36.59 | 0 | 0 | 0 | 38.39 | | |
| 18pm | | | | | | | | | | | | | | | | | | | | | | |
| 19pm | | | | | | | | | | | | | | | | Daily Delieved Energy | | | 8790.00kwh | | | |
| | | | | | | | | | | | | | | | | Daily Generated Energy | | | 8941.93kwh | | | |
| | | | | | | | | | | | | | | Mntly Accu. Del. Energy | | | | | 227640.00kwh | | | |
| Outgoing | | | LV Side | | | Site Consumed | | | Current | | -0.81 | FaS Pressure | | | 0.55 | Mntly Accm Gen Energy | | | 230604.02Kwh | | | |
| 6am | 18pm | Qty. | 6am | 18pm | Qty. | 6am | 18pm | Qty. | Battery Voltage | | 132.81 | 415V Voltage | | | 401.8 | Accum Delivered Energy | | | 1189560.00kwh | | | |
| 1274 | 1277 | 8790 | 1339 | 1342 | 8863.1 | 210.35 | 211.08 | 78.84 | Bus Voltage | | 124.58 | System Frequency | | | 50.08 | Accu. Generated Energy | | | 1209761.82Kwh | | | |

## APPENDIX C

$C_1$ Rstudio Simulated Values for the Year 2013

| **Month** | **Energy Gen. (kWh)** | **Optimised Energy (kWh)** | **Max. Irrad (Wh/m$^2$)** | **Min. Irrad. (Wh/m$^2$)** | **Max. Envir. Temp. ($^o$C)** | **Min. Envir. Temp.($^o$C)** | **Cell Temp. ($^o$C)** |
|---|---|---|---|---|---|---|---|
| Jan. | 242555.8 | 340340.2 | 1002 | 932 | 36.2 | 35.0 | 50.7 |
| Feb. | 240770.0 | 445679.3 | 1072 | 930 | 36.0 | 34.5 | 42.5 |
| Mar. | 299741.8 | 416871.6 | 1002 | 879 | 36.0 | 34.0 | 54.4 |
| Apr. | 278799.0 | 386632.1 | 1107 | 723 | 37.0 | 35.0 | 60.0 |
| May | 292741.4 | 329473.0 | 1086 | 779 | 36.9 | 30.9 | 58.4 |
| Jun. | 254220.0 | 105787.3 | 872 | 78 | 32.0 | 22.8 | 54.8 |
| Jul. | 203324.7 | 292890.9 | 1004 | 144 | 34.0 | 27.5 | 52.7 |
| Aug. | 116057.2 | 186551.9 | 873 | 332 | 29.5 | 21.8 | 42.6 |
| Sept. | 269507.7 | 375682.5 | 979 | 375 | 33.0 | 21 | 52.4 |
| Oct. | 327921.7 | 339897.3 | 1150 | 384 | 34.0 | 30.9.0 | 55.3 |
| Nov. | 321748.2 | 426281.1 | 946 | 890 | 36.0 | 33.8 | 56.4 |
| Dec. | 270171.2 | 373478.7 | 1056 | 640 | 35.2 | 28.6 | 55.8 |
| Total | 3117558.7 | 4019565.9 | | | | | |

**$C_2$** Rstudio Simulated Values for the Year 2014

| **Month** | **Energy Gen. (kwh)** | **Optimised Energy (kwh)** | **Max. Irradiance (wh/m²)** | **Min. Irradiance (wh/m²)** | **Max. Evir. Temp. (°C)** | **Min. Evir. Temp. (°C)** | **Cell Temp (°C)** |
|---|---|---|---|---|---|---|---|
| Jan | 293001.4 | 351601.0 | 1006 | 910 | 37.0 | 29.8 | 55.0 |
| Feb | 214454.5 | 257344.7 | 1078 | 983 | 36.5 | 30.5 | 55.0 |
| Mar | 395064.3 | 474076.5 | 1002 | 925 | 36.0 | 31.0 | 44.2 |
| Apr | 360307.8 | 432368.7 | 1139 | 952 | 35.6 | 29.8 | 57.5 |
| May | 347509.1 | 417010.2 | 1097 | 723 | 36.9 | 30.0 | 58.0 |
| Jun | 354440.7 | 487328.1 | 1175 | 943 | 35.8 | 30.4 | 41.0 |
| Jul | 343339.6 | 512889.8 | 1127 | 571 | 35.0 | 32.0 | 50.3 |
| Aug | 277333.1 | 332799.0 | 834 | 519 | 33.2 | 30.2 | 54.5 |
| Sept | 328237.5 | 393884.3 | 1224 | 975 | 33.2 | 22.4 | 57.0 |
| Oct | 382538.8 | 459045.9 | 1101 | 930 | 35.7 | 30.4 | 56.0 |
| Nov | 319835.7 | 383802.1 | 992 | 925 | 35.9 | 30.9 | 55.7 |
| Dec | 3471767.5 | 4766120.3 | 962 | 905 | 33.8 | 30.0 | 41.5 |
| Total | 7087830 | 9268270.6 | | | | | |

**$C_3$** Rstudio Simulated Values for the Year 2015

| **Month** | **Energy gen. (kWh)** | **Optimised Energy (kWh)** | **Max. Irrad ($Wh/m^2$)** | **Min. Irrad. ($Wh/m^2$)** | **Max. Invir. Temp. ($^oC$)** | **Min. Envir. Temp.($^oC$)** | **Cell Temp. ($^oC$)** |
|---|---|---|---|---|---|---|---|
| Jan. | 368764.8 | 472517.1 | 956 | 898 | 35.1 | 33.1 | 53.0 |
| Feb. | 280540.1 | 366647.4 | 889 | 504 | 36.0 | 34.6 | 58.7 |
| Mar. | 337681.4 | 435217.0 | 1124 | 811 | 36.2 | 34.5 | 58.5 |
| Apr. | 337408.8 | 434889.9 | 1055 | 986 | 36.4 | 35.2 | 53.1 |
| May | 341967.2 | 440359.9 | 1079 | 469 | 37.4 | 35 | 55.9 |
| Jun. | 244077.0 | 322891.5 | 1069 | 640 | 33.5 | 32 | 62.1 |
| Jul. | 223190.7 | 297828.1 | 1025 | 699 | 35.0 | 33.1 | 57.3 |
| Aug. | 264371.1 | 347244.6 | 992 | 742 | 35.0 | 34.1 | 55.8 |
| Sept. | 241623.9 | 319948.0 | 1015 | 897 | 36.1 | 34.5 | 56.8 |
| Oct. | 278378.8 | 364053.9 | 1047 | 992 | 36.8 | 35.5 | 56.5 |
| Nov. | 283399.8 | 370079.1 | 1056 | 864 | 35.4 | 34.6 | 57.2 |
| Dec. | 251515.7 | 321818.1 | 1048 | 984 | 35.1 | 33.3 | 56.6 |
| Total | 3452919.3 | 4493494.6 | | | | | |

$C_4$ Rstudio Simulated Values for the Year 2016

| Month | Energy Gen. (kWh) | Optimised Energy (kWh) | Max. Irrad ($Wh/m^2$) | Min. Irrad. ($Wh/m^2$) | Max. Envir. Temp. ($^oC$) | Min. Envir. Temp.($^oC$) | Cell Temp. ($^oC$) |
|---|---|---|---|---|---|---|---|
| Jan. | 240154.2 | 307684.3 | 1006 | 368 | 35.5 | 33.6 | 50.7 |
| Feb. | 246899.9 | 324279.2 | 1041 | 631 | 36.7 | 35.6 | 57.5 |
| Mar. | 296774.2 | 384728.3 | 1016 | 642 | 37.5 | 36.1 | 58.4 |
| Apr. | 276038.7 | 350645.7 | 1130 | 455 | 37.0 | 35.1 | 60.2 |
| May | 289842.8 | 365810.7 | 1090 | 658 | 35.6 | 33.1 | 59.2 |
| Jun. | 264977.1 | 345971.8 | 1056 | 916 | 34.0 | 30.9 | 58.3 |
| Jul. | 174866.0 | 237838.3 | 1028 | 921 | 31.8 | 29.6 | 58.7 |
| Aug. | 274559.6 | 358370.8 | 1092 | 662 | 31.6 | 29.4 | 56.7 |
| Sept. | 324954.9 | 418845.2 | 1038 | 894 | 32.5 | 30.4 | 55.4 |
| Oct. | 38713.40 | 58455.4 | 1024 | 846 | 34.8 | 32.7 | 48.9 |
| Nov. | 316637.4 | 409964.2 | 1033 | 936 | 37.2 | 35.0 | 51.2 |
| Dec. | 368049.7 | 470558.9 | 1065 | 923 | 34.6 | 32.6 | 49.9 |
| Total | 3112467.9 | 4033152.8 | | | | | |

## APPENDIX D

### Rstudio Simulation Codes Module Equation

```
max <- function(x3, x2){

p <- 1-(0.00485*(x2 - 25)*0.93*0.15*x3*150*16729.71)

p

}
```

2013 Optimal values

```
max(1002/1000, 50.7)  340340.2

max(1072/1000, 42.5)  445679.3

max(1002/1000, 54.4)  416871.6

max(1107/1000, 60.0)  386632.1

max(1086/1000, 58.4)  329473.0

max(872/1000, 54.8)   105787.3

max(1004/1000, 52.7)  292890.9

max(873/1000, 42.6)   186551.9

max(979/1000, 52.4)   375682.5

max(1150/1000, 55.3)  33989.3

max(946/1000, 56.4)   426281.1

max(1056/1000, 55.8)  373478.7
```

2014 Optimal values

```
max(1006/1000, 55)   351601.0

max(1078/1000, 55)   257344.7
```

max(1002/1000, 44.2) 474076.5

max(1139/1000, 57.5) 432368.7

max(1097/1000, 58) 417010.2

max(1175/1000, 41) 487328.1

max(1127/1000, 50.3) 512889.8

max(834/1000, 54.5) 332799.0

max(1224/1000, 57) 393884.3

max(1101/1000, 56) 459045.9

max(992/1000, 55.7) 383802.1

max(962/1000, 41.5) 4766120

2015 Optimal values

max(956/1000, 53) 472517.1

max(889/1000, 58.7) 366647.4

max(1124/1000, 58.5) 435217.0

max(1055/1000, 53.1) 434889.9

max(1079/1000, 55.9) 440359.9

max(1069/1000, 62.1) 322891.5

max(1025/1000, 57.3) 297828.1

max(992/1000, 55.8) 347244.6

max(1015/1000, 56.8) 319948.0

max(1047/1000, 56.5) 364053.9

max(1056/1000, 57.2) 370079.1

max(1048/1000, 56.6) 321818.1

2016 Optimal Values

max(1006/1000, 50.7) 307684.3

max(1041/1000, 57.5) 324279.2

max(1016/1000, 58.4) 384728.3

max(1130/1000, 60.2) 350645.7

max(1090/1000, 59.2) 365810.7

max(1056/1000, 58.3) 345971.8

max(1028/1000, 58.7) 237838.3

max(1092/1000, 56.7) 358370.8

max(1038/1000, 55.4) 418845.2

max(1024/1000, 48.9) 58455.4

max(1033/1000, 51.2) 409964.2

max(1065/1000, 49.9) 470558.9