More than 90 percent of Ghanaian households burn wood or charcoal for cooking. Akosombo Dam on the Volta River is the country's main source of electricity since 1965. Low water levels in the Volta River have periodically caused power shortages in the country since 2007. Ghanaian governments have been pursuing national electrification policy to provide electricity to every Ghanaian community by 2020. However, more than half of the population remains without access to grid-based electricity. Part A of this book analyzed data on sun hours in Northern Ghana to ascertain the potential of solar energy as an alternative energy source. Part B gives an Aqueous Processing approach for Upgrading Metallurgical-Grade Silicon to Solar-Grade. This book could serve as a guide to the Solar Technology Industry, Suppliers, Government agencies, Non Governmental bodies, Researchers in the area of solar energy, or anyone else who may be considering utilizing solar energy. The Governments of Ghana including Non Governmental Organizations could take advantage of the "free" source of energy to provide solar energy materials to communities in Northern Ghana to improve the living standards of the people.

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Solar Energy as a Potential Alternative

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DEDICATION

TO THE BELOVED OTTUOR'S FAMILY OF DAKOMPILAYIR-TUNA AND ALL READERS

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ACRONYMS AND ABBREVIATIONS

BSH – Bright Sunshine Hour

BS – Bright Sunshine

IEO - International Energy Outlook

GCEP - Global Climate & Energy Project
KNUST- Kwame Nkrumah University of Science and Technology

NREL - National Renewable Energy Laboratory

MSD - Meteorological Services Department

NED - Northern Electricity Department

MG-Si - Metallurgical Grade-Silicon

SoG-Si - Solar Grade Silicon

Eh- redaction or oxidation potential

KYOCERA **-** Kyoto Ceramic Co., Ltd.

PV – Photovoltaic

AC – Alternative Current

DC - Direct Current

AGROTEC - Agricultural Operations Technology

GIS - Geographic Information Systems

SWERA - Solar and Wind Energy Resource Assessment

Si - Silicon: B – Boron: Al – Aluminium :Ga – Gallium

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May the good Lord bless you all! Amen.

CHAPTER ONE

1.0 Introduction

1.1 Solar Energy

Energy plays a significant role in life. Humans need energy to operate in industries, agriculture, transport and services. Due to increasing population and technological development, humans consume more energy than before, resulting in higher air pollution, damming of rivers, creation of nuclear waste, and other environmental drawbacks. Almost all energy used today is non-renewable which takes a long time to reproduce.

Solar energy therefore originates from the nuclear reaction within the sun's hot core (i.e. about 6×10^{6}K), and is transmitted to the sun's surface by radiation and hydrogen convection (Roger et al., 2003). Solar energy is the radiant light and heat from the sun that has been harnessed by humans since ancient times using a range of ever-evolving technologies. Solar energy contributes 99.98% of all the energy that drives processes on Earth (Dorothy, 1998).

The sun is an average yellow star that has been radiating energy for nearly five billion years and it consists of hydrogen (70%) and helium (28%) (Kevin, 2001). The sun converts 508 million tons of hydrogen atoms into helium atoms every second, known as nuclear fusion. During the fusion process which occurs at 15 million degree Celsius, a huge amount of energy is released ($3.7\text{x}10^{26}$ J/s) and it is this energy that heats and light the earth. This energy is in the form of electromagnetic radiation which travels as waves and can be described in terms of its wavelength and frequency.

The sun is the primary source of energy for the processes of change at the earth's surface and in the atmosphere (Howard, 1999). Solar radiation provides nearly all the energy that reaches the earth, and it is the fundamental energy source to be considered in a study of the climate system.

Also, the sun is the main source of electromagnetic radiation for all the planets; that is, the source of energy injected into our atmosphere is the sun, which is continually shedding part of its mass by radiating waves of electromagnetic energy and high energy particles into space. This constant emission represents all the energy available to the earth, except for a small amount emanating from the radioactive decay of earth minerals. The sun, our primary source of energy for the Earth, radiates a wide range of electromagnetic waves from infrared to ultraviolet, which only reach us because they can carry energy across the vacuum space (John et al., 1996).

Solar radiation along with secondary solar resources such as wind and wave power, hydroelectricity and biomass accounts for most of the available renewable energy on Earth. Meanwhile, only a minuscule fraction of the available solar energy has been used today. Knowing that no system can run without an input of energy, and living things are not exception (Richard, 1933). For all major ecosystems, both terrestrial and aquatic, the initial source of energy is the sunlight (John et al., 1996). Even though cosmologist predicts that the sun will expire someday (a few billion years from now), but for all practical purposes the sun is an everlasting source of energy.

The amount of solar energy reaching the earth is dissipated in various ways. Some part is reflected back into space, some heats the atmosphere, land and oceans, driving ocean currents and winds. The sun supplies the energy needed to cause evaporation and thus to keep the hydrologic cycle going; it allows green plants to generate food by photosynthesis. More than ample energy is still left over to provide for all human energy needs, in principle. The energy is distributed all over the whole surface of the earth. In other words, it is a much dispersed resource.

However, the intensity of sunlight is a variable parameter which differs from one region to another, and day to day as weather condition changes. The two areas in which solar energy is being used categorically are in space heating and in the generation of electricity, and that together account for the need to harness solar energy.

Direct production of electricity using sunlight is accomplished through photovoltaic cells, also called simply “solar cells”. They do not emit pollutants during operation. For many years they have been the principal power source for satellites and for a few remote areas on earth difficult to reach power lines. Areas of strongest sunlight in the United States have incidents radiation of the order 250 watts per square meter (Carla, 1992). The international energy outlook in 2010 (IEO 2010), projects the total world consumption of market energy to increases by 49 % within 2007-2035 (Figure 1b). The expectation for renewable energy of worlds electricity generation is to increase from 18 %-23% from 2007-2035 (Fig. 1c).

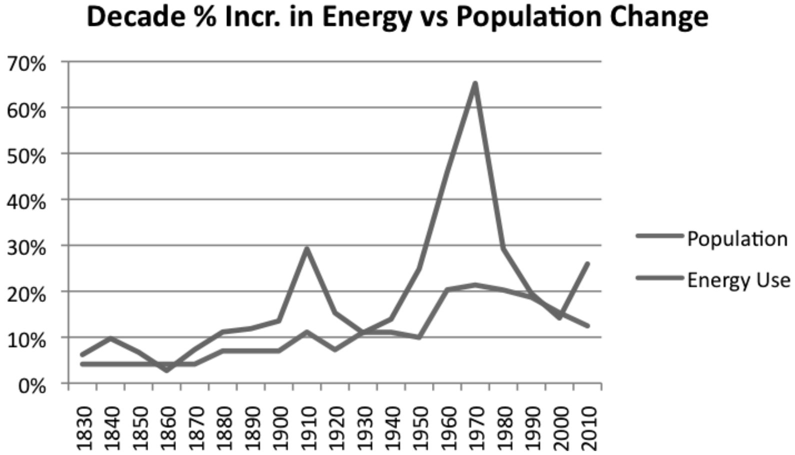


Figure 1.1 (A) Decade percentage increases in energy use compared to population growth (Adapted from Energy Bulletin, 2012).

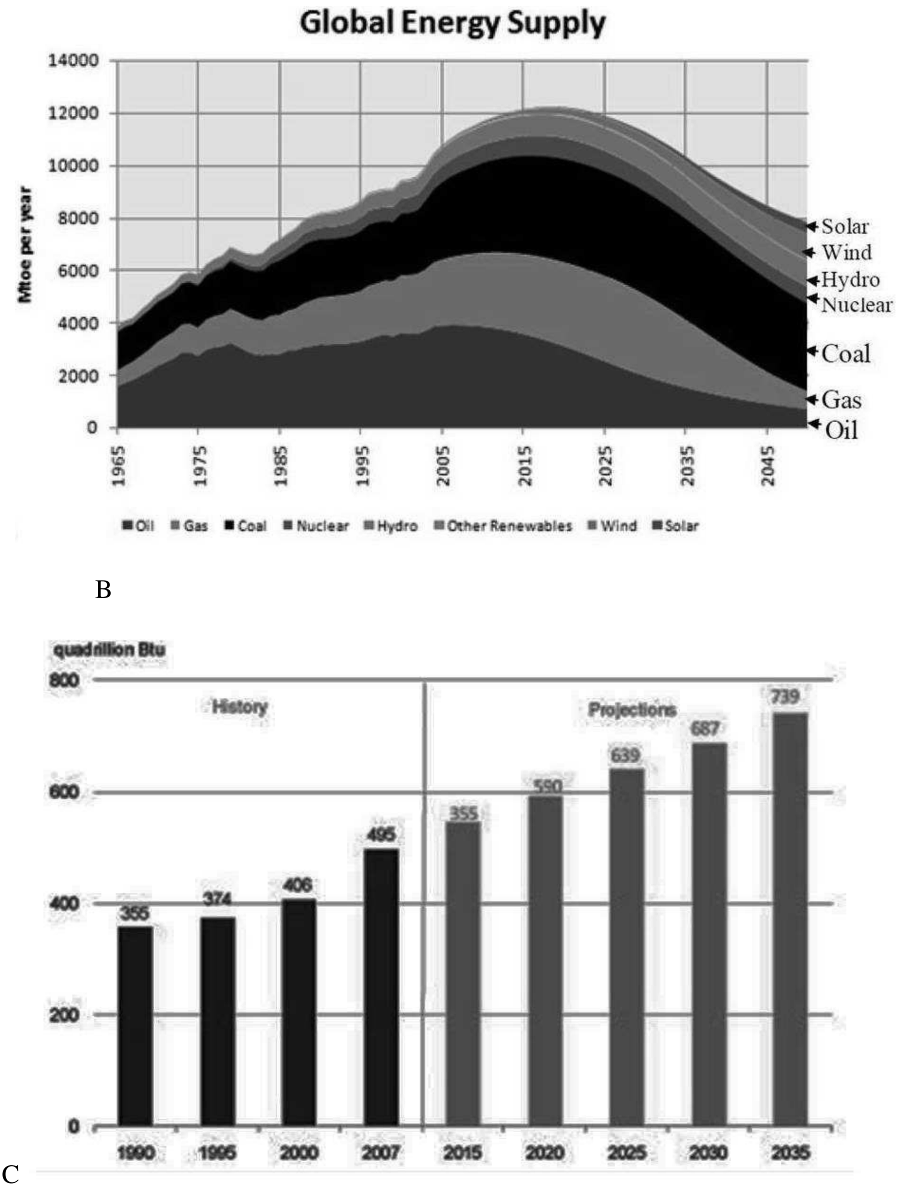


Figure1.1: (B) Global energy supply, (C) World marketed energy consumption (1990-2035). Source: Adapted from U.S. Energy Information Administration, 2010 (IEO2010) Projections.

1.2 Social, Technical and Environmental Aspects of Solar Energy

Photovoltaic solar energy is promoted as a sustainable energy supply technology. Solar energy as a basic source of energy is both non-depledable, and non-polluting. Non-depletable in the sense that, the sun output is remarkably constant; the radiant energy from the sun, called the solar constant strikes the Earth's atmosphere at about 2 calories per cm^2 per minute. The light from the sun is a form of pure energy which does not contain any substance that can pollute the environment. "All the matter and pollution involved in the production of light energy are conveniently left behind the sun some 150 million kilometres away in space" (GCEP, 2006). The energy from the sun is renewable and it helps to protect the environment. In addition, it does not contribute to global warming, acid rains or smog.

1.3 Solar Outputs

The visible solar radiation (i.e. light) comes from a 'cool' (~6000K) outer surface layer called the photosphere. Temperatures rise again in the outer chromospheres (10000K) and corona (10^6K), which is continually expanding into space (Roger et al., 2003). The out flowing hot gases (plasma) from the sun, referred to as the solar wind (with a speed of 1.5×10^6 km/hr), interact with the earth's magnetic field and upper atmosphere (Roger et al., 2003).

The earth intercepts both the normal electromagnetic radiation and energetic particles emitted during solar flares. The sun behaves virtually as a black body; that is, it absorbs all energy received and in turn radiates energy at maximum rate possible for a given temperature.

1.4 Problem Statement

More than 90 percent of Ghanaian households burn wood or charcoal for cooking, but gas and electrical sources of energy are other alternatives (Microsoft ® Encarta ® 2008). Power generated by the Akosombo Dam on the Volta River is the country's main source of electricity since 1965. In 2003 Ghana generated 5.4 billion kilowatt-hours of electricity, virtually all in hydroelectric plants. Until the mid-1990s Ghana was a regular exporter of electricity, but low water levels in the Volta River have periodically caused power shortages in the country since 2007 (Ghana Energy Commission, 2008).

After several years of lower than average rainfall, Ghana's primary generator, the Akosombo Dam, is only able to provide for about 30% of the country's demand (Ghana Energy Commission, 2007). This has resulted in several power shortages and rotating blackouts through the country. At the same time Ghanaian governments have been pursuing a national electrification policy to bringing electricity to every community by 2020. Still, more than half of the population remains without access to grid-based electricity. It is very expensive to build long-distance transmission lines to serve small communities, especially when these communities are relatively poor and cannot afford to pay rates high enough to cover the cost of these services. This then calls for the need for solar energy to support the energy problem in Northern Ghana and the nation as a whole.

1.5 Goal of the Project

The goal of the project is to analyze data on sun hours in the Northern sector of Ghana and ascertain its potential with regard to the energy supply to Northern sector of Ghana, as an alternative energy source.

1.6 Limitations in Solar Energy Transmission

The average amount of solar energy arriving at the top of the atmosphere is about 1330W/m^2 (Williams et al., 1995). About half of this energy is absorbed or reflected by the atmosphere (more at latitudes than at the equator). The energy system of the Earth is in an approximately steady state condition. That is, the amount of energy received by the whole Earth system is approximately equal to the amount of energy flowing out of the system. As shown (Figure 1.2), more than half of all incoming solar radiation is returned to space before doing any work at the earth's surface. That is, about 25 percent is reflected to space by particles or clouds in the atmosphere with 5 percent been reflected on the Earth surface, while 25 percent is absorbed by clouds and the atmosphere. This leaves about 45 percent of incoming solar radiation to be absorbed by the earth's surface (Dorothy et al., 1998).

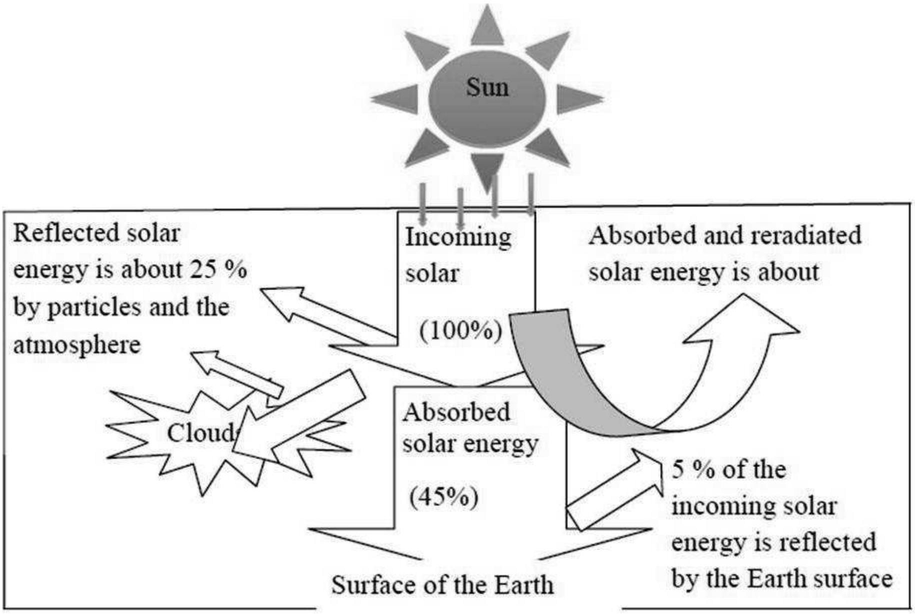


Figure 1.2 Typical Partitioning of Solar Radiation (Source: Redrawn from Dorrothy, 1998).

The cloud covers reduces the amount of radiation that reaches the earth's surface through the reflection of some incoming radiation back to space. The time and day of a year and a change in the reflectivity (i.e. albedo) of the earth affects the amount of radiation absorbed on the earth's surface. Not all the sunlight that reaches the earth penetrates its atmosphere and warms the ground; some is reflected by the atmosphere or by earth's surface.

Moreover, the distance from the sun: the annually changing distance of the earth from the sun produces orbit around the sun and this constitute to the seasonal variation in solar energy received by the earth (Stephen, 1983). Owing to the eccentricity of the earth's, the sun is near to the earth on 3rd January at the perihelion than on 4th July at the aphelion (Roger et al., 2003).

Solar energy is intermittent in its availability, and thus requires that efficient storage or backup systems should be constructed so that power can be supplied continuously. It is also diffuse; it provides a low density of energy per unit of surface collection areas (Colin, 1999).

CHAPTER TWO

2.0 Literature Review

2.1 Solar Cells

The sun serves as a giant nuclear furnace in space, constantly bathing our planet with a free energy supply (Williams et al., 1995). Solar heat drives winds and the hydrologic cycle which is obtained from the thermonuclear reaction in the sun. This reaction is essentially the fusion of hydrogen atoms. This type of energy can be viewed in two aspects; thermal (heat) and electrical (photovoltaic) aspects.

The direct production of electricity from sunlight can be accomplished through photovoltaic cells, also known as solar cells. Solar energy conversion is considered to be the most important alternative energy source for the 21st century, because it is cleaner and inexhaustible than other conventional energy resource. The discovery of photovoltaic effect by Becquerel in 1839 and the creation of the first photovoltaic cell in the early 1950s opened entirely new perspectives on the use of solar energy for the production of electricity. Since then, the evolution of solar technologies still continues at an unprecedented rate. Nowadays, there exist an extremely large variety of solar technologies, and photovoltaic's (PV) have been gaining an increasing market share for the last 20 years.

Nevertheless, global generation of solar electricity is still small compared to the potential of this resource. The current cost of solar technologies and their intermittent nature make them hardly competitive on an energy market still dominated by cheap fossil fuels. From a scientific and technological point of view, the greater challenge is to find new solutions for solar energy systems so that they will become less capital intensive and more efficient. Many research efforts are addressing these problems. Low-cost and/or high-efficiency photovoltaic device concepts are being developed.

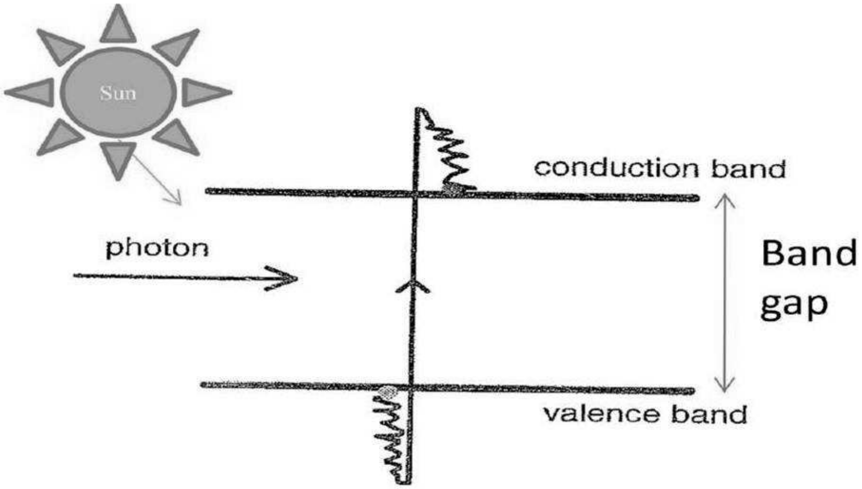
Solar thermal technologies are reaching a mature stage of development and have the potential of becoming competitive for large energy supply.

An inventory of PV installations in the country (Ghana) taken by the Ministry of Energy, revealed that the installed solar PV capacity could exceed 1MW. The Ministry has also installed a 50kWp PV-grid integrated roof demonstration facility at its premises and has also produced technical specifications for solar home systems and communal systems for schools, community and health centers.

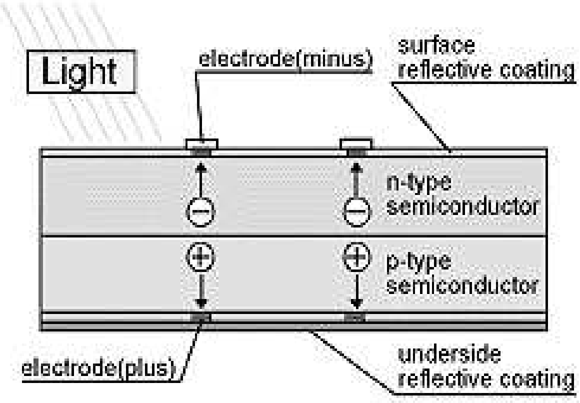
2.2 The Science behind Solar Cells (PV)

Photovoltaic module serves as the key components used to convert sunlight into electricity. Silicon (Si) crystal is the most common semiconductor material used in the conversion of solar energy, based on photovoltaic effect. The property of a material to be able to convert sun light into electric energy means that, it must have the ability to absorb the incident photon through electron promotion to higher energy states, and also there must be an electric field to accelerate the promoted electrons to a direction that will result in electric current. Thus, electrons at the lower energy state are excited by either spontaneous or stimulated emission to move them across the energy gap into the conduction band (Fig. 2.1a). The presence of an electric field to causes charge separation or to accelerate the promoted electrons to a direction that will result in electric current. This creates two polarities such that with the aid of conducting wires, current can flow from the positive polarity to the negative (Fig. 2.1b).

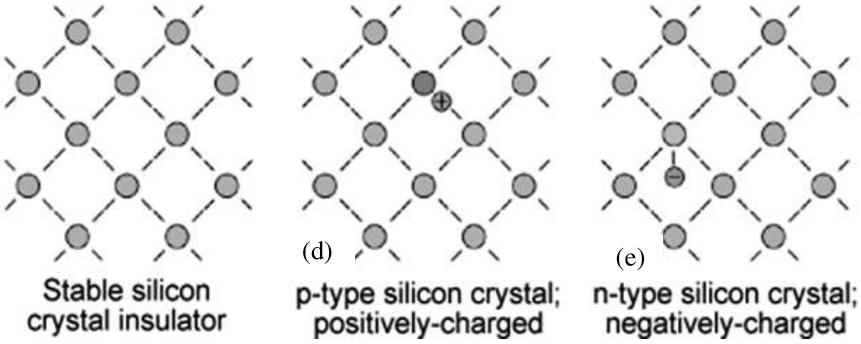
The binding energy of the excess electron is relatively small as such it is easily removed from the impurity atom, thus it becomes a conducting electron. This is known as the n-type extrinsic semiconductor (Figure 2.1e) when Si is doped with pentavalent impurity such as phosphorus. On the other hand, when an impurity such as a trivalent substitution impurity; B, Al, and Ga are added to silicon, it results in deficiency of an electron. In this case a hole is created, and the holes are positively charged responsible for its electrical conductivity. This is also known as the p-type extrinsic semiconductor (Figure 2.1c).



(a) Illustration of how PV Works by the principle of Photovoltaic effect



(b) A p-n junction is formed by placing p-type and n-type semiconductors next to one another.



(d)

(e)

(c) Intrinsic Semiconductor

Figure 2.1 Schematic Representation of the Science behind Solar Cell. Source: adapted from Solar by KYOCERA.

2.3 The Opportunities for PV-Cells

PV production have been projected to increase about five times for the next couple of years (Figure 2.2). It is expectected that c-Si will remain the most dominant material, and thin-film is also expected to rapidly grow.

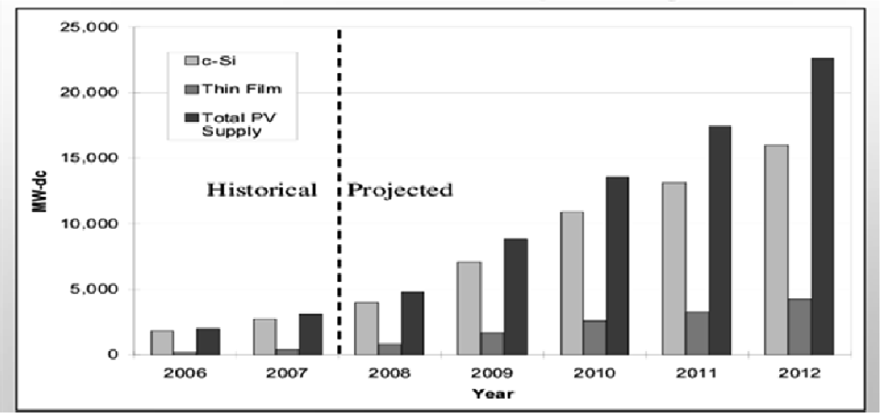


Figure 2.2 indicates the projection of PV production. Source: Median values from projections by 11 industry analysis (Nov. 2007-Jan. 2009).

Solar energy is intermittent in its supplies; therefore it requires a storage system like the batteries to store available energy at all times. It requires a detailed understanding of several consideration factors to design an efficient solar harvesting system that will yield a potential benefits in energy harvesting. Solar panels are the most harvesting components, whereas the batteries and ultra-capacitors serve as the storage elements. Technically, the rating of all the electronic devices must matches the desired functionality and efficiency required from the system.

Diodes are used to ensure that charges from the module flow in one direction onto the battery. Controllers such as blocking diode are connected between the negative terminal of the panel and the battery to prevent the back flow of charges into the panel during overcharging.

2.4 The Role of Silicon as a Material

Apart from oxygen, silicon is in abundance than any other element on the Earth crust. The production of this element into metallic is costly. The reason being that silicon as an element can easily combine with other elements, especially with oxygen. "Silicon comprises of more than a quarter of the Earth crust, however it is never found in its pure elemental state" (GLOBALINSIGHT, 2006). Silicon as a semiconductor device has a wide band gap separating the valence band, and the conduction band.

Predominantly, the element silicon is mostly employed in the creation of most semiconductor devices. There are several technological advancements including theoretical ways to help convert the plentiful, cheap, and low grade material into the ultra-high purity material needed in semiconductor device fabrication.

2.5 Factors that Indicates a Glowing Future for Solar Energy

2.5.1 Solar and the Economy

There is an abundant sunshine in Northern Ghana with an average of 8 hours per day (Met office, Ghana 2008). This indicates that solar energy can serves as an alternative energy source of power to generate both heat and electricity. The energy from the solar panel is a form of direct current (DC) which requires to be converted into alternative current (AC) using inverters.

It is very expensive to build long-distance transmission lines to serve small communities in Africa, especially when these communities are relatively poor and they cannot afford to pay rates high enough to cover the cost of these services. Most governments in Africa like Ghana have the policy to provide electricity for all Ghanaian communities by 2020, and solar energy can serve as alternative energy to help achieve the set goal. It is obvious that with solar energy, there is no recurring cost after installation but it is expensive during purchasing and installation of a solar system.

However, little maintenance is required in a properly installed solar energy system. It can be assume that, the work required to maintain a solar electric systems is less as compared to other traditional forms of electric generation such as hydroelectricity and gas power generators. Solar Electric Systems only requires regular inspections of the equipment. "While the price of petroleum products has been unstable over the last decade, prices of solar electric equipment have been steadily declining (AGROTEC, 1990).

Regional Programme on Agricultural Operations Technology for small holder farmers in East and Southern Africa have supported two projects on-farm energy, on photovoltaic's (PV) in Uganda and the other on solar drying of fruit and vegetables in Lesotho. The results from both projects are encouraging and have demonstrated that solar energy is indeed a viable source of power which can be tapped and used by farmers in rural areas of Africa (Mark, 1998).

In areas like Northern Ghana where most house wholes cooked with wood, there is now serious deforestation and associated problems. Women must spend days searching for and carrying firewood simply to cook meals. There is however, no lack of sun shine and these women and men will turn to build solar cookers and this simple technology will have a profound effect on their lives and the environment.

2.5.2 The Current Market State and Opportunities of Solar Energy Materials

Silicon has a good world market record for the 21st century especially in its crystalline form despite the amorphous is equally relevant. From solid state physics, it is however, not the ideal material to use for photovoltaic energy conversion. The efficiency of silicon strongly depends on higher purity level, and the higher purity of the crystalline perfection. Despite this limitations, silicon still stand a good position in the market because the technology already produces in large quantities for microelectronics market (Adolf et al., 2002). There is a great expectation for the new solar materials like the purification of metallurgical grade silicon (MG-Si) with aqueous processing technology to lower the cost, and to increase the efficiency of solar cells. Even though one can say that the present technology is relatively matured, yet there is the potential to reduce the cost. “As for other industrial products, manufacturing volume, cost follows a learning curve which indicates that for every doubling of manufacturing volume, cost drops by 20 %” (Adolf, 2002).

The market for amorphous silicon seems not to be improving. The expected development will be the source of solar grade silicon using aqueous processing.
A dramatic reduction in the cost and increase in the efficiency of PV cells have been revealed by the graph below over the past 25 years (Figure 2.3).

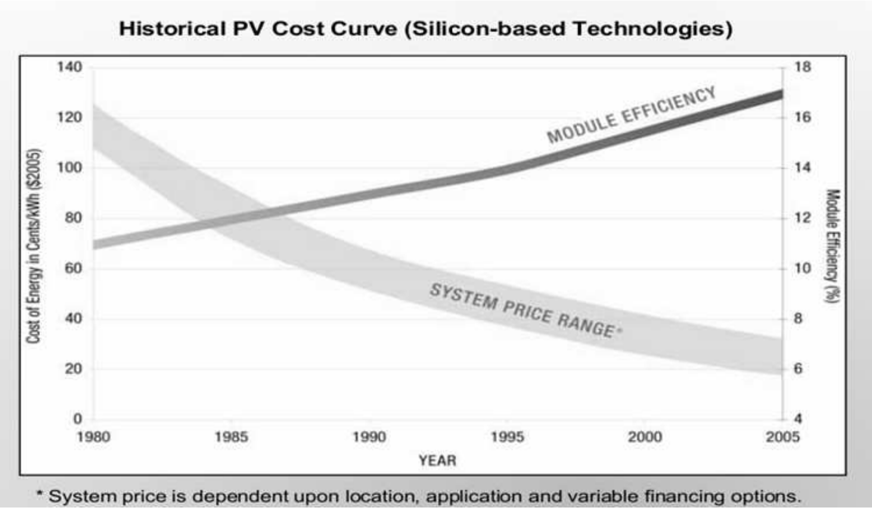


Figure 2.3 Trends in the system pricing and cell efficiencies. Adapted from US Industry and Market Outlook, (2006 Barnes Reports: www.barnesreports.com).

The current market trends gives the consumer privileges in the form of incentives, regulatory pressure and technological advancement, all driving solar energy to cost low relative to the conversional energy sources.

The release programs and regulations that may include tax rates and terriff laws in some of the key markets have contributed immensely in cutting down consumers solar cost over the past thirty years. In spite of the wide use of solar PV systems, the cost and performance merits are needed to move the market beyond the flat plate PV systems, and keen the competition of electricity from fossil fuels.

2.5.3 Importance of Silicon versus Non-Silicon based Materials

Silicon use displaced Germanium in most uses because silicon has better thermal stability, and it is more economical in comparing to Germanium. Gallium arsenide has some properties like higher breakdown voltage and electron mobility which sound superior to silicon but its low drift velocity electrons, or hole mobility makes gallium arsenide circuits to have higher power consumption than silicon based. It is also impossible to form a stable, adhering insulating layer on gallium arsenide that is analogous to the layer of SiO_2. The Mechanical and processing properties permit the production of wafers with diameter of 300 mm or more, whereas the maximum diameter attainable with gallium arsenide is currently limited to about 150 mm (GLOBALINSIGHT, 2006).

Despite the fact that the non-silicon techniques have received a fair amount of media and research attention, they face a number of financial and technical limitations including more usage of scarce, and expensive source materials (example Ga and In).

However, they offer effective practical way to keep solar cell conversion efficiencies high. "Panels made with non-silicon materials will require more cells if their efficiencies are lower, as with CdTe and CuInSe, or fewer if their efficiencies are higher, as with GaAs and CuInGaSe, to produce the same amount of power. The cost of the panel, and the module, depends both on the cost of the cells themselves and the number of them required to collect the sunlight.

While gallium arsenide-based panels could require less than half the number of polycrystalline silicon cells to generate the same amount of power, cell material costs could be approximately five times higher than the current cost for high purity silicon (GLOBALINSIGHT, 2006). Table 1 shows the performance of some solar cell materials.

Table 1 Typical Efficiencies of Some Solar Cell Materials

Cell type	Cell Efficiency
High efficiency monocrystalline silicon	> 20 %
Monocrystalline silicon	16 %
Polycrystalline silicon	15 %
Polycrystalline ribbon silicon	13 %
Amorphous silicon	8 %
CdTe	9 %
GaAs	>30 %
CuInSe	11 %
CuInGaSe	20 %

Source: Adopted from Piper Jaffray and Global Insight estimates, 2006.

2.5.4 Other Reviews

Eugen Rutagarama brought solar lighting to dozens of villages bordering the Virunga Bwindi mountain (gorilla conservation areas in Uganda), Rwanda and the Democratic Republic of Congo to help in maintaining the park from firewood collection.

A non-governmental organization, SWERA began a project in Ghana at August, 2002 following the approval by the Energy Commission of Ghana to assess every part of the country for indications; of wind energy potential, and solar energy resource for the deployment of these technologies for various applications (non-grid, grid connected, heating, etc). The assessment was based on available data, and site inspection.

Meanwhile, the Geodetic Engineering Department further developed the Geographic Information Systems (GIS) data sets of the Electricity Company of Ghana grid network, road network and land cover, and mini hydro sites. NREL produced medium resolution (40km) solar resource maps of Ghana on direct, diffuse, global and latitude tilt radiation. The German Aerospace provided high resolution (10km) solar resource map of Ghana.

The Meteorological Service Department together with other institutions such as the Solar Energy Applications Laboratory of KNUST have collected and analyzed solar energy data from all over the country. Prior to SWERA, data was collected mainly by the Meteorological Services Department (MSD) making use of Bellani-distilation pyranometres. Some of the data collected included; solar radiation, sunshine hour duration, relative humidity and air temperature. The MSD measured global solar radiation data until 1988 when they changed over to measuring duration of bright sunshine using Campbell-Stokes sunshine recorders.

Different small scale solar systems are useful devices in areas with a high amount of solar irradiation for providing hospitals with additional energy where the conventional energy supply is insufficient. Particularly for specialized devices like water pumps, medical sterilizers, water distillation and emergency lighting systems, the energy demand can be covered through solar energy.

In the Upper East District of Ghana, the District hospital in Bawku was fortunate to have between 4.7 to 6.4 kWh/m^2 of solar irradiation per day. Solar systems were able to be installed and tested during the project. In addition, a solar steam autoclave for sterilizing surgical instruments, two photovoltaic systems as emergency lighting systems and a solar flat plate collector were installed and tested (World renewable energy congress, 1994).

Passive solar technologies were already used by ancient civilizations for warming and/or cooling habitations and for water heating. The Renaissance, concentration of solar radiation was extensively studied. In the 19th century, the first solar-based mechanical engines were built (Butti, 1980).

Deng Solar Energy Systems are in the process of developing and assembling solar PV systems in Ghana. They also produce solar water heaters suitable for homes, hospitals and industrial pre-heating. This single investment shows that there is a vast potential for solar energy systems in Ghana. The rural areas have long been recognized as areas where it is cost effective to harness renewable energy for development. Solar energy systems could be more economical than the other conventional energy systems for our rural areas.

As at October 2008, Africa's first ever solar-powered car race was underway in South Africa to raise the awareness about alternative energy and to promote science and technology in Africa.

2.6 Empirical Models

The basis of designing a solar energy conversion device and solar energy usage demands for a solar radiation data (Gopinathau, 1992). The duration in sunshine in an area depends on factors such as; the topography of the selected site, and the prevailing meteorological conditions of the place such as, water vapor content, air temperature, pressure, humidity, wind direction, and force. More importantly the clearness of the sky and the height above sea level (Ready, 1971). There are other theoretical empirical models postulated which focused on the computation of the insolation (Prescott, 1940), (Abdel-Wahab, 1985; Hamid, 2003).

The original correlation proposed by Angstrom was expressed on the basis of clear sky global solar radiation and sunshine duration given as:

$$G = G_o(a + b\,(S/N)) \tag{2.1}$$

The linear form of equation (2.1) was also expressed as (Prescott, 1940):

$$\frac{G}{G_o} = (a + b(S/N)) \tag{2.2}$$

Where G_o is the extraterrestrial solar radiation on a horizontal surface in KW/m^2 given by equation (2.3).

$$G_o = \frac{24}{\pi} x I_{sc} x E_o \left[\cos\varphi cos\delta sin\omega + \frac{\pi\omega}{180} sin\varphi sin\delta\right] \tag{2.3}$$

Where E_o is known as the correction factor of the Earth orbit, and hence ω is the sunrise or sunset hour angle given as:

$$E_o = 1 + 0.033\cos\left(\frac{2\pi dn}{265}\right) \tag{2.4}$$

$$\omega = cos^{-1}(tan\varphi tan\delta) \tag{2.5a}$$

Where δ is the declination angle of the sun, given in degrees (Spencer, 1975):

$$\begin{aligned}\delta = [0.006918 - 0.399912cos\tau + 0.070257sin\tau - 0.006758cos2\tau \\ + 0.000907sin2\tau - 0.002697\ cos37 + 0.002697cos3\tau \\ + 0.00148sin3\tau]\frac{180}{\pi}\end{aligned} \tag{2.5b}$$

Where τ is the day angle in radiance given by:

$$\tau = \frac{2\pi(dn - 1)}{365} \tag{2.6}$$

The absolute percentage error of global solar radiation at a site was calculated (Khalil, and Fathy, 2008).

CHAPTER THREE

3.0 Methodology

3.1 Project Location

This project is aimed at collecting and analyzing data on sun hours in Northern Ghana. The Republic of Ghana is located on the West Coast of Africa, situated between latitudes 4^{o} and 11.5^{o} north of the equator. Ghana has a total land area of 238,537 square kilometers and is bordered by La Côte D'Ivoire on the west, Togo on the east, Burkina Faso on the north, and the Atlantic Ocean on the south. The landscape of Ghana's comprises of a coastal savanna, the middle forest zones and the dry savanna zone of the north (Mainly Northern Sector).

The study area covers the three regions in the North namely; WA (Upper West Region), Navrongo (Upper East Region), and Tamale (Northern Region) of Ghana, located within latitude 8.5° and 11° North of Equator. Northern Ghana has a land area of 98,000 square kilometers which is about 41 percent of the total land area of Ghana (Songsore, 1992).

Northern Ghana is very large; it was very costly and time-consuming in trying to obtain a data on every part. In other words, specific cluster method of sampling was employed during the project to collect secondary data at the Ghana Metrological Agency Departments at WA, Tamale and Navrongo, which was confirmed from the headquarters Met station in Accra. This gives a representative of the information for the Northern Ghana. Cluster sampling is used when the population is large or when it involves subjects residing in a large geographic area (Allan, 2004).

3.2 Measuring Solar Radiations

A scientific understanding of a phenomenon and processes in the climate system mostly begins with observation, which is the basic for description, analysis, and explanation of variation in time and space (Howard, 1999). Increasing attention to solar power as an energy resource in the late 20th century has demonstrated the value of the climatic record for practical application as well. Several instruments measures the duration of sunshine and Solar Radiations**:** this includes the foster switch, pyranometers, electronic recording solar meter, actinography and among others.

3.3 The Campbell-Stokes Sunshine Recorder

The sunshine recorder is an instrument used by the meteorologist for recording the actual duration of sunshine and the degree of its intensity (Figure 3.1). A sunshine recorder is used to indicate the amount of sunshine at a given location.

Traditionally, sunshine recorders are divided into two groups. In the first group the time of the occurrence of the event is provided by the sun itself and in the second case a clock type device is used to provide the time scale. The older type of recorders required the interpretation of the results by an observer and these may differ from one person to another. Fortunately for these days, the use of electronics and computers made it possible to record sunshine duration that does not rely on observer's interpretation. At the same time, the newer recorders can also measure the global and diffuse radiation.

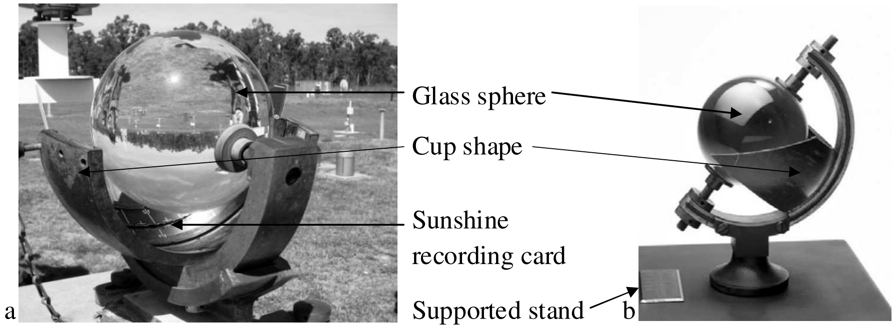


Figure 3.1 Shows the Pictures of Campbell-Stokes Sunshine Recorders: The materials for the sphere were ‘crown’ glass, colourless (a) or very pale yellow (b).

3.4 Advantages of Campbell-Stokes Sunshine Recorder

All the synoptic stations visited were measuring the number of bright sunshine hours per day using the device, Campbell–stokes sunshine recorder. The principle of operation of the Campbell–stokes sunshine recorder is simple. It is a reliable instrument and suitable to be installed at metrological stations in country-wide. The genius of this device is also related to the way in which the data is recorded, which avoids overwriting naturally.

3.5 Procedure in Data Collection

The daily card is fixed under the cup-shape of the sunshine recorder early in the morning before the sunrises. But depending on the season, a card is fixed direct opposite to the direction of the sun rays.

The device is mounted in such a way that the brightness of the sun falls on the optical pure glass sphere of diameter 10cm, that works like a magnifying glass.

The sun rays are focused to a point which causes the magnifying glass to burn a horizontal linear mark on the card.

The duration of the sun hours for the day is determine by considering the intensity and length of burns on the calibrated sun card as the sun arcs from east to the west. Thus the passage of the sun across the sky translates into a linear burn pattern along the card which may be analyzed by the observer to give different measurements of sunshine durations.

This instrument actually provides a simple operational way to distinguish bright sunshine (BS) and non-bright sunshine conditions. When a trace is marked then that period is classified as Bright Sunshine and conversely no visible trace implicitly means that no BS was recorded for that period. If the day is in and out of clouds, it burns a series of dots (Figure 3.2). The sun has to be out and clear to put a burn mark/ line on the card. From the burn marks you can accurately have to change the cards daily, unless it was cloudy for the entire day.

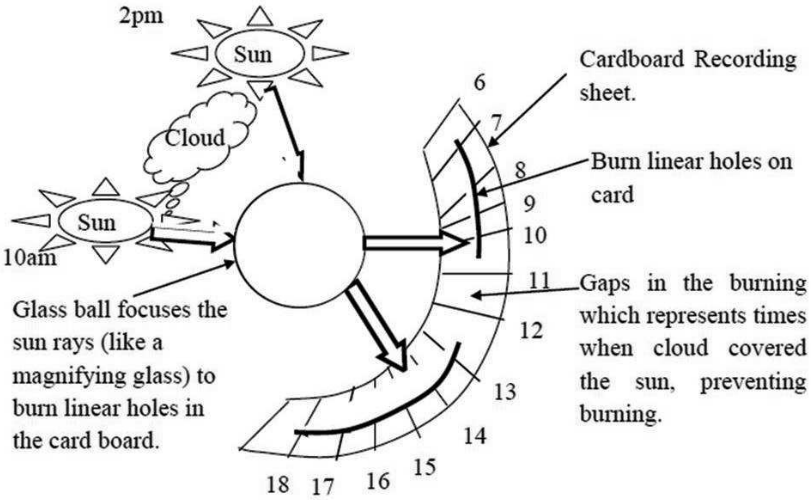


Figure 3.2 Illustrates how the Sunshine Recorder works. Not drawn to scale (Redrawn from bjr seven, 2008).

Obviously, this is a rather simplistic explanation of the way this device works, which uses different data cards (Figure 3.3) for instance, the hemisphere and the season of the year.

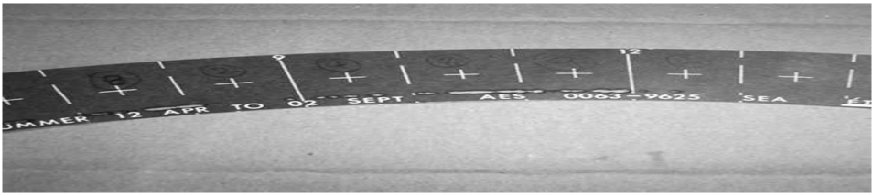


Figure 3.3 Shows a summer card graduated in 30 minutes intervals (Source: from Navrongo Met. Station, 2009).

3.6 Precautions at Selected Solar Measurement Sites;

Location of the sites observed were selected in such a way that the observations are true representative on a scale require from the station. A station in the synoptic should make observation to meet the scale requirement. All the sites were protected to prevent entry by unauthorized persons. Hence all the sunshine records were installed on a level surface on a concrete stand. The devices were placed well away from trees and any other large obstructions. Also observers performed basic routine checks of equipment quality as part of normal observing practices.

3.7 Sources of errors on the instrument

- This isn't of course an exact scientifically well-defined distinction and it still requires an experienced user to set the paper correctly and, more importantly, to read the trace in a reliable manner. It's not easy, for example, on days with frequent short sunny intervals to locate the start and end of each individual trace consistently. And there are other imperfections with Campbell-Stoke Sunshine Recorders, for instance sunshine is often too weak to burn a trace within an hour of sunrise or sunset even under conditions that would otherwise qualify as bright sunshine. Traces also burn more readily in very dry weather compared to humid air.

- **Poor maintenance of the instrument** by allowing dirt to collect on the glass sphere reduces the intensity of burn marks on cards. This was observed at the Navrongo Metrological Station where a playing field was just near to the instrument.

- The instrument's over records on days of broken cloud. Systematic errors may be as large as 20% (Met office surface data user guide, www.mccyllyweb.com/wall paper/ campbell.html).
- A short burn of bright sunshine can give a burn representing at least 0.1 hour while analysis of a sunshine cards state that, the start and end parts of the burn should be discounted, even so the analysis of a card on days of varying sun and clouds is open to many interpretations.

- **Visibility estimated by observer**: Observations should be made at ground level not from observation towers/ rooftops.

CHAPTER FOUR

4.0 Results and Discussion

4.1 Bright Sunshine Hours (BSH)

The design of a solar energy conversion system requires precise knowledge regarding the availability of global solar radiation and its components at the locations of interest. Solar radiation reaching the earth's surface depends upon climatic conditions of the place; therefore a study of solar radiation under local climatic conditions is essential. In developing countries such as Ghana, due to the absence of measuring instruments, solar radiation data was not available at the stations visited.

In the absence of solar radiation data, the need for an empirical model to predict and estimate the Northern Ghana solar radiation seems inevitable. These models use climatologically parameters of the location under study. Among all such parameters, sunshine hours are the most widely and commonly used. The models employing this common and important parameter are called sunshine-based models from the data obtained using the Campbell-Stoke sunshine recorder.

This models uses only bright sunshine hours as input parameter while others use additional climatologically data together with bright sunshine hours. In some of the models geographical and seasonal parameters are also taken into account to reflect the latitudinal and seasonal variation of the air mass. The first empirical correlation using the idea of employing sunshine hours for the estimation of global solar radiation was proposed by Angstrom (Angstrom et al., 1924).

4.2 Results, Analysis and Interpretations

Daily observations of bright sunshine duration were obtained in hours for a period of 10 years from three locations which includes; Navrongo, Wa, and Tamale representing the northern sector of Ghana. These locations were identified to have satisfied data which was confirmed at the National Meteorological department at Accra. More to the point they also represent the regional meteorological stations in the northern sector of Ghana. The summary of the average values for each month is represented in the Tables (4.1-4.6) and graphical forms for analysis (Fig. 4.1-4.7).

There are variations in the values ranging from 5.3-10.0 hours. The highest value ever recorded was 10 hours in the month of November in 2006 and the least value, 5.3 hours occurred in August, 2003. From the mean monthly results calculated, December is the month with the highest sun hours over the other 11months with a mean value of 9.18 hour and August always records the minimum sunshine which was found to be 5.97 hours. This can be interpreted by clouds cover as a result of rains in the month of August in the area. Raining period is at its peak in the month of August.

Table 4.1 Mean monthly Values of Sunshine Hours for Navrongo (Jan.1999 to Dec. 2008).

Measured Bright Sunshine Durations in (Hours) Over Ten Years										
Year Month	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
JAN	9.2	8.8	9.2	8.0	8.4	8.9	7.5	9.2	7.7	9.7
FEB	8.3	9.1	9.0	9.2	8.7	7.1	6.7	8.6	9.5	8.2
MAR	8.8	7.8	8.9	7.6	8.0	5.7	7.4	7.8	7.9	8.8
APR	7.3	8.8	8.3	8.0	8.2	7.5	7.9	8.1	6.3	8.2
MAY	8.6	8.0	8.5	8.7	9.0	7.5	9.0	7.4	7.8	8.1
JUN	9.1	7.9	8.1	7.5	7.0	7.4	7.0	7.8	8.3	7.3
JUL	9.0	6.8	6.9	7.4	7.7	6.5	5.7	7.6	6.5	6.7
AUG	6.8	6.7	5.6	6.1	5.3	6.2	5.9	6.0	5.4	5.7
SEP	5.8	6.2	7.2	7.8	7.0	6.4	7.0	6.8	7.3	6.6
OCT	8.0	5.8	8.8	8.1	9.1	9.1	8.9	8.4	8.6	8.7
NOV	8.5	9.4	9.1	9.4	9.2	8.9	8.7	10.0	9.1	9.5
DEC	9.2	8.5	9.8	9.6	9.3	9.3	9.7	9.3	9.0	9.4

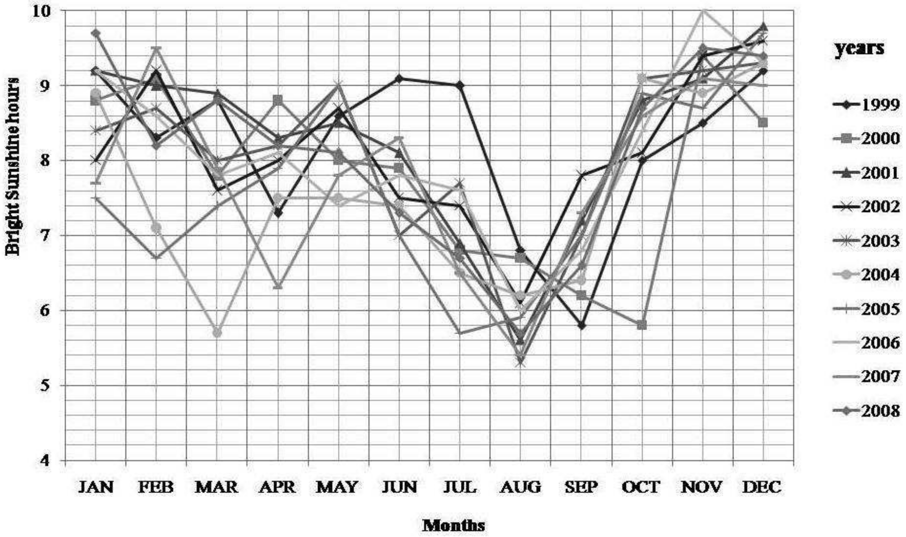


Figure 4.1 Plot of Sunshine hours for Navrongo from Jan 1999 to December 2008.

It is observed that there has being several variations in the values of the sun hours in Navrongo. These go from month to month across all the years. Meanwhile, the month of August is found to be the month with the minimum records of Bright Sunshine hours, which can be taken to be the worst month. The value for June and July in 1999 indicates nearly constant records.

The values of sunshine hours for 2004 decreased linearly from 8.9 hours at January to 5.7 hours at March as shown in the plot above (Figure 4.1). The sun hours in 2005 and 2006 have wider ranges (6.7- 9 hours) and (6.0-10.0 hours). The maximum sunshine hour is 10.0 hours which happened in 2006 within the month of November. Hence forth November and December are good months of sunshine in Navrongo from the graph above (Figure 4.1).

In other to determine accurately the month(s) with good sunshine hours, the mean sunshine hours were determine by averaging all the sun hours for the ten year period for each month (Table 4.2).

Table 4.2 Mean monthly sunshine hours for Navrongo from Jan.1999 to Dec. 2008

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean sun hours	8.7	8.4	7.9	7.9	8.3	7.7	7.1	6.0	6.8	8.4	9.2	9.3

The mean monthly sunshine hours in the Table above indicates that December has the highest sunshine hours in Navrongo which was determined to be 9.3 hours prior to November with 9.2 hours and the lowest sunshine has been found to be in August with 6.0 hours. A clear representation of the data in Table (4.2) is given (Figure 4.2).

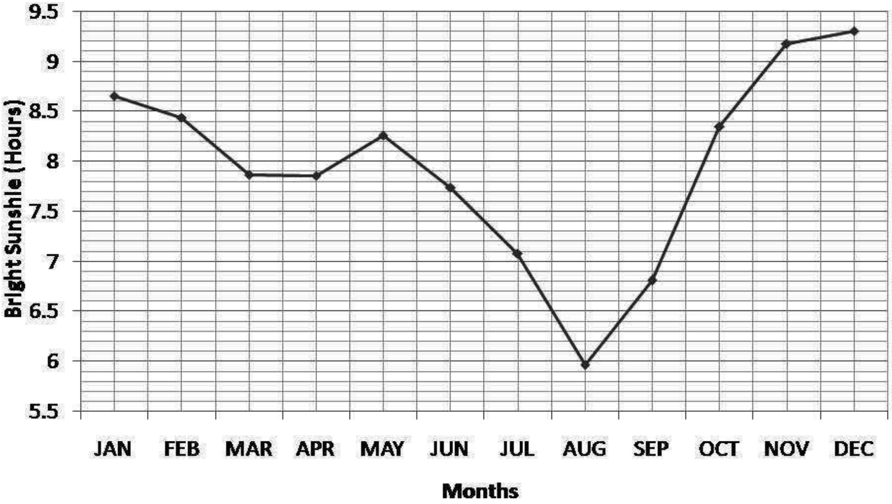


Figure 4.2 Plot of Mean Monthly Sunshine hours for Navrongo from Jan 1999 to Dec 2008.

The plot above indicates clearly the trend of the Bright sunshine against the 12 months in Navrongo. From January, the trend decreases from 8.66 hours to April at 7.86 hours and goes up to 8.30 hours in May. The sun hours decreased in August from 5.97 hours, and continued upward to 9.33 hours in December. The variations in the sunshine hours for a month were as a result of the weather conditions such as rainfall, cloud cover, and the season in that month.

All the daily readings of sunshine hours for Wa were then averaged as shown in Table 4.3 below. It was not easy to analyze every result over the ten year period; it was simple to reduce all the data to monthly basis.

The data (Table 4.3) indicated an unexpected low values in the year 1999 from the month of January to September at Wa. Efforts were made to understand what could be the reason. Report from the Met Head office at Accra stated that it was actually due to lack of sunshine cards during that period and an incomplete data’s were reported. The maximum monthly mean bright sunshine hour’s value stands at 9.05 hours in the month of November.

The mean sun hours indicates the good months with higher values and the worst months are those with the least records. For instance, the months of November, December, October, January and February are the good months whilst the worst months also ranges from June, July, August and September.

Table 4.3 Mean monthly Values of Sunshine Hours for WA

Measured Bright Sunshine Durations in (Hours) Over Ten Years										
Year / Month	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
JAN	2.8	8.7	9.3	8.4	8.6	8.9	7.2	9.3	7.6	9.5
FEB	2.2	9.6	9.1	9.2	8.7	7.6	7.2	9.0	9.4	8.3
MAR	2.6	7.6	8.4	7.7	8.3	6.5	7.4	7.6	8.2	8.7
APR	3.1	8.1	7.8	7.3	8.0	7.6	8.0	8.1	6.8	8.3
MAY	3.0	7.9	8.3	8.6	8.8	7.8	8.8	7.5	7.5	8.2
JUN	2.2	7.7	8.4	7.5	6.3	7.2	6.6	7.4	7.8	7.4
JUL	1.5	6.6	6.2	7.0	6.4	5.5	5.3	7.0	6.4	6.7
AUG	0.4	6.4	5.2	5.5	5.6	5.6	5.2	6.1	5.1	5.1
SEP	1.2	5.6	5.8	6.5	6.6	6.5	7.0	6.6	6.7	6.2
OCT	7.6	7.5	7.5	8.3	8.7	8.8	8.7	8.7	8.6	8.8
NOV	9.1	9.2	9.1	9.5	8.8	8.4	8.3	9.7	9.2	9.2
DEC	9.1	8.7	9.1	9.4	9.2	8.4	9.5	9.1	9.0	8.8

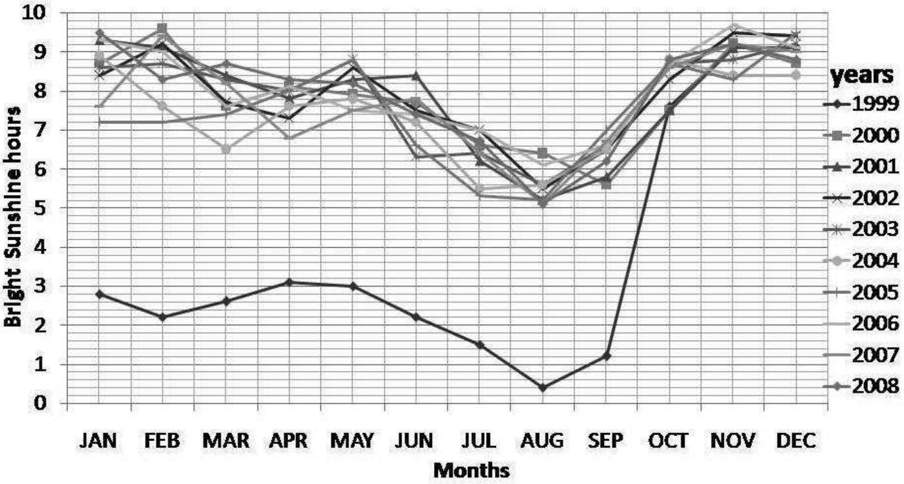


Figure 4.3 Plot of Mean Monthly Sunshine hours for Wa from (Jan 1999 to Dec 2008.

I infer that the bright sunshine hours varies from month to month for all years which may be due to some weather factors such as season, altitude, the intensity of sunshine and cloudy conditions experienced at some point in the year.

Plot of the values all indicates that the mean maximum sun hours occurred in the month of November. Also, the tabulated values and their graphical representation above indicate that August records the minimum mean sun hours over the year with a value of 5.02 hours. Even though there are outliers records in 1999, the trend still indicate that November records the highest while August indicating the least ever as 0.4 hours.

Table 4.4 Mean monthly sunshine hours of Wa from Jan1999 to Dec 2008.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean sun hours	8.0	8.0	7.3	7.3	7.6	6.9	5.9	5.0	5.9	8.3	9.1	9.0

From the mean monthly sunshine hours above, the highest value was realized in November to be 9.1 hours with December nearly the same also with 9.0 hours. The minimum average monthly sunshine hours were in August which is 5.0 hours (Fig. 4.4).

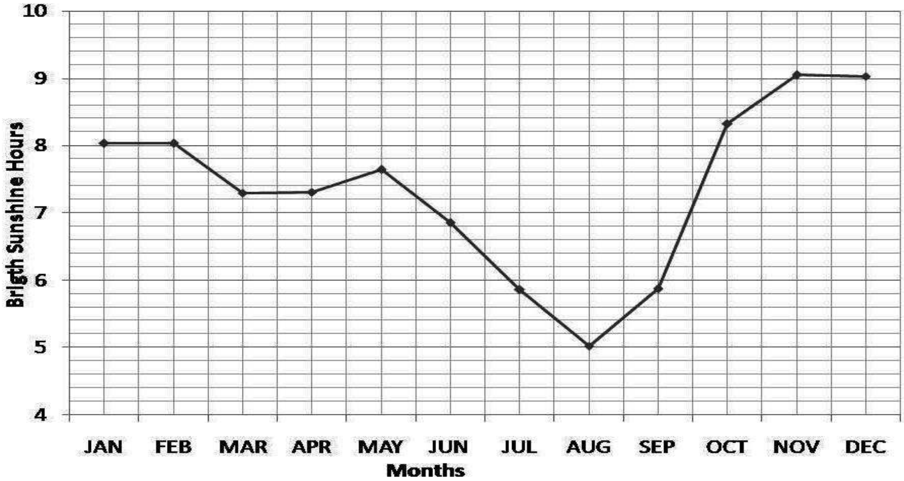


Figure 4.4 Plot of mean monthly Sunshine (hours) for WA from January 1999 to December 2008.

It is clearly shown that the trend remains constant for January and February after which it decrease slight in March. The hours of the sun remains constant for March and April and increase slightly to 7.6 hours. However, the trend from April decreases linearly to 5.0 at August. Besides that the sun hours continuously increase up to 9.0 hours in November and decreasing insignificantly through December. Clearly, November and December are the good months of Bright sunshine hours and the worst month of all is August as reported before.

The values of sun hours recorded in Tamale did not differ so much like the former locations (Table 4.5). The data could be interpreted by the same weather conditions affecting Wa and Navrongo. Solar output is also a factor because the sun behaves like a black body that it turn to absorb all the energy it received and radiate some at maximum temperature.

Table 4.5 Mean monthly Values of Bright Sunshine Hours for Tamale from January 1999 December 2008.

Measured Bright Sunshine Durations in Hours Over Ten Years										
Year / Month	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
JAN	7.8	7.8	8.7	6.5	8.4	8.4	6.3	8.5	6.1	9.0
FEB	8.1	8.7	8.4	8.8	9.1	7.0	6.8	9.0	8.8	6.5
MAR	8.4	6.6	8.4	7.6	7.7	5.7	7.3	7.5	7.1	8.0
APR	7.8	8.5	7.3	8.0	7.7	6.9	7.8	8.2	6.3	7.6
MAY	7.2	8.0	7.9	7.8	8.7	7.6	8.4	7.2	6.9	8.2
JUN	6.8	7.0	7.6	7.4	6.4	6.7	6.6	7.5	7.4	6.8
JUL	6.2	5.9	5.6	6.5	6.1	5.3	4.9	6.5	6.0	6.3
AUG	5.6	5.6	5.7	5.6	4.5	5.1	5.0	5.7	5.0	6.6
SEP	5.1	5.7	5.6	6.7	6.2	5.7	6.6	5.3	5.3	6.8
OCT	7.1	8.1	5.6	8.2	8.8	9.1	8.1	8.3	8.2	7.5
NOV	9.6	9.2	9.2	9.1	8.6	8.8	8.5	8.9	8.9	8.8
DEC	8.2	8.3	9.2	9.0	9.0	8.2	9.0	8.4	8.2	8.3

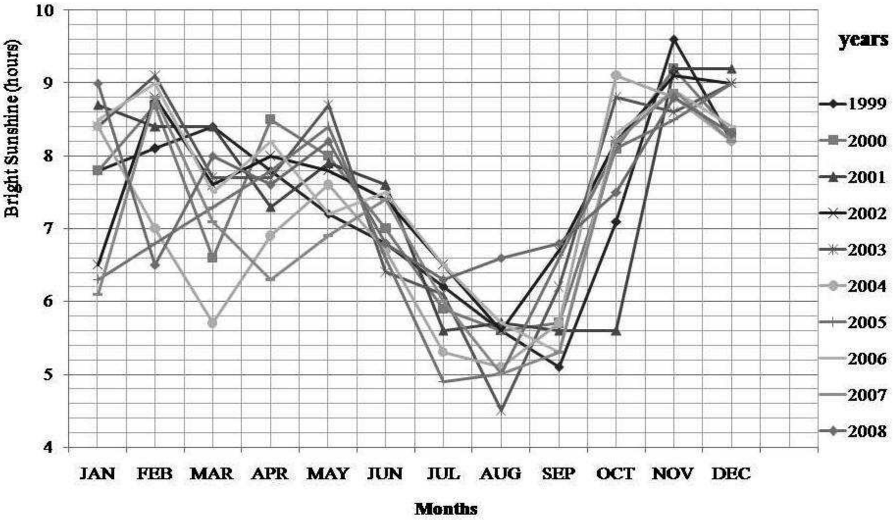


Figure 4.5 Plot of Sunshine hours for Tamale from January 1999 to December 2008.

From the analysis of this data, the pattern is clear to determine the mean minimum and maximum values of the months over the years. The results of Tamale have also satisfied with Wa and Navrongo. The month November is still the good month with the maximum mean sun hours, 8.96 hours at Tamale at the same time as August is the worst month as usual recording the minimum mean values of 5.44 hours. Summary of data from Table 4.5 is presented in Table 4.6.

For instance factors such as seasonal changes distance from the sun, cloud cover surface reflectivity and among others.

Table 4.6 Mean monthly sunshine hours of Tamale from Jan.1999 to Dec. 2008

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean sun hours	7.8	8.1	7.4	7.6	7.8	7.0	5.9	5.4	5.9	7.9	9.0	8.6

From the mean monthly sunshine hours of Tamale, the highest value was realized in November to be 8.96 hours whilst the least monthly mean valued at 5.44 hours in the month of August (Fig. 4.6).

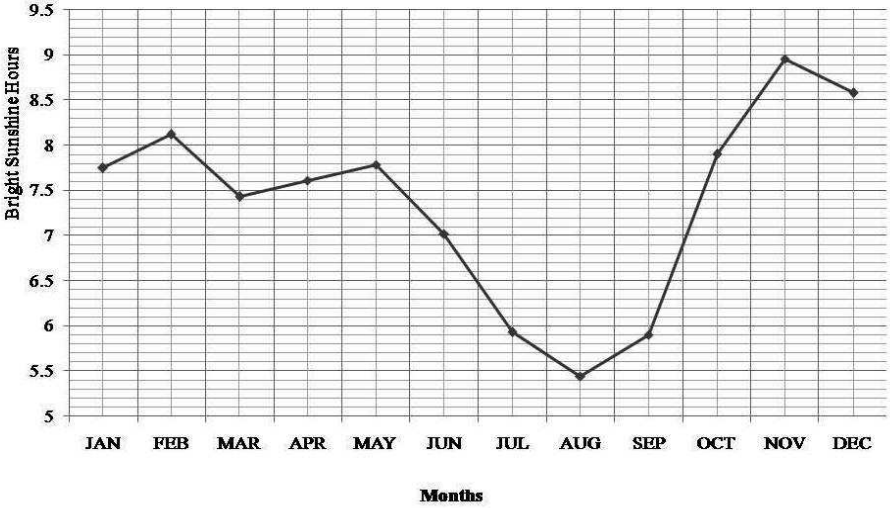


Figure 4.6 Plot of Mean Monthly Sunshine hours for Tamale from Jan 1999 to Dec 2008.

The trend increases at January from 7.75 to 8.12 hours where it decreases slightly again. There is a linear increasing trend from March at 7.43 to 7.79 hours in May. Figure 4.6 indicates that the least monthly mean sunshine occurs in August and November gave a record of 8.89 hours as higher than the other eleven months. Combination of the average sun hours is given (Fig.4.7).

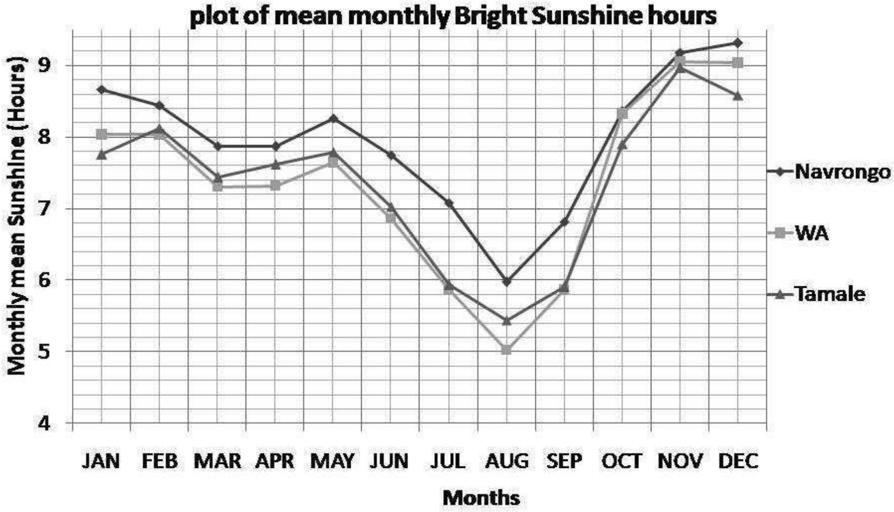


Figure 4.7 Shows the combined plot of the mean monthly sunshine (hours) for each month over ten years for the three regions in the Northern sector of Ghana.

It was observed that the data for Navrongo was higher than all the other locations for all the months across the period of 10 years indicating Navrongo has longer hours of bright sunshine as compared to the other two locations (i.e. Wa and Tamale).

Meanwhile the data for Wa and Tamale are almost overlapping which also was due to the fact that these two regions lies within almost the same latitude as presented in section 3.1. But to be specific, the results for Tamale were higher than Wa within the months of February to September, and from October to December through January, Wa recorded values higher than Tamale due to seasonal variation of the sun’s altitude. This period is known in Ghana as “Harmattan”.

4.3 Energy Calculations from the Sun hours obtained

Employing Solar power = $1 \text{ x } 10^3 \text{ x } \frac{4}{\pi} \text{ x } 10^{14} \cong 1.28 \text{ x} 10^{17}$ W (Julian, 2009) (4.1)

Implying that the available solar energy per second = $1.28 \text{ x} 10^{17}$ J, (1W = 1J/S)

The energy value can be calculated as energy E= Time(s) x solar power (W) (4.2)

1hr = 60m = 60s x60s = 3600seconds (4.3)

Energy for a day (E_d) = Solar Power (W) X Time (s)

$E_d = 1.28 \text{ x } 10^{17}$W x Time (s) x 1day (4.4)

Implying energy per day = Time (sun hours) x 3600 sec x 1day x $1.28 \text{ x} 10^{17}$ W (4.5)

Refer to appendices I for the calculations on the energy values of Navrongo, Wa and Tamale. The values of the energy differences for the three locations representing the Northern sector of Ghana are summarized in Table 4.7.

Table 4.7 Table of values for the minimum and maximum energy received per day.

Geographical Location	Maximum energy E_{max} (10^{21} J/day)	Minimum energy E_{min}(10^{21} J/day)	Energy differences (10^{21} J/day)
Navrongo	4.3	2.8	1.5
WA	4.2	2.3	1.9
Tamale	4.1	2.5	1.6

The energy difference indicates the deviation of the minimum energy value from the maximum energy value.

However, even the minimum energy value is still good enough to adapt solar energy as an alternative energy source.

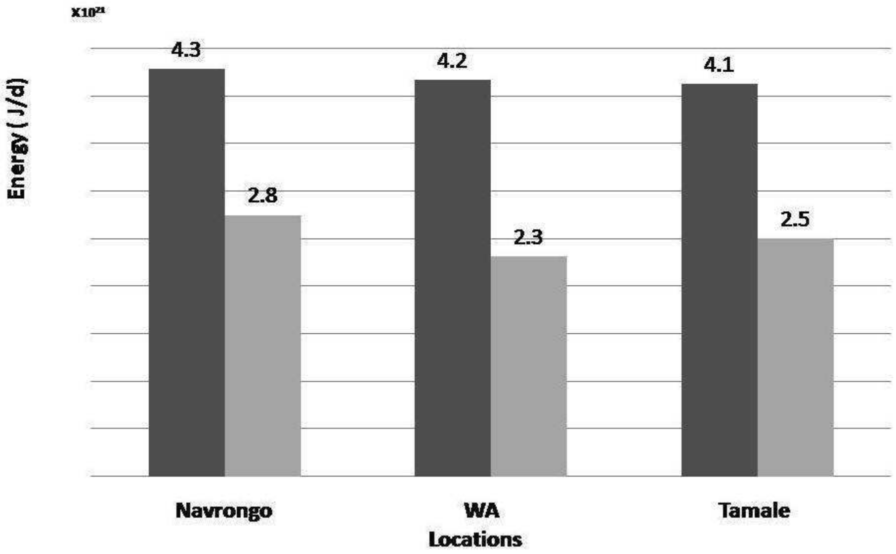


Figure 4.8 Bar chart of energy values for good months (i.e. dark colour charts) and the worst months (i.e. light grey charts).

From the figure above, the energy variation of Navrongo is the different between the maximum and the minimum energy = $4.290\text{x}10^{21}$-$2.751\text{x}10^{21}$ = 1.5 $\text{x}10^{21}$J/day.

The variation in the energy for Wa = $4.170\text{x}10^{21}$ - $2.3.13\text{x}10^{21}$ = 1.9 $\text{x}10^{21}$ J/day.

Also the energy range for Tamale = $4.129\text{x}10^{21}$ – 2.50710^{21} = 1.6 J/day.

4.4 Discussion versus Interpretations

The energy values vary based on the sun hours. Hence forth Navrongo produces the higher energy values of 4.3 $\text{x}10^{21}$J/day and $1.6\text{x}10^{24}$J/y, followed by Wa with $4.2\text{x}10^{21}$J/day and 1.5x 10^{24}J/year and then Tamale with 4.1 x 10^{21}J/day and 1.5x 10^{24} J/year.

The results thus agreed with the work of Julian Chen, 2009 who presented a lecture on the topic, Physics of Solar Energy. His energy value per day stands at 9.856 x10^{21}J and the annual energy value was 3.6x10^{24}J/year. His values are higher than what we reported but not so large when compared to the energy supply to Northern Ghana. His work was carried out in driest and tropical dessert areas of the Arabian Peninsula. This value indicates that there are much more sun hours in his research area than the present locations.

A similar research carried out in the country by Solar and Wind Energy Resource Assessment *(*SWERA*)* revealed that, Wa, the capital of the Upper West region, has the highest level of solar irradiation (5.524 KWh/m^2-day) and May is the month with the highest solar irradiation (5.897 KWh/m^2-day), with August recording the lowest measurement (4.937kWh/m^2-day).

However, the Electricity infrastructure of Northern Ghana is 144 MJ (Guide to Electric Power in Ghana, 2004). When compared to the energy from the sun it is appreciable with regard to the energy supply by the Northern Electricity Department (i.e. 90 MJ/s).

The results were interpreted based on the fact that solar sensors (Campbell-Stoke sun shine recorders) typically measure the visible wavelengths of sunlight. Hence measurement of Bright Sunshine (BS) usually relates only to visible light data and the device will not give a record if clouds should cover the sun.

Traditionally, weather observers have logged daily totals of what is termed ‘bright sunshine hours’ (BSH). This term reflects the qualitative difference in brightness and wellbeing that we experience when the sun is shining brightly from a blue sky as contrasted with dull, overcast days.

However, a month with a higher-than average recorded total of BSH will obviously indicate a period with more frequent clear skies like the months of November and December and less cloud cover than usual.

Measuring BS hours with any precision is not easy, by comparison with most other weather parameters and their measurements are trickier. In practice, there are some variations due to the different depths and clarity of atmosphere that the light is passing through at different sun angles, refraction effects etc., but these are secondary issues. But what is missing and what is understandably precious to many dedicated weather observers (and indeed to the increasing number of scientists looking for evidence of changes in weather pattern over the year) is any comparability to existing historical sunshine records. And many of us privately also cling on to the idea of bright sunshine as a worthwhile parameter.

CHAPTER FIVE

5.0 Conclusion and Recommendations for Part A

5.1 Conclusion

From the analysis, solar energy has a large potential to be a major fraction of a future carbon-free energy portfolio. This is so because the findings shows that the minimum energy value per day stand at 2.3 $x10^{21}$J/d which is much greater than the energy supply to Northern Ghana per day 7.8 $x10^{12}$J/d by Northern Electricity Department (NED), but technological advances and breakthroughs are necessary to overcome low conversion efficiency and high cost of presently available systems.

Analysis of the data on solar energy in Northern Ghana has ascertained its potential with regard to the energy supply to Northern Ghana by NED. From the findings in the current work, the available energy from the sun is sufficiently large enough for all our energy needs.

Hence forth, it can thus be considered as an alternative source of energy which can be harvested with diverse solar energy materials. In spite of this high potential, solar energy technologies are not as widely diffused into the Ghanaian society as one would have wished mainly due to the low level of information and technical know-how about solar energy technologies in general.

Also, solar energy is intermittent in its availability, and thus requires that efficient storage or backup systems be constructed so that power can be supplied continuously.

5.2 Recommendation

Considering the fact that, solar energy has exceeded the energy supply to Northern Ghana by NED, the recommendation therefore is that solar energy can serves as an alternative energy source in Northern Ghana. The energy value calculated based on the sun-hours is large enough for the implementation of solar technologies. Thus the abundance of solar energy (an average of 8.0 hours per day) is particularly conducive for the installation of solar energy systems.

If we want solar energy to significantly contribute to the energy supply of Northern Ghana, then we must also think of how to get into the manufacturing of solar devices within our capacity as a nation. This is because manufacturing scale is another key requirement for decreasing the cost of solar technologies. The reason had been that, large-scale production lowers the cost of active materials and production.

However, there is a great technological challenge that requires investment of larger financial and intellectual resources to find innovative solutions. More research and development will therefore increase competitiveness of solar technologies.

Solar energy is recommendable because of its environmental safety: it is non-polluting, non-depledable, a renewable source of energy and a “free” source of energy that does not require mining it or drilling to obtaining it.

But the deployment of solar technologies for energy production on a large scale requires the involvement of both political and economic players, and we must also further consider the improvements in the conversion efficiency and reduction of manufacturing cost.
In other to utilized power efficiently, it is recommended that, power should be proportioned to the appliance used in each housed hold.

PART B: CHAPTER SIX

6.0 Aqueous Processing Route for Upgrading Metallurgical-Grade Silicon to Solar-Grade

- The co-authors contributed equally to the part B of this book. Our goal in this section was to provide two alternative aqueous chemical processing schemes for purifying **Metallurgical Grade Silicon** (MG-Si) to produce **Solar Grade Silicon** (SoG-Si).
- The main objective is to remove Fe from the MG-Si.

6.1 Proposed Way of Making Solar Cells Cheaper

The cost of purifying silicon controls the market price of a solar cell or the panel. In view of this, we proposed an aqueous means of purifying the metallurgical grade-silicon which is not energy intensive to make silicon cheap for solar energy materials. “The concentration of impurities within the poly-silicon has the biggest effect on the efficiency of solar cells and it is the most critical variation in determine manufacturing cost” (Bunang-gu et al., 2009). The metallurgical refining methods are presently used as alternative instead of the commercial high cost process like Siemens process.

6.1.1 The Need for Purifying Metallurgical Grade-Silicon (MG-Si)

In recent years, the alternative solution to produce solar grade (SoG) silicon (Si) is by purifying it using the metallurgical route. The efficiency of a solar cell is deteriorated by metal impurities in metallurgical grade (MG) silicon. Some of these impurities include Fe, Al, Ti, and Cu. It is therefore necessary to remove these metal elements from the MG-Si to upgrade silicon. Using low cost metallurgical grade silicon to serve as a starting material for making solar grade silicon (SoG-Si) will be a way to make solar cells less expensive (Morita et al., 2003).

The application of an element in the productions of solar grade depends on the required purity level. But it is not all the elements listed in the Table 6.1 that are equally deleterious, affording manufacturers some flexibility in the purification processes. For the purpose of most application, impurity content of Boron and phosphorous must be reduced to very low levels. "The earliest attempts to obtain higher purity material from metallurgical and chemical grade silicon were based on the low temperature, selective acidic dissolution of granular silicon, but such techniques are not adequate for the efficient production of material with impurities reduced to the parts per billion levels " (GLOBALINSIGHT, 2006).

Table 6.1 Shows a Typical Silicon Metal Composites

Element	Metallurgical Grade (%)	Chemical Grade (%)
Silicon	96.99	> 98.9
Iron	0.4 – 1.0	0.1 – 0.5
Aluminium	< 0.5	0.2- 0.4
Calcium	0.2 – 0.3	0.02 – 0.2
Mn, Ti, Pb, B, As, C, Cu, Mg, Mo, Na, P, Sb, and W	Also present	Also present

Source: Adapted from Global Insight, Inc., 2006 (USA).

Assuming technology continuous to progress and mature, metallurgical will gradually replace the modified Siemens as a raw material for photovoltaic of today. Metallurgical method can be seen as an efficient method that is energy saving, reducing emissions, and large scale clean production of poly-crystalline. But the current metallurgical technology is not yet matured enough to be applied to a large-scale production. There is indeed progress in the purification of metallurgical silicon which seems to meet the requirement of solar cell production, despite low cell efficiency. There is still the need for improving upon this technology by further purification such as aqueous based technologies.

6.2 The Driving Force Behind Aqueous-based Technologies over the conventional thermochemical techniques

Aqueous Processing are water-based chemical technologies and water serves as a good solvent to facilitate the dissolution of solids. This is as a result of the interaction of water with a wide variety of chemical species because of its ability to donate and receives protons (H^+) (Osseo-Asare, 2010).

The driving force behind the growing interest in aqueous-based technologies compared to the conventional thermochemical techniques for purifying MG-Si can be determine by the merits of aqueous processing over conventional thermochemical technique for the purification of MG-Si. This includes:

1. Capital Investment: less initial capital investment is required to operate an aqueous processing plant. It can be suggested that the smallest aqueous processing plan will probably have a capacity and will be more economical than the conventional thermochemical.
2. Safety is assured in aqueous processing because it does not involve any flammable solvent in the process, and explosions. There are fewer expectations of fire hazards, less operational dangers, and it does not involve air pollution from solvent losses. In fact, aqueous processing controls pollution because it eliminates solvents that may have been lost to the atmosphere.
3. For simplicity, there are fewer processing steps involved in aqueous processing than in the conventional thermochemical techniques for purifying MG-Si.
4. Another advantage of aqueous technologies is that it has the ability of utilizing

other chemicals in the removal of substances that are undesirable.

5. The technology has a wider range of applications beyond purification of MG-Si. It can be used in oil extraction, mineral processing, hydro-metallurgy, battery discharge and among others.
6. Off course we want to avoid having metal catalyst remaining in the semiconductor material. Aqueous technologies have the ability to eliminate solvent extraction and desolventization, and the ability of discontinuous operations.

6.3 Aqueous Chemical Processing Schemes for Purifying MG-Si to Produce SoG-Si

Aqueous processing is mainly water-based chemical process technology. Water been the most abundant solvent is the medium for aqueous processing. “Water is the most abundant solvent, and it has some unique properties, which facilitates the dissolution of solids, while at the same time leaving room (under changed conditions) for the reversed process of solid formation from solution (crystallization and precipitation) to occur” (Osseo-Asare, 2010).

6.4 Water Stability Diagram

Thermodynamic data

Reaction		log k values
$^{1}/_{2}\,H_2O = {}^{1}/_{4}\,O_{2\,(g)} + H^+ + \bar{e}$	(1)	- 20.75
$H_2O + \bar{e} = OH^- + {}^{1}/_{2}\,H_{2\,(g)}$	(2)	− 14.0
$H^+ + \bar{e} = {}^{1}/_{2}\,H_{2\,(g)}$	(3)	0

The decomposition of water can take two possible route, yielding oxygen and hydrogen respectively.

(1) Highly oxidizing condition

$H_2O \rightarrow O_{2\,(g)}$

${}^{1}/_{2}\,H_2O = {}^{1}/_{4}\,O_{2\,(g)} + H^+ + \bar{e}$ log k = - 20.75

The Reaction Quotient, $Q = \frac{[H^+][O_{2\,(g)}]^{1/4}\{\bar{e}\}}{[H_2O]^{1/2}} = \frac{[H^+]\{\bar{e}\}{}^{1}/_{4}[PO_2\,]}{[H_2O]^{1/2}}$, taking log on both sides and at standard condition (finitely dilute solution) $[H_2O] = 1, \text{and}[PO_2\,] = 1$

$\therefore\ P\varepsilon \geq 20.75 - PH$

$Eh\ \geq 1.22 - 0.0590PH$

(2) Reducing condition

$H^+ \rightarrow H_{2\,(g)}$

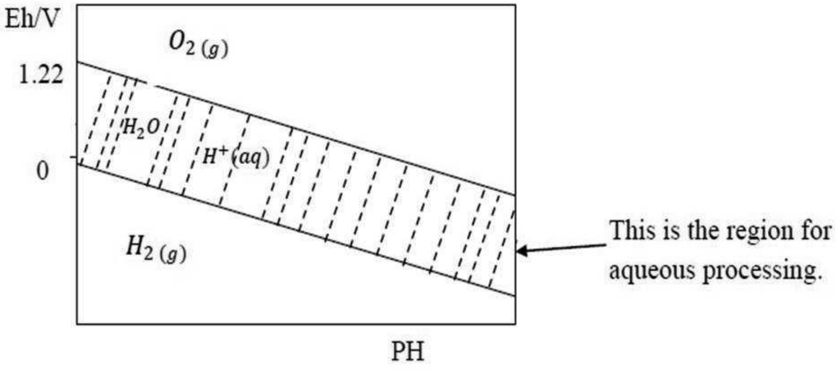
$H^+ + \bar{e} = {}^{1}/_{2}\,H_{2\,(g)}$ $\qquad$ $\log k = 0$

With a similar procedure in the highly oxidizing condition, the Pε and Eh relation for reducing conditions are

$\therefore P\varepsilon \leq -PH$

$Eh \leq -0.059PH$

The relative stability equations for both highly oxidizing condition and reducing condition are represented graphically (Fig. 6.1).



This is the region for aqueous processing.

Figure 6.1 Shows the Stability of water (Not drawn to scale).

Iron (Fe) is one of the major impurities in the metallurgical grade silicon. The efficiency of the solar cell is deteriorated by the metal impurities such as Fe in the MG-Si. Fe forms 0.4 to 1.0% of the impurity level in MG-Si. The percentage of Fe must be reduced to make the MG-Si very effective. In this project we present a theoretical approach by which Fe could be removed from the MG-Si.

Iron in the form of Fe^{2+} combines with silicon to form Fe_2Si (iron silicide). In order to remove Fe from MG-Si the following Eh-PH Pourbaix diagrams were considered; $Fe\text{-}H_2O$-system, $Si\text{-}H_2O$-system, and $Fe\text{-}Si\text{-}H_2O$-system.

6.5 Iron – Water Stability Diagram ($Fe\text{-}H_2O$ System)

Thermodynamic Data

Reaction	**Log k**
$Fe = Fe^{2+} + 2\bar{e}$	16.17
$Fe_2O_3 + 2\bar{e} + 6H^+ = 2Fe^{2+} + 3H_2$	26.93
$Fe_3O_4 + 2\bar{e} + 68 = 3Fe^{2+} + 4H_2O$	36.81
$Fe^{3+} + \bar{e} = Fe^{2+}$	13.04

Species of interest relating to this project are Fe, Fe^{2+}, Fe^{3+} and Fe_2O_3.

(i) Considering ($Fe^{2+} \rightarrow Fe_2O_3$)

$2Fe^{2+} + 3H_2O = Fe_2O_3 + 2\bar{e} + 6H^+ \ \log k = -26.93$

$Q = \frac{[Fe_2O_3][\bar{e}]^2[H^+]^6}{[Fe2+]^2[H_2O]^3}$, where $[Fe_2O_3] = [Fe2+] = [H_2O] = 1$ at standard conditions and log Q = log k at equilibrium.

$\log Q = \log[H^+]^6 + \log\{\bar{e}\}^2$

If log Q < log k, $\log[H^+]^6 + \log\{\bar{e}\}^2 \leq \log\ k$

$P\varepsilon \geq 13.465 - 3PH$, but the redaction or oxidation potential, Eh = 0.059 Pε

$Eh \geq 0.794 - 0.177PH$

Similarly the relative stability equations for $Fe^{2+} \rightarrow Fe^{3+}$, $Fe \rightarrow Fe_2O_3$, $Fe \rightarrow Fe^{3+}$,

$Fe \rightarrow Fe^{2+}$, and $Fe_2O_3 \rightarrow Fe^{3+}$ are summarised in the section 6.5.1 below

6.5.1 Relative stability equations for Fe – H_2O system

Reaction	Equation	Line
$Fe^{2+} \rightarrow Fe_2O_3$	$Eh \geq 0.794 - 0.177PH$	1
$Fe^{2+} \rightarrow Fe^{3+}$	$Eh \geq -0.769$	2
$Fe \rightarrow Fe_2O_3$	$Eh \geq 0.053 - 0.059PH$	3
$Fe \rightarrow Fe^{3+}$	$Eh \geq -0.062$	4
$Fe \rightarrow Fe^{2+}$	$Eh \geq -0.477$	5

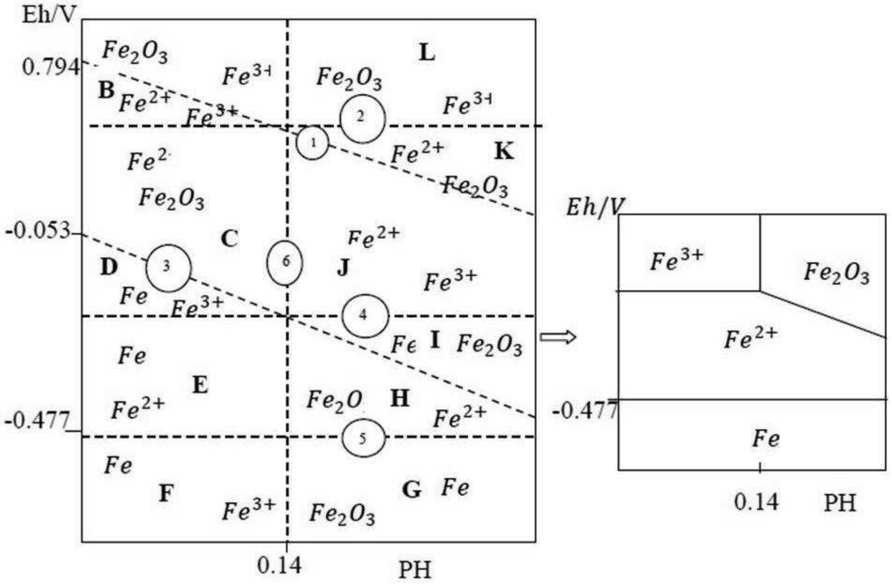


Figure 6.2 shows the iron-water system: (A) Before elimination, and (B) After elimination (not drawn to scale).

Table 6.2 Eliminations of the unstable species and lines for iron and its oxides

Region	Competing species	Law (Equation)	Stable species	Action
A	Fe_2O_3 / Fe^{3+}	6	Fe^{3+}	Eliminate line 1, to obtain combined region A-B
B	Fe^{2+} / Fe^{3+}	2	Fe^{3+}	-
C	Fe^{2+} / Fe_2O_3	1	Fe^{2+}	Eliminate line 3 to obtain combined region C-D
D	Fe / Fe^{3+}	4	Fe^{3+}	-
E	Fe^{2+} / Fe^{3+}	2	Fe^{2+}	-
F	Fe / Fe^{3+}	5	Fe	Eliminate line 6 to obtain combined region F-G
G	Fe / Fe_2O_3	3	Fe	-
H	Fe^{2+} / Fe_2O_3	1	Fe^{2+}	Eliminate line 6 to obtain combined region H-F, also line 3 can be eliminated
I	Fe / Fe_2O_3	3	Fe_2O_3	Eliminate line 4 to obtain combined region I-J,
J	Fe^{2+} / Fe^{3+}	2	Fe^{2+}	-
K	Fe^{2+} / Fe_2O_3	1	Fe_2O_3	Eliminate line 2 to obtain combined region K-L
L	Fe_2O_3 / Fe^{3+}	6	Fe_2O_3	-

6.6 Silicon-Water Stability Diagram

6.6.1 The selected thermodynamic data for Si- H2O are presented below

(4) Reaction	log K
$Si + 2H_2O = SiO_2 + 4H^+4\bar{e} - - - - - - - - - - - - (1)$	56.87
$Si + 3H_2O = HSiO_3^- + 5H^+ + 4\bar{e} - - - - - - - - -(2)$	42.24
$SiH_4 + 3H_2O = HSiO_3^- + 9H^+ + 8\bar{e} - - - - - - - - (3)$	35.93 (Xiage, 2001)

The species of interest in this project are ($Si, SiO_2, HSiO_3^-$ and SiH_4)

($\mathbf{i}$) $\mathbf{Si \rightarrow HSiO_3^-}$, using equation (2)

$Si + 3H_2O = HSiO_3^- + 5H^+ + 4\bar{e} - - - - - - - - -(2)$ $\quad$ $\mathrm{logk} = 42.24$

$$\mathbf{Q} = \frac{[HSiO_3^-][H^+]^5[\bar{e}]^4}{[Si][H_2O]^3}$$

Assuming $[Si] = [H_2O] = [HSiO_3^-] = 1$, at standard condition

$\log Q = \log K$ at equilibrium

$\Rightarrow \mathbf{Q} = [H^+]^5[\bar{e}]^4$, taking logarithm at both side

Log Q = 5 $\log[H^+] + 4\log[\bar{e}]$, and at equilibrium $\log Q = \log k$

$\Rightarrow \log k = -5PH - 4P\varepsilon$

If $\log k \geq \log Q$, it implies that Si dissolves to form stable $HSiO_3^-$

$P\varepsilon \geq -10.56 - 1.25PH,$

$\Rightarrow Eh \geq -0.623 - 0.074PH$

Similarly the relative stability equations for others are summarized below

(ii) (Si→ $\mathbf{SiH_4}$)

Considering equation (1) and (2), $Si + 4H^+ + 4\bar{e} = SiH_4$ $\quad\quad$ $\log k = 6.31$

$Eh \leq 0.093 - 0.059PH$

(iii) ($\mathbf{SiO_2} \rightarrow \mathbf{HSiO_3^-}$)

Using equation (1) and (2) $SiO_2) + H_2O = HSiO_3^- + H^+$ $\quad$ $\log k = -14.63$

$PH \geq 14.63$

(iv) ($\mathbf{SiH_4} \rightarrow \mathbf{SiO_2}$)

Using equation this equation , $SiH_4 + 2H_2O = SiO_2 + 8H^+ + 8\bar{e}$ $\quad$ $\log k = 50.56$

$Eh \geq -0.373 - 0.059PH$

(iv) ($\mathbf{SiH_4} \rightarrow \mathbf{SiO_2}$)

Using equation (3), $SiH_4 + 3H_2O = HSiO_3^- + 9H^+ + 8\bar{e}$ $\quad\quad$ $\log k = 35.93$

$Eh \geq -0.265 - 0.066PH$

(v) (Si→ $\mathbf{SiO_2}$)

Using equation (1) $Si + 2H_2O = SiO_2 + 4H^+ 4\bar{e}$ $\quad\quad$ $\log k = 56.87$

$Eh \geq -0.839 - 0.059PH$

6.6.2 Relative Stability Equations for the Si – H$_2$O system

Reaction	Equation	Line
$\mathrm{Si} \rightarrow \mathrm{SiH_4}$	$\mathrm{Eh} \leq 0.093 - 0.059\mathrm{PH}$	1
$\mathrm{SiH_4} \rightarrow \mathrm{HSiO_3^-}$	$\mathrm{Eh} \geq -0.265 - 0.066\mathrm{PH}$	2
$\mathrm{SiH_4} \rightarrow \mathrm{SiO_2}$	$\mathrm{Eh} \geq -0.373 - 0.059\mathrm{PH}$	3
$\mathrm{Si} \rightarrow \mathrm{HSiO_3^-}$	$\mathrm{Eh} \geq -0.623 - 0.074\mathrm{PH}$	4

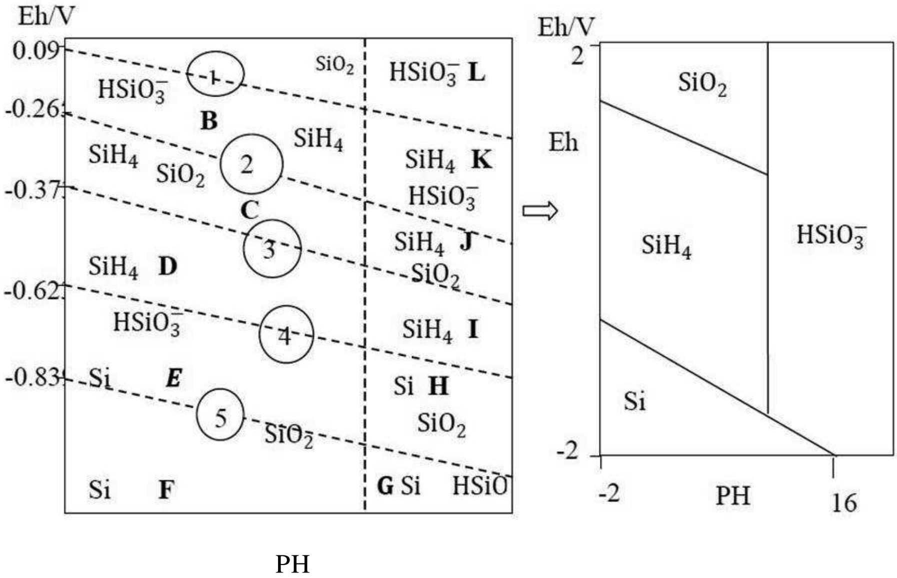


Figure 6.3 Shows the Si – H$_2$O system: (A) Before eliminations, and (B) After eliminations (not drawn to scale).

Table 6.3 Elimination of the unstable species and lines for silicon and its oxides

Region	Competing species	Law (Equation)	Stable species	Action
A	Si /SiO_2	5	SiO_2	Eliminate line 1, to obtain combined region A-B
B	SiH_4 /$HSiO_3^-$	2	$HSiO_3^-$	-
C	SiH_4 / SiO_2	3	SiO_2	Eliminate line 2 to obtain combined region B-C
D	SiH_4 / $HSiO_3^-$	2	SiH_4	Eliminate line 4 to obtain combined region D-E
E	Si/SiO_2	5	SiO_2	-
F	Si/SiO_2	5	Si	Eliminate line 6 to obtain combined region F-G
G	Si/ $HSiO_3^-$	4	Si	-
H	Si/SiO_2	5	SiO_2	Eliminate line 4 to obtain combined region H-I
I	SiH_4 /$HSiO_3^-$	2	SiH_4	-
J	SiH_4 / SiO_2	3	SiH_4	Eliminate line 2 to obtain combined region J-K
K	SiH_4 / $HSiO_3^-$	2	$HSiO_3^-$	Eliminate line 1 to obtain combined region K-L
L	Si / $HSiO_3^-$	4	$HSiO_3^-$	-

6.7 Iron – Silicon-Water Stability Diagram (Fe-Si-H_2O System)

6.7.1 Selected thermodynamic data for Fe-Si-H2O system are presented below

Reaction	Equation	Log k
$\mathrm{Fe} = \mathrm{Fe}^{2+} + 2\bar{e}$	(1)	16.17
$\mathrm{Fe_2Si} + 3\mathrm{H_2O} = 2\mathrm{Fe}^{2+} + \mathrm{HSiO_3^-} + 5\mathrm{H}^+ + 8\bar{e}$	(2)	25.13
$\mathrm{Si} + 3\mathrm{H_2O} = \mathrm{HSiO_3^-} + 9\mathrm{H}^+ + 8\bar{e}$	(3)	42.24
$\mathrm{SiH_4} + 3\mathrm{H_2O} = \mathrm{HSiO_3^-} + 5\mathrm{H}^+ + 8\bar{e}$	(4)	43.59
$\mathrm{HSiO_3^-} + \mathrm{H}^+ = \mathrm{SiO_2} + \mathrm{H_2O}$	(5)	14.63

Selected Fe^- containing species for this project are ($\mathrm{Fe_2Si}$, Fe and Fe^{2+}). The relative stability equations for these pair are: $\mathrm{Fe_2Si}$/ Fe, $\mathrm{Fe_2Si}$ /Fe^{2+}, and Fe / Fe^{2+} . The decomposition of $\mathrm{Fe_2Si}$ produces these different species of silicon (Si, $\mathrm{SiO_2}$, $\mathrm{HSiO_3^-}$ and $\mathrm{SiH_4}$).

(i) Considering $\mathrm{Fe_2Si} \rightarrow$ Fe in the $\mathrm{HSiO_3^-}$ region (1a).

Using equation (1) and (2),

$\mathrm{Fe_2Si} + 3\mathrm{H_2O} = 2\mathrm{Fe} + \mathrm{HSiO_3^-} + 5\mathrm{H}^+ + 4\bar{e}$ log k = -7.21

$$Q = \frac{[\mathrm{Fe}]^2[\mathrm{HSiO_3^-}][\mathrm{H}^+]^5[\bar{e}]^4}{[\mathrm{Fe_2Si}][\mathrm{H_2O}]^3}$$

At standard conditions $[\mathrm{Fe}] = [\mathrm{HSiO_3^-}] = [\mathrm{Fe_2Si}] = [\mathrm{H_2O}] = 1$

$\Rightarrow Q = [\mathrm{H}^+]^5[\bar{e}]^4$, taking log on both sides gives log Q = 5 log$[\mathrm{H}^+]$ + log$[\bar{e}]$

At equilibrium, log Q = log k. Also when log k $\geq$ logQ, it implies that $\mathrm{Fe_2Si}$ dissolves to Fe.

$\text{Log k} \geq -5PH - 4P\varepsilon, \Rightarrow P\varepsilon \geq 1.80 - {}^{5}/_{4}\,PH$

$\therefore Eh \geq 0.106 - 0.074PH$

(ii) $Fe_2Si \rightarrow Fe$ in SiO_2 region (1b)

Likewise using equation (1), (2) and (5)

$Fe_2Si + 2H_2O = 2Fe + SiO_2 + 4H^+ + 4\bar{e}$ log k = 7.42

$\therefore Eh \geq -0.109 - 0.059\ PH$

(iii) $Fe_2Si \rightarrow Fe$ in SiH_4 region (1c)

$Fe_2Si + 4H^+ + 4\bar{e} = 2Fe + SiH_4$ log k = - 50.8

$\therefore Eh \leq -0.75 - 0.059PH$

(iv) $Fe_2Si \rightarrow Fe$ in Si region (1d)

Using equation (1), (2) and (3) $Fe_2Si = 2Fe + Si$ log k = -49.45

$49.45 \leq 0$

(B) **Also considering $Fe_2Si \rightarrow 2Fe^{2+}$ in the $HSiO_3^-$ region (2a)**

$Fe_2Si + 3H_2O = 2Fe^{2+} + HSiO_3^- + 5H^+ + 8\bar{e}$ log k = 25.13

$\therefore Eh \geq -0.185 - 0.0368PH$

(ii) $\mathbf{Fe_2Si \rightarrow 2Fe^{2+}}$ in the $\mathbf{SiO_2}$ region (2b)

Using equation (2) and (5), $Fe_2Si + 2H_2O = 2Fe^{2+} + SiO_2 + 4H^+ + 8\bar{e}$ log k = 39.76

$\therefore$ Eh $\geq -\,0.293 - 0.029$ PH

(ii) $\mathbf{Fe_2Si \rightarrow 2Fe^{2+}}$ in the $\mathbf{SiH_4}$ region (2c)

Using equation (2) and (4), $\mathbf{Fe_2Si} + 4H^+ = 2Fe^{2+} + SiH_4$

PH ≤ -4.615

(iii) $\mathbf{Fe_2Si \rightarrow 2Fe^{2+}}$ in the Si region (2d)

using equation (2)and (3) , $\mathbf{Fe_2Si} = \mathbf{2Fe^{2+}} + 4\bar{e} + Si$ log k = 16.17

$\therefore$ Eh $\geq -\,0.5251$

(C) Considering Fe→ $\mathbf{Fe^{2+}}$

Using equation (1), Fe = $Fe^{2+} + 2\bar{e}$ log k = 16.17

$\therefore$ Eh ≥ -0.477

(v) 6.7.2 Relative stability equations for the Fe – Si – H_2O

Reaction	**Equation number**	**Equation**
$\mathbf{Fe_2Si \rightarrow Si}$	1a	Eh $\geq 0.106 - 0.074$PH
	1b	Eh $\geq -0.109 -$
	1c	0.059 PH
	1d	Eh $\leq -0.75 - 0.059$PH

		$49.45 \le 0$
$\mathbf{Fe_2Si \rightarrow 2Fe^{2+}}$	2a 2b 2c 2d	$Eh \ge -0.185 -$ $0.0368PH$ $Eh \ge -0.293 -$ $0.029\ PH$ $PH \le -4.615$ $Eh \ge -0.5251$
$\mathbf{Fe \rightarrow Fe^{2+}}$	3	$Eh \ge -0.477$

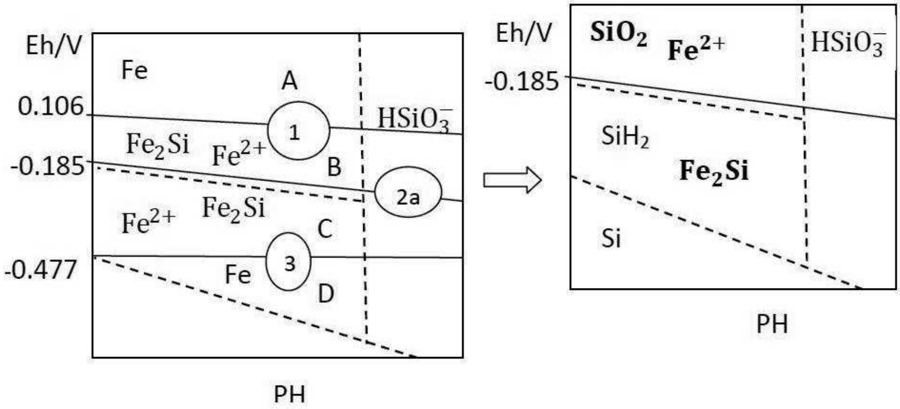


Figure 6.4 Fe-HSiO$_3^-$-H$_2$ O: (A) Before, (B) After eliminations (not drawn to scale).

In region B the competing species are Fe_2Si/Fe^{2+}. Using equation 2a, $Fe^{2+}$is stable hence line 1a can be eliminated. Likewise line 3 in region C can be eliminated since Fe_2Si is stable.

6.8 The Fe - SiO_2- H_2O System

Following a likewise procedure in the Fe-$HSiO_3$-H_2O System, the Fe - SIO_2- H_2O system is shown (Fig. 6.5).

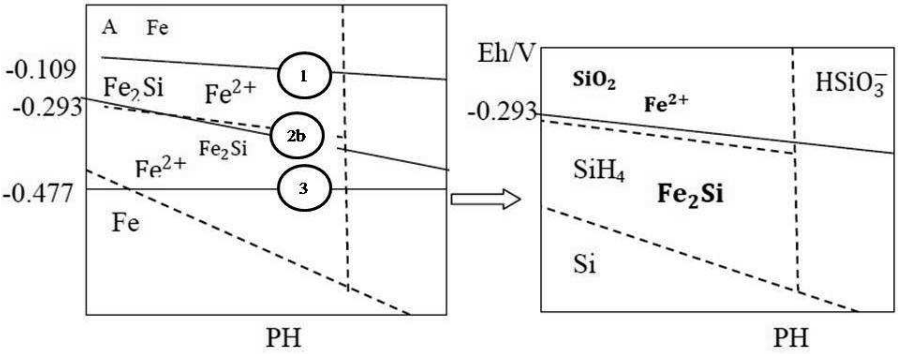


Figure 6.5 Shows the Fe – SiO2 – H2O System: (A) Before elimination, (B) After elimination (not drawn to scale).

6.9 The Fe – SiH_4 – H_2O System.

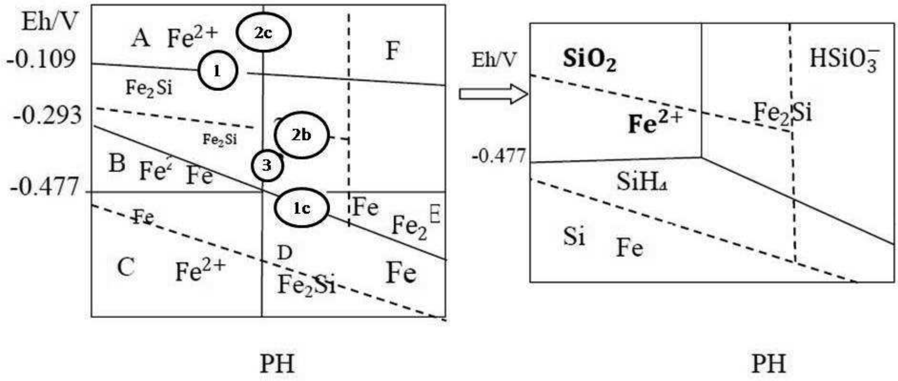


Figure 6.6 Fe – SiH4 – H2O System: (A) Before, and (B) After elimination (not drawn to scale).

6.10 Fe – Si – H_2O System

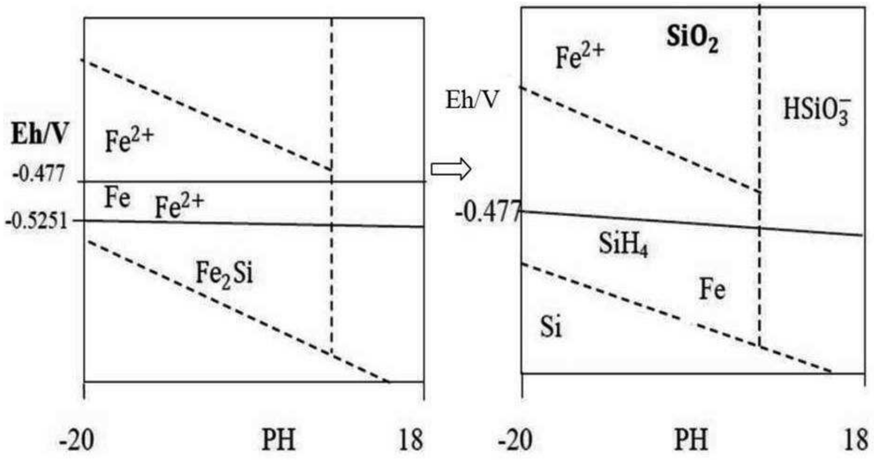


Figure 6.7 Fe – Si – H_2O System (not drawn to scale).

Fig. (6.5), (6.6), (6.7) combines to give a composite stability diagram shown below.

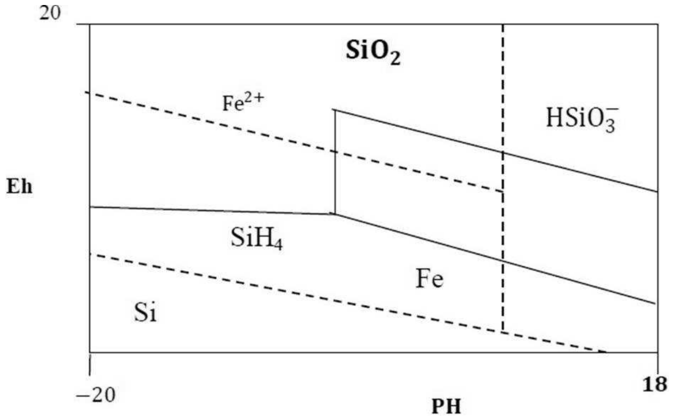


Figure 6.8 shows the composite stability diagram (not drawn to scale).

6.11 Dissolution Windows and Dissolution Reaction Paths

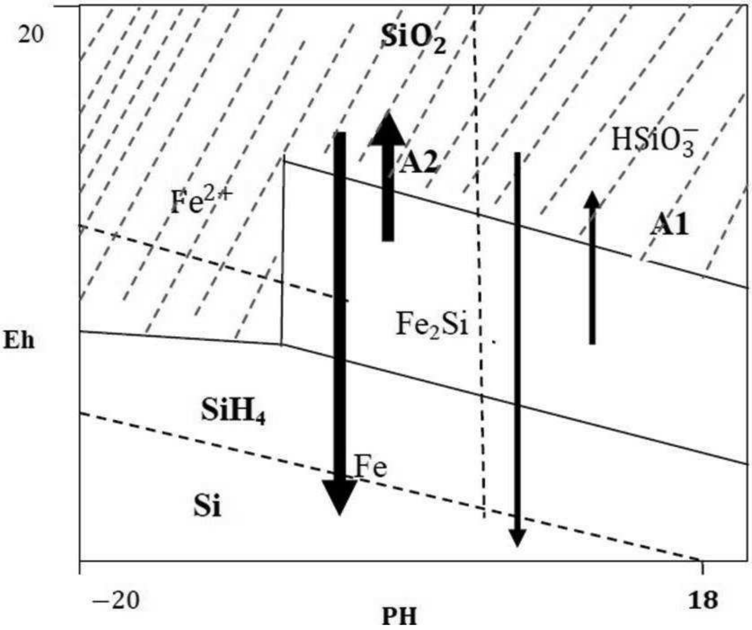


Figure 6.9 Selective dissolution windows (not drawn to scale). The shaded region shows the selective dissolution window.

6.11.1 Reaction Path (A_1)

6.11.1.1 Oxidation Acid Dissolution:

Dissolution reaction

$Fe_2Si+3H_2O = 2Fe^{2+} + HSiO_3^- + 5H^+ + 8e^-$ (1)

Precipitation reaction

$HSiO_3^- + 5H^+ + 4e^- = Si + 3H_2O$ (2)

6.11.2 Reaction Path (A_2)

6.11.2.1 Oxidative Acid Dissolution

Dissolution reaction

$Fe_2Si+2H_2O = 2Fe^{2+}\ SiO_2 + 4H^+ + 8e^-$ (3)

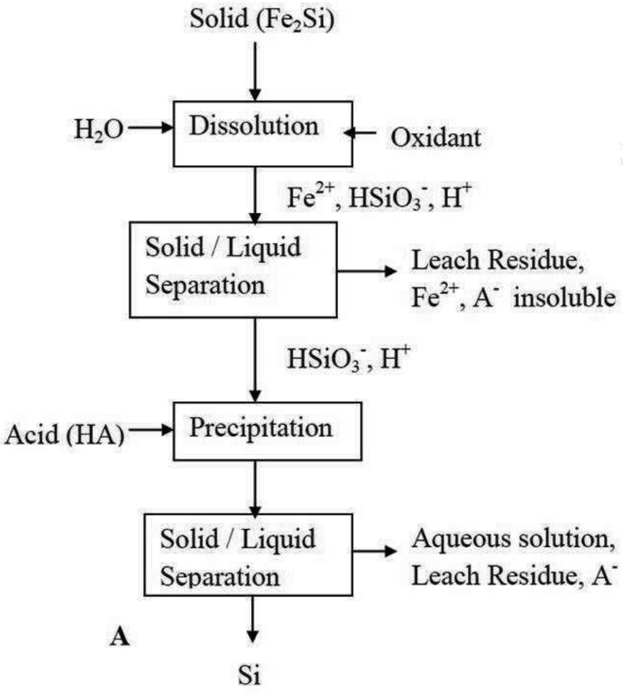
Precipitation reaction

$SiO_2 + 4H^+ + 4e^- = Si + 2H_2O$ (4)

Using (4) $Fe_2Si+2H_2O = 2Fe^{2+}\ SiO_2 + 4H^+ + 8e^-$

6.11.3 Conceptual Flow Diagrams

Reaction Path A1



Reaction Path A2

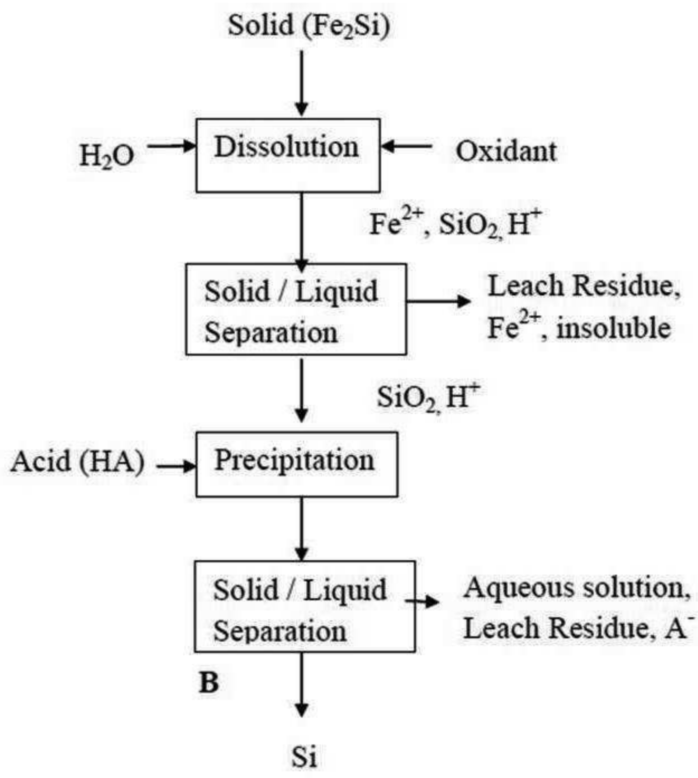


Figure 6.10 Conceptual Flow Diagrams: (A) Reaction Path A1, (B) Reaction Path A2.

6.11.4 Cell Voltage Calculations

(a) Considering the Oxidation Acid Dissolution (Reaction Path A1)

$Fe_2Si+3H_2O = 2Fe^{2+}\ HSiO_3^- + 5H^+ + 8e^-$ $\log k = 25.13$

$\underline{HSiO_3^- + 5H^+ + 4e^- = Si + 3H_2O \qquad \log k = -42.24}$

$Fe_2Si = 2Fe_2^{2+} + Si + 4e^-$ $\log k = -17.11$

$Q = \frac{[Fe^{2+}]^2[Si][\bar{e}]^4}{[Fe_2Si]}$

At standard conditions, $[Fe^{2+}] = [Si] = [Fe_2Si] = 1$

$\log Q = \log k, \Longrightarrow \log k = 4\log\,[\bar{e}]$

$\Longrightarrow P\varepsilon = -\frac{\log k}{4} = 4.2775$

$\therefore$ Eh = 0.2524 V

The cell voltage for non-oxidation acid dissolution (reactive path A1) is 0.2524 V.

(b) Considering the oxidation acid dissolution (reaction path A2)

$Fe_2Si + 2H_2O = 2Fe^{2+} + SiO_2 + 4H^+ + 8\bar{e}$ $\log k = 39.76$

$\underline{SiO_2 + 4H^+ 4\bar{e} = Si + 2H_2O \qquad\qquad \log k = -56.87}$

$Fe_2Si = 2Fe^{2+} + Si + 4\bar{e}$ $\qquad \log k = -17.11$

$Q = \frac{[Fe^{2+}]^2[Si][\bar{e}]^4}{[Fe_2Si]}$, at standard condition $[Fe^{2+}] = [Si] = [Fe_2Si] = 1$

At equilibrium, log Q = log k

$\text{Log}\,k = [\bar{e}]^4, \Longrightarrow \log k = -4\,P\varepsilon, \Longrightarrow P\varepsilon = -\frac{\log k}{4} = 4.277$

Eh = 0.2523V

The cell voltage for oxidation acid dissolution (reaction path A_2) is 0.2523V.

6.12 Summary and Conclusion on Part B

Solar energy has been the concerned alternative energy in the 21st century because it is non-depleting and non-pollution. The market trends of solar energy materials have shown a decreasing in price with increasing efficiency. The technologies for the production of MG-Si are still expensive. Silicon has a good world market record for the 21^{st} century especially in its crystalline form despite amorphous is equally relevant. It is however, not the ideal material to use for photovoltaic energy conversion. The efficiency of silicon strongly depends on higher purity level, and the higher purity of the crystalline perfection.

These processing routes are not expensive as compared to other thermochemical processing techniques for purifying MG-Si. With aqueous processing routes, safety is assured because it does not involve flammable solvent in the process. These processes have fewer processing procedures than other techniques for purifying MG-Si. Also, they control pollution because they eliminate solvent that may have been lost to the atmosphere. These technologies also have a wide range of applications beyond purifying MG-Si. It can be used in the oil extraction, mineral processing, hydrometallurgical, battery discharge, and the likes.

The main drawbacks for these processing route is that they cannot be use to determine the kinetics of the process. Iron can be removed from the MG-Si, but the time for its removal cannot be determined using this processing route. The cell potential calculated shows that the two reaction paths produce the same cell potentials of 0.252 V.

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APPENDICES

4.3.1Energy Calculation for Navrongo

The maximum energy (E_{max})value per day for Navrongo= $Time_{max}$ (s) x Ps (w), where $Time_{max}$ is the monthly maximum mean sun hours and Ps is the solar power.

$Time_{max}$ = 9.18hours= 9.31 x 3600s x 1day = 33,516.

Then, the energy per day $E_{max.d}$ = 33,516s x $1.28x10^{17}$Wx 1day = 4.290 $x10^{21}$J/d

And the maximum energy per year $E_{max.y}$ = $4.290x10^{21}$J/day x 365.25days = $1.567x10^{24}$J/y.

The minimum energy ($E_{min.d}$) value per day for Navrongo= $Time_{min}$ (s) x Ps (W) The minimum mean sunshine value is 5.97hours, $Time_{min}$ = 5.97 x 3600s = 21,492s.

The minimum energy per day is E_{min}= 21,492sec.x $1.28x10^{17}$W x 1day = 2.751 x 10^{21}J/d.

The minimum energy per year E_{min} = 2.751 x 10^{21}J/day x 365.25days = $1.004x10^{24}$J/y.

4.3.2 Energy Calculation for WA

The maximum energy (E_{max}) value per day forWA = $Time_{max}$ (s) x Ps (w)

$Time_{max}$ = 9.05hours = 9.05 x 3600s x 1day = 32,580 s.

Then, the energy per day $E_{max.d}$ = 32,580 sec x $1.28x10^{17}$Wx1day= $4.17x10^{21}$J/d.

And energy per year $E_{max.y}$ = $4.17x10^{21}$J/day x 365.25days = 1.523 x 10^{24}J/y.

The mean minimum sunshine value is 5.02hours, $Time_{min}$ = 5.02 x 3600s.= 18,072s.

The minimum energy per day is E_{min}= 18,072secx $1.28x10^{17}$Wx 1d= $2.313x10^{21}$J/d

The minimum energy per year = $2.313x10^{21}$J/dayx365.25days = 8.449 x 10^{23}J/y

4.3.2 Energy Calculation for Tamale

Time = 8.96hours = 8.96 x 3600s = 32,256s

The maximum energy per day $E_{max.d}$ = 32,256sec.x1.28x10^{17}Wx1d = 4.129 x 10^{21}J/d

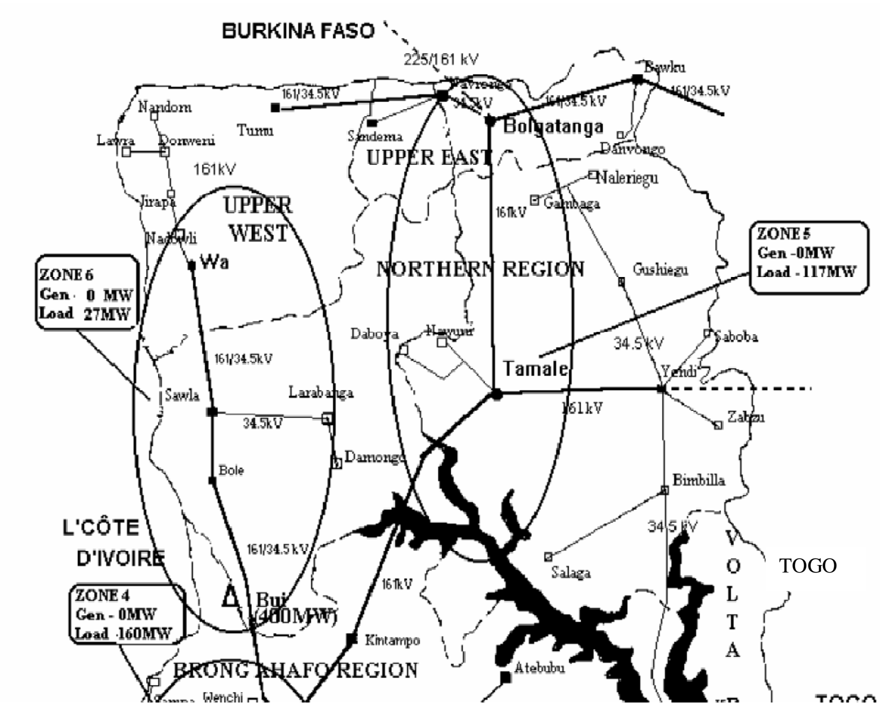
The maximum energy per year $E_{max,y.}$ = 4.129 x 10^{21}J/day x 365.25 days = 1.508 x 1024J/y

The mean minimum sunshine value is 5.02 hours, $Time_{min}$= 5.44 hours = 5.44 x 3600s = 19,584s.

The minimum energy per day is E_{min}= 19,584s x 1.28x10^{17}W x 1d = 2.507x10^{21}J/d.

The minimum energy per year =2.507x10^{21}J/d x 365.25days. = 9.156 x 10^{23}J/y.

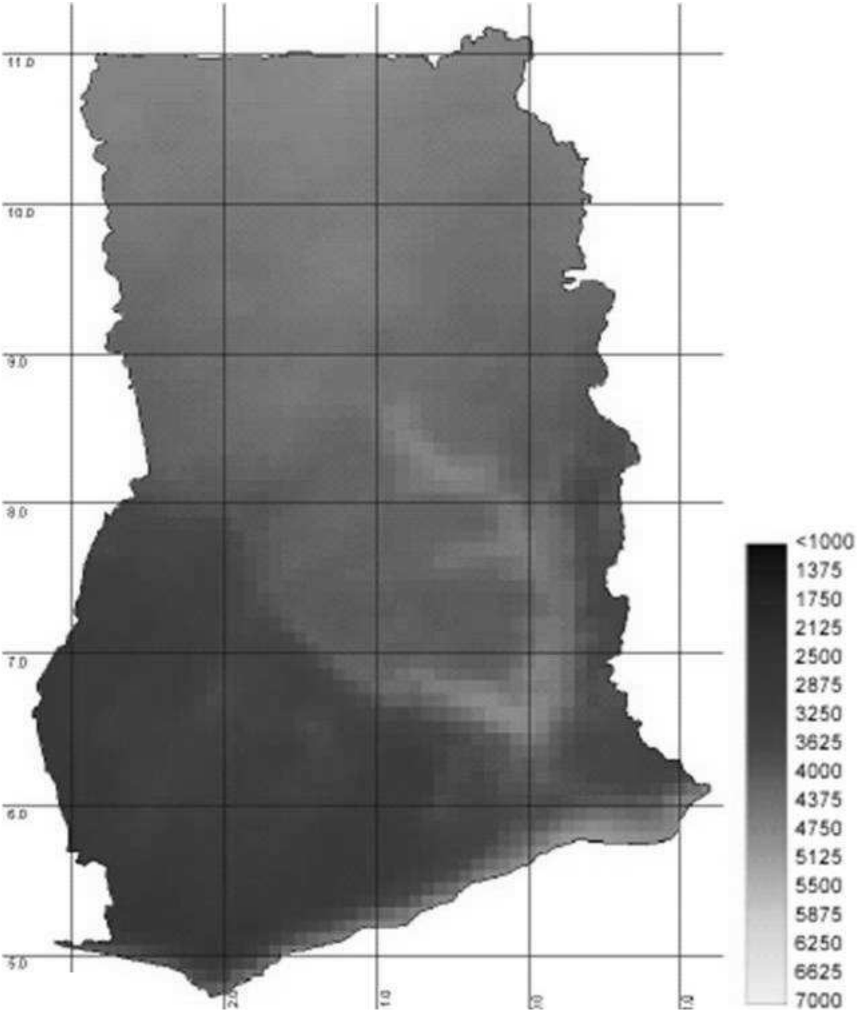
Table 4.4A The Energy Calculated from the Monthly averages of the highest and minimum sun shine hours.



Southern Ghana

Figure A1 Electricity Infrastructure of Northern Ghana. Source: Ghana Energy Commission, March 2005.

Annual Report on DLR Activities within SWERA



Ghana Annual Average daily total sum of DNI in Wh/m^2/day (3-years average).

Figure A2 Solar radiation map of Ghana. Source: SWERA Ghana Project, 2002.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