ASSESSING THE VIABILITY OF POWERING TELECOM BASE STATION

WITH SOLAR PV-DIESEL HYBRID SYSTEM: A CASE STUDY AT A

TELECOM CELL SITE

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES, KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, GHANA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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DECLARATION

I hereby declare that this thesis submission is the result of my own original work towards MSc. under the supervision of the undersigned, and that it contains no materials previously published by another person nor material which has been accepted for the award of any other degree of the university except where due acknowledgment has been made in the text.

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I

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ABSTRACT

The quest by telecom operators to provide voice and data services are seriously challenge by the unavailability of the grid in some part of Ghana. Diesel generators are commonly used to provide the needed power.

Despite Ghana having a good solar radiation and sunshine durations, telecom companies are yet to take full advantage of the falling cost of installing a solar PV system. This thesis assess the technical and economic viability of a solar- hybrid system to power a telecom base station.

Technical information was obtain from an outdoor telecom based station in Ghana located at is latitude 5^0 46' N longitude 0^0 4' E which has an annual solar radiation of 5.24kWh/m^2/d and the average load consumption of 6.35 kW. The base station is not connected to the grid and is being powered by a 16 kW diesel generator. HOMER software was used to analyse the technical and economic performance for a proposed solar PV/diesel hybrid power system for this base station.

The result indicates that, for the proposed hybrid system, despite its high initial cost, it is technically and economically better than the diesel generator only system which has a low initial cost. The hybrid system will consist of 23kW solar PV system, 10kW diesel generator and a battery bank of 86.4 kWh of storage energy. The operating cost per year, total NPC and cost of energy are USS 21,128/yr USS 307,622 and USS 0.611 'kWh respectively. The analysis indicates that 14kW (instead of the 16kW) diesel generator can be used to operate the site at a cost of USS 38,512/yr. the initial cost will be USS 21,950. The total NPC is USS 371,054 and the levelized cost of energy is USS 0.737/kWh.

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List of Symbols and Abbreviations

RBS	Radio Base Station
CDMA	Code Division Multiple Access
BTS	Base Transceiver Station
GSM	Global System of Mobile Communication

UNCTAD	United Nation Conference on Trade and Development
REN21	Renewable Energy Network for the 21 st Century
kWh	Kilowatt-hour
Kilowatt	
CDM	Clean Development Mechanism
PV	Photovoltaic
HOMER	Hybrid Optimisation Module for Electric Renewables
NASA	National Aeronautic and Space Agency
GhC	Ghana Cedis
US$	United States Dollars
DC	Direct Current
AC	Alternating Current
aSi	Amorphous Silicon
BOS	Balance of System
MPPT	Maximum Power Point Tracker
STC	Standard Test Condition
Isc	Short circuit current
I_{mp}	Maximum power current
V_{oc}	Open circuit voltage
V_{mp}	Maximum power voltage
V_{mp}	Maximum power voltage
CAPEX	Capital Expenditure
OPEX	Operation Expenditure
	Diesel Generator
	Operation and Maintenance
NPC	Net Present Cost
NPV	Net Present Value
	Capital Recovery Factor
COE	Cost of Energy
	Carbon (IV) Oxide (Carbon Dioxide)

Chapter One - Introduction

1.1 Background

A base transceiver station (BTS) is a piece of equipment that facilitates wireless communications between user equipment (UE) and a network. UEs are devices like mobile phones (handsets), WLL (wireless landline) phones, and computers with wireless internet connectivity (Wikipedia, 2014). BTS is also referred to, as the radio base station (RBS), or simply, the base station (BS), receives and transmit radio signals and provide local access to the network. Though the term BTS can be applicable to any of the wireless communication standards, it is generally associated with mobile communication technologies like GSM (Global System for Mobile communication) and CDMA (Code Division Multiple Access)

A typical BTS site has a two way power supply, the grid power and a diesel-powered generator. In location where the grid is not available (or extending the grid is not economically feasible), it is traditionally powered by two diesel generators. The BTS equipment is usually housed in a shelter. The shelter comprises the BTS equipment, an air conditioner a battery bank and security lights.

Unreliable grid power supply has forced the telecom operators and tower companies in Ghana to rely heavily on diesel power generators as a backup power source to run the network. The trend in usage of diesel generator power for grid-connected telecom tower sites shows that the usage of diesel generator has increased from an average of 3.66 hours/day in 2011 to 4.27 hours/day in 2012. (GSM Association, 2013)

Ghana with a network of 5,583 tower sites, has 638 sites (—11% of the network) deployed in locations without access to grid power supply. An off-grid site consumes on average 1,300 litres of diesel every month in Ghana. Diesel cost constitutes about

58% of the total direct costs of powering an on-grid site. The major portion of this cost includes the cost of the diesel consumed to run the site.

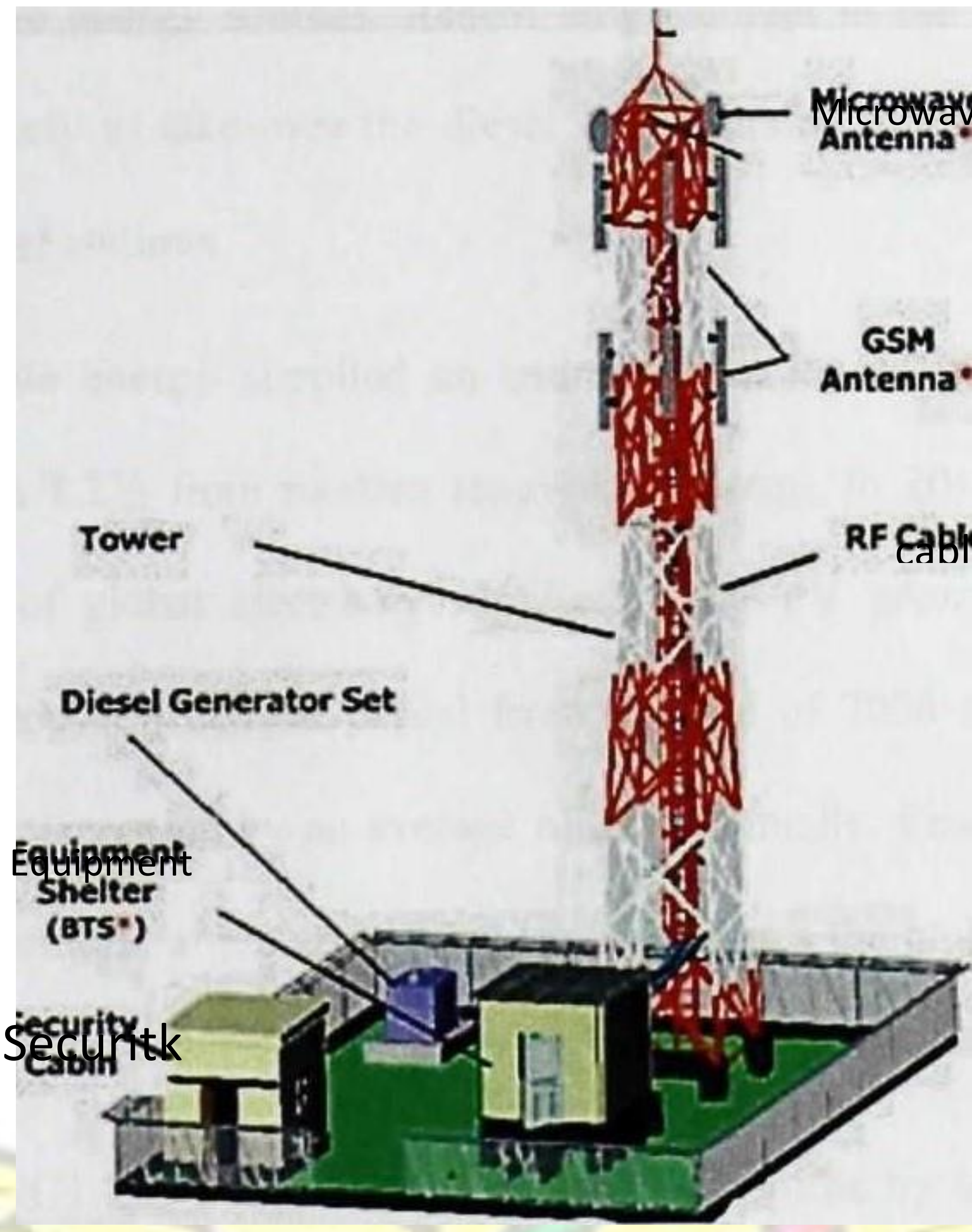


Figure 1.1- A typical BTS site.
Source: (GTL Infrastructure Limited, 2010)

Another challenge facing the mobile telecom operators in Ghana is challenging terrain, poFtial thefts of fuel, cost of refuelling and maintenance cost of diesel generator. More so, escalating prices of fuel could in the long run, affect network stability, increase cost of mobile communication and data services as well as prevent expansion of the services to rural areas.

This thesis seeks to assess-the viability of powering telecom base station with solar PV-diesel hybrid system in Ghana, an alternative option for powering telecom base station.

1.2 Justification

Diminishing fossil fuel reserves and concerns for the environment have push for the need for alternative energy sources. Recent advancement in the renewable energy technologies is likely to take-over the diesel generators as the best technology for off-grid mobile base stations.

In 2010, renewable energy supplied an estimated 16.7% of global final energy consumption, with 8.2% from modern renewable energy. In 2011, it generated an estimated 20.3% of global electricity supplied. Solar PV grew fastest of all the renewable technology during the period from the end of 2006 through 2011 with operating capacity increased by an average of 58% annually. From figure 1.2, solar PV capacity in operation at the end of 2011 was 10 times the global total five years earlier (REN21, 2012).

According to (UNCTAD, 2010), a pilot project in Namibia by Motorola, indicates that solar PV and wind turbine technologies are now at the point where they can power telecoms base stations.

For a majority of very remote and dispersed users, decentralized off-grid renewable electricity may be less expensive than extending the power grid. (REN21, 2012)

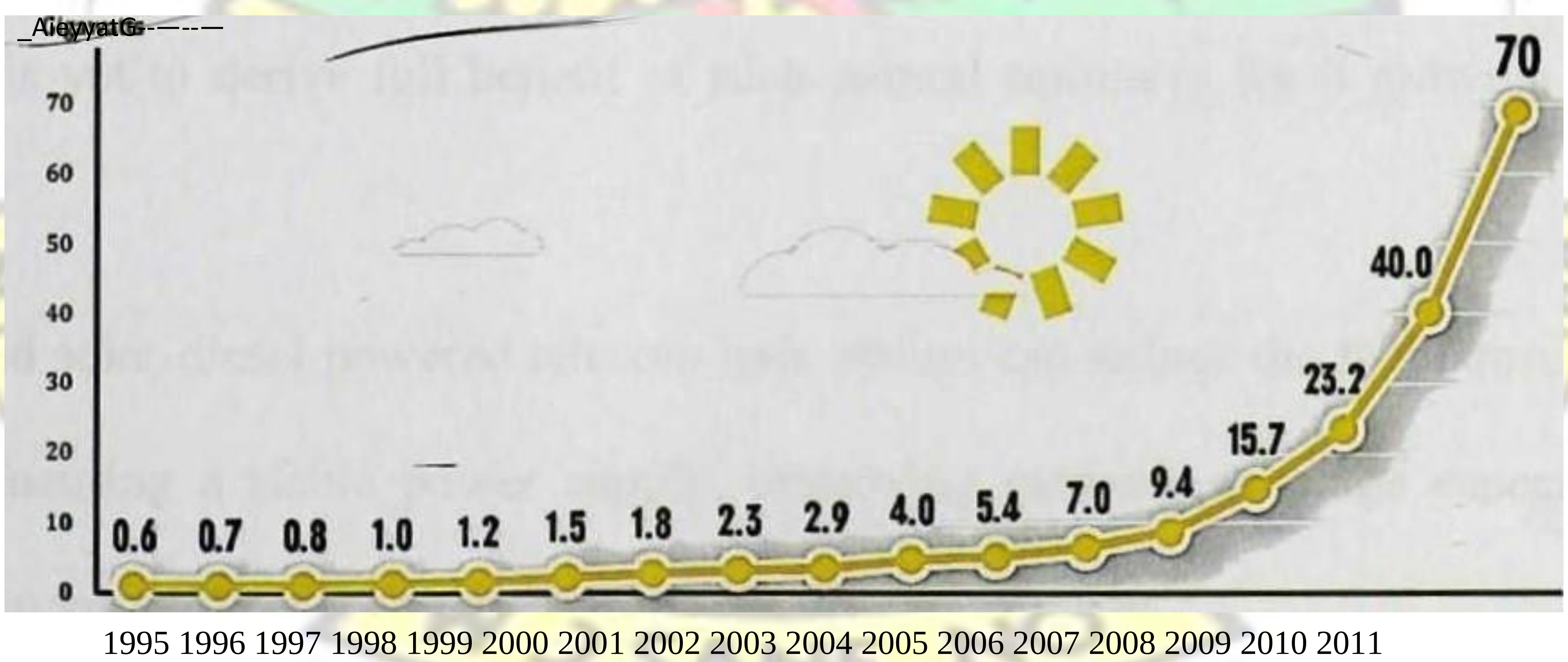


Figure 1.2 Solar PV Total World Capacities, 1995-2011.
Source: REN21

Research (Renewable Energy World, 2011) also predicts that the price of wind and solar energy will continue to fall and it is expected, especially in the case of solar technologies that they will become very close to competitive with fossil fuels over the next five to ten years.

A number of telecom operators all over the world are teaming up with telecom power providers to run their off-grid sites with hybrid systems, using various renewable energy sources combined with diesel generators. In some cases, the site is powered solely by one or more renewables, which eliminates the use fossil fuels.

In January 2010, Vodafone Qatar and Alcatel-Lucent announced the deployment of the first hybrid powered Base Station in Qatar, using an integration of solar and wind energy. Other companies such as flexenclosure, Ampair telecoms, fortune CP, sky built power etc. are providing telecom hybrid power systems based on renewable energy for telecom base stations in various part of the world including some African countries.

Ghana has monthly average of solar radiation between 4.4 and 5.6 kWh/m^2/day with a sunshine duration of 1800 to 3000 hours per annum. The northern part of the country recAves the highest solar radiation of 6 kWh/m^2/day on average. However,

Ghana is yet to derive full benefit of such natural resources for it growing energy .—-needs.

A hybrid solar-diesel powered telecom base station can reduce the fuel consumption while ensuring a stable power supply, improving network coverage especially in remote areas while at the same time saving the environment.

Implementing a solar powered base station, telecom operators can increase their revenue by way of a financial reward through the Clean Development Mechanism (CDM) and may sell if any, excess power generated to the community in which they operate.

1.3 Aims and objectives

In Ghana, the cost and challenges associated in running an off-grid base station with diesel generators can discourage telecom operators from expanding their networks. However, telecom operators are yet to take advantage of the continuous fall in the cost of installing a solar system. The aim of this thesis is to assess the viability of powering a base station with a solar PV-diesel hybrid system. The results will be used to provide recommendation for telecom operators in Ghana.

The aim of this thesis will be achieved by fulfilling the following research objectives:

1. Conduct a market survey of prices of solar panels and other system component in Ghana
2. Identify the power requirement of the telecom base station under study
3. Technically and economically, assess the diesel generator only system and compare to a proposed hybrid system.

1.4 Methodology

Literature-material was reviewed on theoretical and technical application of the use of solar PV technology and other components.

The HOMER software version 2.68 beta was obtained from homer energy LLC and the necessary literature materials needed to get familiar with the use of the software.

Technical and economic information including the Global Positioning System (GPS) location of the site under study was obtained from the network operator and maintenance technicians.

Prices of components from local retail outlets were obtained through a survey together with online (internet) information, personal and telephone communications with dealers of solar PV modules, system components and diesel generator sets.

Both the technical and economic analysis was done using the HOMER software to arrive at fair conclusion.

1.5 Scope of Work and Thesis Organisation

The thesis is composed of five chapters. The first chapter presents the background information, justification and the objective, which includes the problem statement and the methodology of the thesis. It provides information on the power problems faced by telecom operators in Ghana and the use of solar PV on the global scale. Chapter 2 presents the theoretical framework of solar PV technology including solar PV/diesel hybrid system configuration and life cycle cost method.

Technical and economic parameters are presented in chapter three. The financial and economic data are also presented here.

The analyses of the results are presented in chapter four while chapter five covers the conclusions and recommendations.

Chapter Two- Literature Review and Theoretical Framework

2.1 Hybrid Energy Systems

A hybrid energy system may be defined as a combination of two or more energy conversion devices that when integrated, overcome limitations that may be inherent in either. (Figure 2.1 depicts the concept of a PV/diesel hybrid system). Hybrid energy system refers to those applications in which multiple energy conversion devices are used together to supply an energy requirement. Hybrid systems are often used in isolated applications and normally include at least one renewable energy source in the configuration. Hybrid energy systems are used as an alternative to more conventional systems, which typically are based on a single fossil fuel source. Hybrid energy systems may also be used as part of distributed generation (DG) application in conventional electricity grid.

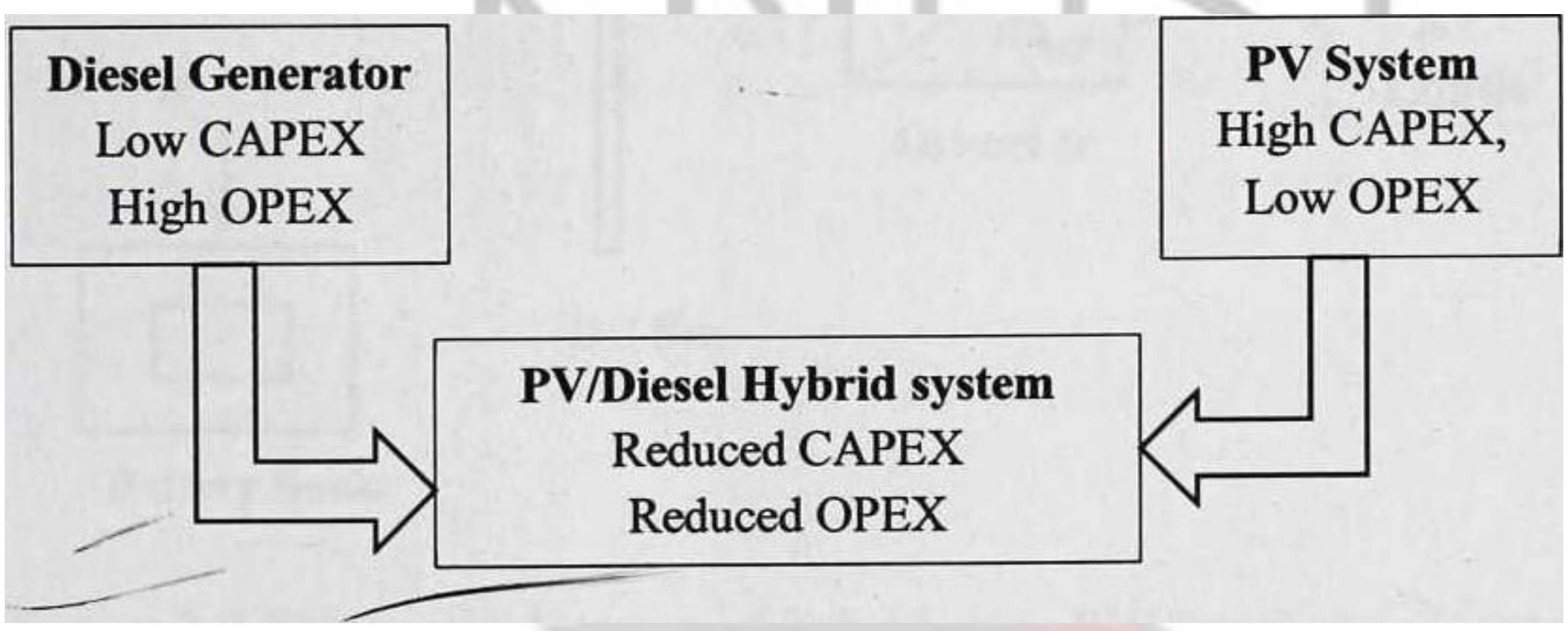


Figure 2.1 An economic over view of a PV/diesel hybrid system

2.1.1 Types ofsolar PV/hybrid system Configuration

Solar PV generate direct current (DC) power while the diesel generator produce an alternating current (AC), therefore to integrate them there is the need to bring them to a common form. Most household appliances requires AC power to operate hence inverters are used to convert DC to AC. This allows the PV generator to work in parallel or in alternation with the diesel generator. Muselli et al 1999 suggest the following types of solar hybrid system as cited by (Azoumah, et al., 2010)

2.1.2 Hybrid solar PV/diesel series system

In this system, the diesel generator does not supply the load directly. A rectifier convert is to a DC bus before it is converted back to AC to supply the load. This leads to conversion losses generated in the system; however, there is no power interruption in the event of operating the diesel generator or PV generator to charge the battery bank.

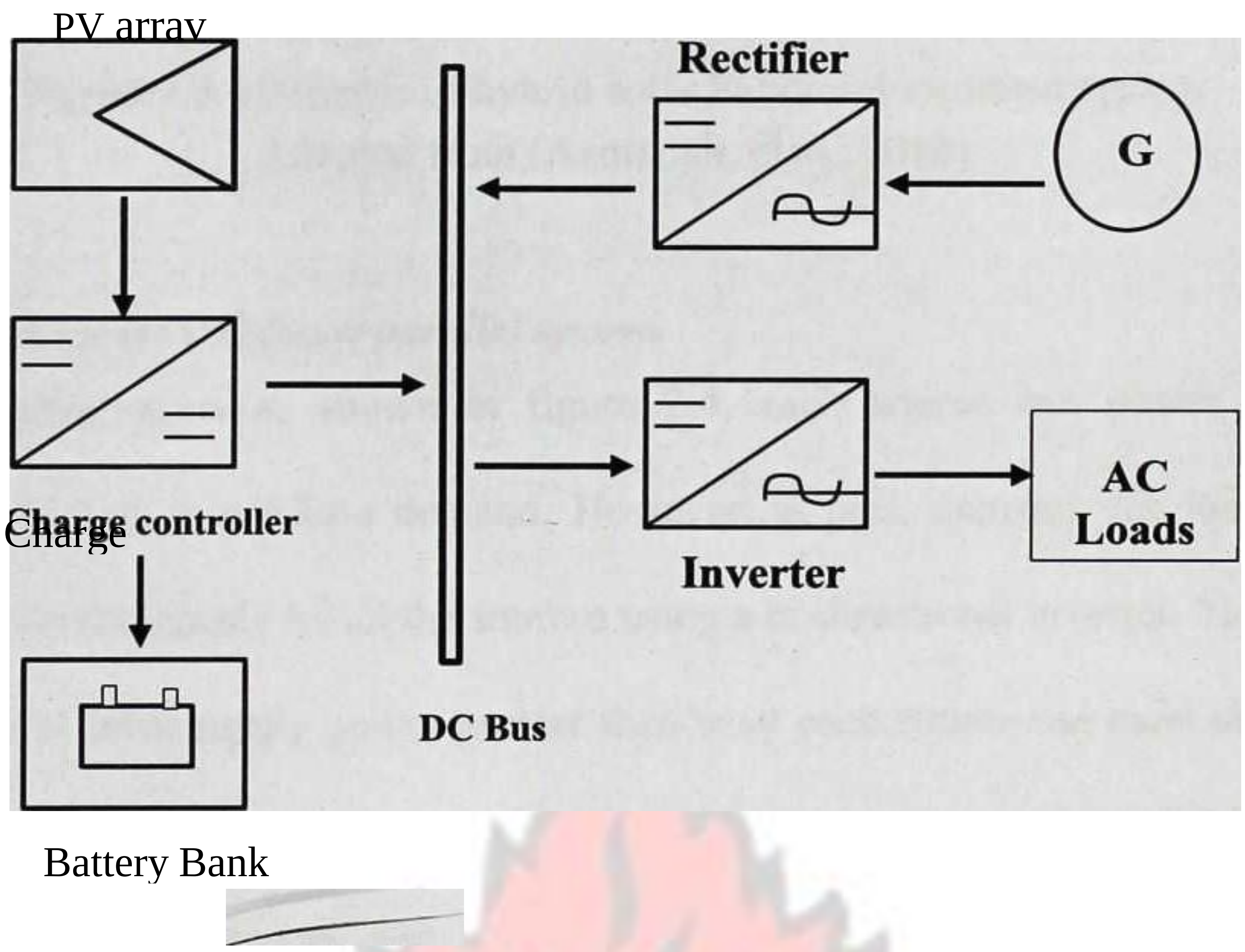


Figure 2.2 Schematic diagram of hybrid solar PV/diesel series system
Adapted from (Azoumah, et al., 2010)

2.1.3 Hybrid solar PV/diesel switched system

In this configuration, the load is powered directly by the diesel generator. The PV generator or the batteries can supply the load through an inverter. The generator can also charge the batteries. Conversion losses are significantly reduced. However, this configuration requires an automatic switching system, which results in improved overall efficiency.

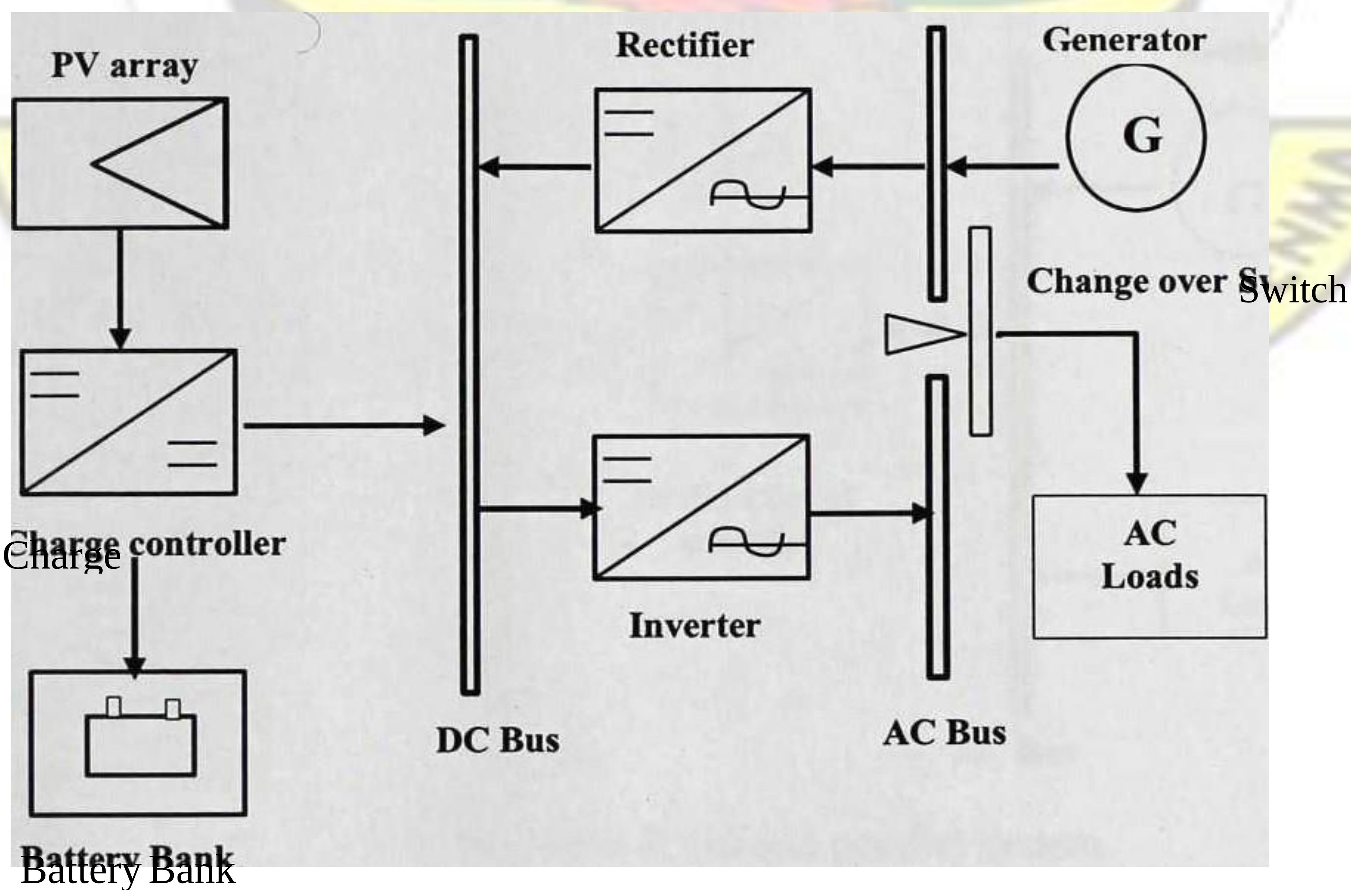
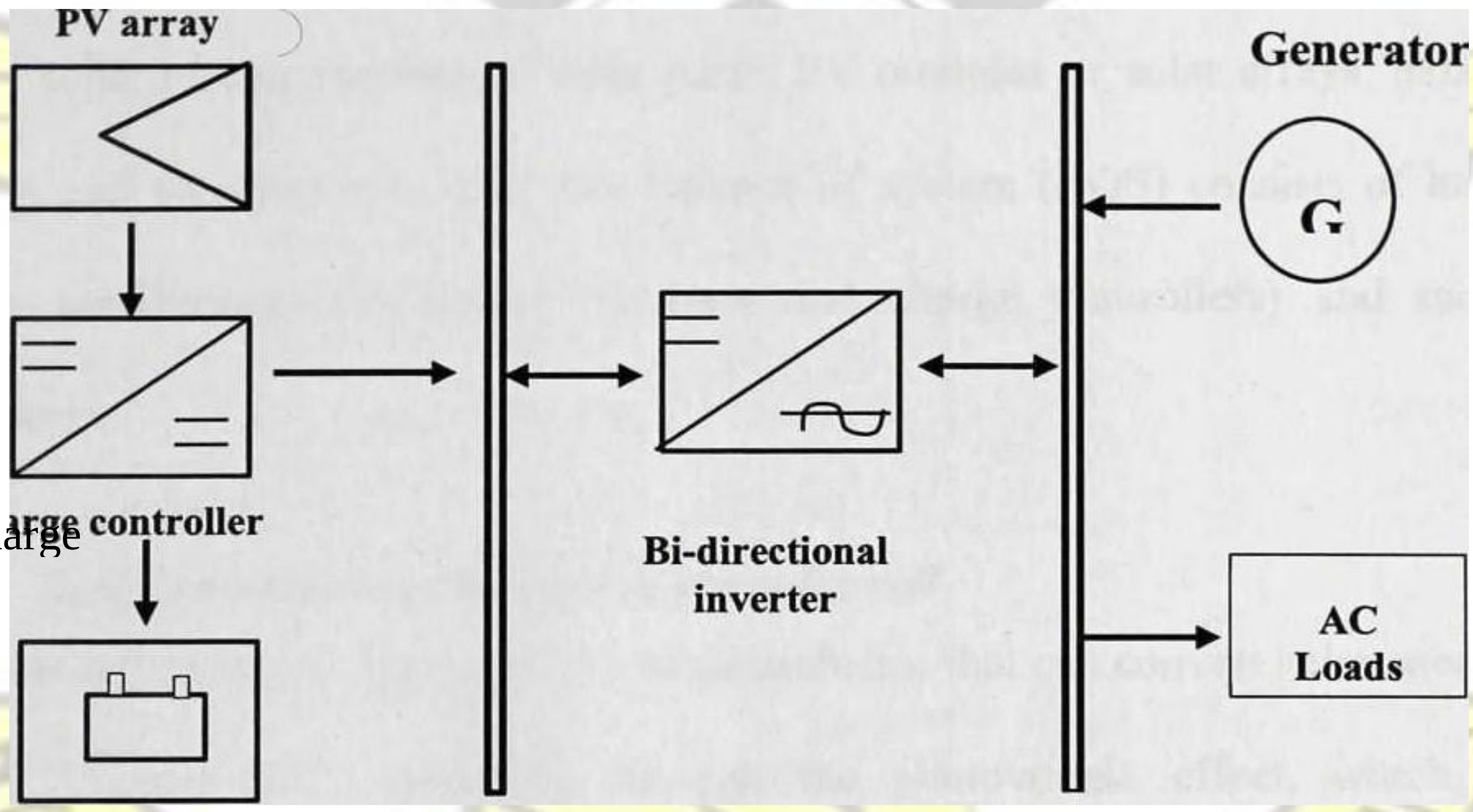


Figure 2.3 schematic ofhybrid solar PV/diesel switched system
Adapted from (Azoumah, et al., 2010)

2.1.4 Hybrid solar PV/dieselparallel system

In this configuration as shown in figure 2.4, each source can power the load separately at low to medium demand. However, at peak demand, the load can be powered simultaneously by all the sources using a bi-directional inverter. This allows the system to meet supply power greater than what each source can meet alone. The ability of the system inverter to synchronise with the generator allows for flexibility

with modular components and allows integration of others energy sources as renewable as conventional to support the photovoltaic system. More so, the generator size can be reduced. This system can be connected with the grid for certain conditions.



- Hybrid solar PV/diesel parallel system.
Adapted from (Azoumah, et al., 2010)

2.1.5 Proposed hybrid configuration

Unlike most domestic appliances that required, AC power source, most telecom equipment requires a DC power source to operate. For indoor site, where airconditioners are used, AC power is required. This thesis proposed the hybrid solar PV/diesel parallel system.

2.1.6 Components ofSolar PV/Hybrid Enerv System

A review of some of the technologies used in solar PV/ diesel hybrid systems is considered in this hesis. The review covers the following components:

- Solar PV systems; including batteries, power converters and mounting structures.
- Diesel generator
- Supervisory control and load management systems.

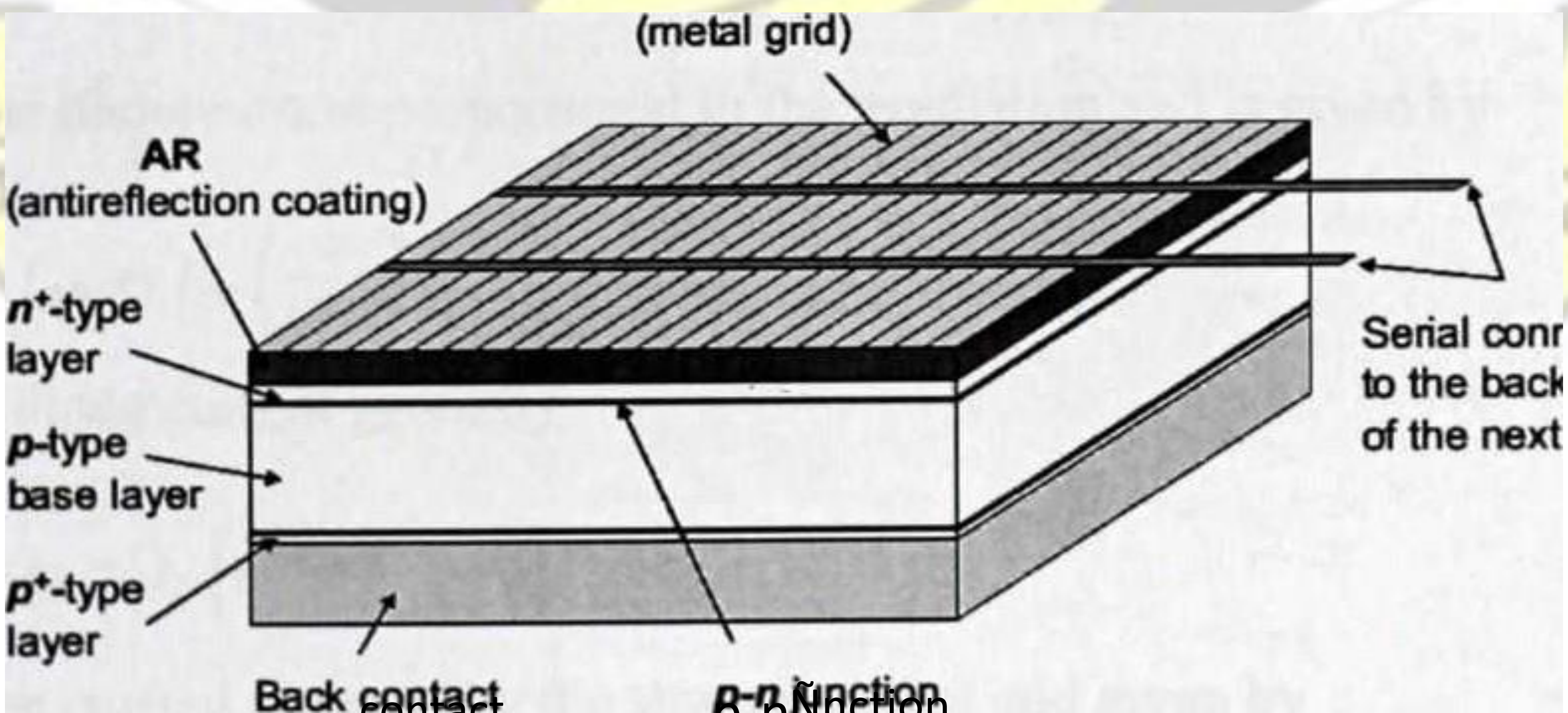
2.2 PV System

A PV solar system consists of three parts: PV modules or solar arrays, balance of system and the electrical load. The balance of system (BOS) consists of batteries, power conditioners (inventers, rectifiers and charge controllers) and mounting structures.

2.21. Basic operationalprinciples of the solar cell

A solar cell shown in figure 2.5 is a semiconductor that can convert solar energy into Direct Current (DC) electricity through the photovoltaic effect, which is the generation of a potential difference at the junction of two different materials in response to visible or other radiation.

Front contact



Serial connections the back contact cell

Figure 2.4- AOpical structure of c-Si solar cell. Source: (Zeman, 2011)

When light enters the cell, some of the photons of the light are absorbed by the semiconductor atoms, freeing electrons from the negative layer of the cell to flow through an external circuit and back into the positive layer. This flow of electrons constitutes an electric current. The photocurrent that is internally generated in a solar cell is proportional to the irradiance.

22.2. Mathematical modelling ofthe solar cell

The equivalent circuit diagram of the solar cell is shown in figure

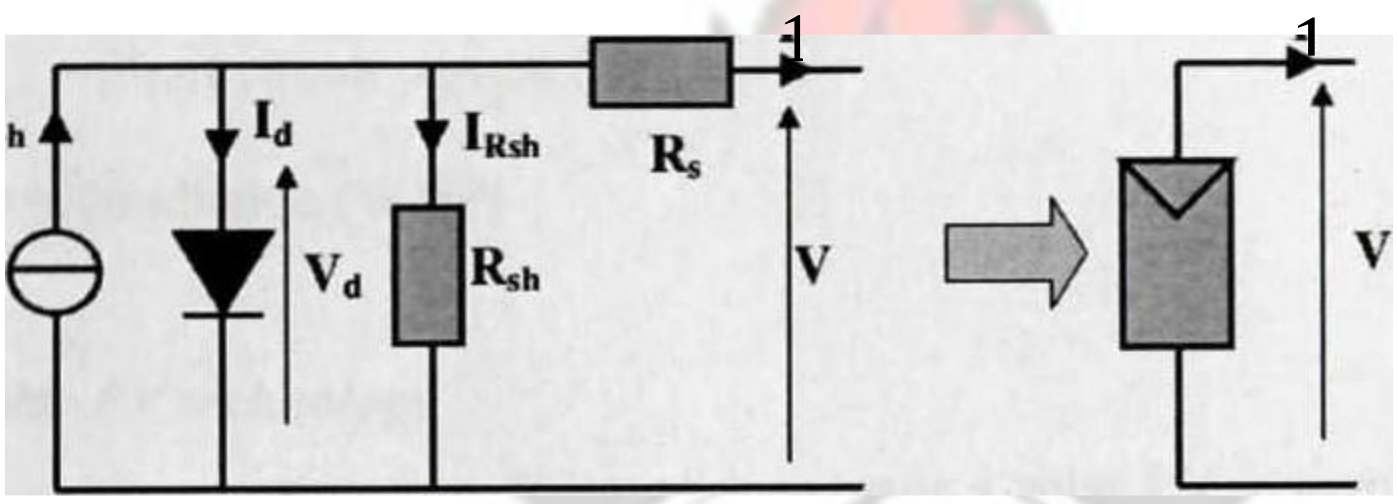


Figure 2.5 - Equivalent circuit diagram of a solar cell

The mathematical modelling for the solar cell circuit in figure 2.8 is given by equation

$$- \quad _{ph} \quad _{RSh} \qquad 2.1$$

Where

Iph = the photocurrent proportional to the irradiation and is given by

$$I_{ph} = I_{sc}\left(\frac{\Phi}{1000}\right) \qquad 2.2$$

Id = the diode current given by

Id = 10 — 11 2.3

IRsh is the current diverted by the shunt resistant and given by

$$I_{R_{sh}} = \frac{V+r_sI}{R_{sh}} \qquad 2.4$$

Rsh

Substituting equations (2.2), (2.3) and (2.4) into (2.1) gives the mathematical model of a real solar cell given in equation

$$1 = Isc \frac{\quad}{1000} - 10 \left[e^{\frac{q(V+r_s I)}{V_T}} - 1\right] - \frac{V+r_s I}{R_{sh}} \qquad 2.5$$

Where VT is the thermodynamic potential is given by

2.6 q

10 = Dark current (Reverse saturation current of the diode), (A)

q = charge ofelectron (1.6 x 10—23 C)

k = Boltzmann's constant (1.38 x 10—23 J/'K)

V = Voltage output (V)

Isc = Short circuit current (A)

Φ is Irradiation (W/mZ)

2.23. Solar PV technology

Many crystalline or thin film PV modules power a solar PV system. Individual PV cells are interconnected to form a PV module. This takes the form of a panel for easy installation. There are two broad categories of technology used for PV cells, namely, crystalline silicon, as shown in Figure 2.7 which accounts for the majority of PV cell production; and thin film, which is newer and growing.

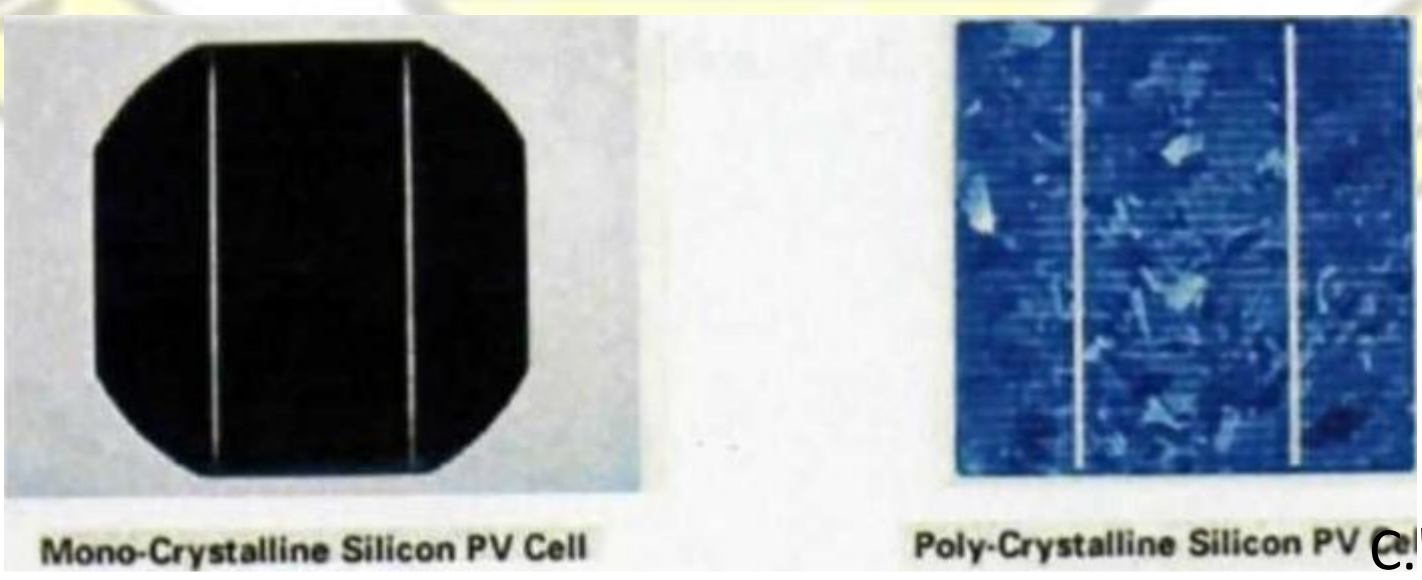


Figure 2.6 - Mono and poly-crystalline PV cell.
Source (Tan, et al., 2010)

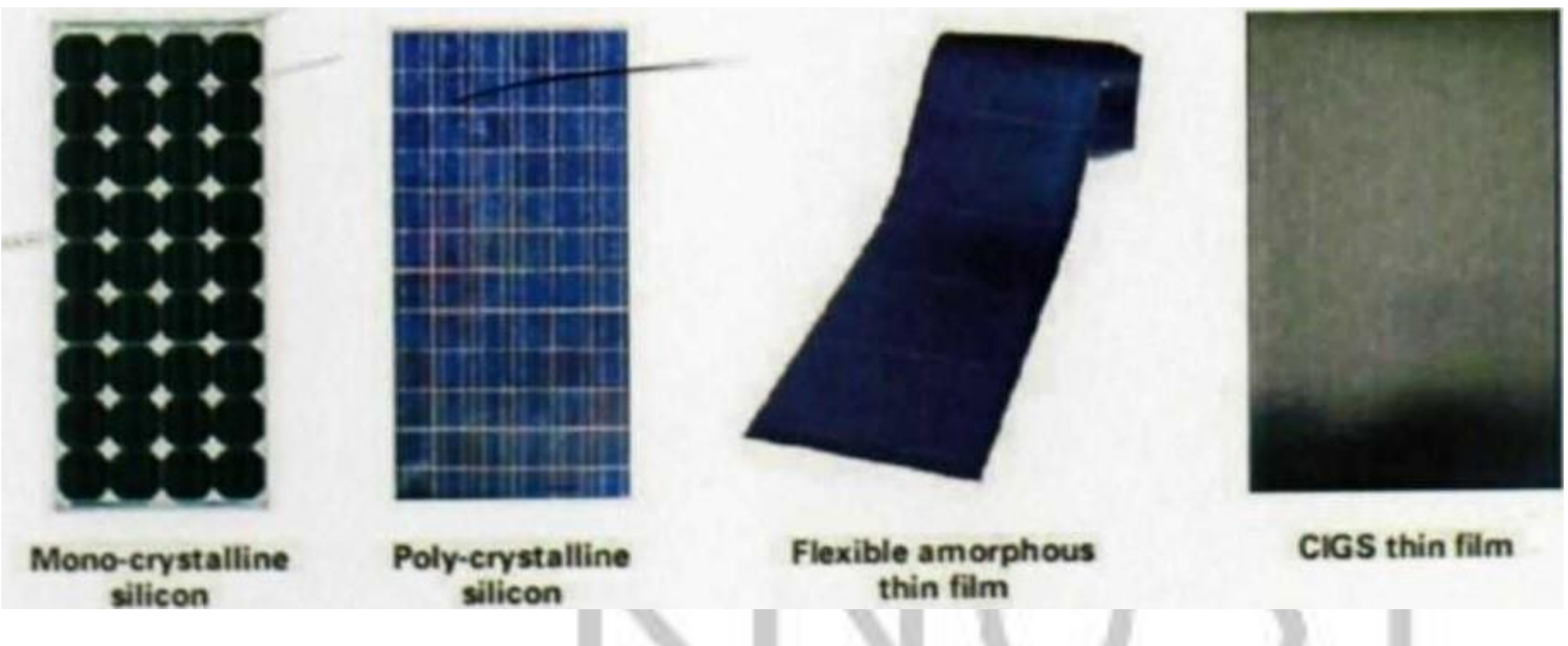


Figure 2.7 - Common PV technologies.
Source (Tan, et al., 2010)

Cry•øallme cats frtgn sibam wafes tha typcalty t SO-200 mscrcms fifth of a mtlltmare) thick. nun film is by depositing of semiconductor materialbarely 0.3 to 2 micrometre thick glaø or stainlesssta

substrates The vuious PV echnologies arø their agtvaston efficiaxies are shown

in 2.1

Table2.1. Convasion efficiaxies of various PV mcxiules technologies

Tech	Moduk
Mono-crystallinesilicon	12.5-15%
alline silicon	11
C Indium Gallium Selenide (CIGS	10-
Cadmium Telluride (CdTe)	9-12%
Silicon (a-Si)	

Source: (Tan, al., 2010)

2.3 Solar PV module

A solar cell is a unit that delivers only a certain amount of electrical power. In order to use solar electricity for practical devices, which require a particular voltage or current for their operation, a number of solar cells have to be connected together to form a solar panel, also called a PV module. For large-scale generation of solar electricity the solar panels are connected together into a solar array. Solar modules are called the PV power generators.

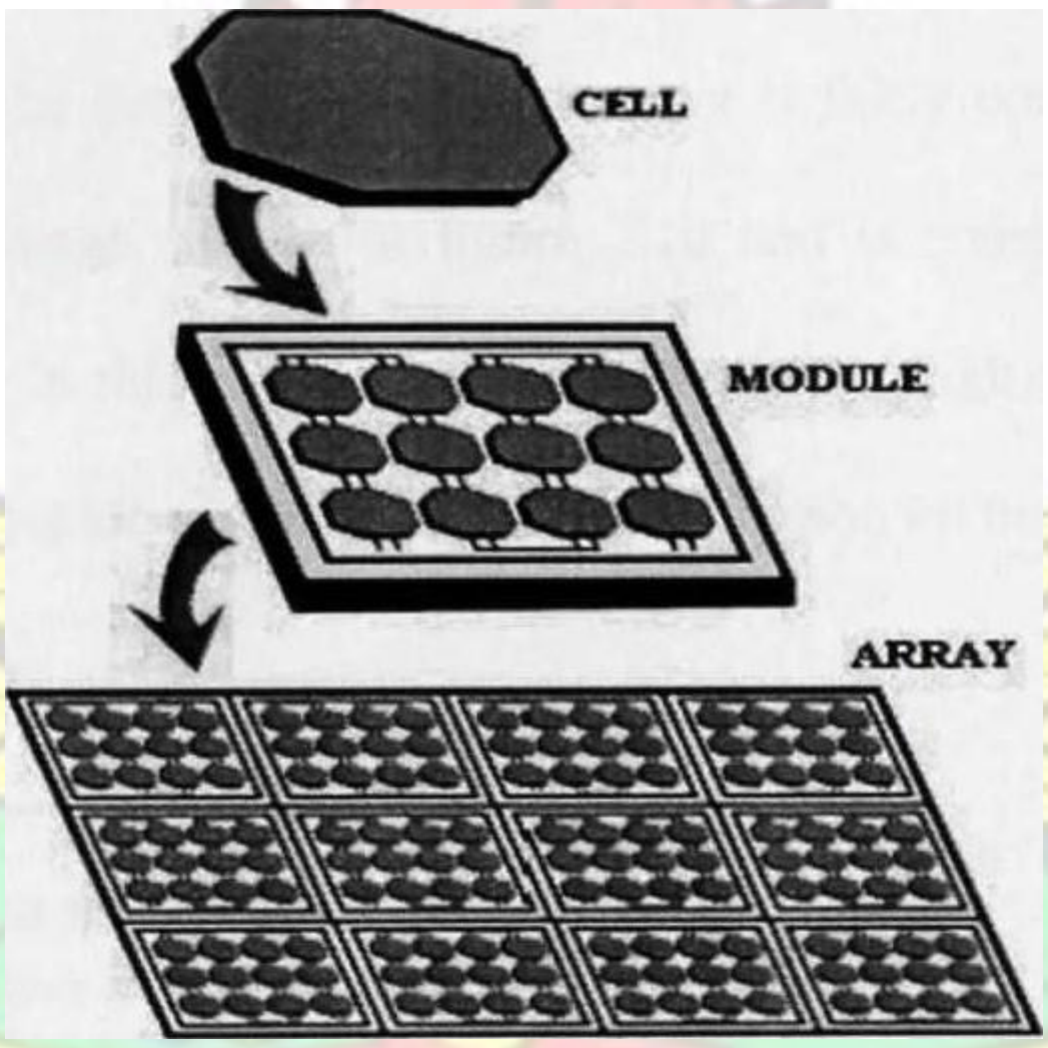


Figure 2.8- Solar cell, Module and Array

23.1 Standard test condiÌõïõfõPV module

A Standard Test Condition (STC) has been established so that PV device output can be compared. These standard values are as follows:

1. Cell temperature: The STC for cell temperature is 25 degrees Celsius. Not air temperature.

2. Irradiance: is the intensity of the solar radiation striking the earth. The STC value for irradiance is 1,000 watts per square meter (W/m^2). The 1 ,000 W/m^2 value represents full sun, or peak sun, which is common to many terrestrial locations.

3. Air mass: Air mass is a representation of how much atmosphere sunlight must pass through to strike the earth. The STC value for air mass is 1.5 (AM 1.5). Actual air mass values vary widely depending on one's location on the globe, the time of year, and the time of day.

23.2 Characteristics ofcurrent— voltage curve (I— V)

The standard representation of the output of a PV device (cell, module, or array) is called the current-voltage curve. The output current is fairly constant over most of the operating voltage range, shown in figure 2.10 and is considered as a type of constant current source in this range. Eventually though at high enough voltage, the relatively level current rapidly falls off past a "knee" region on the curve.

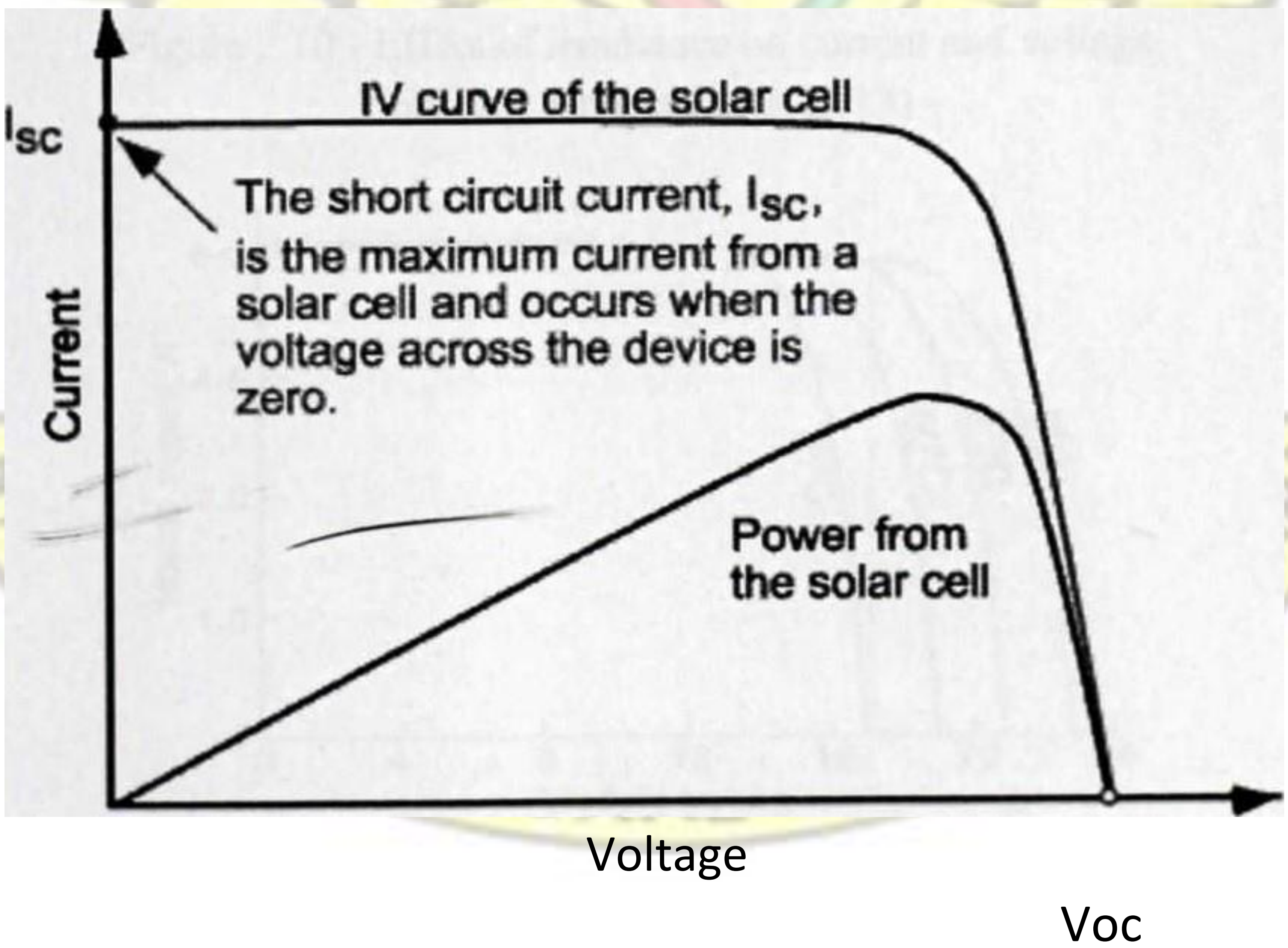


Figure 2.9 - Current- voltage characteristic curve of a Solar PV
Source: (Honsberg, et al., 2013)

23.3 Performance parameters ofa PV module

Irradiance - The Isc (short circuit current) is directly proportional to the light intensity, and the Voc (open circuit voltage) varies more slowly in a logarithmic relationship as shown in figure 2.11. The ratio of the Isc to the light intensity or irradiance G is given by the equation 2.7

ISCI Iscz

2.7 Irradiance Gl Irradiance G2

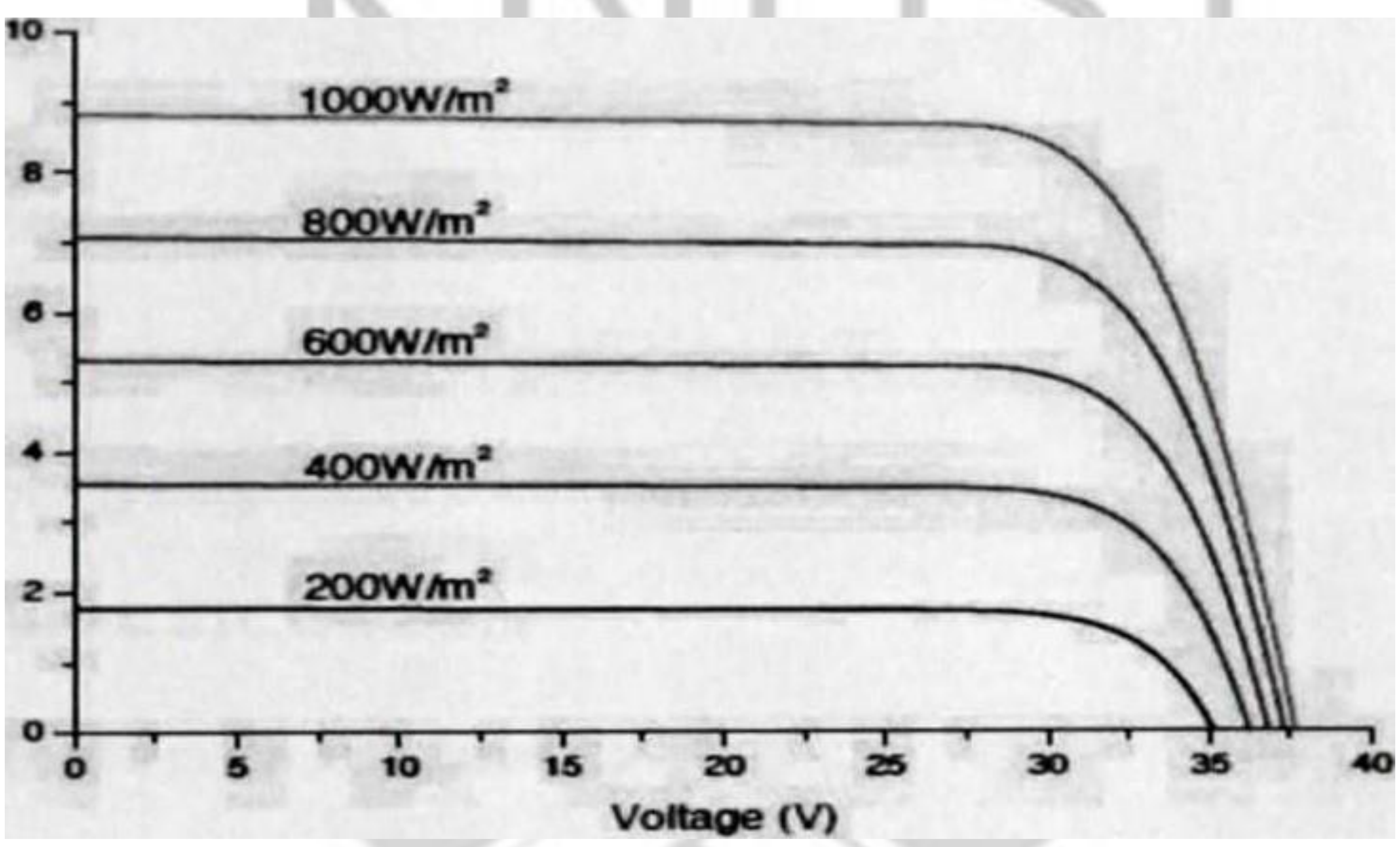


Figure 2.10 - Effect of irradiance on current and voltage Source: (Savana Solar, 2013)

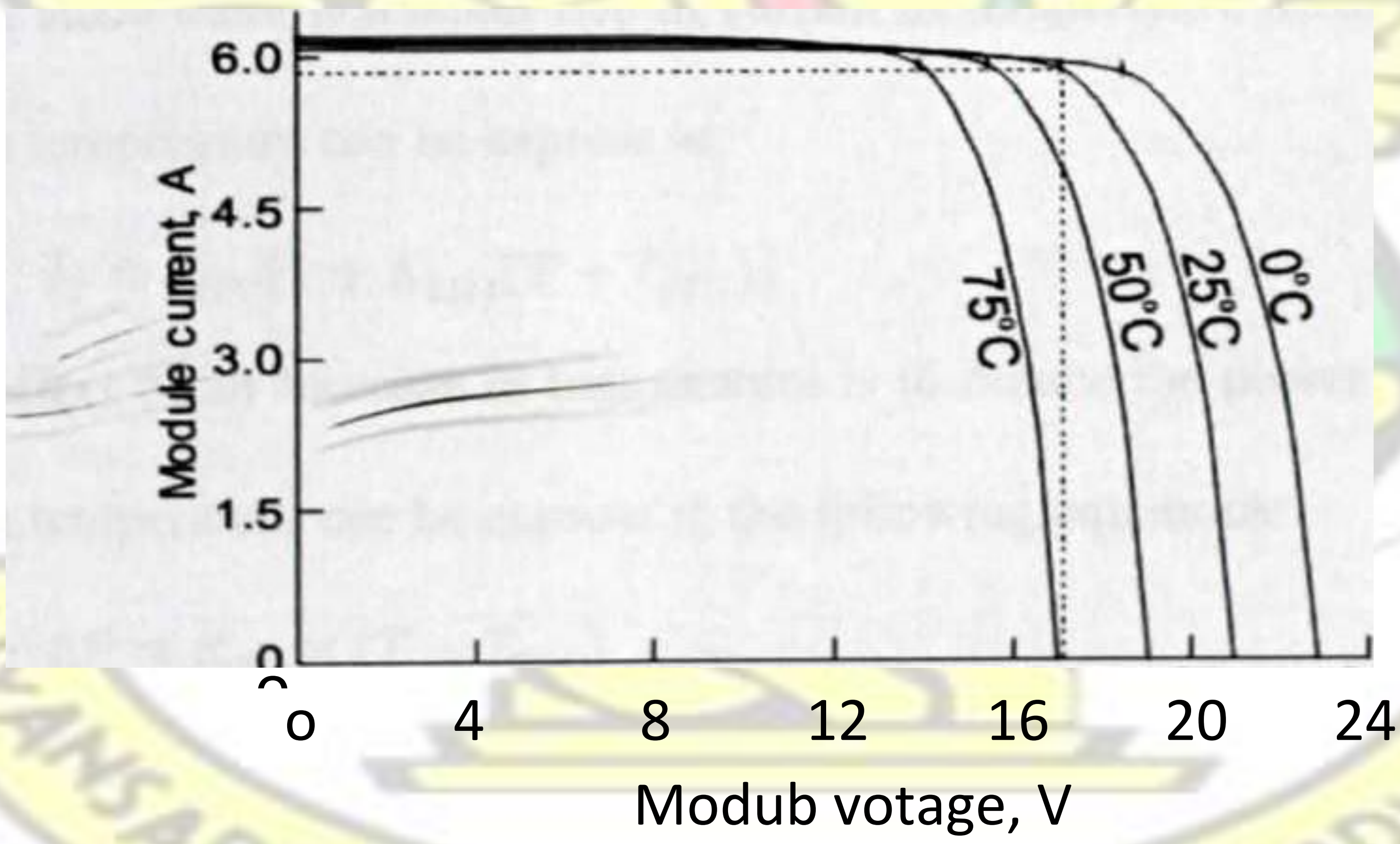


Figure 2.11 - Effect ofTemperature on current and voltage

Temperature - For a silicon crystal material, an increase in cell temperature affects performance by decreasing Voc as indicated in figure 2.12 and with a small rise in current at low voltages. The change in voltage is directly proportional to the rise in temperature represented by following equation.

AV = KK(V) X (T — TSTC) 2.8

x Vs-rc x (T — Tsrc) 2.9

AV $= \%K_{K(V)}$ >

$V_T = V_{STC} - \Delta V$ 2.10

Where

AV: Voltage losses (Volts)

% KT(O: Voltage temperature coefficient 0/0/^{0}C KT(V):

Voltage temperature coefficient Volts/^{0}C

VSTC.• Voltage at STC conditions

VT: Voltage at a given temperature T

Combining equation 2.8 and 2.9, the voltage at a given temperature can be express as

VT = VSTC[I — — TSTC)] 2.11

Similarly, since there is a small rise in current as temperature increased, the current at a given temperature can be express as:

IT = Isrc[l + — TSTC)] 2.12

The net effect of an inggase-in-temperature is to reduce the power P available. The change in temperature can be express in the following equations:

AP = X (T — TSTC) 2.13

AP = 0/0KTœ)Psrc x (T — TSTC) 2.14

$P_T = P_{STC} - \Delta P$ 2.15

Where

AP is Power changes (Watt)

0/0KTœ) is Power temperature coefficient % PC

KT(P) is the Power temperature coefficient Volts PC

PSTC is the Power at STC conditions

PT is the Power at a given temperature T

Tilt and orientation angle of solar module - The performance PV array or modules depend also on the orientation and its tilt angle with the horizontal plane. These parameters affect the amount of solar energy received by the surface of the PV panel.

The maximum performance is achieved when the modules are perpendicular to the sun's rays. Normally, an array should face true south (azimuth 00) in the Northern Hemisphere like Ghana. For best annual performance, the tilt angle is tilted to equal the latitude of the location.

23.4 Performance modelling ofPVModule

The power output of solar PV module considered is a function of the solar irradiance incidence on it and the cell or module temperature.

Combining equations 2.7, 2.13, and 2.15, the maximum power output from a solar module can be express as:

$$= P_{module} \frac{G}{G_{STC}} \times [1 - K_T(T_r$$

output module,STC T module 2.16

Where

Pout-put is in power, kW

G is the solar irradiance at the location in (kW/m^2)

KT is the temperature coefficient of maximum power (/ ^{o}c)

Gsæ=1000 W/m^2 at T=25^{0}C

Introducing solar PV derating factor[i] the equation 2.16 can be written as

IT

output = fpv X Pmodule X 2.17

Is-rc

Where

IT (kW/m) is the total global solar radiation incident on the PV array and ISTC — 1000(W/m^2), which is the standard amount of radiation used to rate the capacity of PV modules.fpv is the PV derating factor.

23.5 Sizing ofsolar PVarray

The size of the solar power depends on the average daily energy consumption of the electrical loads. In this case at the BTS site, and has to match the solar PV output taking into account the losses in the system. Since our design will include converter and a battery bank, the solar PV array capacity is given by equation 2.18

Ed

2.18

array Hi X"batt

Ed is the daily energy demand, Hi (Wd) expressed in (kWh/m2/d) is the monthly average solar radiation and is the converter efficiency and is the efficiency of the battery bank.

Depending on the available modules, the number of modules in a string and the number ofstring can be found by using these equations:

Number of modules in a string

vpvs

ms 2.19

Number of string in parallel

$$= \frac{PV_{array}}{P_m \times N_{ms}}$$ 2.20

sp

---

[1] derating factor is a scaling factor to account for the effects of dust on the panel, wire losses, elevated temperature, or anything else that would cause the output of the PV array to deviate from that expected under ideal conditions

Where Vpvs is the voltage of the PV system, which is 48V for most telecom equipment and Vm, is the voltage ofthe PV module at peak power.

2.4 Battery

In solar PV/diesel hybrid system, all the electrical energy produced by PV array or the diesel generator cannot always be used when it is produced, because the demand for energy does not always coincide with it production. The simplest means of electricity storage is to use the electric rechargeable batteries. The primary functions of a storage battery in PV systems are:

1. Energy storage capacity
2. Voltage and current stability
3. Supply of surge or high peak current to electrical loads

In most PV systems, lead-acid batteries are commonly use due to their wide availability in many sizes, low cost and well understood performance characteristics. In some applications, where high reliability is essential, nickel-cadmium batteries are used, but high cost limits their use in most PV applications. This thesis reviews leads acid batteries used in PV applications.

24.1 Battery types and£lasg--——•1 Icaáons

Electrical storage batteries can be divided into two major categories, primary and secondary batteries.

Primary batteries - can store and deliver electrical load but cannot be recharged.

They are not used in PV system because they cannot be recharged.

Secondary batteries — can store and deliver energy and can be recharged. They are usually used in PV systems and automobiles.

24.2 Basic design and construction

Manufactures have variation in the details of their battery construction but some common construction features can be described for some common batteries. Some of the important components of battery construction are described below

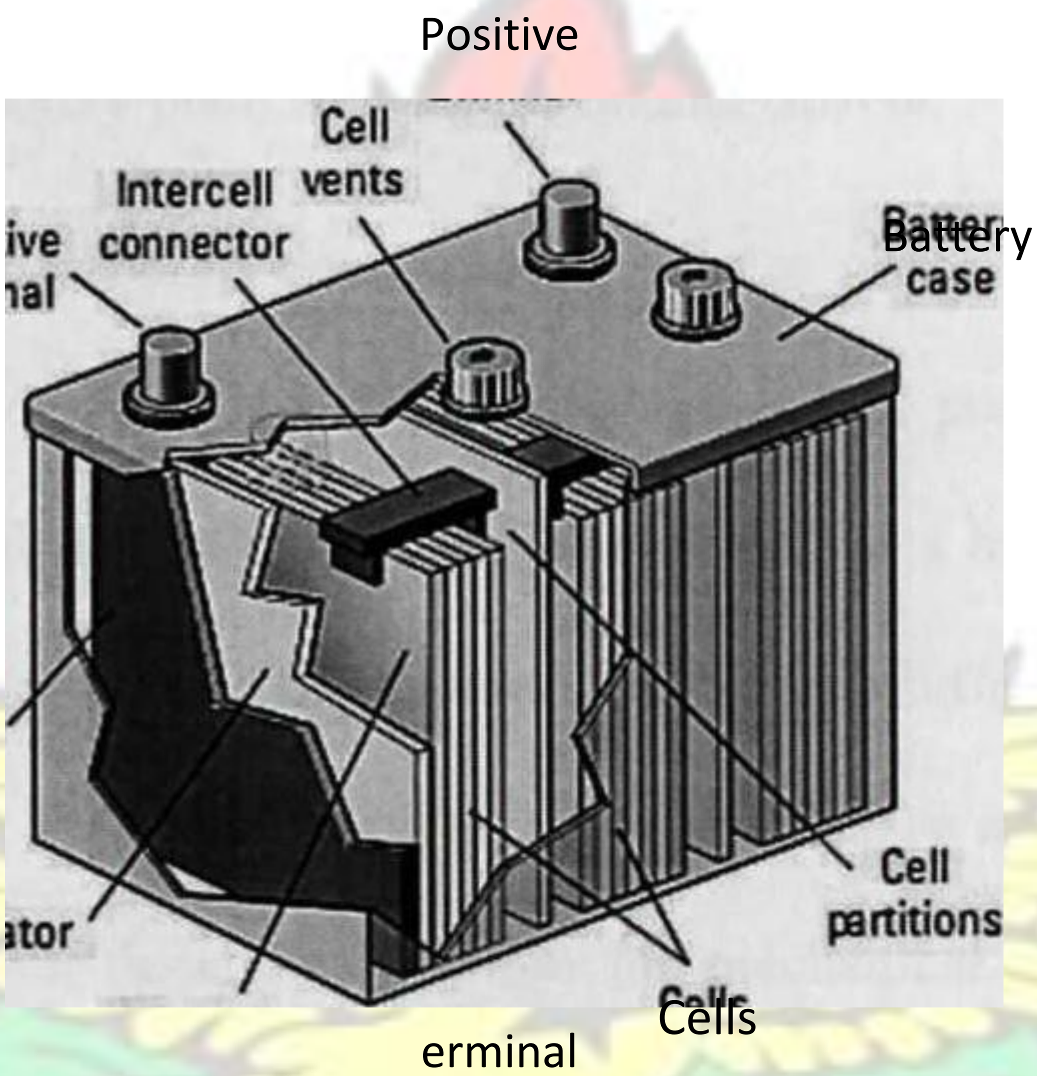


Figure 2.12 - Basic components of battery construction
Source: (Mayfield, 2010)

Cell — the cell is basic electrochemical unit in a battery consisting of a set of positive and negative plates divided by separators immersed in an electrolyte solution enclosed in a case. In a typical lead acid battery, each cell has a nominal voltage of about 2.1 so there are six series in a nominal 12-volt battery.

The active raw material - the active material in a battery is the raw material that forms the positive and negative plates and is reactant in the electrochemical cell. The amount of active material in a battery is proportional to the capacity a battery can deliver. In lead acid battery, the active material is lead dioxide (Pb02) in the positive plate and metallic sponge lead (Pb) in the negative plates, which react in a sulphuric acid (H2S04) solution during battery operations.

Electrolyte — the electrolyte is a conducting medium that allows the flow of current through ionic transfer or the transfer of electrons between plates in a battery. In a lead acid battery, the electrolyte is a dilute sulphuric acid solution, either in a liquid (flooded) form or gelled or absorbed in glass mats.

Grid — in a lead-acid battery, the grid is typically a lead alloy framework that support the active material on a battery plate and which conduct current.

Plate — a plate is a basic component consisting of a grid and active material sometimes called electrode. They are generally a number of positive and negative plates in each battery cell, typically connected in parallel at a bus bar or inter-cell connector at the top of the plate. The thickness of the plate affects the deep cycle performance of a battery. Thin plate result in maximum surface area, which delivers high current but not much thickness to allow for mechanical durability and for prolong discharges.

Separator — a separator is a porous, insulating divider between the positive and negative plates in a battery used to keep the pates from short-circuiting and which allows the flow of electrodes and ions between the positive and negative plates.

Elements — the-element is define as a stack of positive and negative plate groups and separators assembled together with plate straps interconnecting the positive and ŒSative plates.

Terminal posts - are the external positive and negative electrical connections to a battery. In lead acid battery, the terminal post are generally lead or lead alloy, stainless steel or copper plated steel for greater corrosion resistance.

Cell vents — during battery charging, gases are produce within a battery that may be vented to the atmosphere. In sealed or valve-regulated batteries, the vent are designed with a pressure relieve mechanism, remained closed under normal condition

Case — commonly made from hard rubber or plastic, the case contains the plates, the separators and electrolyte in a battery. The case is typically close, with the exception of inter-cell connectors, terminals post and vents or caps

2.43 Lead acid battery classification

Many lead-acid batteries used in PV system are often classify in terms of the following categories

SLI batteries — starting lighting and ignition (SLI) batteries commonly used in automobile starts are designed primary for shallow cycle service and not for long life and deep cycle service. Sometimes they are use in PV systems in developing countries. Although not recommended for PV systems, SLI batteries may provide up to two years of useful service in small stand-alone PV systems with average depth of discharge limited to 10 - 20% and

Motive or traction batteries — This type of lead acid batteries are design for deep discharge cycle service typically used to operate vehicles and equipment such as golf cart, forklift—They are very popular in PV systems due to their deep cycle capability long life and durability.

Stationary batteries — this type is commonly used in uninterruptible power supply (UPS) to provide back-up power to computers, telecom equipment and other critical loads.

24.4 Lead acid batte?' chemistry

The basic lead—acid cell consists of sets positive and negative plates divided by separators and immersed in a case with an electrolyte solution. In a fully charged lead-acid cell, the positive plates are lead dioxide (Pb02), and the negative plates are sponge lead (Pb) and the electrolyte is a dilute sulphuric acid solution.

When a battery is connected, to an electrical load, current flows from the battery, as the active materials are converted to lead sulphate (PBS04).

2.45 Lead acid cell reaction

The following equations show the electrochemical reaction for the lead acid cell. During the battery discharge, the direction of the reactions listed goes from left to right. During battery charging, the direction of the battery reaction are reverse and the reaction go from right to left.

At the positive plate or electrode

Pb02 +4H+ + Pb2+ + 2H20

Pb2+ + SO;- PbS04

At the negativeplate or electrode

Ph ⇔Pb Pb2+ + 2ë

Pb2+ + sopo PbS04

Overall, lead acid cell reaction

Pb + + 2H2S04 2PbS04 + 2H20

24.6 Types oflead acid batteries

There are several types of lead acid batteries used in a PV system. Table 2.2 shows types of lead acid batteries used in PV systems and their characteristics.

Table 2.2 - Types of Lead - acid batteries

Battery type	advantages	disadvantages
Flooded lead-acid		
Lead-antimony	Low cost, wide availability, good cycle and high temperature erformance	High water loss and maintenance

Lead-calcium open vent	Low cost wide availability, low water loss, can replenish electrol e	Poor deep cycle performance, intolerant to high temperatures and over char e
Lead-calcium sealed vent	Low cost, wide availability, low water loss	Poor deep cycle performance, , intolerant to high temperatures and over charge, cannot r lenish electrol e
Lead antimony/calcium hybrid	Medium cost, low water loss	Limited availability
Captive electrolyte leadacid (VRLA)		
Gelled	Medium cost, little or no maintenance, less susceptible to freezing, in any orientation	Fair, deep cycle performance, intolerant to high temperatures and over charge, limited availabili
Absorbed glass matt	Medium cost, little or no maintenance, less susceptible to freezing, installed in any orientation	Fair, deep cycle performance, intolerant to high temperatures and over charge, limited availabili

Source: (Dunlop, 1997)
Battery performance characteristics

Ampere-hour — the common unit of a battery's electrical storage capacity obtain by integrating the discharge current in amperes over a specific live period. It is equal to transfer of one ampere over one hour.

Capacity — a measure of a battery's ability to store or deliver electrical energy, commonly expressed in unit amperes-hour.

A battery's energy can be expressed in kilowatt-hour by the following equation

$$E_{battery}(kWh) = \frac{E_{battery}(Ah) \times Norminal\ voltage\ (V)}{1000} \quad 2.21$$

Rate ofchange/discharge - of a battery is expressed as a ratio of the nominal battery capacity to the charge or discharge time-period in hours. A battery's capacity is directly affected by the rate at which the battery is discharged. Batteries used in PV systems are typically rated at a temperature of 25 degrees Celsius and at a discharge rate over a time-period of 20 hours. This rate is referred to as the C rate and is written as C/20. The C represents the capacity value, and the 20 represents the number of hours of discharge time.

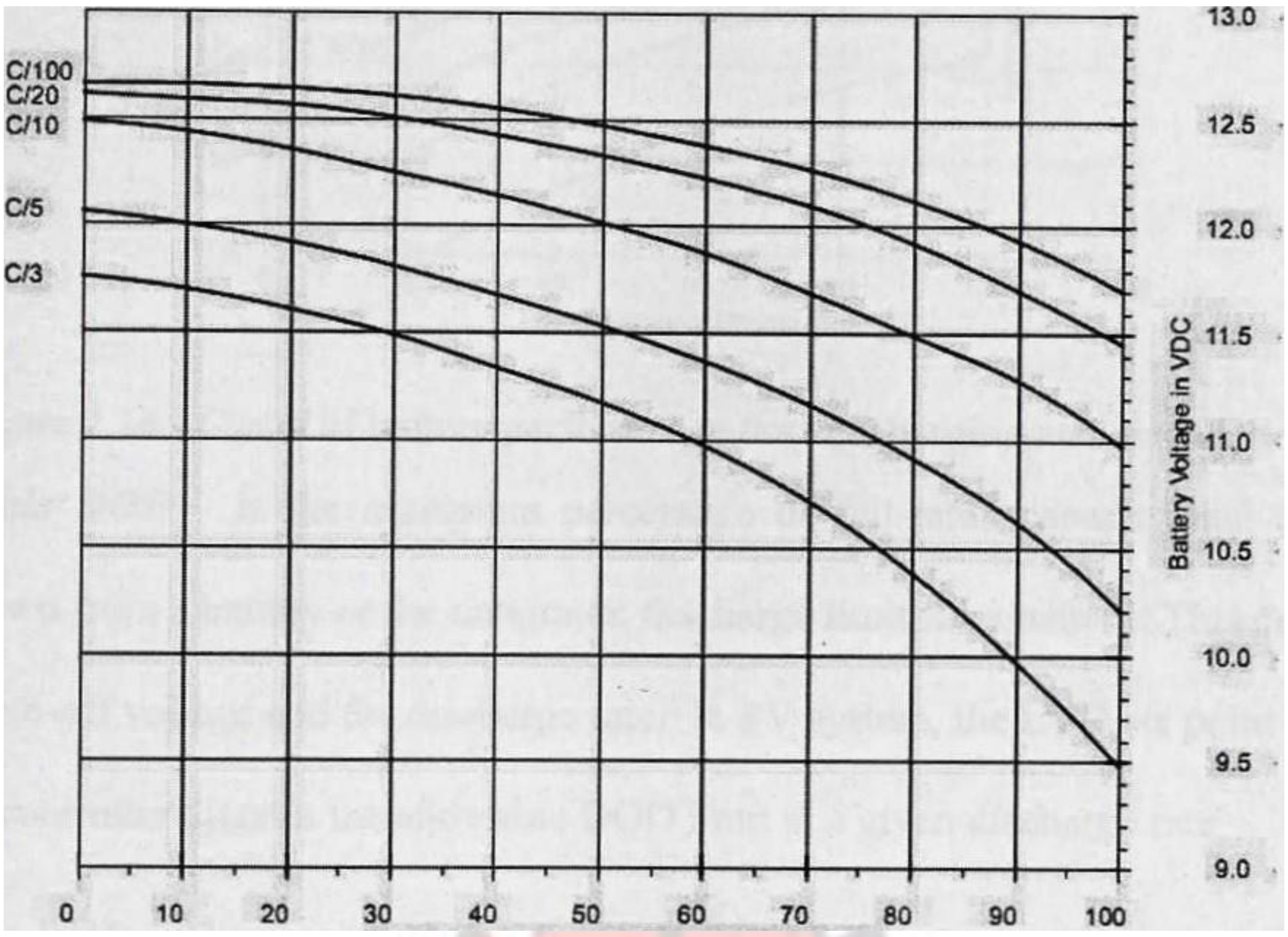
Figure 2.14 is a typical grapth of a battery state of discharge and a battery performance which shoys-that-trstow discharge rate results in a greater number of amp-hours delivered from the same battery than a fast discharge rate. (The battery voltage indicate the battery's state of charge)

Depth ofdischarge (DOD) — of a battery is defined as the percentage of capacity that has been withdrawn from a battery compared to the total fully charged capacity. The deeper the depth of discharge, the shorter is the battery life.

State ofcharge (SOC) — is defined as the amount of energy in a battery expressed as a percentage of the energy stored in a fully charged battery. Relation between state of charge and depth of discharge is given by

$$DOD + SOC = 100\% \qquad 2.22$$

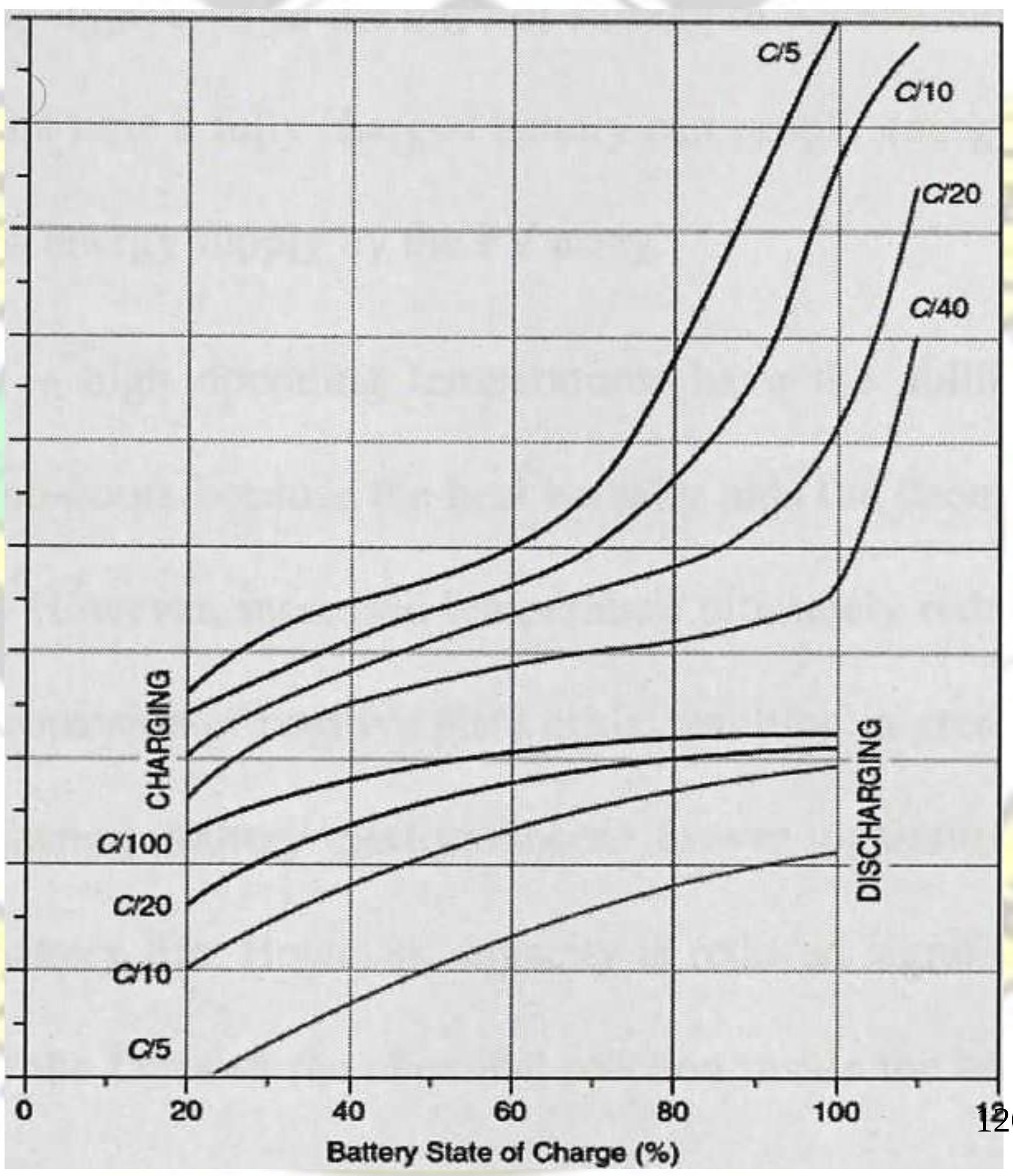
Figure 2.17 shows that, during charging, the voltage rises faster with the rate of charge, as the battery nears 80% SOC. Charge controllers are designed to slow the charging rate as the battery approaches its fully charged condition.



Battery state of DISCHARGE %

Figure 2713 - Graph of-bãFýGltage versus energy delivered from the battery

Source: (Stack exchange inc., 2014)



120

16.0

15.5

15.0

14.5

14.0

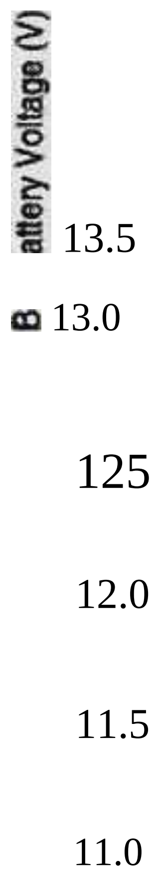


Figure 2.14 - Graph of battery performance during charging and discharging

Allowable DOD - Is the maximum percentage of full-rated capacity that can be withdrawn from a battery or the maximum discharge limit for a battery. This depends on the cut-off voltage and the discharge rate. In PV system, the LVD set point on the charge controller dictates the allowable DOD limit at a given discharge rate.

Average DOD - The average daily depth of discharge is the percentage of the full rated capacityfthat is withdrawn from the battery with the average daily load profile.

The allowable DOD and the average DOD are inversely related to the battery autonomy.

Self-discharge rate — in an open circuit mode without any charge or discharge current, a battery undergoes a reduction in the state of charge due to internal mechanism and internal losses. In general, higher temperatures result in higher discharge rate.

Autonomy — generally expressed as the days of storage in a stand-alone PV system. Autonomy refers to the time a fully charged battery can supply energy to the system loads when there is no energy supply by the PV array.

Temperature effects — high operating temperatures have the ability to deliver a greater number of amp-hours because the heat actually aids the chemical process as figure 2.16 indicates. However, increased temperature ultimately reduces a battery's life, due accelerated corrosion of positive plate grids, resulting in greater gassing and electrolytes loss affecting battery performances. Lower operating temperatures generally increases battery life. However, capacity is reduced significantly at lower temperatures because the fact that the chemical reaction inside the battery is slowed down and is not as efficient.

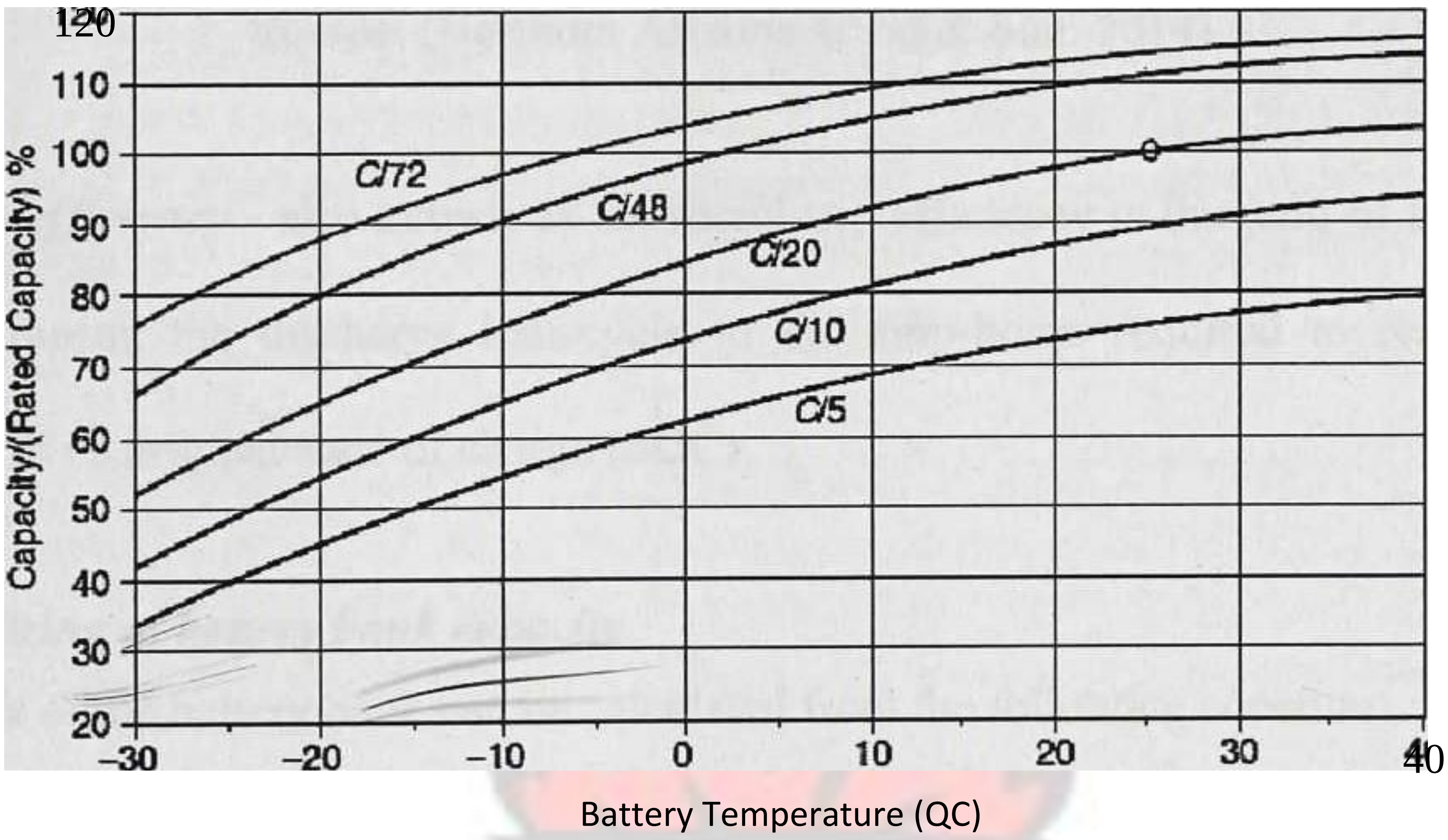


Figure 2.15 - Temperature effect on battery capacity

Battery life — battery life depends on a number of design and operation factors. In general, as long as the battery is not overcharged, over-discharged, or operated at excessive temperatures, the lifetime of a battery is proportional to its average state of charge.

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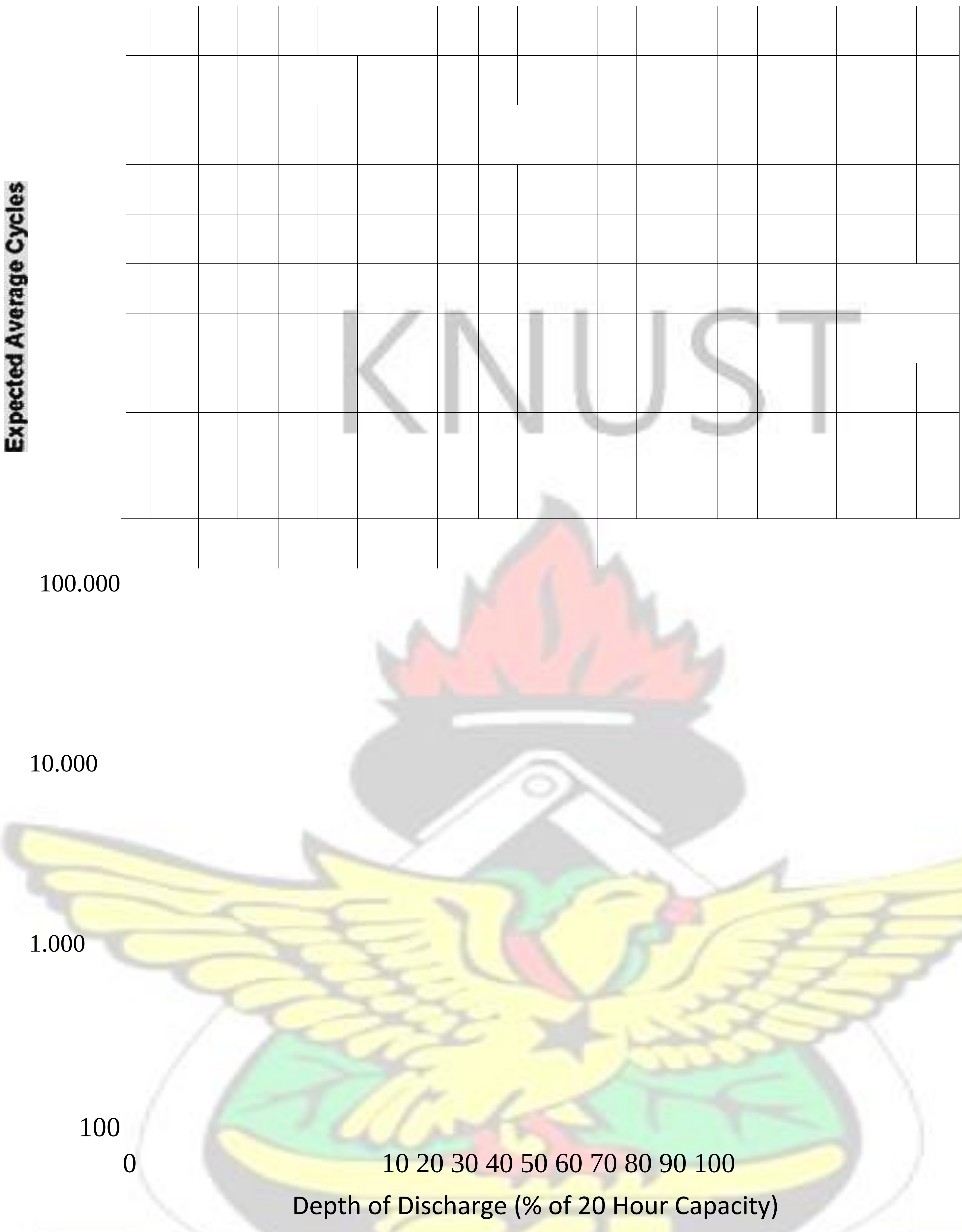

Figure 2.16 - Effect of battery DOD on average life cycle
Source: (Northern Arizona Wind & Sun, 2014)

Battery efficiency - also known as the round trip efficiency is the ratio of amp-hour drawn during the discharge half-cycle to the amp-hours required to restore the battery to its original state of charge (SOC).

2.4.7 Sizing ofbattery bank capacity

The size oftF€battery bankõÉÓalculated from the following equation

ET XTaut

2.23 VBBXBeffXDOD

Where

ET is the daily energy consumption demand in (Wh)

Bef is the battery efficient

VBB is the battery nominal voltage (12V, 24V, 48V etc.)

DOD is the depth of discharge in percentages

Taut is the number of days of battery autonomy

2.5 Converter

A converter is a device that converts electric power from dc to ac in a process called inversion, and/or from ac to dc in a process called rectification.

Since the power produce by solar PV/diesel hybrid system is a mixture of AC and DC source, this requires AC/DC conversion, which can be performed as a solid-state inverters and rectifiers.

An inverter converts DC current to AC, while a rectifier converts AC current to

DC. The power flow through solid-state inverters and rectifiers can be modelled by the following equation (Georgilakis , et al., 2008)

2.24 out,conv i,conv

Where

out, convis the output power, Pi, convis the input power, and a and are constants. The value of p, often called the "standing losses," is small compared to the capacity of the inverter and it is ignored in this thesis.

2.6 Charge controller

The primary ñmction of a charge controller in the PV/diesel hybrid system is to maintain the battery at thÞest_possible state of charge while protecting it from overcharge by the PV array and the diesel generator. The algorithm or control strategy of the battery charge controller determines the effectiveness of the battery charging and PV utilisation and ultimately the ability of the system to meet the load demand. Some charge controllers incorporate low voltage load disconnect (LVD) features to disconnect the load from the battery when the voltage drop too low to prevent over discharge of the battery. In the PV/ diesel Hybrid system, at a certain minimum depth of discharge, the diesel generator is expected to provide the power needed by system based on the supervisory control system and the dispatch strategy.

The important function of the battery charge controller and the system control are; (Dunlop, 1997)

1. prevent battery overcharge — limits the energy supply to the battery by the PV array and the diesel generators when battery becomes fully charge
2. Prevent battery overcharging — to disconnect battery from electrical load when the battery reaches low state of charge.
3. Provide load control function — to automatically connect and disconnect an electrical load at a specific time. For example in our case operating aviation light or security light from sunset to sunrise.

2.6.1 Sizing and selection ofcharge controllers

Charge controllers should be sized according to the voltages and currents expected during operation of the PV/diesel hybrid system. The controller should be able to handle any peak or surge current conditions from the PV and maximum current from the generator or that required by the electrical load. The size of the charge controller is determined by multiplying the highest maximum current that the hybrid system can generate by a factor of safety.

The Charge controller characteristics must be chosen in respect of the following conditions:

- Nominal current of the charge controller: ICC > Max (IPVG, IGen, Iload)
- Nominal voltage of the charge controller must be equal to the system voltage

The selection of the charge controller involves several factors that are considered. While the primary function is to prevent battery overcharge, other functions may also be used, including low voltage disconnect, load regulation and control, control of the backup energy sources (diesel generator) diversion of energy to and auxiliary load and system monitoring. The following are some of the basic consideration for selecting charge controllers to satisfy the requirements of PV/diesel hybrid system:

- System voltage
- PV, diesel generator and load current
- Battery type and size
- cost
- Environmental operating condition
- Mechanical design
- System indicators, alarms and meters
- Over current, disconnects and surge protection devices
- Regulation algorithm and switching element design
- Regulation and load disconnect set points

2.7 Mounting structures

In solar PV system there must be mounting structures to which PV modules are fixed and directed towards the sun. The principal aim of the mounting structures is to hold the PV modules securely in place, which usually means that they have to resist local wind forces. The further requirements are not to cause shading of the modules and to be arranged so that there is an easy access to the modules for the maintenance or repair. The PV modules may be placed on a sun-tracking system but at an additional cost. For this analysis, sun-tracking device is not considered.

2.8 Load

The appliances, lights and equipment being powered by a PV solar system constitute electric loads of the PV system. In this case, the main electrical load is the BTS equipment and other electrical loads at the site. The energy efficiency of this equipment contributes to overall system efficiency and economy. The BTS load varies according to the functionality of the equipment as shown in table 2.3 (Motorola, 2007). Most new equipment which are energy efficient consume in the range of 0.6kW - 1.0kW while current deployed equipment consumes power which ranges from 1-2kW (GSMA Development Fund, 2009)

At a typical base station, the number of BTS housed determines the power demand. The power demand ranges from 1 kW to 8.5 kW where more than 80% of these configurations have a demand less than 3.5 kW (Intelligent Energy Company, 2012).

Table 2.3 Load consumption of a BTS according to technology type

Type of Base Station	Power required
GSM Base Station 2/2/2	600-1800W
GSM Base Station 4/4/4	900 -2300W
UMTS Node B Macro/Fibre 2/2/2	750 - looow
UMÎSNodeB Macro/fib 4/4/4	1300 - 1700W
Large WiMax Base Station	1.3kW (4 Sector)

Source: (Motorola, 2007)

The power consumed by a BTS does not vary significantly over the day. The site used for this analysis is a GSM base station with a BTS configuration of 4+4+4.

2.9 Diesel generator

Diesel generators are commonly used in hybrid energy systems. A diesel generator is the combination of a diesel engine with an electric generator (often an alternator) to generate electrical energy. The diesel engine is normally connected directly to the synchronous generator. Diesel generators typically consist of three main functional units: a diesel engine, a synchronous generator with voltage regulator, and a governor.

The fuel injection system is an important part of the diesel engine. Its function is to inject the proper amount of fuel into the proper cylinder at the appropriate time in the cycle. A voltage regulator ensures the proper voltage is produced. The frequency of the AC power is directly proportional to the engine speed, which in turn is controlled by the governor. Through a set of linkages, the governor regulates the amount of fuel that can be injected at any time according to how far the operating speed differs from nominal. As the electrical load on the generator increases, more fuel is injected.

2.9.1 Diesel generator in Solar PV hybrid system

The use of diesel generator in solar hybrid systems depends on the percentage contribution of the solar energy system to the load demand. Solar hybrid systems are design to utilise maximum-of-the-solar energy produce therefore the diesel generators are not normally use on a daily basis but used as a backup source.

2.9.2 Diesel generator operating characteristics

The generator will consume fuel to produce electricity and possibly heat as a byproduct. The principal physical properties of the generator are its maximum and minimum electrical power output, its fuel curve, which relates the quantity of fuel it consumes, its operating efficiency, its expected lifetime in operating hours and the type of fuel it consumes.

2.9.3 Generator Fuel consumption

The fuel consumption of a diesel generator is determined by the size of the generator and the load at which the generator is operating. However, the fuel consumed by a generator to produce power is assumed to be linear curve with slope and intercept on the Y-axis as shown in figure 2.18 according to the linear model by Skarstein and Uhlen (1989).

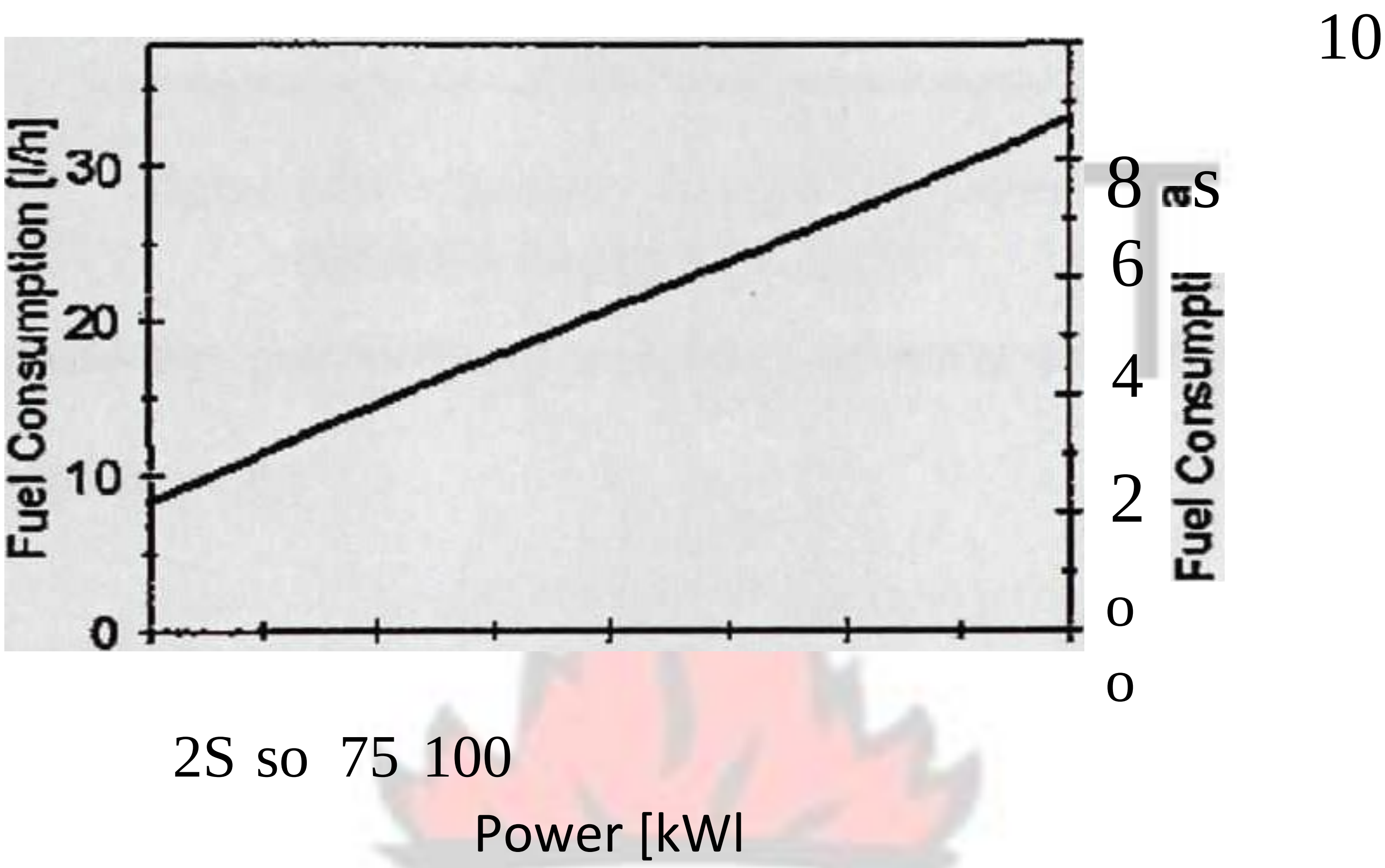

Figure 2.17 - Diesel fuel consumption and electrical power output curve (Barley, et al., 1995)

2.9.4 Diesel generator efficiency

Under rated operating condition, the efficiency of a diesel engine is a product of two efficiencies namely the efficiency of the engine, ranging from 20 to 40 0/0, and the efficiency of the __________ alternator rangin from 70% to 99 0/0. The generator efficiency is affected if it is not used at its rated power and under the standard conditions such as atmospheric pressure, temperature and humidity as stated by the manufacture.

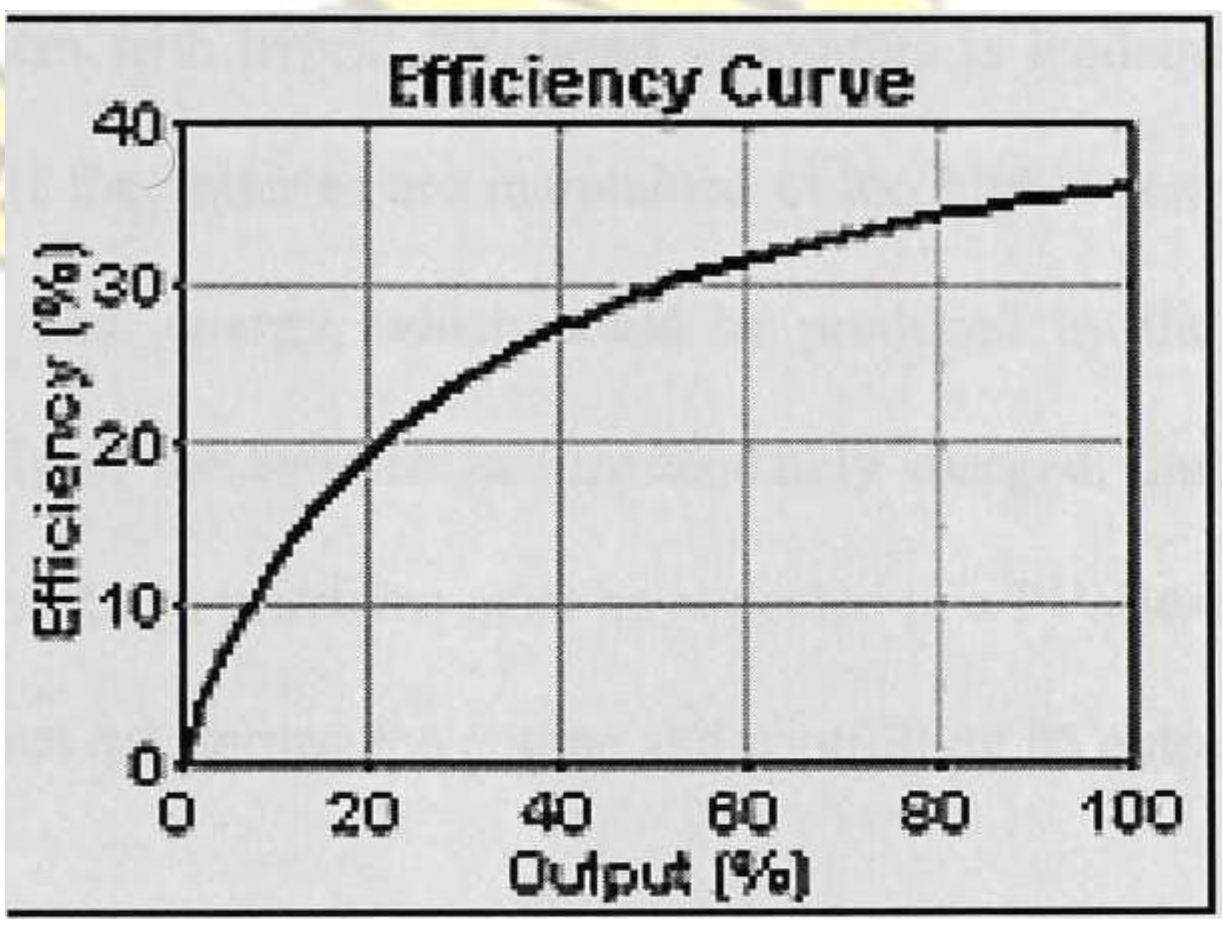

Figure 2.18 - Generator fuel efficiency curve (HOMER Energy LLC, 2012)

Typically, the minimum recommended load that a generator should run is between 25-50% of it rated capacity.

2.9.5 Modelling diesel generator

The quantity of fuel consumption by a diesel generator in litres per hour as a function of its rated power Pr (kW) and output power P(kW) is given by the equation 2.25 as suggested by Skarstein and Uhlen (1989), cited by (Barley, et al., 1995)

$$q = 0.246\,P + 0.08415\,Pr \qquad 2.25$$

Where q is in litres per hour. The fuel cost per run hour of generator is then equal to the product of the diesel price in $/ litre with the corresponding fuel consumption in litres/hour.

2.Äo— PV/diesel Hybrid Control and Load Management System

In PV/diesel hybrid systems, the diesel engine must be started when battery reaches a given discharge level and stopped again when battery reaches an adequate state of charge. The back-up generator can be used to recharge batteries only or to supply the load as well.

A common problem with hybrid PV/diesel generators is inadequate control of the diesel generator. If the batteries are maintained at too high a state-of-charge by the diesel generator, then, energy, which could be produced by the PV generator, is wasted. Conversely, if the batteries are inadequately charged, then their operational life will be reduced. Such problems must be expected in a PV/diesel hybrid system if an automatic system for starting the engine and controlling its output is not installed.

210.1 Function ofthe hybrid control system

The controller itself consists of three main functional units:

- sensors

- logical unit
- control commands

Sensors provide information on power levels, operating conditions etc. The information gathered from the sensors is directed to the logical unit. The logical unit is based on a computer or microprocessor. It will make decisions based on an internal algorithm and the data from the sensors. The decisions made by the logical unit are referred to as dispatch decisions, since their function relates to dispatching of the various devices in the system. The dispatch instructions from the supervisory controller aæsent to controllers-ofthë-various devices in the system.

2.10.2 Dispatch strategies

For hybrid systems which include batteries, there is the need to decide how the batteries are charged and which dispatchable system components (the generators or the battery bank,) have priority to serve the system loads when solar PV (non-dispatchable) energy source is not able to meet the load requirement.

Various strategies proposed by (Barley and Winn 1995) as cited by (Ani, et al., 2013) are normally used. For each strategy, ideal batteries are considered and one-hour intervals in which the system parameters remain constant, without taking into account losses or the influence of the cycles in their lifespan. Three basic control strategies proposed:

Load following strateo - Under the load-following strategy, a generator produces only enough power to serve the load, and does not charge the battery bank.

Therefore, the Set point of the State of Charge is 0%.

Cycle charging - Under the cycle-charging strategy, whenever a generator operates, it runs at its maximum rated capacity (or as close as possible) and charges the battery bank with the excess electricity produced. The batteries are charged to 100% of their capacity every time the diesel generator.

Predictive control stratew - The charging of the batteries depends on the prediction of the demand and the energy expected to be generated by means of renewable sources, resulting in a certain degree of uncertainty. With this strategy, the energy loss from the renewable energies tends to decrease.

2.11 Economic analysis

The economic analysis used in this thesis is based on the life cycle cost (LCC). The LCC is a commonly used method for the economic evaluation of a number of alternatives (example energy producing systems) based on the principles of the 'time value' of money. The LCC method summarises expenditure and revenue occurring over time into a single parameter (or number) so that an economically based choice can be made.

2.11.1 Life cycle cost

LCC methodology takes the parameters of inflation and interest applied to money and uses a model based on the 'time value of money' to project a 'present value' for an investment at any time in the future. Some important variables and definitions that are used to evaluate the economic performance of the hybrid system using the life cycle costing analysis and are discussed in the next section.

2.11.2 Time Value ofMoney and Present Worth Factor

If an amount with a present value, PV (also called present worth) is invested at an interest (or discount) rate r (expressed as a fraction) with annual compounding of interest. At the end of the first year the value has increased to PV (1+r), after the second year to PV $(1+r)^2$, etc. Thus, the future value, FV, after N years is:

$$FV = PV(I + \qquad 2.26$$

The ratio PV/FV is defined as the present worth factor PWF, and it is given by:

$$PWF = \frac{PV}{FV} = (1+r)^{-N}$$ 2.27

211.3 Levelizing

Levelizing is a method for expressing costs or revenues that occur once or in irregular intervals as equivalent equal payments at regular intervals.

The present valúe PV of revenue or cost expected at the end of the jth year as a single amount can be express as the sum of the revenue or cost over N years using equation 2.53.

$$PV = \frac{A}{1+r} + \frac{A}{(1+r)^2} + \cdots + \frac{A}{(1+r)^N} = A\sum_{j=i}^{N} \frac{1}{(1+r)^j}$$

2.28

Where A is the annual amount to be paid in each year. This can be calculated using an equation for a geometric series:

PV = ALI - (1 + 2.29

2.11.4 Capital Recovery Factor

The capital recovery factor (CRF) is used to determine the amount of each future payment required to accumulate a given present value when the discount rate and the number of payments are known. The capital recovery factor is defined as the ratio of A to PV and, using Equation (2.29)

$$CFR = \frac{r(1+r)^N}{(1+r)^N - 1}$$

2.30

2.11.5 Net Present Value

The net present value (NPO is defined as the sum of all relevant present values.

From equation (2.26), the present value of a future cost, C, evaluated at yearj is:

$$PV = C/(1+r)^j$$ 2.31

Thus, the NPVof a cost C to be paid each year for N years is:

$$NPV = \sum_{j=1}^{N} PV_i = \sum_{j=1}^{N} \frac{C}{(1+r)^j}$$

2.32

This thesis uses the net present cost (NPC) to represent the life cycle cost of the system. The-NPC is the cost-TäTüõðf NPV. With the NPC cost are positive and revenue are negative.

This thesis also assumes that all prices escalate at the same rate over the project lifetime and a real interest rate-(inflation-adjusted) rather than the nominal interest rate, inflation have been factored out when discounting future cash flows to the present. Then the equation used in comparing the economic performance of energy alternative in this thesis is thus given by

$$NPC = NPV = \sum_{j=1}^{N} PV_i = \sum_{j=1}^{N} \frac{C}{(1+r)^j} = \frac{C_{T,ann}}{CRF(r,N)}$$

2.33

T,ann X [(1 + r)

NPC = r(1 +

2.34

Where Crann is the total annual cost of operating each component the energy system including the capital cost, fuel cost, operating and maintenance cost and any other cost associated in operating the system along with any revenue generated.

2.11.6 Salvage value

The salvage value of each component at the end of the project lifetime is calculated from the following equation;

$$S = crep \frac{Rrep}{Rcomp}$$

2.35

Where S is the salvage value, Crep is the replacement cost of the component; Rrem is the remaining life of the component, and Rcomp the lifetime of the component.

211.7 Levelized Cost ofEnergy

This thesis considered the most basic form of calculating cost of energy, using the levelized cost of energy, COEL, is given by the sum of annual levelized costs for energy system-divided by the-áïãergy production. Thus:

$$COEL = \frac{)(\text{Levelised annual costs})}{\text{Annual energy production}} \quad 2.36$$

This type of definition is generally used in a utility-based calculation for cost of energy.

Sometimes, the levelized cost of energy is defined as the value of energy (units of \$/kWh) that, if held constant over the lifetime of the system, would result in a cost based net present value. Using this basis, the COEL is given by:

$$COEL = \frac{(NPC)(CRF)}{\text{Annual energy production}} \quad 2.37$$

Chapter Three - Data Presentation and Analysis

3.1 Site Load

The site under study is an outdoor site, the electronic equipment and the battery bank are not housed in a shelter hence air conditioners for cooling the electronic equipment and battery bank are avoided. The number of BTS at the site is three. These are the 900 MHz, 1800 MHz and the 3G (2100 MHz) cabinet, each having an average power consumption of 2 kW. A 16kW diesel generator only powers the site.

The following equipment loads are estimated (GSMA Development Fund, 2009)

3.1.1 Ventilation equipment

Most new sites now use forced ventilation or heat exchangers, which consumes about 0.2 kW of power.

3.1.2 Lighting Loads

Varies between 50 W-200 W depending on need for security and safety — e.g. aircraft warning lights, security lights

3.1.3 Monitoring equipment loads

These consume about 0.1 kW if installed.

The load at the site was observed not to vary significantly over the day, so the load profile- is assumed constant. The daily load profile is presented in table.

Table 3.1- Hourly load variation

Assumed hourly load variation Load (kW)					
Hour	Equipment				Total load
	Total BTS load	Ventilation	Light	Monitoring	
0-1	6	0.2	0.2	0.1	6.5
1-2		0.2	0.2	0.1	6.5
2-3	6	0.2	0.2	0.1	6.5
3-4		0.2	0.2	0.1	6.5
4-5	6	0.2	0.2	0.1	6.5
5-6		0.2	0.2	0.1	6.5
6-7	6	0.2		0.1	6.3
7-8		0.2		0.1	6.3
8-9	6	0.2		0.1	6.3
9-10		0.2		0.1	6.3
10-11	6	0.2		0.1	6.3
11-12		0.2		0.1	6.3
12-13	6	0.2		0.1	6.3
13-14		0.2		0.1	6.3
14-15	6	0.2		0.1	6.3
15-16		0.2		0.1	6.3
16-17	6	0.2		0.1	6.3
17-18		0.2		0.1	6.3
18-19	6	0.2	0.2	0.1	6.5
19-20		0.2	0.2	0.1	6.5
20-21	6	0.2		0.1	6.5
21-22		0.2	0.2	0.1	6.5
22-23	6	0.2	02	0.1	6.5
23-24		0.2	0.2	0.1	6.5

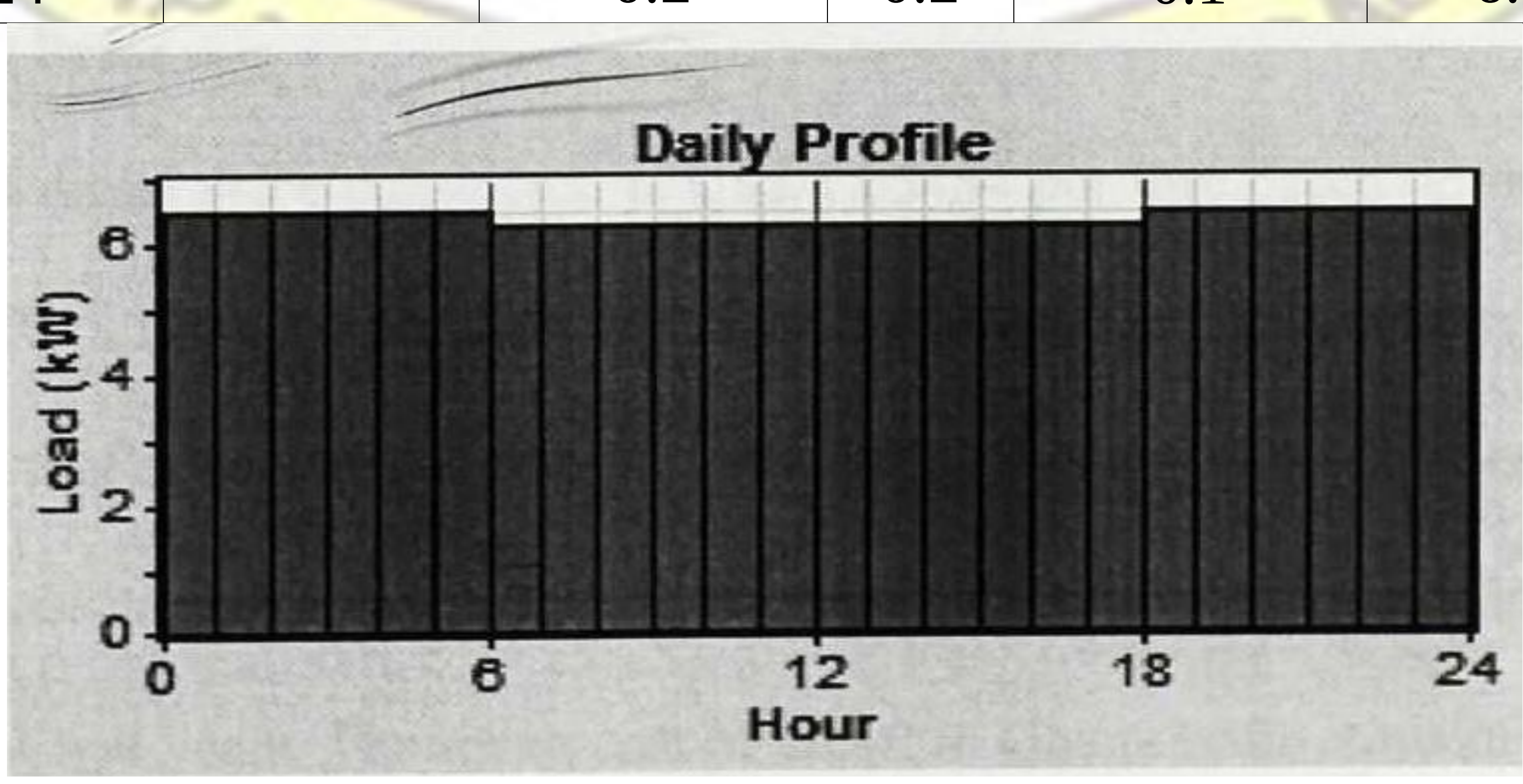

Figure 3.1 Daily load profile

3.2 The solar resources

The solar resources were obtained from NASA surface meteorology and solar energy database. In was imported directly by homer by entering the site GPS coordinate which is latitude 5^{0} 46' N longitude 0^{0} 4' E. The annual solar radiation of this area is 5.24 kWh/m^2/d.

Table 3.2 - Solar radiation data and clearness index

Month	Clearness index	Daily solar radiation(kWh/m2/d)
January	0.534	5.023
February	0.537	5.346
March	0.534	5.549
April	0.526	5.477
May	0.509	5.155
June	0.500	4.942
July	0.469	4.672
August	0.492	5.036
September	0.503	5.193
October	0.561	5.625
November	0.600	5.700
December	0.559	5.147
Average	**0.526**	**5.237**

3.3 Diesel Price

The average diesel price considered is US$ 1.05484 per litre based on the exchange rate of GH</$ 3.100 as at 14th July 2014 (National Petroleum Authority, 2014). The total cost of fuel delivered was taken as US$ 1.13per litre, which includes (7% of the diesel cost as cost of delivery). Figure 3.3 shows the trend of diesel price in Ghana over the past five years. The rising cost of diesel in Ghana cedis is mainly due to the depreciation of the currency. Sensitivity analysis will be considered for a 10% increase rate in fuel cost (US$ 1.243, 1.367, 1.5 /litre)

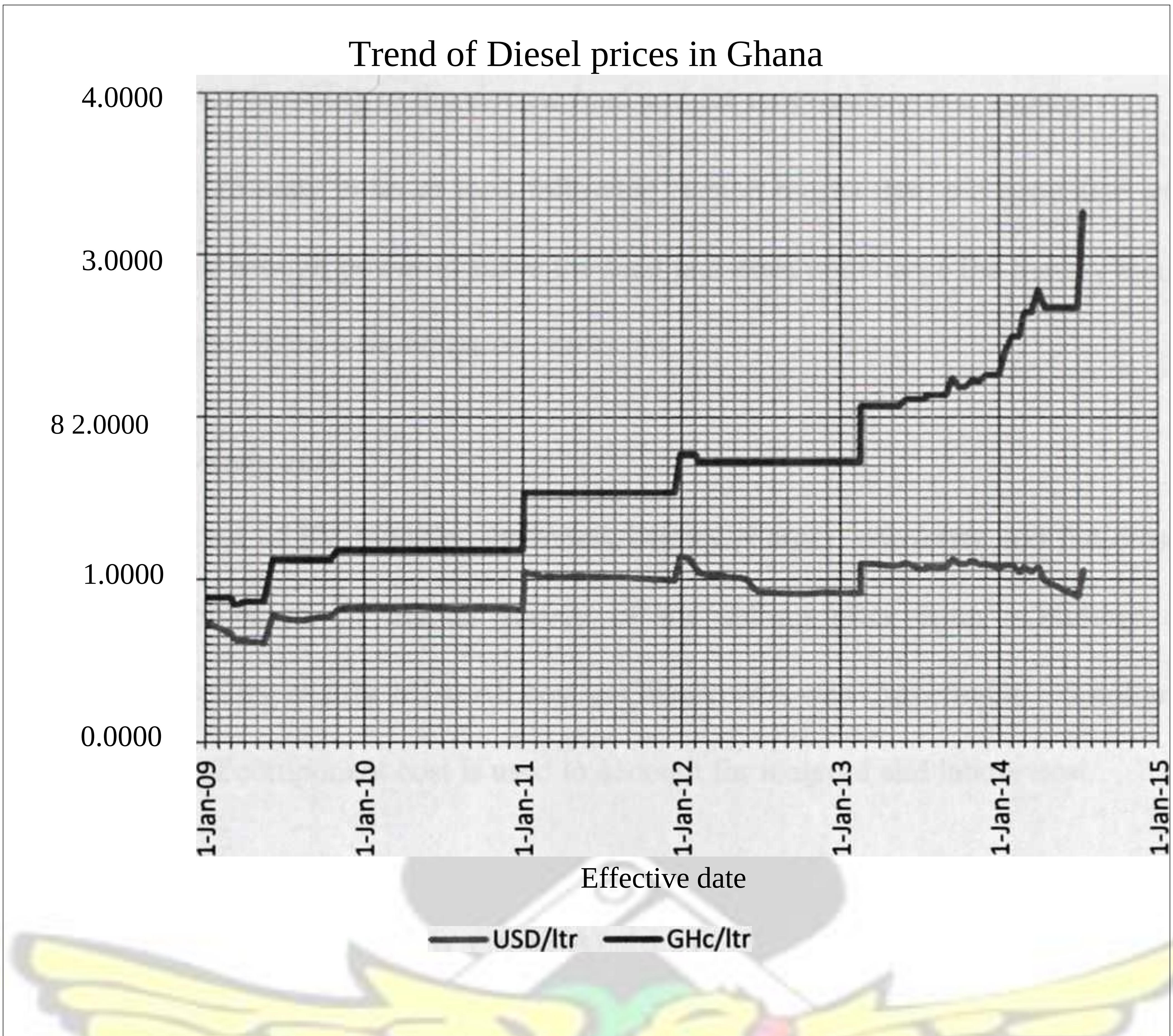

Figure 3.2-Graphical representation of diesel price in Ghana

Diesel prices figures in Ghana between January 2013 and January 2014 is presented table 5.7 of appendix A

3.4 Economics and constraints

The analysis is conducted in US dollars; the annual real interest rate considered is 10%rThe expected life span is 25 years. There is no capacity shortage for the system. The capacity shortage is the shortfall that occurs between the required operating capacity and the actual amount of operating capacity the system can provide. Minimum renewable fraction is set at zero per cent (this allows homer to consider Genset only system). The operating reserve as a percentage of hourly load is 10 % and the operating reserve as a percentage of solar power out-put is set at 25%.

Operating reserve provides a safety margin that helps ensure reliable electricity supply despite variability in the electric load and the renewable power supply.

The dispatch strategy is set at load following, which means that, the generator will produces only enough power to serve the load and does not charge the battery bank.

It is assume that there is no emission constraint.

3.5 Technology cost

The capital cost of PV modules, batteries, battery charger, converter and the diesel generator are based on market survey of the selling price from a number of companies/dealing at July 2014. All cost in Ghana cedis was converted to US dollars. 10% margin of component cost is used to account for material and labour cost.

3.6 Diesel Generator

The total cost of installing 8 kW (10 WA), 16 kW (20 WA) and 24 kW (30 WA) diesel generator set is estimated at US$ 12,200 US$ 15,600 and US$ 20,000 respectively (Rounded to the nearest hundreds). See table 5.4 of appendix A. Replacement cost is assumed to be US$11,500 US$13,000 and US$19,000 respectively.

The ninimum allowableload-err-the-generator is set at 40% of its rated capacity. The lifetime operating hours assumed to be 20,000 hours (normally given by the manufacture). Operating and maintenance cost is US$0.38 per hour ($190 per 500 hours).

3.7 Converter

The installation and replacement cost of a 1kW converter taken as USS561 and USS510. See table 5.3 of appendix A. The efficiency of 95% is assumed. The operation and maintenance cost is taken as USS5 per year. Capacity relative to inverter 100% and Efficiency 85%.

3.8 Batteries

The installation and replacement cost for the battery is estimated at US$2/Ah and US$ 1.8 /Ah (see table 5.2 of appendix A). The HOMER in-built battery considered is Trojan L16P, 6V 360 Ah sealed lead-acid. The capital and replacement cost of battery is therefore estimated at US$720 and US$ 648 respectively. For a sealed lead acid battery does not require maintenance but will assume US$ 2 per year per battery as cost of maintenance cost.

3.9 Photovoltaic system

The installation cost for the solar system is determined as follows

Component	Cost (USS/W)
Solar module	2.05
Installation	0.93
Total	2.98

See table 5.1 of appendix A.

A 1 kW PV system is estimated to cost US$-3000. A range of 16 kW to 32 kW with increments of 1 kW is considered for the photovoltaic array. Other factors considered are; PV derating factor of 80%, expected lifetime of 25 years and operation and maintenance is assumed to cost US$5 per string of 1 kW (for removing dust from the surface of the panels). 10% and 20% reduction of the cost of the PV system is considered since the price of the PV system keep falling.

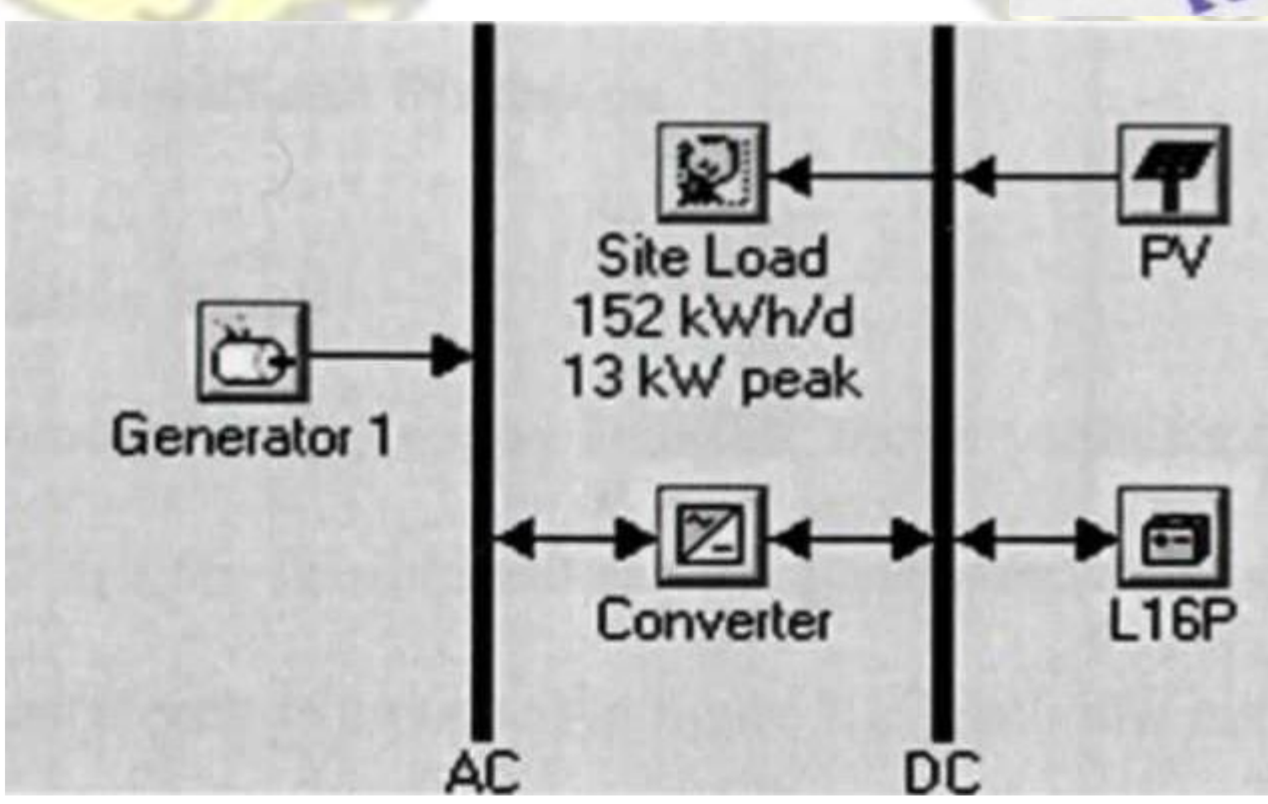

Figure 3.3 - Proposed schematic diagram of the system configuration

3.10 Cost and component summary

The components and cost is summarised in the below;

Annual interest rate — 10%

Project life span — 25%

Table 3.3- : Component and cost summary used in the analysis

Component	Initial cost	Replacement cost(USS)	O&M cost	Capacity	Life time
Diesel generator	12,200	11,500	USS 0.38/run hr	8 kW	20,000 hrs
	15,600	13,000	0.38/run hr	16 kW	20,000
	20,000	19,000	US$ 0.38/run hr	24kw	20,000
Converter	600	540	USS 100/ ear	1kW	15 years
Batte	720	648	USS 7/ ear	360Ah 6V	10
PVS stem	3000		USS5/ ear	1kW	25 ears
Fuel diesel	1.13	1.13		Per litres	

Chapter Four - Result and Discussion

4.1 Optimisation Result

Optimisation process carried out by HOMER shows various system configurations sorted by NPC that are feasible and can adequately serve the system load and the constraint imposed on it as presented in figure 4.1. Each row in the figure represents a feasible system configuration.

Diesel Price ($A-)FT3 PS/ Capita MIAiplier
a fw re-ans.

										NPC	COE (SAM,)	Renv	Desd	OTS)

18		8							
1	12	8	10	s 79270	24.695	s 303.430 0.603 s	0.40	16.093	5.814
7	12	8	10	s 76270	25.032	303.489 0.603 s	008	16.331	5.912
19	12	8	10 s 82270 9		24.390	303,662 0.603 s	0.41	15.869	5.722
19	12	8	$81.709	s	24.476	303.874 0.604 s	0.41	15815	5.761
18	12	8	$78.709 11 $		24.825	304.046 0.604 s		16.158	5863
18	12	8	79.831		24.702	304.048 0-604 s	0.40	16.088	5.810
16	12	8	10	$ 73270	25.433	304.126 0.604	036	16.611	
17	12	8	9	s 75.709	25168	$304.164 0.604 s	0.38	16.402	5.964
20	12	8	10	s 85270	24.133	304.323 0.604 s	0.43	15.679	5.644
19	12	8	11	S82.831	24.412	304.423 0.605 s	0.41	15.874	5723
1	12	8	11	s 76.831	25.074	304.430 0.605 s	0.38	16.346	5.918
7	12	8	9	SU.709	24.210	304.467 0.605	L43	15.721	5681
20		8							

Figure 4.1- Optimisation result sorted by NPC

Figure 4.2 also shows optimisation result based on various categories also sorted by NPC. The various categories are:

Solar + DG tþatteries

Solar + DG-— DG +

batteries

DG only

Sensitivity variables

Diesel Price ($/L) 1.13 PV Capital Multiplier 1

Double click on a system below for simulation results.

PV (kW)	DG (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
18	12	8	10	$ 79,270	24,695	$ 303,430	0.603	0.40	16,093	5,814
23	14		11	$ 89,921	29,572	$ 358,345	0.712	0.42	20,116	6,974
	14		12	$ 21,482	38,512	$ 371,054	0.737	0.00	26,475	8,760
	14	8	10	$ 26,120	38,088	$ 371,850	0.738	0.00	26,010	8,582

Figure 4.2 Optimisation result based on categories

4.2 Simulation Results

The simulations provide information concerning the electricity production, economic costs and environmental characteristics of each system, such as the C02 emissions.

For this thesis analysis, the diesel generator only system is compared to a proposed hybrid system.

42.1 Diesel generator only system

For a site being powered by diesel generator only, homer suggests system architecture of 14 kW diesel generator and 12 kW converter. The total NPC is US$ 371,054, levelized cost of energy is US$ 0.737/kWh and the annualized operating cost is US$

38,512/yr. The graphs in figure 4.3 and the tables 4.1 summarises the simulationr results.

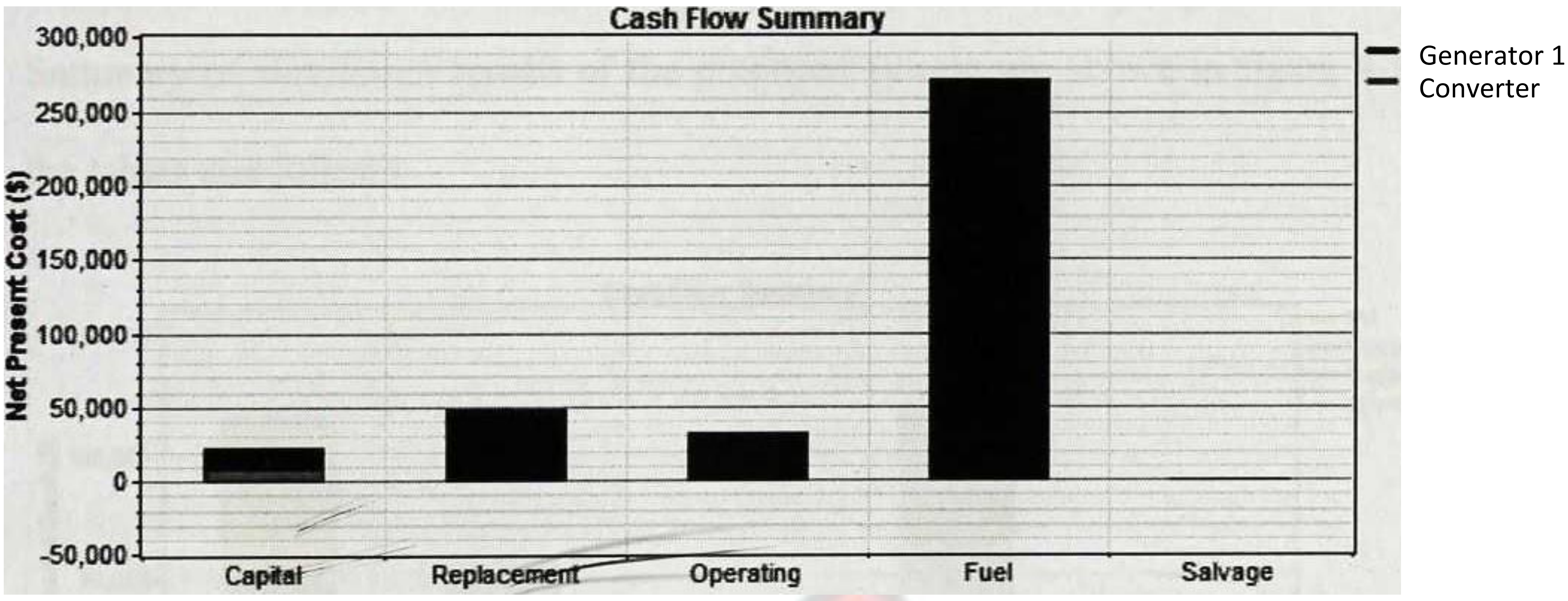

Figure 4.3 - Bar chart showing Cash flow summary of diesel only system.

4.22 Proposed system

The most optimised of the simulation result in figure 4.1 has battery autonomy of I .91 hours. This may not be favourable for use in a remote telecom site.

The system architecture of the proposed solar hybrid system, (as highlighted in figure 4.4) comprises 23 kW PV system, 10 kW diesel generator, 40 L16P batteries (load following) and 9 kW converter. The operating cost per year, total NPC, and cost of energy are US$ 21,122 US$ 307,622 and US$ 0.611 (kWh respectively.

Diesel Price ($/L) 1.13 PV Capital Multiplier 1

Double click on a system below for simulation results.

PV (kW)	DG (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
17	12	16	11	$ 82,591	24,785	$ 307,569	0.611	0.39	15,679	5,648
18	12	16	11	$ 85,591	24,457	$ 307,591	0.611	0.41	15,405	5,537
23	10	40	9	$ 115,899	21,122	$ 307,622	0.611	0.52	11,701	4,346
19	12	16	10	$ 88,030	24,195	$ 307,651	0.611	0.42	15,176	5,448
16	12	16	10	$ 79,030	25,194	$ 307,720	0.611	0.37	16,005	5,784
23	12	8	12	$ 95,392	23,408	$ 307,868	0.611	0.47	15,136	5,417
24	12	8	10	$ 97,270	23,211	$ 307,956	0.612	0.48	15,008	5,367

Figure 4.4 - Proposed hybrid system shown in highlight

Summary of simulation results of the proposed system are shown in figure 4.5 and the tables that follows

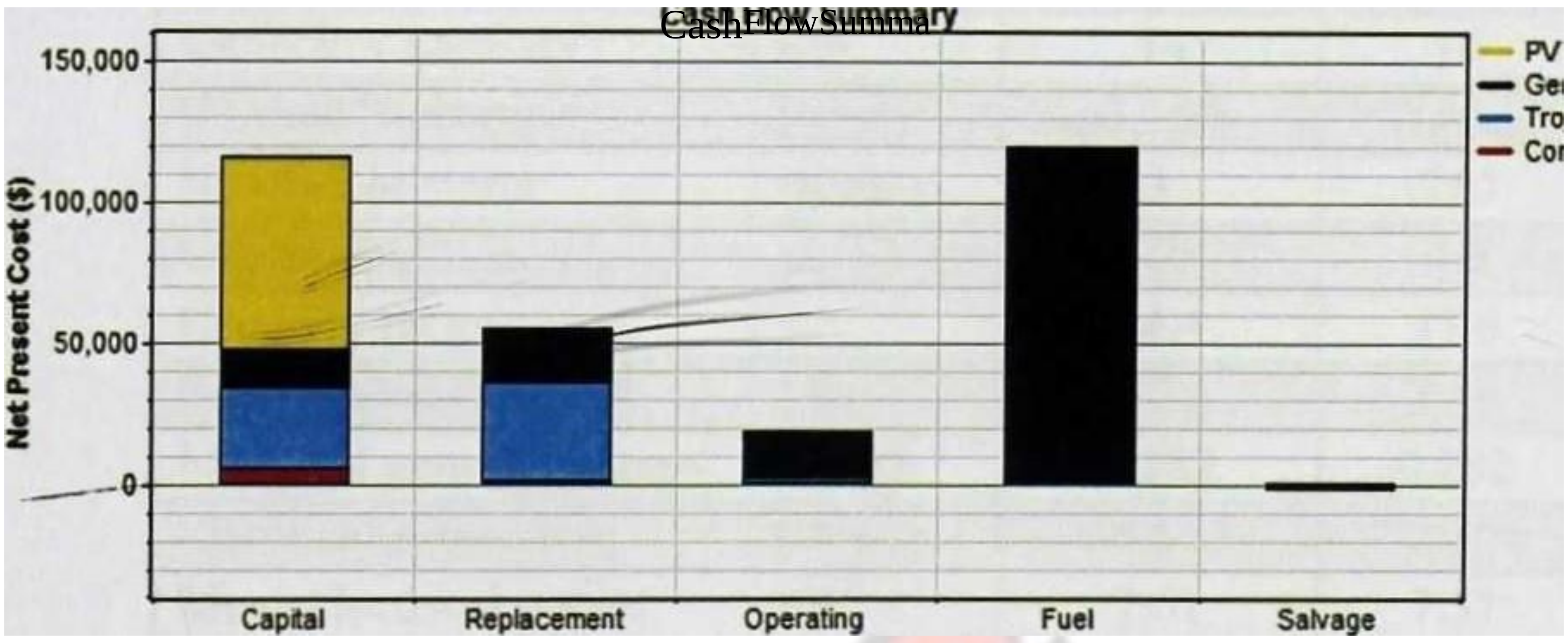

Figure 4.5 - Bar charts showing cost summary of proposed hybrid system

Table 4.1 - Cost summary of diesel generator only system and proposed system

Diesel Generator only system						
Component	Capital	Replacement ($)		Fuel (S)	Salvage	Total
Generator	14,750	46,041	30,216	271,553	-58	362,501
Converter	6,732	1,465	545	o	-188	8,553
System	21,482	47,506	30,760	271,553	-247	371,054
Proposed Hybrid system						
Component	Capital	Replacement		Fuel ($)	Salvage	Total
PV	69,000	o	1 ,044		o	70,044
Generator	13,050	19,163	14,991	120,013	—622	166,594
TrojanL16P	28,800	34,523	1,815	o	-570	64,569
Converter	5,049	1,099	408			6,415
System	115,899	54,784	18,258	120,013	-1,333	307,622

Table 4.2 - Generator operating characteristics of the hybrid and diesel system

		diesel only s tern,	hybrid s tem

Quantity	Units	Value	Value
Generator capacity	kW	14	10
Hours of operation	hr/yr.	8,760	4,346
Number of starts	starts/yr.	1	910
Operational life	yr.	2.28	4.6
Capacity factor		54.4	37.6
Fixed eneration cost	$/hr	2.28	1.88
Marginal generation cost	$/kWh	0.282	0.282
Electrical production	kWh/yr.	66,657	32,895
Mean electrical output	kW	7.61	7.57
Min. electrical output	kW	5.6	4
Max. electrical output	kW	14	10
Fuel consumption	L/yr.	26,475	11,701
Specific fuel consum tion	L/kWh	0.397	0.356
Fuel energy input	kWh/yr.	260,511	115,133
Mean electrical efficiency		25.6	28.6

Table 4.3 - Comparison of electrical energy of hybrid and diesel only system

Electrical characteristics				
	diesel only system		hybrid system	
	kWh/yr.		kWh/yr.	
Production				
PV array			35,445	52
Generator 1	66,657	100	32,895	48
Total	66,657	100	68,340	100
Consumption				
DC primary load	55,479	100	55,469	100
Excess electricity	1,386	2.08	6,669	9.76
Unmet electric load	0.609		11.3	0.02
Capacity shortage	10.9	0.02	50.7	0.09

Table 4.4 - Comparing emissions of the hybrid and diesel only system

Emission		
	diesel onl	hybrid s tem
Pollutant	Emissions (kg/yr.)	Emissions (kg/yr.)
Carbon dioxide	69,717	30,811
Carbon monoxide	172	76.1

Unburned hydrocarbons	19.1	8.42
Particulate matter	13	5.73
Sulphur dioxide	140	61.9
Nitrogen oxides	1,536	679

Table 4.5 - PV system characteristics of proposed system

PV characteristics		
uanti	Units	Value
Rated ca aci	kW	23
Mean ou ut		4
Mean ou ut	kWh/d	97.1
aci factor		17.6
Total roduction	kWh/	35,445
Minimum ou	kW	
Maximum ou ut	kW	22.3
PV etration		63.9
Hours of o ation	hr/	4,380
Levelized cost	S/kWh	0218

Table 4.6 - Battery operating characteristics of proposed hybrid system

battery characteristics		
Quantity		Value
String size		8
Strings in parallel		5
Batteries		40
Bus voltage (V)		48
Nominal capacity	kWh	86.4
Usable nominal capacity	kWh	60.5
Autonomy	hr	9.55
Lifetime throughput	kWh	43,000
Battery wear cost	S/kWh	0.654
Average energy cost	S/kWh	0
Energy in	kWh/yr.	8,820
Energy out	kWh/yr.	7,551
Storage depletion	kWh/yr.	54
	kWWy•T.	1,214
Annual throughput	kWh/yr.	8,190
Expected life	yr.	525

4.3 Discussion

4.3.1 Economic cost

Comparing the two systems, the proposed system will require additional investment of US$ 94,417. Despite its high initial cost, the hybrid system will be able to make a savings of US$ 63,432 over the life-time of the proposed system by reducing the NPC from US$-371,054 to USS307,622 and a reduction in the cost of energy as presented in table 4.7

Table 4.7 - Economic comparison of simulation results.

Parameter	DG only	Proposed hybrid system
Initial cost	US$ 21,950	US$ 115,899
Operational cost	USS 38,512/yr	US$ 21,128/yr
NPC	US$ 371,054	US$ 307,622
COE	$ 0.737/kWh	US$ 0.611/kWh

Table 4.8 - Economic indicators

Metric	Value
Present worth	$63,432

Annual worth	$ 6,988/yr.
Return on investment	18.10%
Internal rate of return	18.70%
Simple payback	4.43 yrs.
Discounted payback	7.58 yrs.

Using the diesel only system as a base system and compared to the proposed hybrid system as the current system, the economic indicators presented in table 4.8 shows that the positive value of the present worth means the hybrid system will save money over the project lifetime as compared to the base system. The present worth is the difference between the net present costs of the base case system and the current system. The return on investment of 18.10% is the benefit gain from investing additional USS 94,417 in the hybrid system over the lifetime of the project. The internal rate of return is the discount rate at which the base case and current system have the same net present cost. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system. The internal rate of return and the payback period are all good indicators that the hybrid system is a viable option

43.2 Technical analysis

From the table 4.2, it is seen that the fuel consumption is significantly reduced by about 55.8% in the hybrid system. Fuel cost is a major the major contributor to the NPC as shown in figure 4.3, figure 4.5 and in table 4.1. The reduced fuel consumption can be attributed to the reduced operational hours of the generator in the hybrid system which leads to an increase in its operational life of 4.6 years. This means less frequent maintenance, overhauling and replacement which leads to a better reliability. Table 4.2 shows that the fixed generation cost for the generator in the hybrid system is cheaper than that of the diesel only system by USS 0.4/hr. Fixed generation cost of energy is the cost per hour of running the generator without producing electricity. The marginal cost of energy is the additional cost per kilowatt hour of producing electricity from the generator.

Furtheremore, The 10 kW—gratorin the proposed hybrid system will run at a better efficiency of 28.6% compared to 25.6% of the 14kW generator in the only diesel system.

The table 4.3 also shows that the hybrid system produces more electricity in excess than diesel only system. This excess can be used for other purpose such as charging of laptop and mobile phone by technician who visit the site for maintenance work.

With the proposed hybrid system, the nominal battery capacity is 86.4 kWh and the usable capacity is 60.5 kWh as presented in table 4.6. In case of power failure from the diesel generator in times of low or no solar radiation, 9.55 hours of battery autonomy will provide technicians ample time to travel to the site and restore power and to do maintenance without the BTS suffering any power disruption. Details of the battery size is also presented in table 4.6.

4.3.3 Performance analysis

The graph in figure 4.6 shows how the primary dc load is met by the diesel generator, the PV power and the battery for a typical day like January 3. During the period between 12 mid-night, the generator run to meet the load required. After 6 am the load demand drops a little and as the PV system is able to meet the load, the diesel generator goes off. During this period it is seen that the battery state of charge (0/0) rises indicating that the solar energy is used to charge the batteries, excess electricity is also produced during this period.

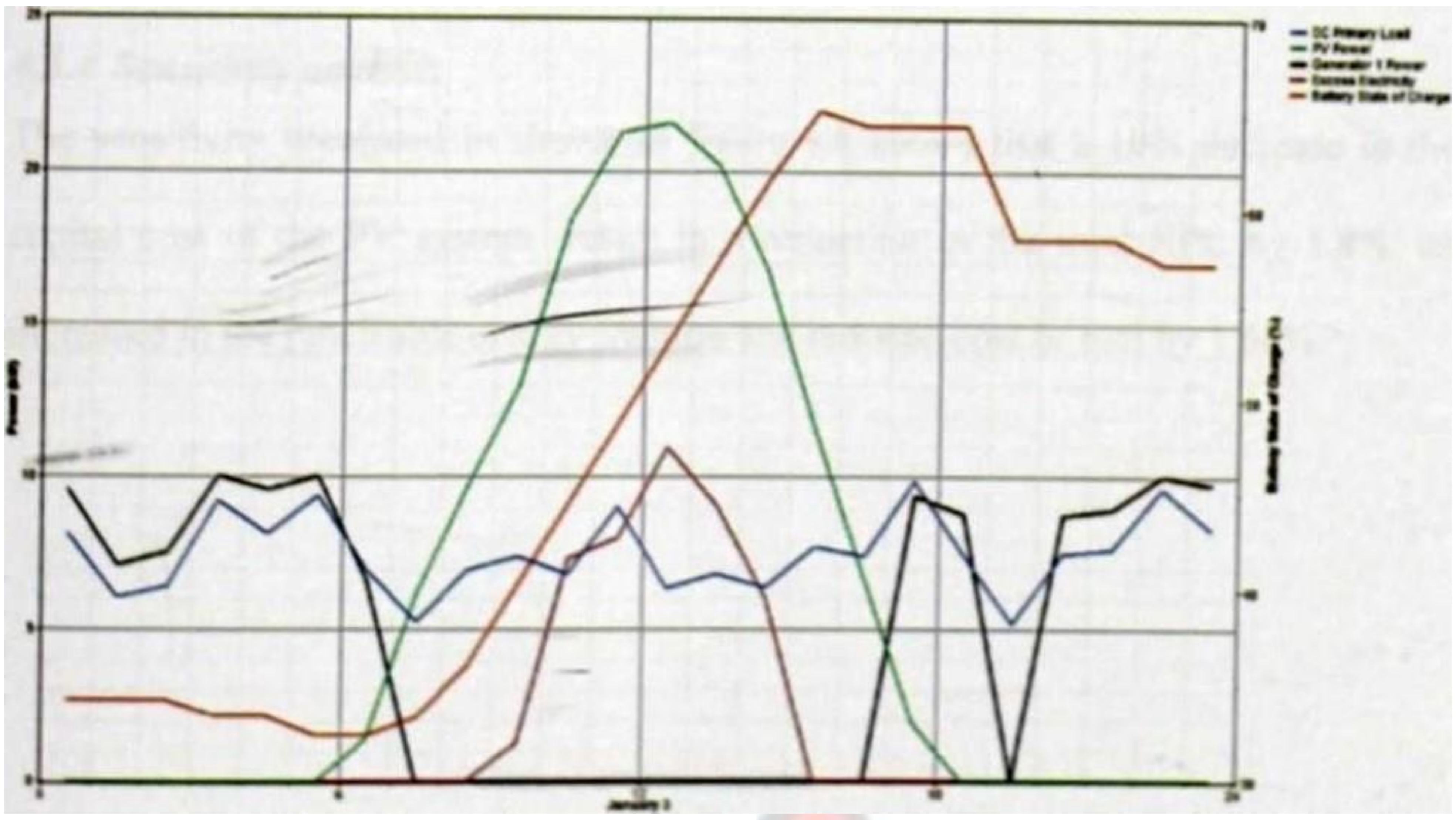

Figure 4.6 Components performance in a typical day

As the PV-power reduces around 6 pm and the load demand rises, generator steps in to provide the needed power. At this time, the battery state of charge is constant. As the load demand comes down, the generator is off and battery bank then provide the power as indicated by the sharp drop in the battery state of charge. This continues into the night until the sun comes up again the next day as seen in figure 4.7

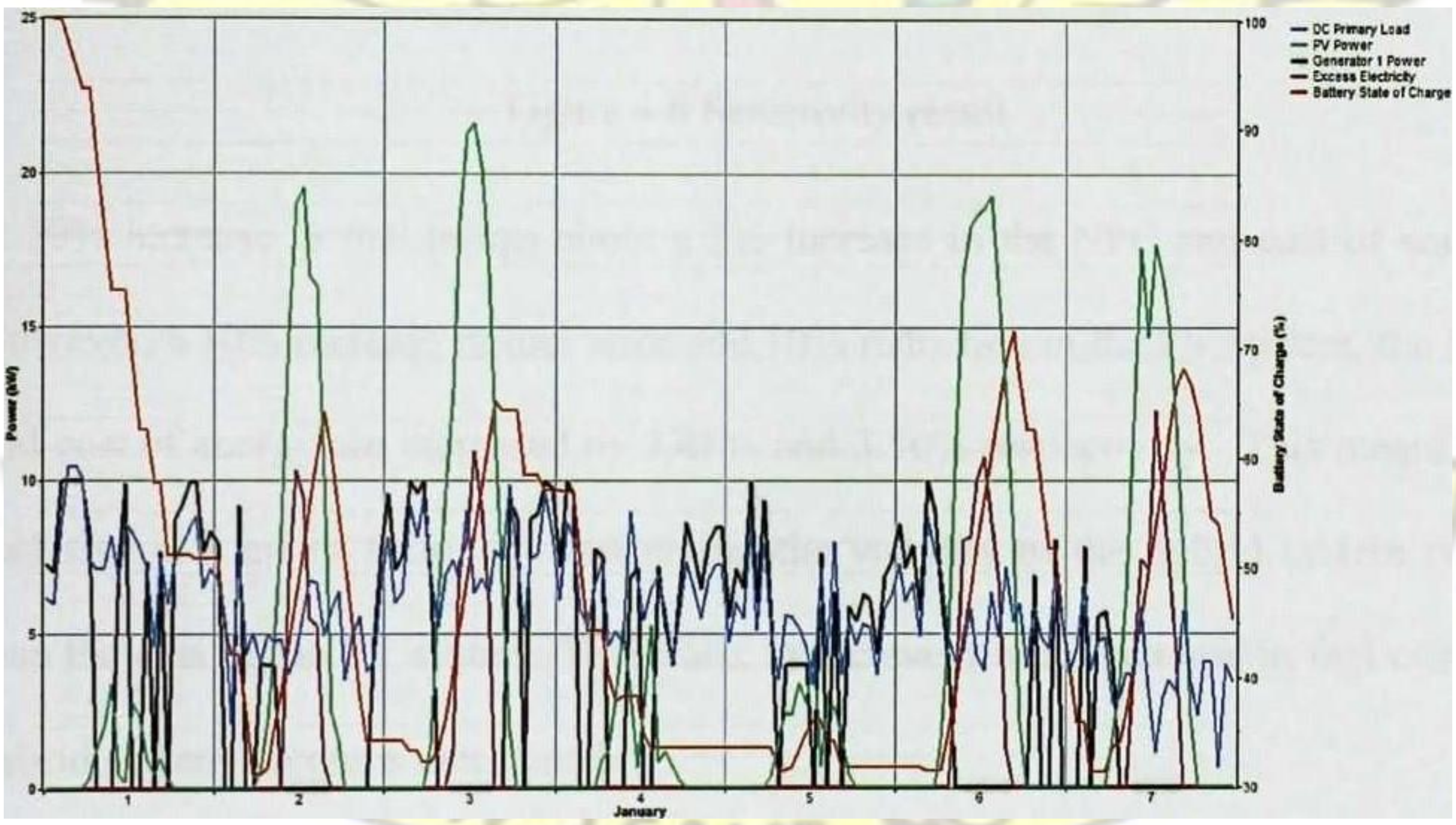

Figure 4.7 Components performance over some days

4.3.4 Sensitivity analysis

The sensitivity presented in shown in figure 4.8 shows that a 10% decrease in the capital cost of the PV system result in a reduction in the total NPC by 1.8%, an increased in thëGenewable eneõÑäCViGn and reduced cost of fuel by 1.66%.

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							Hial		NPC	COE (SfkVTh	Ren. Frac.	Diesel (L)	DG
1.130	1.00	18	12	8	10		s 79270	24.695	s 303.430	0.603	L40	16.093	5.814
1.130	0.90	19	12	8	10		s 76570	24.390	s 297.962	0.592	0.41	15.869	5.722
1.130	0.80	21	12	8		10	s 75.670	23840	s 292066	0.580	0.44	15.475	5558
1240		18	12	8		10	s 79.270	26.466	s 319.499	0634	0.40	16.093	5.814
1240		19	12	8		10	$ 76.570	26.136	s 313.807	0623	Œ41	15.869	5.722
1240		21	12	8		10	s 75."1	25542	s 307517	0.611	0.44	15.475	5558
		19	12	8	10		s 82.270	28.199	s 338233	0.672	0.41	15869	5.722
1.370		21	12	8		10	$81,970	27.554	s 332078	0659	044	15.475	5.558
			12	8		10		27275	s 325.65)	0.647	0.46	15.3m	5.486
	1.00	21	12	8		10	s 88.270	29.566	s 356638	0.708	0.44	15.475	5.558
		22	12	8		10	s 84.670	29.264	s 350.304	0.696	0.46	15.300	5.486
			12	8		10	s 78.01)	29.264	s 343.704	L683	0.46	15.3(n	5.486
1.0			12	8									

Figure 4.8 Sensitivity result

A 10% increase in fuel brings about a 5% increase in the NPC and cost of energy. However, a 10% increase in fuel price and 10% reduction in the PV system, the NPC and cost of energy are increased by 3.41% and 3.36% respectively. This means that fuel cost is a major factor in determining the viability of the hybrid system rather than the cost of the PV system. Therefore, in the event of an increase in fuel cost the hybrid system becomes more viable.

43.5 Emission analysis

The simulation results also shows there will be a significant reduction in emission of some green house gases and other pollutant in the proposed solar hybrid system. Carbon dioxidœwhich is a major GHG will be reduced by about 55.8%. Other GHG gases and pollutant is shown in table 4.4.

Chapter Five - Conclusion and Recommendation

5.1 Conclusions

Based on the result obtained and the analysis, this study conclude that using solar hybrid system to power telecom base station is much more better than using the stand alone diesel generator in areas where there is no access to the electrical grid.

From the economic point of view, despite the high initial cost, the proposed solardiesel hybrid with batteries in it lifespan, achieve lower overall cost by way of lower NPC.

Technically, the control algorithms will take full advantage of the solar energy when it is available and reduces the diesel generator run-hours. This increases the lifespan and performance of the diesel generator. The battery autonomy ensures reliability of power supply, which brings about the required stability of the network.

The significant reduction of fuel consumption by the diesel generator means that pollution of the atmosphere because of emission of C02 and other greenhouse gases, which cause global warming, will be minimised thereby saving the environment.

In concluding further, the suitability of the proposed diesel- solar hybrid system with battëñes was based on technical and economic assessment. Therefore, using solardiesel hybrid technology for a telecom base station is very much viable.

5.2 Recommendation

The continuous fall in installation price of solar PV system, present itself as the best option to replace the diesel generator. It is recommended that, telecom operators in Ghana should take advantage of this and consider installing solar hybrid system at their telecom base stations to minimise the use of the diesel generators, especially in areas where there is no access to the grid or the grid is not reliable.

The northern part of Ghana will be most appropriate since available data shows they have much higher solar energy than the south.

Where solar hybrid systems are deployed, further studies should be done on the viability of adding at least one more renewable energy such as wind energy to the hybrid system. This could further reduce the diesel consumption and save more money.

The Government should encourage telecom operators to incorporate renewable energy in their base station to reduce the dependence on the grid and diesel fuel.

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Appendix A: Technology cost data collected in Ghana

The following table shows prices of some system components collected in Ghana as at the end of July 2014. The exchange rate use is 1 US dollar = 3.4 Ghana cedis as at 31 July 2014 (http://www.oanda.com/currency/converter/)

Table 5.1 price data solar module prices collected

dealer	Module rice	Type	(GHO	US$	US$/watt
1	120	poly	749.3	220.38	1.84
	50	poly	327	96.18	1.92
	30	poly	218	64.12	2.14
2	130	poly	650	191.18	1.47
	170	mono	900	264.71	1.56
3	130		750	220.59	1.70
	245		1500	441.18	1.80
	50		350	102.94	2.06
4	100	poly	600	176.47	1.76
5	120	poly	600	176.47	1.47
6	250	poly	2500	735.29	2.94
7	130	poly	1139	335.00	2.58
	30	mono	289	85.00	2.83
	50	mono	445	130.88	2.62
	80	mono	715	210.29	2.63
	100	mono	894	262.94	2.63
	130	mono	1160	341.18	2.62
	190	mono	1696	498.82	2.63
	300	mono	2672	785.88	2.62
	30	poly	243	71.47	2.38
	50	poly	358	105.29	2.11
		Poly	573	168.53	2.11
	140	poly	1004	295.29	2.11
	280	poly	2003	589.12	2.10
8	50	poly	350	102.94	2.06
9	50	poly	250	73.53	1.47
	200	poly	900	264.71	1.32
10	170	poly	900	264.71	1.56
	110	poly	600	176.47	1.60
11	200			302.00	1.51
12	50	poly	250	73.53	1.47
Average rice					2.05

Table 5.2 Price data of deep cycle solar battery collected

Dealer	Capacity Ah	Price GHc	price	USS/Ah
1	100	750	220.59	2.21
2	100	585	172.06	1.72
3	100	600	176.47	1.76
	200	1400	411.76	2.06

4	100	600	176.47	1.76
	170	750	220.59	1.30
5	100	350	102.94	1.03
6	200	1050	308.82	1.54
7	170	800	235.29	1.38
8	170	1200	352.94	2.08
9	100	750	220.59	2.21
	165	900	264.71	1.60
	190	1200	352.94	1.86
11	170	1781	523.82	3.08
12	170	900	264.71	1.56
	100	450	132.35	1.32
	100	400	117.65	1.18
	200	1000	294.12	1.47
13	200		500.00	2.50
14	170	950	279.41	1.64
15	20	200	58.82	2.94
	100	650	191.18	1.91
16	100	750	220.59	2.21
17	200	1050	308.82	1.54
18	170	720	211.76	1.25
Average cost				1.80
Installation				1.99

10% of battery assumed as installation cost, which includes material and labour.

Table 5.3- Price Data of converter collected

	Capacity (W)	Price (GHO	US$	US$/Watt
1	150	230	71.88	0.48
2	300	111.1		0.12
	600	1842	575.63	0.96
	3000	6630	2071.88	0.69
3	800	2950	921.88	1.15
	1200	3800	1187.50	0.99
	1600	4550	1421.88	0.89
	1500	2200	687.50	
4	1480	1400	437.50	0.30
	1600	1750	546.88	0.34
	2000	1950	609.38	0.30
	4000	3750	1171.88	0.29

5	2000	3170	990.63	0.50
6	4000	4500	1406.25	0.35
	1600	3200	1000.00	0.63
	800	1000	312.50	0.39
	750	850	265.63	0.35
	500	780	243.75	0.49
7	2000	1750	546.88	0.27
8	6000	4500	1406.25	0.23
Average				0.51
Average installation cost				0.561

10% of converter cost is assumed as installation cost, which includes material.

Table 5.4- Price data of diesel generator

	Diesel generator Capacity/kW				
dealer	8kW	10.4kW	12kW	16kW	24kW
	38,000.		47,000.00		60,000.00
2	38,622.00		45,978.26	53,334.78	60,691.30
3				54,637.50	68,479.00
4	40,250.00			43,400.00	56,000.00
5				46,400.00	61,200.00
6	34,000.00	42,301.00		43,871.00	64,060.00
7				47,000.00	58,163.00
GHC	37,718.00	42,301.00	46,489.13	48,107.21	61,227.61
US$	11,093.53	12,441.47	13,673.27	14,149.18	18,008.12
Installation cost	12,202.88	13,685.62	15,040.60	15,564.10	19,808.93

Table 5.5- Prices of charge controller

dealer	Capacity	Price GHC	price US$	US$/A
1	20	300	88.24	4.41
2	10	194	57.06	5.71
	10	119.7	35.21	3.52
	60	763.8	224.65	3.74
3	20	400	117.65	5.88
4	40	760	223.53	5.59
	30	450	132.35	4.41
5	40	1152	338.82	8.47
	30	1350	397.06	13.24

6	40	1495	439.71	10.99
7	60	2800	823.53	13.73
	20	630	185.29	9.26
8	30	400	117.65	3.92
average				7.14

Table 5.6- Installation cost of some PV system

	Installed capacity	Installation cost GHC	Installation cost (US$)	installation cost(US$/W)
21	1000	1020	458	0.458
2	400	1680	494	1.235
3	480	1600	470	0.979
4	240	1000	294	1.225
5	400		600	1.5
6	500	1275	375	0.75
7	1000	1180	347	0.35
average				0.93

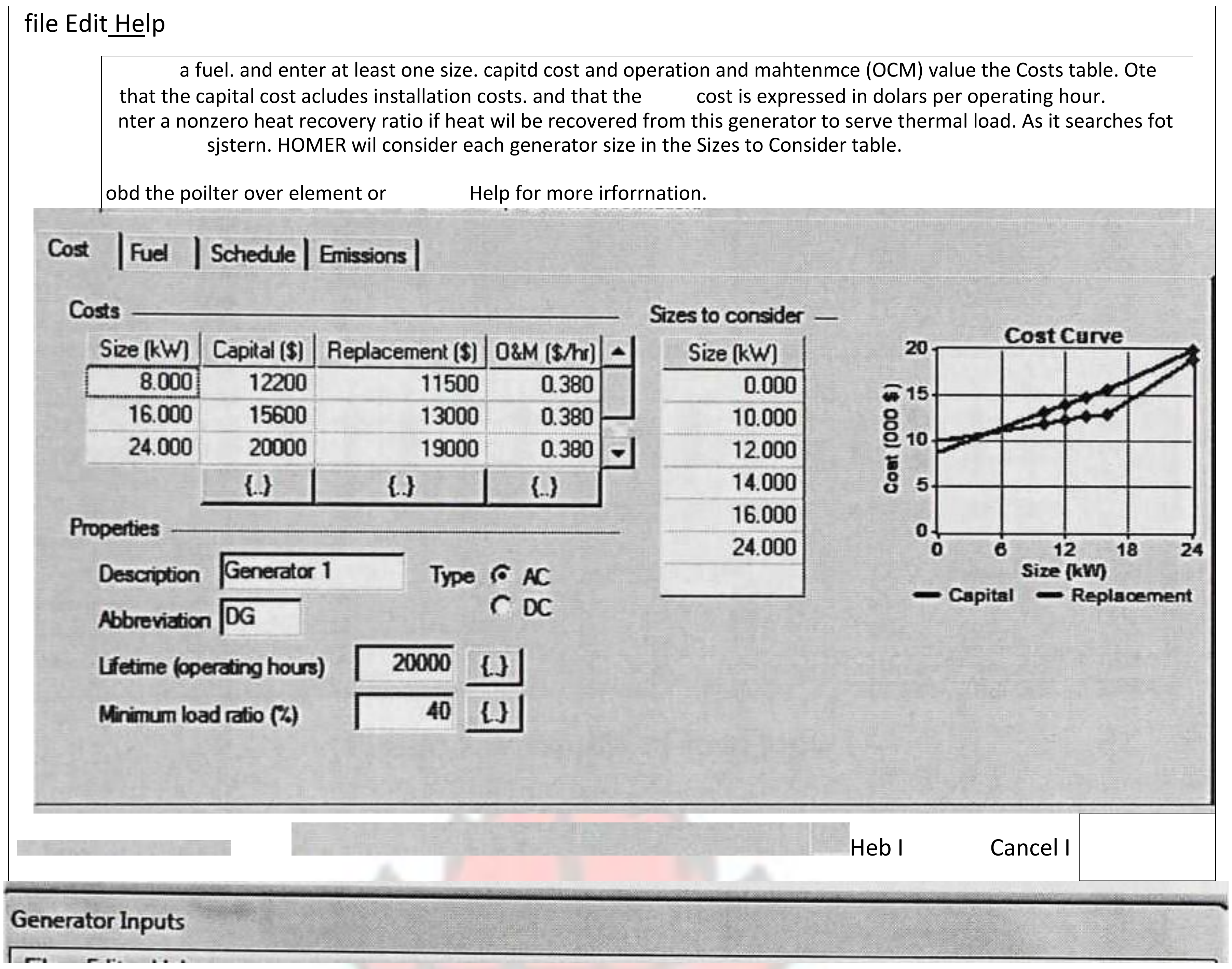
Installation cost includes labour and engineering management, mountings, accessories and charge controller.

2 Information on from source was in January and the exchange rate was GHC 2.2264/USS).

Table 5.7 mesel prices and exchange rate (National Petroleum Authority, 2014)

EFFECTIVE DATE	Exchange rate GHC/US$	Ex-pump price GHC	Ex-pump Price Uşş
1-Jan-13	1.8857	1.7236	0.9140
16-Jan-13	1.8867	1.7236	0.9136
1-Feb-13	1 .8869	1.7236	0.9135
16-Feb-13	1.8870	1.7236	0.9134
17-Feb-13	1.8870	2.0683	1.0961
1-Mar-13	1.8893	20683	1 .0948
16-Mar-13	1.8902	2.0683	1 .0942

1-Apr-13	1.8970	20683	1 .0903
16-Apr-13	19041	2.0683	1 .0862
1-May-13	19077	2.0683	1.0842
16-May-13	1.9041	2.0683	1.0862
I-Jun-13	1.9216		1 .0986
16-Jun-13	.9440		1 .0860
1-Ju1-13	1.9883		1.0618
16-Ju1-13	1.9932		1.0592
17-Ju1-13	1 .9932	2.1379	1 .0726
I -Aug-13	1.9919	2.1379	1.0733
16-Aug-13	19984	2.1379	1 .0698
1-Sep-13	1.9958	2.1379	1.0712
16-Sep-13	1.9980	2.2426	1.1224
1-Oct-13	1 .9997	2.1891	1.0947
16-Oct-13	20002	2.1891	1.0944
1-Nov-13	2.0056	2.2313	1.1125
16-Nov-13	20401	2.2200	1.0882
1-Dec-13	2,0695	2.2600	1.0921
16-Dec-13	2.0902	2.2600	1 .0812
Man- 14	1148	2.2600	1 .0687
16-Jan-14	2.2264	2.4200	1.0870
1-Feb-14	2.3010	2.5000	1.0865
16-Feb-14	2.3973	2.5000	1 .0428
1-Mar-14	2.4656	2.6500	1 .0748
16-Mar-14	2.5335	2.6500	1 .0460
I -Apr-14	2.5984	2.7900	1.0737
16-Apr-14	2.7039	2.6800	0.9912
1-May-14	2.7686	2.6800	0.9680
16-May-14	2.8158	2.6800	0.9518
1-Jun-14	2.8786	2.6800	0.9310
16-Jun-14	2.9312	2.6800	0.9143
1-Ju1-14	3.0132	2.6800	0.8894
14	3.1000	3.2700	1.0548



Appendix B: Samples of HOMER input

Figure 5.1 Generatot sample input

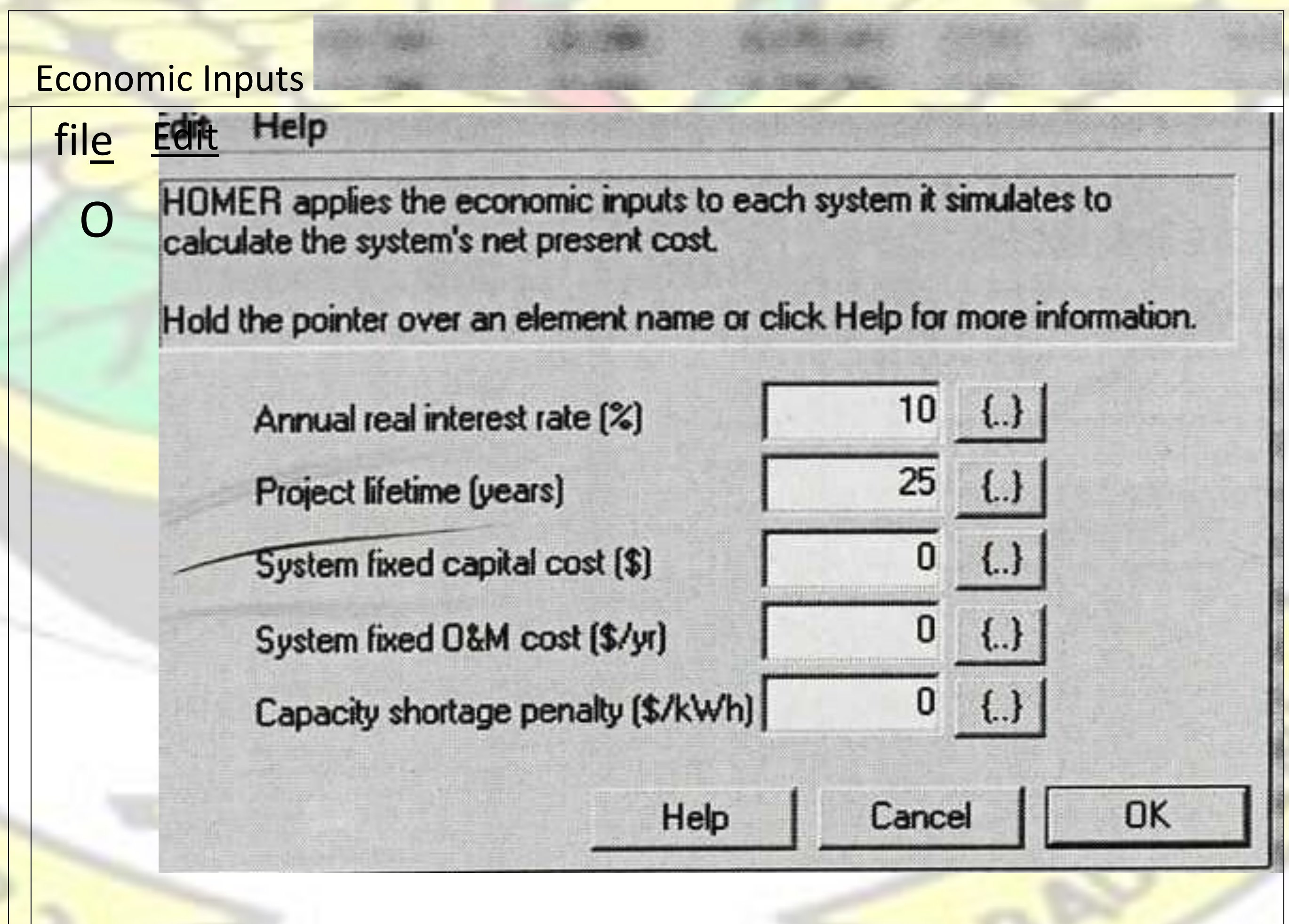


Figure 5.2 : sample of economic input

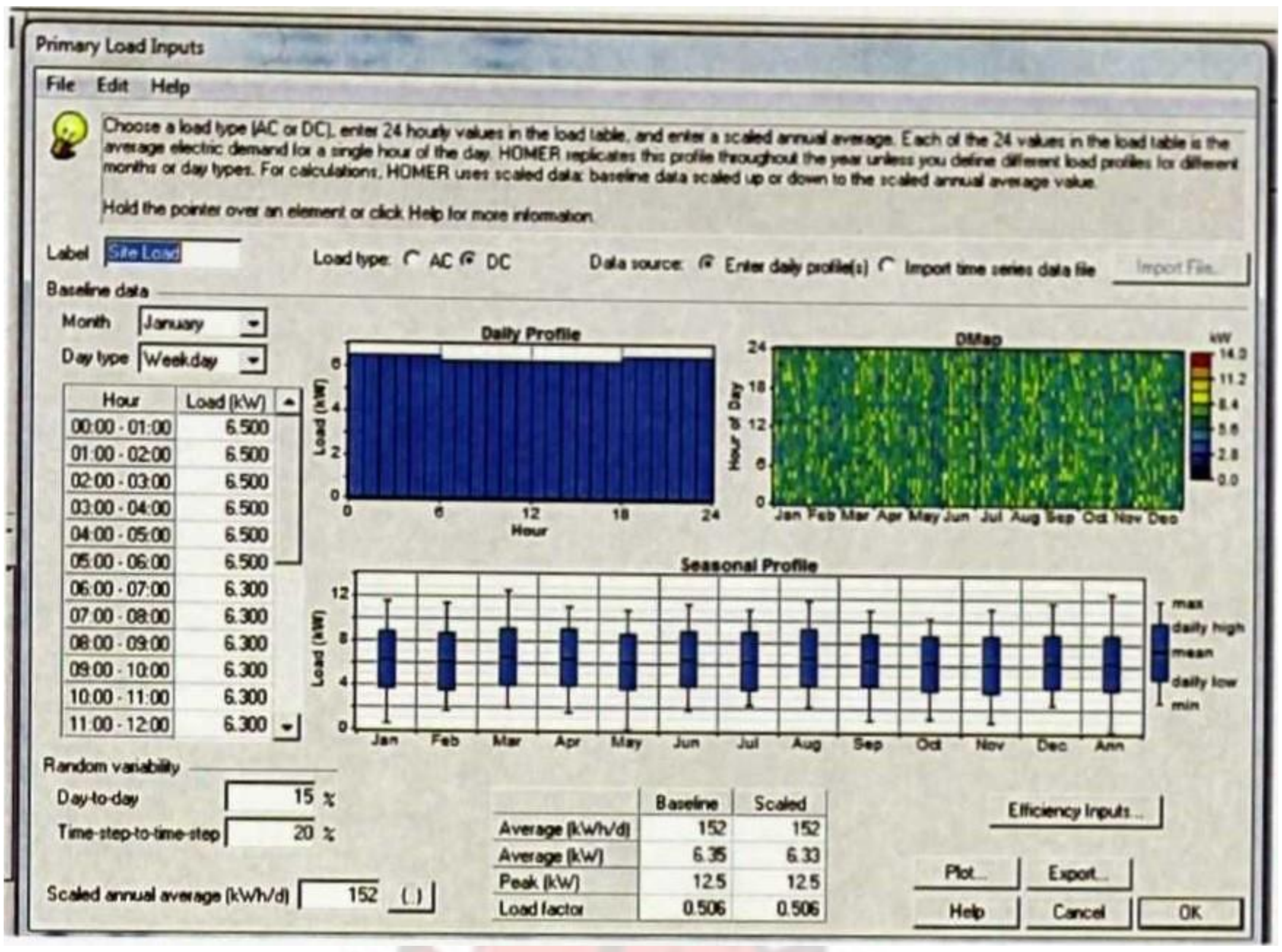


Figure 5.3 sample of load input

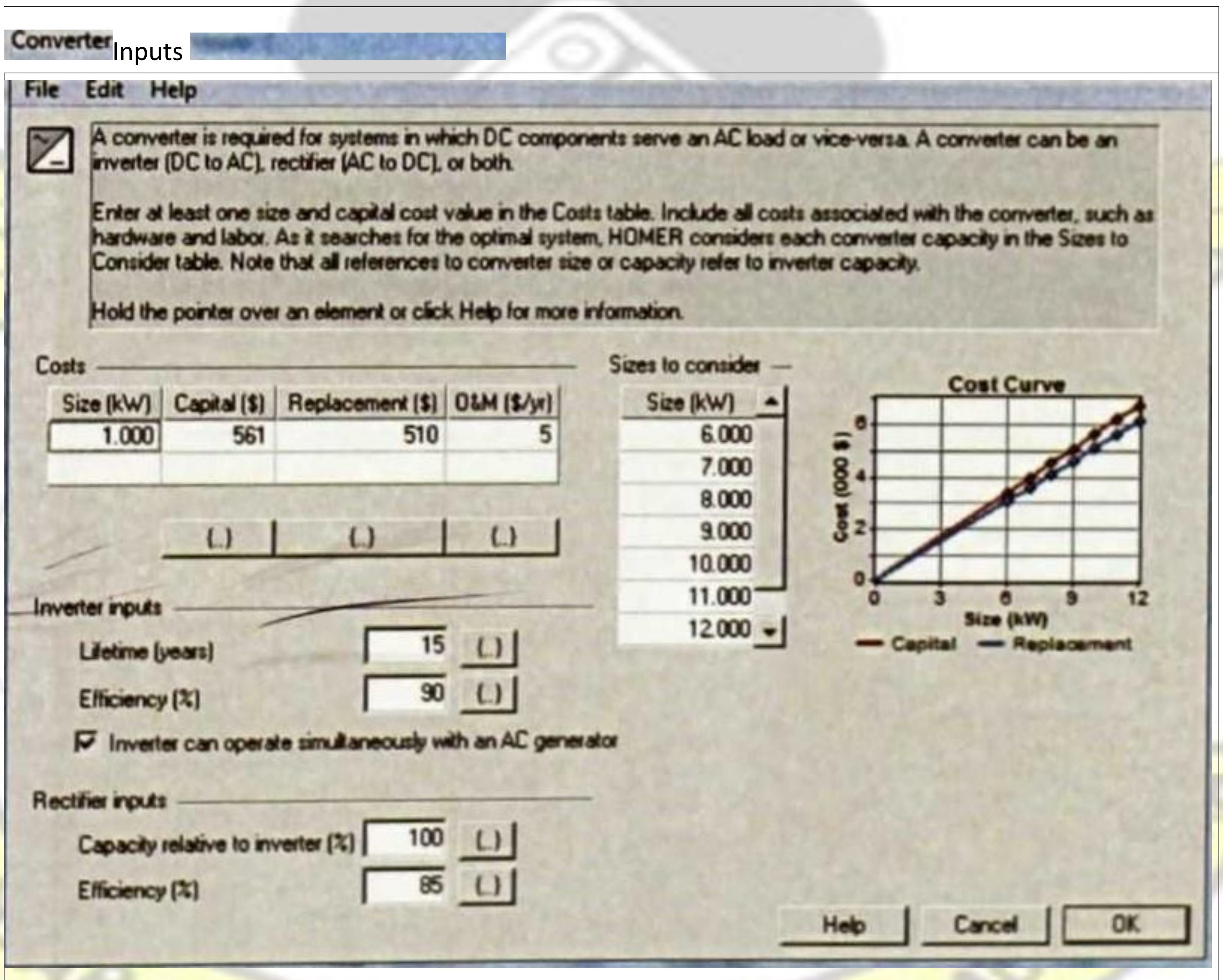


Figure 5.4 : sample of converter input

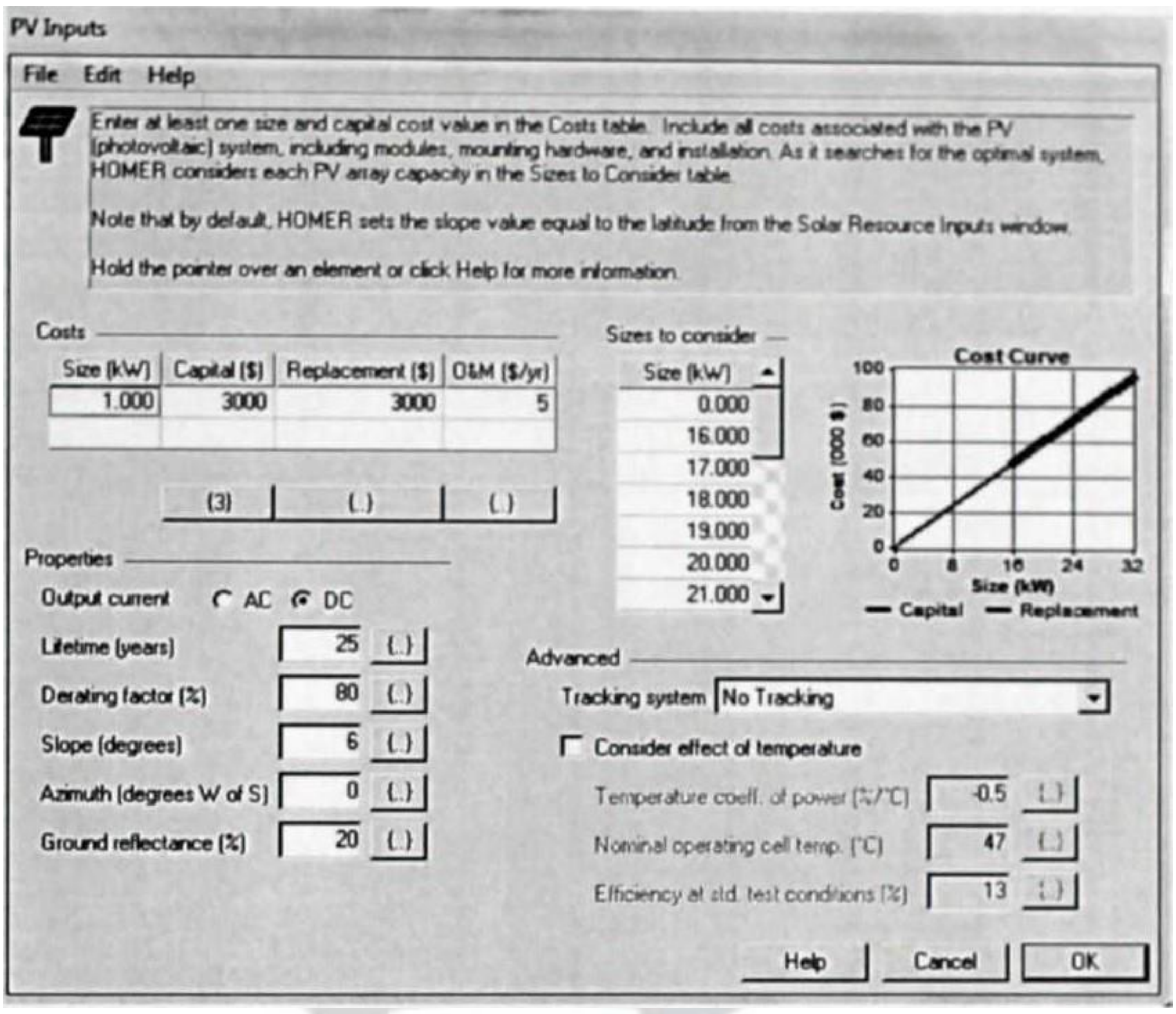


Figure 5.5 Sample of PV input

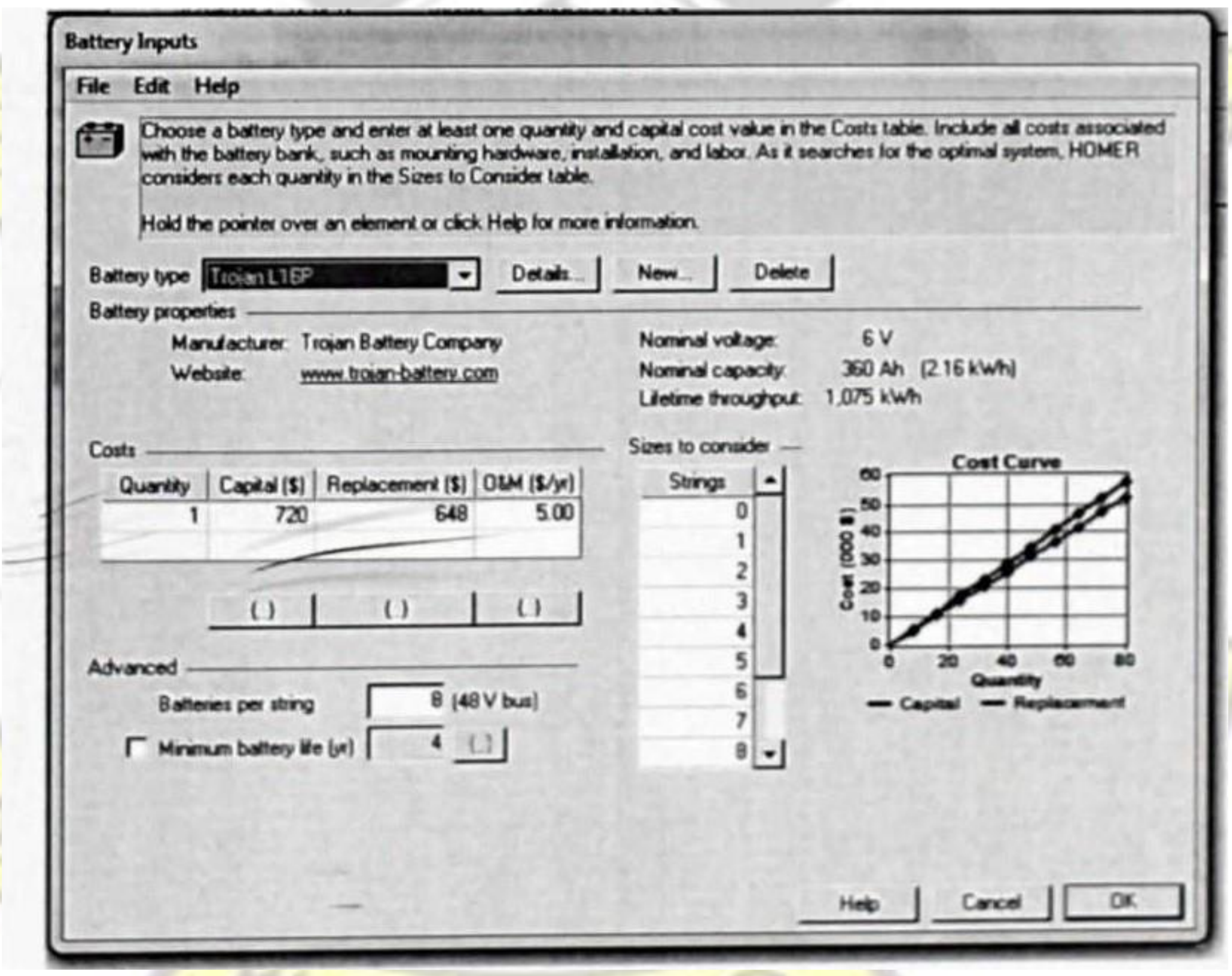


Figure 5.6 Sample of battery input

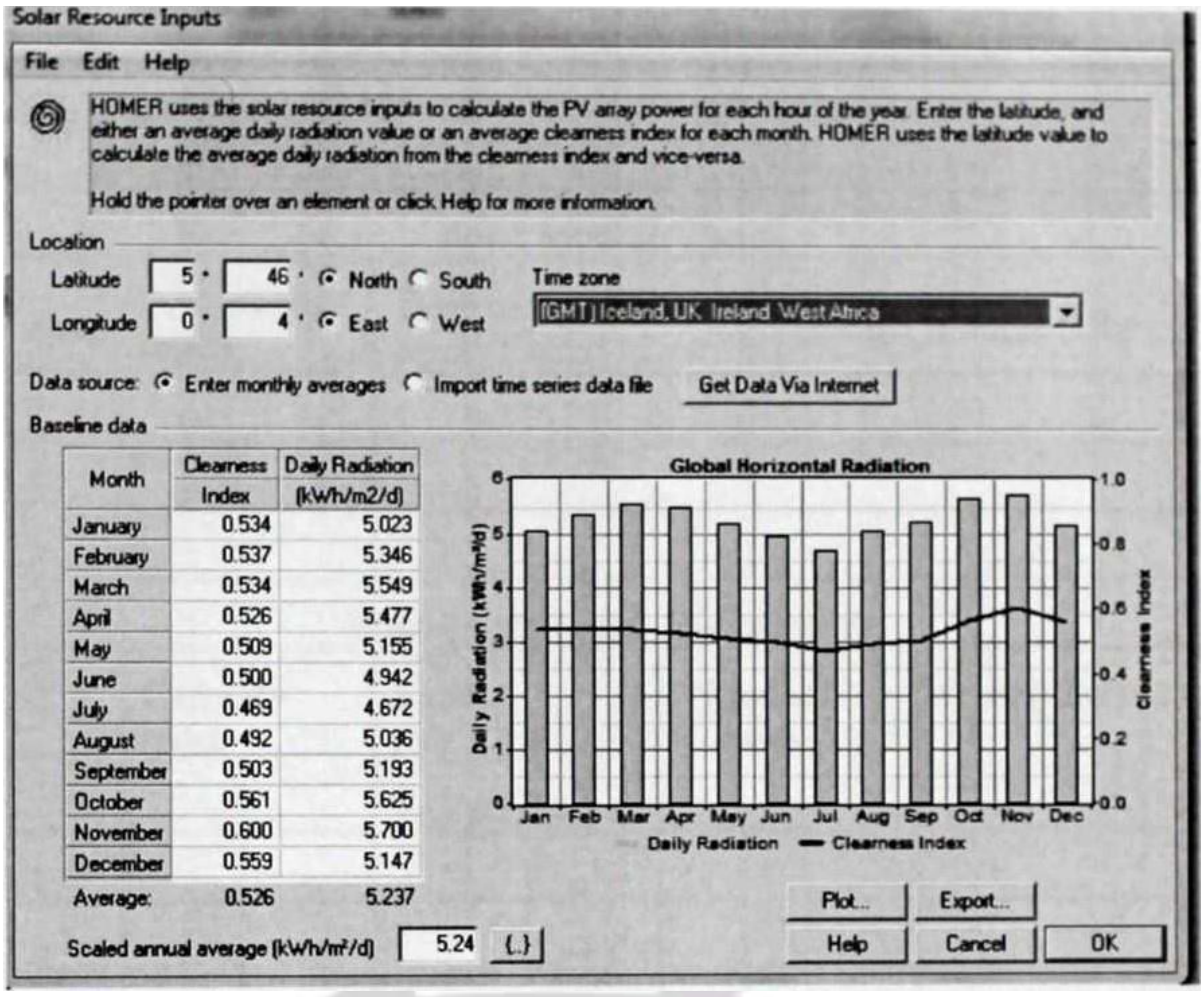


Figure 5.7 Sample of solar resource input

Appendix C: Sample questionnaire for data collection

Solar Module/ Panel			
item	Peak power watt	Type (mono/poly talline	Price per module (Gh<)
1			
2			
3			
Rechar eable lead acid batteries			

	Capacity (Ah)	Type (VRLA/FLA/ AGM/GEL	Nominal voltage	Price (Gh€)
1				
2				
3				
Char e controllers/Re ators				
	Ca aci		volta e	Price Gh
1				
2				
3				
Converter [Inverter				
	Ca aci VA/k		volta e	Price Gh
1				
2				
3				
Installation cost Gh				
Installed capacity(kW)		Cables and material cost		Labour and engineering cost