

**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,
KUMASI, GHANA**

COLLEGE OF ENGINEERING

**COMPARATIVE STUDY OF ELECTRICITY STORAGE
BATTERIES FOR SOLAR PHOTOVOLTAIC HOME SYSTEMS**

**A THESIS PRESENTED TO THE SCHOOL OF GRADUATE STUDIES,
KWAME NKRUMAH UNIVERSITY OF
SCIENCE AND TECHNOLOGY KUMASI, IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE IN MECHANICAL ENGINEERING**

BY

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CERTIFICATION

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

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ABSTRACT

The installed capacity of solar PV systems in Ghana was about 1MWp in the year 2003. This capacity is expected to increase significantly as the Strategic National Energy Plan (SNEP) seeks to enhance the role of stand-alone solar photovoltaic systems for off-grid rural communities that could not be electrified economically through grid extension. For such systems, it is now widely acknowledged that the high replacement cost and environmental impacts of chemical storage batteries constitute the key challenges to deployment and sustainability particularly in poor rural settings. On a life cycle basis, the storage batteries normally contribute about 40-45% of system cost. This thesis undertakes a comparative assessment of the technical, economic and environmental characteristics of the currently available electricity storage batteries that could be utilized in stand-alone solar PV systems. The batteries considered are Lead Acid, Nickel Cadmium, Nickel Metal Hydride and Lithium-Ion. The technical assessment was based on cycle-life, discharge and charging characteristics and charge retention. Life-cycle cost was used as the economic performance indicator, while human safety risks and ecological impacts formed the basis of the environmental assessment. The cost and other data for the batteries were obtained from literature (print and online) and survey of the retail market in Ghana. The life cycle cost of electricity storage based on online retail pricing data and 12% discount rate ranged from an average of US\$0.03 cents for lead acid to US\$0.15 cents /Wh for Lithium-Ion batteries. Price data obtained from local suppliers yielded storage costs of 0.17- 0.42Ghp/Wh for deep-cycle solar batteries and 0.93-1.0Ghp/Wh for shallow-cycle automotive batteries on a life cycle cost basis.

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David Ato Quansah

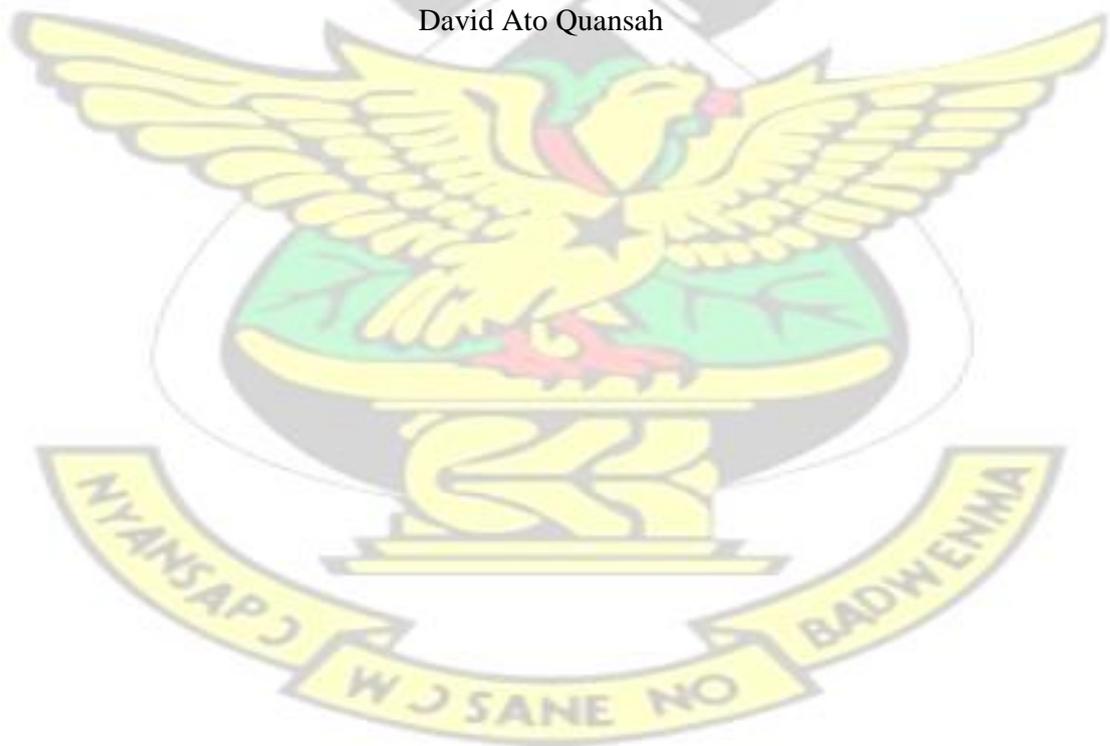


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LIST OF ABBREVIATIONS AND SYMBOLS	

AC	Alternating Current
ALCC	Annualized Life-Cycle Cost
AGM	Absorbed Glass Mat
BCR	Benefit-Cost Ratio
CAES	Compressed Air Energy Storage
DC	Direct Current
DCSB	Deep Cycle Solar Battery

DPP	Discounted Payback Period
E _{max}	Maximum Cell Potential
E _o	Cell Potential measured at Standard Conditions
EUAC	Equivalent Uniform Annual Cost
F	Faraday Constant
ΔG	Gibb's free Energy Change
IACR	International Agency for Cancer Research
IEA	International Energy Agency
IEC	International Electrotechnical Commission
I _{sc}	Short circuit Current
LCC	Life cycle cost
Li-Ion	Lithium Ion
LVD	Low Voltage Disconnect
MCMB	Meso carbon Micro Beads
n	No of electrons n_e
Coulombic efficiency NiCd	
Nickel Cadmium	
NiMH	Nickel Metal Hydride
NOCT	Normal Operating Temperature
NPV	Net Present Value
NTP	National Toxicological Programme (US)
PbA	Lead Acid battery
PV	Photovoltaic

PV/SAPS	Photovoltaic Stand-Alone Power Systems
PW	Present worth q Coulombic
charge Q	Reaction Quotient
R	Universal gas constant
SCAB	Shallow Cycle Automotive Battery
SHE	Standard Hydrogen Electrode
SIR	Savings to Investment Ratio
SOC	State of Charge
STC	Standard Test Conditions
T	Temperature
Voc	Open Circiut Voltage
VRLA	Valve Regulated Lead Acid Battery
W	Work



CHAPTER ONE

INTRODUCTION

1.1 Background

Electricity generation from solar photovoltaic technology globally has increased tremendously over the past 20 years. From an average annual demand of only 21MWp in 1985, it grew to 1460MWp in 2005 and 1744MWp in 2006 [1, 38, 51]¹, with cumulative global deployment estimated at 7.204GWp in the same year. Solar energy utilization in power supply is expected to reach 119TWh in 2030 and over 80% of this is projected to come from photovoltaics, with the rest coming from solar thermal power plants [2]. These are however expected to be grid-connected applications.

Here in Ghana, solar PV capacity in 2003 was estimated at 1MWp [3] and comprised mostly stand-alone systems. With the 2006/07 power crisis, it is expected that many more installations would have been added, especially for private homes that could afford the system. Ghana's target is to generate 10% of its electricity requirements from renewables by the year 2020 and solar PV is expected to contribute a significant fraction [4].

Solar PV will therefore be an integral part of the national electrification programme, especially for remote communities with low population. This would include simple stand-alone home systems that utilize storage batteries to mini-grids and hybrid systems that feed entire communities.

¹ The recently released report in 2008 indicates a 62% (2,826MW) rise in 2007 over 2006.

The stand-alone PV systems, encounter the problem of sustainability on a number of fronts, among which are the initial and replacement cost of the storage batteries [3]. In donor funded projects for which the initial cost is borne by the benefactors, the cost of replacement sometimes results in the abandonment of the PV system altogether. This affects attitudes toward solar PVs in particular and renewable energy technologies in general [6, 7]. The IEA in its Photovoltaic Power Systems (PVPS) programme described the storage battery as the weakest component of the PV systems [8] and World Energy Council in its 2007 Survey of Energy Resources [39] called it a “constraint” to the phenomenal growth in the usage of solar PVs. For offgrid communities, storage systems are needed to provide electricity during the night when the sun does not shine or on cloudy days when the insolation is inadequate to meet the load requirements. This is usually achieved by using diesel generators as back-up to the PV systems or providing storage systems; mainly lead-acid batteries [9, 10, 20]. On a life-cycle basis, the batteries have been estimated at the global level to contribute about 15-23% of the total system cost [1, 3] and in Ghana about 40-45%.

1.2 Objectives of the Study

This work undertakes a techno-economic and environmental assessment of the various batteries commercially available for meeting the storage needs of stand alone solar home

systems. It aims to provide relevant information on the commercially available batteries for use in solar photovoltaic systems on a comparative basis, to assist designers and users of PV systems as well as policy makers in making choices on storage batteries. The overall goal is to reduce the contribution of storage batteries to total system life cycle cost (initial and replacement costs). It will also assist in pointing the direction for indigenous research in solar electricity storage technologies so as to increase the use of solar electricity in off-grid communities.

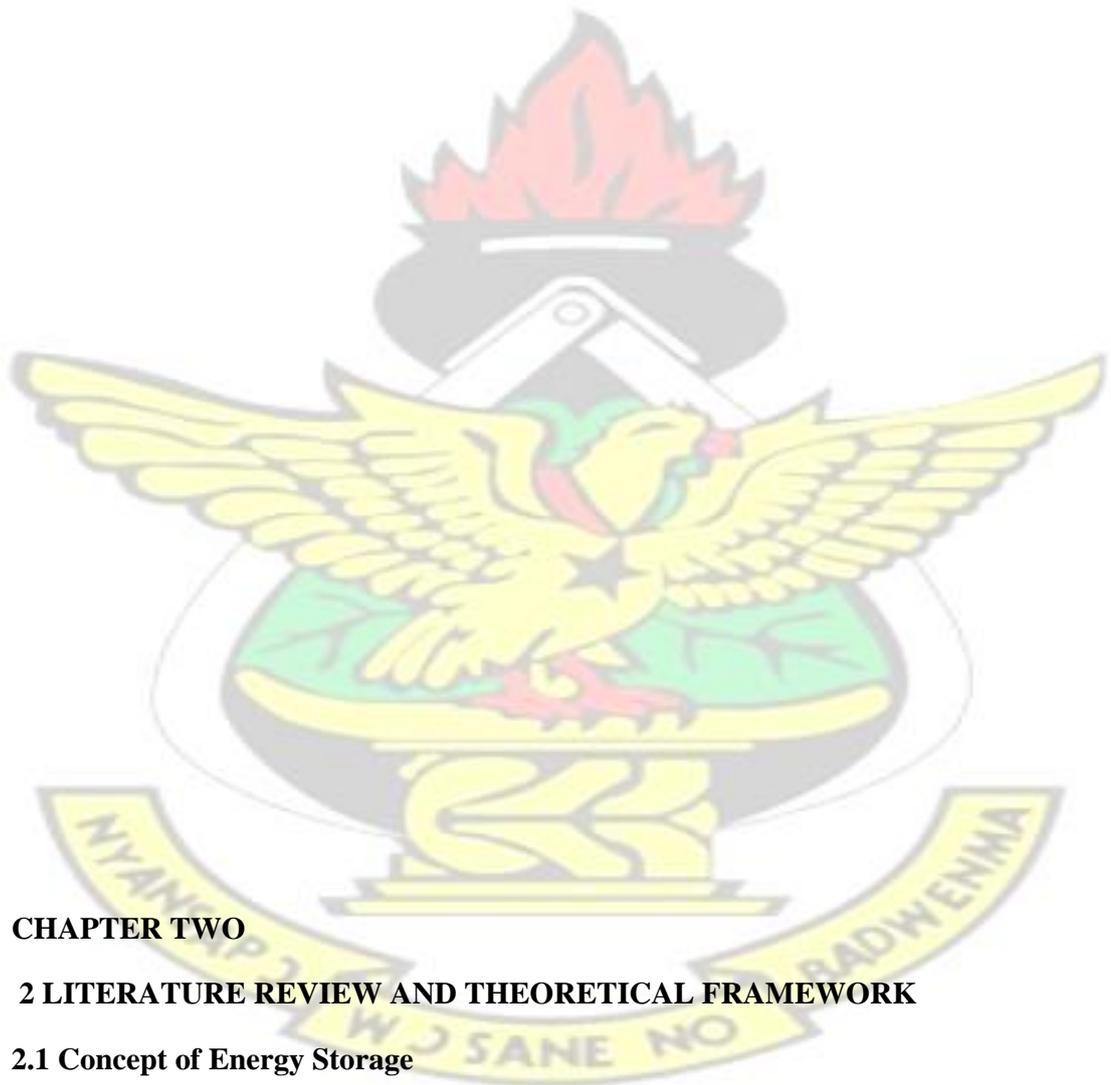
1.3 Methodology

Relevant literature was reviewed to contextualize the problem at the global and national levels and also to clarify theoretical basis of batteries. Information obtained from literature was also used to establish performance and evaluation criteria: technical, economic and environmental. Price survey of local battery retail outlets together with online (internet) information was used to acquire battery price data. Personal communication was also made with local experts in PV system design and installation as part of the survey to acquire information on typical life of batteries. PV system sizing was done with PVSYST 4.1 and data processing and analysis was done in Microsoft excel.

1.4 Structure of the Thesis

This thesis is structured into four chapters. The first chapter presents the background including the problem statement, objectives and methodology. It also provides information on the anticipated role of Solar PV in electricity generation on both the global and national scales, as well as present deployment levels. In Chapter Two the theoretical framework and related literature are presented. It includes configuration of a

typical solar PV system highlighting the role of the storage battery and factors affecting its performance including the basic electrochemistry. It also identifies the performance parameters needed for the technical, economic and environmental assessment of the selected batteries. The data obtained from review of previous works and survey is presented and analyzed in chapter three. The conclusions and recommendations are presented in chapter four.



CHAPTER TWO

2 LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Concept of Energy Storage

Storage is required in stand-alone solar PV systems to guarantee energy supply during times when there is no sunlight or when it is available but not at the required intensity

as on cloudy days. This is so important that even in grid connected applications storage is sometimes provided to improve system reliability.

2.2 Solar Photovoltaic Home System Configuration

A typical solar PV home system has six (6) basic components, as shown in Figure 1 below.

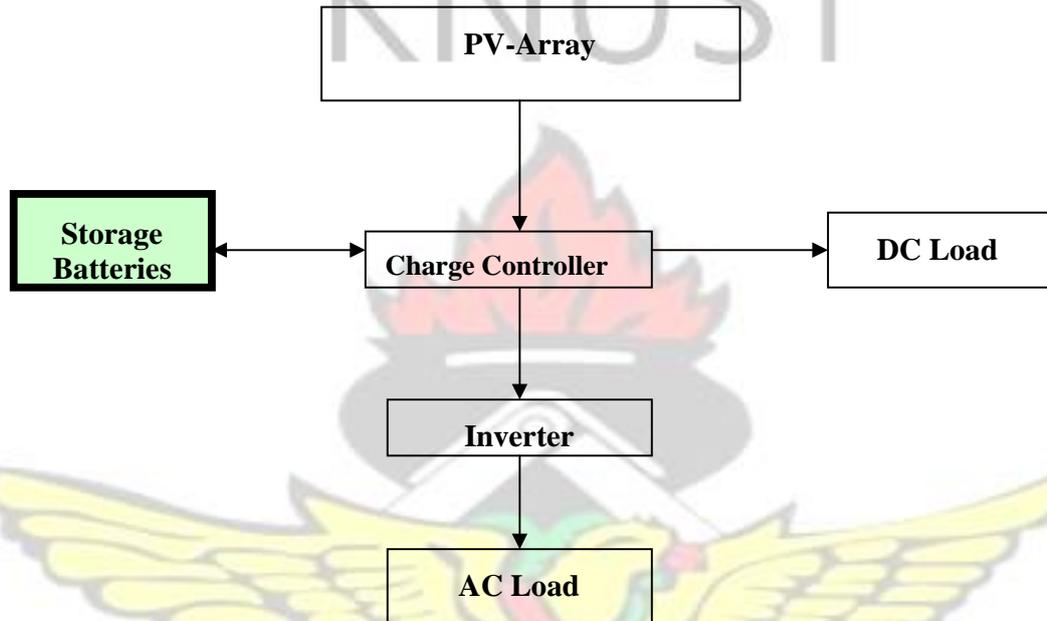


Figure 1: Configuration of a PV system

Adapted from [29]

2.3 System Description

2.3.1 Photovoltaic cells

The basic unit of a solar PV generator is the solar cell. It is made from a semiconductor, mostly silicon (Si) but other materials such as gallium arsenide

(GaAs), copper sulphate (Cu_2SO_4), cadmium telluride (CdTe) and copper Indium Diselenide (CIS) are also used. They have electrical resistivities (ρ) of $10^5 - 10^{-2}$ Wcm

[12]. (after they have been doped by the addition of impurities which alters the electronic configuration. Details of this (PV cells) are described in Appendix E2. To increase the power output the cells are interconnected as shown in Fig 2.

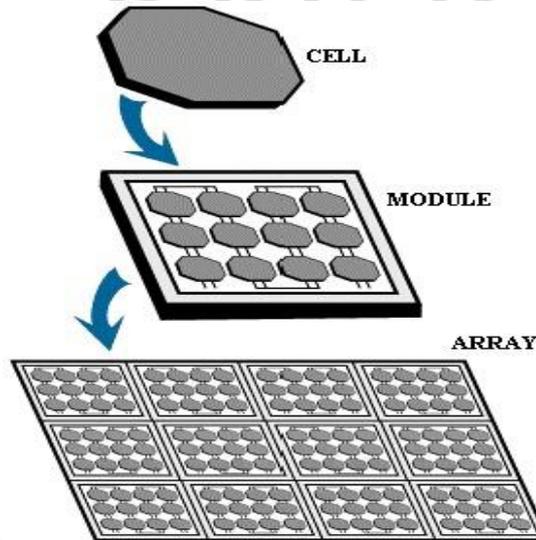


Figure 2 Basic Components of a Solar Panel

2.3.2 Charge Controller

The charge controller usually has the dual function of regulating the current that enters the battery during charging and also protecting the battery from excessive discharge by incorporating a low voltage disconnect (LVD²) feature. Over-charging can lead to gassing, to be discussed later. The controller disconnects the battery from the array when the battery is fully charged and also cuts off the load when the battery is discharged a specified level. The controller is therefore the energy manager in the stand-alone PV system ensuring that the battery is cycled under conditions which do not reduce its ability to deliver its rated capacity over its expected lifetime [47].

² This is a feature that cuts-off the load from the battery to prevent deep discharging.

Controllers have typical efficiencies above 95% [48].

2.3.3 Battery

The role of the battery is to store electricity for later use. It will be treated in much detail later, since it is the main focus of this work.

2.3.4 Inverter

The inverter converts the direct current (DC) from the battery to alternating current (AC) for appropriate loads.

2.3.5 Surge Arresters

Apart from earthing which is the primary protection against lightning, surge arresters such as varistors are incorporated to protect equipment from electrical surges created by lightning. These are employed only in large systems.

2.3.6 Diodes

These are used to prevent backflow of current and also create a bypass for current flow in the event of shading.

2.3.7 Load

This is the technical term that describes appliances and equipment that are powered by the system be they AC or DC equipment. The energy requirement of the load forms the basis for the system design and sizing. Usually a load assessment is carried out first.

2.4 Storage of electricity.

The battery is currently the most mature technology for storage of small quantities of electricity [9]. These electrochemical cells store energy in the bonds of chemical compounds and on demand, convert chemical energy to electrical energy to drive

electrons in an external circuit [11]. There are two types of electrochemical cells based on the thermodynamic nature of the reaction namely:

1. A **voltaic cell** (or **galvanic cell**): This uses a spontaneous reaction ($\Delta G < 0$)³ to generate electrical energy. In the cell reaction, the difference in chemical energy between higher energy reactants and lower energy products is converted into electrical energy as shown in schematically Fig 3, which is used to operate the load i.e the reacting system releases energy that does work on the surroundings. Batteries are classical examples of this type of cell when discharging.

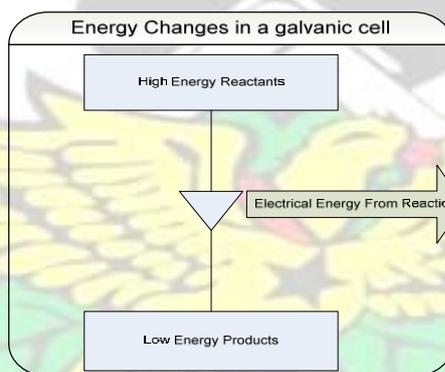


Figure 3 Energy Changes in a Galvanic Cell

2. An **electrolytic cell** is the reverse of a Galvanic cell and it uses electrical energy to drive a non-spontaneous reaction ($\Delta G > 0$). In the cell reaction, electrical energy from an external power supply converts lower energy reactants into higher energy products. From Fig 4 below it is seen that the environment does work on the reacting system. Metal plating and recovery of metals from ores involve electrolytic cells.

³ ΔG is the change in Gibb's free energy between the products and the reactants.

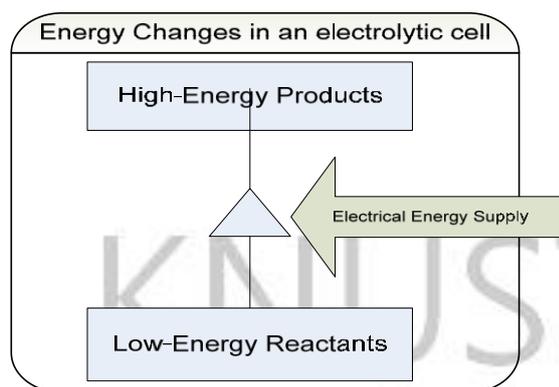


Figure 4 Energy Changes in an Electrolytic Cell

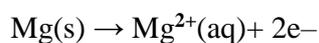
Batteries are galvanic cells connected in series to give the required voltage [11].

In practice a battery is always designed and manufactured for a particular duty; to power a hearing device, a torch, start a car engine or to supply emergency power to a hospital or computer [12]; they are varied in design and chemistry. This thesis will however not deal with primary batteries in which the reaction which produces the electricity proceeds irreversibly in one direction and are discarded after the reactants are consumed in the discharge reaction. The focus shall be on secondary/rechargeable batteries in which the reactions are reversible so that reactants can be restored to their initial state by supplying the products with electricity.

2.5 Basic Electrochemistry of Batteries

2.5.1 Inside the half-cell- Basics

Generally when metals react with non-metals they give away electrons to form positive ions. Suppose a piece of Magnesium metal is immersed in pure water; some magnesium atoms go into solution to form hydrated $Mg^{2+}(aq)$ ions, leaving their electrons behind in the metal:



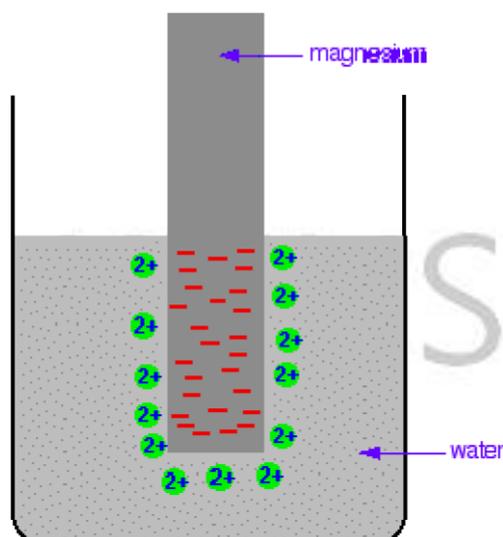


Figure 5: Magnesium ions and Electrons

As this process goes on, the electrons which remain in the magnesium cause a negative charge to build up within the metal surrounded by a buildup of a positive charge layer in the liquid phase [15, 88]. The positive charge layer will tend to stay close because they are attracted to the negative charge on the metal. Some of them will be attracted enough that they will reclaim their electrons and stick back on to the piece of metal. A dynamic equilibrium is established when the rate at which ions leave the surface is exactly equal to the rate at which they recombine with electrons in the magnesium. At that point there will be a constant negative charge on the magnesium and a constant number of magnesium ions present in the solution around it as depicted in Fig 5. If a copper metal were used in the process just described, it will also result in a similar layer of negative and positive charges formed, though its charge build-up would be less than what happens in magnesium since copper is less reactive, as shown in Fig 6 .



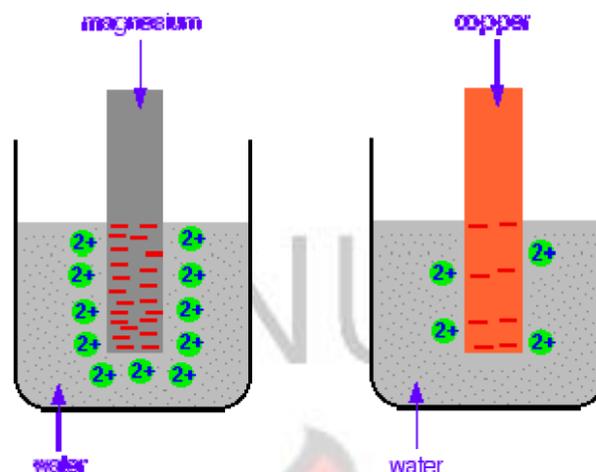


Figure 6 Comparing Copper and Magnesium

If the electrodes in these two half-cells are connected with a wire and the circuit is completed by providing a path for the conduction of ions (positive charges), electrons will flow from the magnesium half-cell (which has a higher concentration of electrons) to the copper half-cell. In Fig 6, the Mg and Cu are called electrodes and they are the solid materials within which the electrons build up.

2.5.2 Description of a Galvanic cell

All galvanic cells regardless of chemistry have certain design features in common:

Anode or negative electrode: This is the electrode at which oxidation occurs during the discharge of the cell releasing electrons in the process. This takes place in the halfcell with a greater build-up (concentration) of electrons.

Cathode or positive electrode: This is the electrode at which reduction occurs in the discharge process. It is the destination for migrating electrons.

Electrolyte: This is an ionically conducting but electronically insulating medium between the two electrodes inside the cell. This medium separates the ionic current from

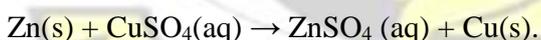
the electronic current. It should be a non-conductor of electrons in order to avoid self-discharge of the cell (ie the electrons going into the electrolyte).

Separator: This electrically and physically isolates the positive and negative electrodes. In the Daniel cell it is the Salt Bridge.

In Fig. 7, when the two half cells are connected, the chemical processes occur simultaneously; the anodic process releasing electrons which are at the same time absorbed by the cathodic reaction to form one complete chemical process which can be summarized as:

$$\text{Mg(s)} + \text{Cu}^{2+} \rightarrow \text{Mg}^{2+}(\text{aq}) + \text{Cu(s)}$$

In the anodic process, the oxidation state⁴ of Magnesium increases from 0 to +2 and hence is referred to as oxidation while in the cathodic process the oxidation state of the copper ion reduces from +2 to 0 and is therefore called a reduction process. Reduction and oxidation processes occur simultaneously in chemical processes and these are referred to as redox reactions. The example below shows the processes that take place in the Daniel Cell which has a zinc anode and a copper cathode. The reaction below is harnessed to create an electric current.



In the example above, Cu^{2+} in $\text{CuSO}_4(\text{aq})$ is reduced to Cu(s) by accepting the two electrons that are donated by Zn(s) which is also transformed to Zn^{2+} in $\text{Zn SO}_4(\text{aq})$. However the electrons are transferred when the reactants collide and no useful work is obtained. To tap the energy available, the two processes- of electron loss(oxidation) and

⁴ Oxidation state is a number assigned to chemical species reflecting the configuration of electrons in their valence shells and also depends on the compounds in which they appear. It changes in reactions depending on the loss or gain of electrons.

electron gain(reduction) must be separated and this is the essential idea behind a galvanic cell, so that the electrons are transferred through an external electrical conductor [13, 14] as shown in the Daniel cell below, Fig 7.

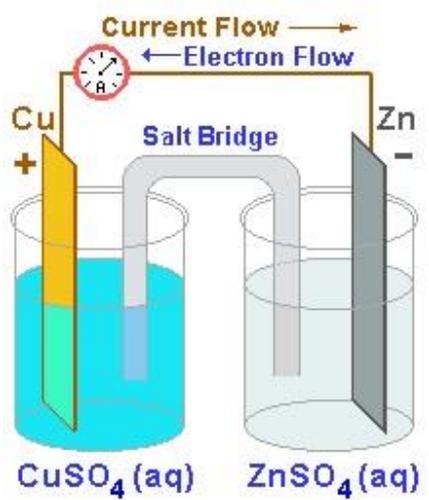


Figure 7 Schematics of a Daniel Cell

2.5.3 Electrode potential and EMF

In an electrochemical cell, electrons build up on the electrodes and the concentration on the electrode determines its electrode potential. When the two half-cells are connected, electrons flow to the electrode with a lower potential. When a highresistance voltmeter is connected across the two electrodes it reads the electromotive force which is the difference between the electrode potentials at the anode and the cathode. The absolute value of the electrode potentials is difficult to determine; it is therefore standard practice to assign a value of 0.00V as the potential of the standard hydrogen electrode (SHE) at $[H^+]=1M$, 1atm and 298K. The potential of all other half-cells are determined relative to this standard. Figure 8 shows a schematic of the standard hydrogen electrode.

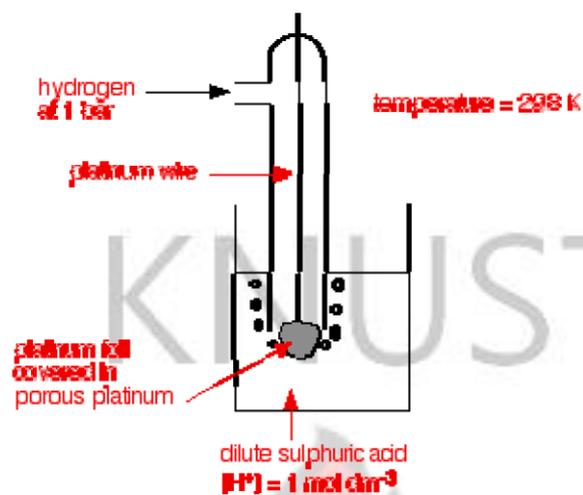
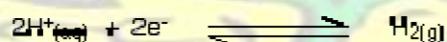


Figure 8: The Standard Hydrogen Electrode Source [89]

As the hydrogen gas flows over the porous platinum, an equilibrium is set up between hydrogen molecules and hydrogen ions in solution. The reaction is catalyzed by the



platinum.

The hydrogen pressure is 1 bar (100 kPa), temperature of 25°C (298K) and a hydrogen ion concentration $[\text{H}^+]=1\text{M}$. This is the reference electrode against which the performances of all others are measured.

2.5.4 Representation of Cell Potentials –Conventions

Half-cell potentials are usually presented as reduction potentials in the form:



The more negative the reduction potential, the more potent the metal is as a reducing agent⁵.



E° indicates standard electrode potential i.e. measurements taken at 298K, 1atm and 1M electrolyte concentration. Lithium as shown above has an electrode potential of -3.04V. Since it is negative it implies that against the SHE, the reverse process is spontaneous ie, donation of e^{-} by Li to become Li^{+} . Larger values of E° indicate higher buildup of electrons on the anode and more potential work through the flow of these electrons in an external conductor. A table of standard reduction potentials is presented in Appendix A and its relationship with the energy output of the cell is explored in Appendix B.

2.5.5 From Electrochemistry to Engineering

From the electrochemistry presented, it can be seen that theoretically what is needed is a difference in potentials for any given pair of electrodes to work in a cell. However in practical design work a number of factors will have to be considered [18,19]. These include:

- Availability and cost of raw materials
- Stability/safety of the reaction mix
- Reversibility of the electrochemical reaction

(This includes the ability of the electrode materials to return to their initial physical states)

⁵ A reducing agent is a chemical species that causes others to be reduced in oxidation state while it is itself oxidized(increasing in oxidation state).

- Conductivity of the components (electrodes, electrolytes etc)
- Operating temperature and pressure
- Manufacturability of components
- Environmental impacts
- Efficiency of cell

The limitations imposed by the factors enumerated above have permitted only certain electrode pairs to be developed into practical and commercially available cells. Even so, research has been on going to improve their performance in terms of the criteria outlined above. Non-metallic electrodes like lead oxide have also been developed with good conductivity and chemical stability at affordable costs. In selecting electrolytes, the same factors as for electrodes, still hold. Issues like electrolyte resistance and its effect on the rate of diffusion as well as viscosity are to be considered as well [12]. The rate of the reactions occurring at the electrodes is also required to be fast at normal environmental conditions. It is also a requirement that the electrolyte should conduct only ions and not electrons.

2.6 Battery Technologies

In this section a number of commercially available chemical storage technologies will be discussed.

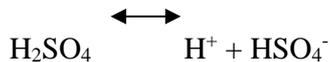
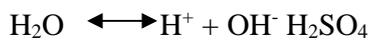
2.6.1 The Lead-Acid Battery

Lead acid batteries were invented in 1859 by Gaston Planté and first demonstrated to the French Academy of Sciences in 1860. About a century and half after its invention it remains a dominant market product and though regarded as a mature technology, it still has extensive research work being undertaken on it to improve performance and reduce size as well as cost. Though the basic chemistry remains the same there has been a

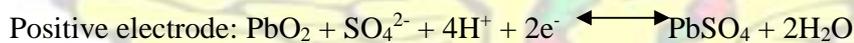
number of variations that have been engineered to meet specific needs and solve identified problems. The electro-active⁶ materials in lead acid batteries are:

- □ Lead oxide (PbO₂) positive plate (cathode)
- □ Pure spongy lead (Pb) negative plate (anode)
- □ Dilute sulphuric acid (H₂SO₄) electrolyte [21]

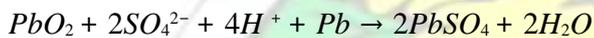
In the electrolyte (aqueous solution of sulphuric acid) of a lead–acid battery, three reactions are at work:



At the (lead and lead oxide) electrodes, the reactions are:



The overall reaction is Change in Gibb's free energy ΔG



Change in Gibb's free energy ΔG :

$$\Delta G = \sum \Delta G(\text{Products}) - \sum \Delta G(\text{Reactants})$$

$$\Delta G = [2\Delta G(\text{PbSO}_{4(s)}) + 2\Delta G(\text{H}_2\text{O})] - [\Delta G(\text{PbO}_2) + 2\Delta G(\text{SO}_4^{2-}) + \Delta G(\text{Pb}) + 4\Delta G(\text{H}^+)]$$

$$= [2 \times -811.1 + 2 \times -237.14] - [-219 - 2 \times 742 - 0 - 0]$$

$$= -394 \text{ kJ}$$

⁶ The species that directly participate in the chemical reaction that generates electricity.

The Gibbs free energy (at standard conditions) for the overall cell reaction $-394kJ$ and this corresponds to the maximum energy that the reaction will release as shown in Appendix B. Data for the computation of ΔG was obtained from Reid C. E, 1990 [90]. Similarly, for all electrochemical reactions that take place in batteries, the theoretically available energy for electrical work can be determined. Lead (Pb) in the above reaction is oxidized from an oxidation state of 0 to +2 (in $PbSO_4$) at the negative electrode while at the positive electrode, Pb is reduced from an oxidation state of +4 (in PbO_2) to +2 in ($PbSO_4$). The electrolyte reactions involve ionisation of water and either single or double ionisation of sulphuric acid. At both electrodes, lead sulphate is formed, from lead oxide at the positive electrode and from lead itself at the negative electrode [22]. At discharge, lead dioxide in positive plates and spongy lead in negative plates react with sulphuric acid in the electrolyte and gradually transform into lead sulphate, during which the sulphuric acid concentration decreases. Conversely, when the battery is recharged, the positive and negative active materials which had been turned into lead sulphate gradually revert to lead dioxide and spongy lead respectively, releasing the sulphuric acid absorbed in the active materials, during which the sulphuric acid concentration increases [23]. A typical lead acid battery with some details of construction is shown in Fig 9.

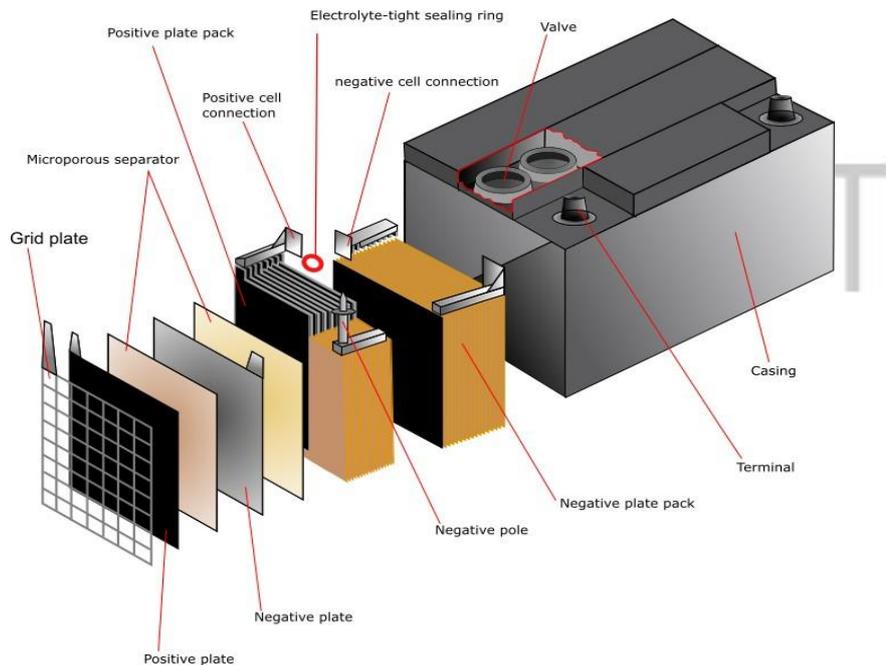


Figure 9 Schematics and Components of a Lead Acid Battery
Source [52]

In practice, the electrodes are alloyed with small amounts of antimony to increase mechanical strength of the soft lead. This however also tends to increase the self-discharge⁷ rate of the batteries. Some batteries use calcium to enhance plate resistance to corrosion and reduce self-discharge.

2.6.2 Classification of Lead Acid Batteries

Lead acid batteries are usually classified in two ways:

First by application (what they are used for) and second by construction (how they are built) [24]. By the first classification, the major types are automotive (also called SLI-starting, lighting ignition), marine, and deep-cycle batteries. The second classification criteria presents; the flooded (wet), gelled and absorbed glass mat (AGM) batteries.

⁷ The self-discharge rate is the rate at which the battery loses stored charge under no-load conditions. ⁸ A large surface area ensures that a lot of the electrode materials are exposed for reaction in order to meet the large currents needed for starting engines.

These (Gel and AGM batteries) may also be referred to as valveregulated in which pressure-release valves seal the cells and loss of water is prevented by internal recombination of hydrogen and oxygen [25].

2.6.2.1 Classification by Application

Automotive batteries

Automotive batteries are used to start and run engines. Engine starting motors need high starting current for a very short time; typically 400-450A for 30sec without the voltage dropping below 7.2V (12V battery systems) [12]. Starting batteries have a large number of thin plates for maximum surface area for the available volume⁸. The plates are composed of a Lead sponge, similar in appearance to a very fine sponge. This gives a very large surface area, but if deep cycled, this sponge will quickly be consumed and fall to the bottom of the cells. Automotive batteries will generally fail after 30-150 cycles if deep cycled, while they may last for thousands of cycles in normal starting use (2-5% discharge).

Deep cycle batteries

These batteries are designed to be discharged down as much as 80% of their capacity time after time, and have much thicker plates. The major difference between a true deep cycle battery and others is that the plates are solid Lead plates - not sponge.

Marine

As the name suggest these are designed for marine application and are usually a "hybrid", falling between the starting and deep-cycle batteries.[25]. In the hybrid, the plates may be composed of Lead sponge, but it is coarser and heavier than that used in starting batteries

2.6.2.2 Classification by Construction

Flooded Lead Acid Batteries

Flooded cells are those where the electrodes/plates are immersed in the electrolyte. Since gases created during charging are vented to the atmosphere, distilled water must be added occasionally to bring the electrolyte back to its required level and concentration. The most familiar example of a flooded lead-acid cell is the 12V automobile battery.

Gelled Lead Acid Batteries

Gelled batteries, or Gel Cells contain acid that has been immobilized by the addition of Silica Gel. The advantage of these batteries is that it is impossible to spill acid even if they are broken and do not need to be kept upright all the time as required in the case of the flooded batteries.

Absorbed Glass Mat (AGM)

This type of sealed battery uses *Absorbed Glass Mats*, between the plates. This is a very fine fiber, Boron-Silicate glass mat. These type of batteries have all the advantages of gelled cells, but can take much more abuse. They are also called *starved electrolyte*, as the mat is about 95% saturated rather than fully soaked. That also means that they will not leak acid even if broken. Nearly all AGM batteries are recombinant in which the oxygen and hydrogen produced during charging recombine to form water.

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Table 1: Comparison of Different Variants of the Lead Acid Battery

Battery Type	Advantages	Disadvantages
Flooded	<ul style="list-style-type: none">Technology is matureHave longest cycle lifeLowest cost per AHTolerant of abuseReady availability of replacements	<ul style="list-style-type: none">Require regular maintenanceStratification of electrolyte is significant

Gel	<p>Easily transported</p> <p>No electrolyte stratification⁸</p> <p>No spillage of electrolyte</p> <p>Good for deep cycle and Low temperature applications</p>	<p>Higher cost per AH</p> <p>Complex charging circuits</p>
AGM	<p>Easily transported</p> <p>Low electrolyte stratification</p> <p>No spillage of electrolyte</p>	<p>Highest cost per AH</p> <p>Complex charging circuits</p>

Source [92, 100, 101]

Figure 10 compares the extent of acid stratification in the flooded, gelled and AGM lead acid batteries. It gives the density of the batteries at the bottom and at the top.

The gap between the density curve at the top and at the bottom indicates the extent of stratification.

⁸ Stratification describes a non-homogeneous distribution of acid concentration within a cell which is caused by insufficient charging and the gravity effect.

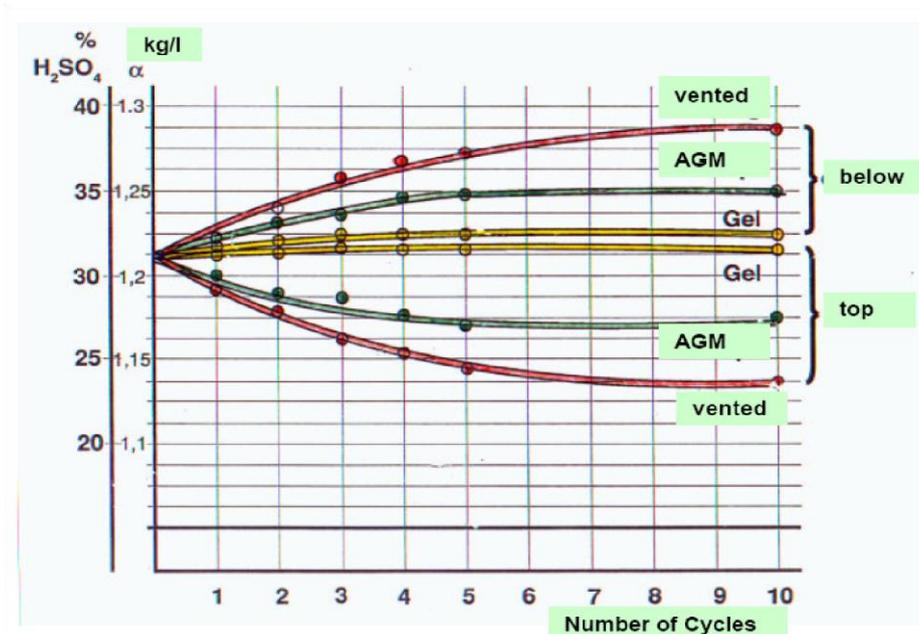
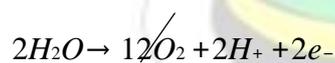


Figure 10: Extent of Stratification in Various Batteries

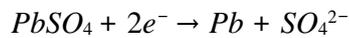
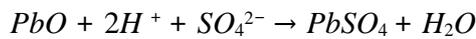
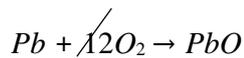
Source [92]

2.6.3 Gassing and Recombination in Lead Acid Batteries

During Charging, electrolysis of water occurs when the batteries are nearing fullcharge. Water is decomposed at the positive electrode and gaseous oxygen is formed as shown in the reaction below; this phenomenon is called gassing.



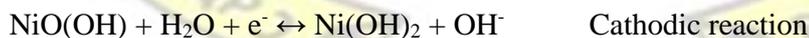
The hydrogen ions however remain dissolved in the electrolyte and are not released as gas. The electrons move toward the anode via the positive electrode. In the vented type of lead acid batteries, the oxygen bubbles up and escapes through the vent. However in the valve regulated lead acid battery (VRLA), a densely porous medium is offered to the oxygen to facilitate its migration to the negative electrode which is typically about 1-2mm away [90]. At the negative electrode the processes below ensure that oxygen is recombined and water is formed.



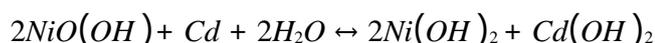
At the negative electrode, lead is oxidized into lead oxide. This lead oxide is further transformed into lead sulphate with participation of hydrogen dissolved in the electrolyte and sulphate ions [90]. Thus the water that was decomposed at the positive electrode is re-converted. The negative electrode is usually oversized and therefore does not get fully charged compared to the positive electrode and therefore the corresponding electrolytic product which will be hydrogen is prevented from forming. In VRLA batteries re-combination efficiencies are around 98% [91].

2.6.4 The Nickel Cadmium Battery

Nickel-cadmium is the most popular alkaline battery and is available in a wide range of sizes. They have very long life and require very little maintenance. Like all rechargeable battery systems they work on the principle that the electrochemical reaction at each electrode is reversible [27]. They use nickel hydroxide $Ni(OH)_2$ for the positive electrode (cathode), cadmium Cd as the negative electrode (anode) and an alkaline, potassium hydroxide KOH as electrolyte [26].



The overall reaction is:



It has a cell voltage of 1.2V [28]. At both the positive and negative plate, the forward reactions indicate the discharge process and the backward, the charging process which restores NiOOH and Cd which possess higher levels of energy.

NiOOH/ Ni(OH)₂. and Cd/ Cd(OH)₂ are viewed as the reversible couples at each electrode, able to transform to each other depending on whether charging or discharging is in effect. Like the traditional lead acid batteries, close to full-charge, gas-generating side reactions start to develop. Oxygen gas starts to evolve from the positive plate through the electrolytic process:



Due to excess capacity (charge-reserve) in the negative electrode as with the lead acid batteries, the electrolytic product of hydrogen is prevented from forming, since it does not reach overcharge. The oxygen will instead migrate to the negative electrode and be absorbed in an oxygen recombination process.

This recombination occurs by the action of two processes:



The first equation represents a direct combination of the oxygen gas with Cd which is present in significant amounts at the anode of a fully charged battery. The second can be seen as a direct reversal of the process that originally generated the oxygen at the cathode. These two reactions that accomplish the oxygen recombination process ensure that the internal pressure is kept at acceptable levels [27].

2.6.5 Nickel Metal Hydride

Patented in 1986 by Stanford Ovshinsky, Nickel-metal-hydride batteries are similar to sealed nickel-cadmium batteries but differ from them in that instead of cadmium,

hydrogen is used as the active element at a hydrogen-absorbing negative electrode (anode). Hydrogen-absorbing alloys have a comparatively short history which dates back about 20 years to the discovery of NiFe, MgNi and LaNi₅ alloys. These are capable of absorbing hydrogen equivalent to about a thousand times their own volumes, generating metal hydrides and also capable of releasing the hydrogen that they absorbed [32]. This electrode is made from a metal hydride usually an alloy of titanium or zirconium (referred to as AB₅ alloys) and rare earth elements such as lanthanum (referred to as AB₂ alloys) that serves as a solid source of reduced hydrogen that can be oxidized to form protons. The electrolyte is alkaline potassium hydroxide. Cell voltage is 1.2 Volts same as NiCd but it outperforms it in many areas including energy density [30] and has about 40% more discharge capacity [31]. The following reactions occur during the charge and discharge operations at the anode:



In the equations above, M represents the hydrogen-storage alloy. MH is formed when hydrogen atoms, from the electrolysis of water, are absorbed by the alloy M. During discharge, the hydrogen atom is released and converted back to water. The positive plate reactions remains the same as that for the NiCd systems [32].

2.6.6 Lithium Ion Batteries

In the search for higher energy density rechargeable cells, employing lithium metal as the active material was always seen as the ultimate goal. Lithium is the lightest metallic element and generates a high voltage relative to the standard hydrogen electrode (-3.045V) [34]. The Li-Ion battery uses aluminum coated with lithium cobalt oxide-

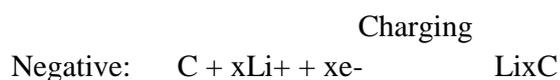
LiCoO₂⁹ (which has very high energy density and stability) as the positive electrode and copper coated with specialty graphite known as Meso carbon Micro Beads (MCMB) as the negative electrode. The electrolyte is an organic solvent optimized for this specialty carbon and is usually lithium-phosphorus hexafluoride, dissolved in an organic solvent such as a mixture of ethylene carbonate and dimethyl carbonate [92-94]. The battery acquired its name from lithium ion because it does not contain any lithium metal. Lithium is added in a way that minimizes disruption of the lattice structure in a process called intercalation [87]. The negative electrode is typically a graphitic carbon. During the charge and discharge processes, lithium ions are inserted or extracted from interstitial space between atomic layers within the active material of the battery as shown in Fig 2.9 [33].

Charge/Discharge Chemical Reaction

In this process, lithium ions are de-intercalated from the positive material and intercalated into the negative material. (Intercalated – a reaction where lithium ions are reversibly removed or inserted into a host without a significant structural change to the host) [33].

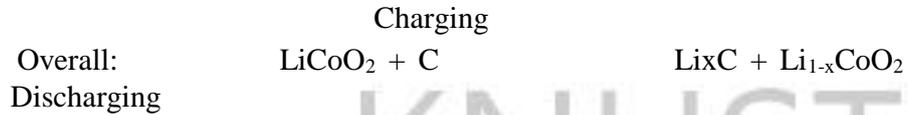


Discharging



⁹ LiMnO₂ has been considered for large operations but has the problem of instability at high operating temperatures. LiNiCoO₂ also known as mixed oxide has been used in some designs.

Discharging



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Figure 11 below shows the operation of a Li-Ion cell.

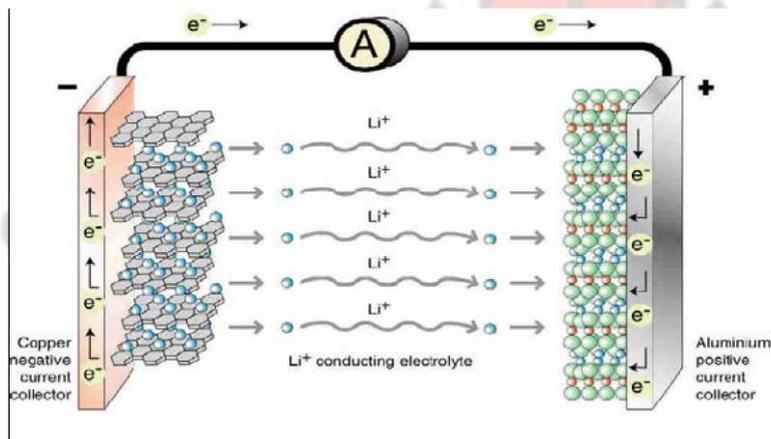


Figure 11: Operation of a Lithium-Ion Battery

Source [34]

2.7 Battery Performance Indicators: Technical, Economic and Environmental

2.7.1 Technical Indicators

A number of performance indicators exist for assessing batteries used in photovoltaic stand-alone power systems (PV/SAPS), they include the following [27, 35]:

- Charging efficiency

- Discharge characteristics
- Storage capacity
- Cycle life

In addition to these parameters, other indicators that are sometimes used include:

- Specific energy, expressed in watt-hours per kilogram (Wh/kg), which measures the quantity of energy stored per unit mass of the battery.
- Energy density expressed in watt-hours per liter of battery volume (Wh/L).
- Specific power density (expressed in W/Kg) which corresponds to the theoretical power delivered per unit mass of battery.

Other desired characteristics in solar electricity storage systems are: a robust design and a wide operating temperature range as well as low maintenance requirements. The last three parameters: specific energy, energy density and specific power will not be regarded as crucial parameters in this thesis because the photovoltaic systems under review are for stationary applications for which weight and size do not make much difference. The technical features of the batteries to be used for this assessment will include: Charging, Discharging, Storage (charge retention) and Cycle-life.

2.7.1.1 Charging Characteristics

This is the process of restoring the charge of the battery after it has been depleted, by connecting an external source of electricity. In our particular case the charging is accomplished by a solar PV module and modulated by the charge controller. For the various battery chemistries a Coulombic efficiency is defined (also known as Faradaic/ amp-hour efficiency or charge acceptance) to be the ratio of amp-hour

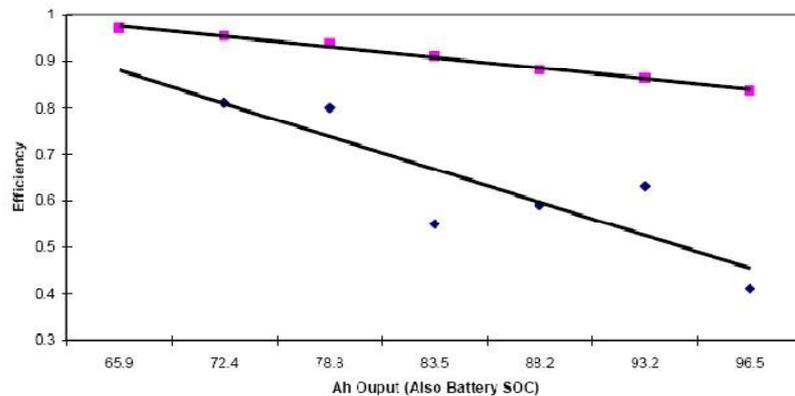


Figure 12: Efficiency of Battery Charging

Adapted from [37] drawn during the discharge half-cycle to the amp-hours required to restore the battery to its original state of charge (SOC) [36].

$$\eta_{coul} = \left| \left| \frac{\text{amp - hours}(discharge)}{\text{amp - hours}(charging)} \right| \right| \times 100\% \dots\dots (1)$$

Also called round-trip efficiency, it depends on a complex array of parameters. Acknowledging the charging process as a chemical reaction taking place in one direction, it depends principally on the quantity of reacting materials (reactants) remaining in the cell [37], the temperature, the charging rate (i.e. current I), the available surface area for reaction. It also depends strongly on the level of parasitic reactions that occur in the battery. Various chargers and charging methods (algorithms) are recommended by manufacturers for specific battery chemistries and models. These could be fast-charging at constant currents, charging at constant voltages, slow-charging, trickle charging and others. From [37] it is seen that the coulombic efficiency

is not constant for the entire charging duration but rather it changes with SOC (see Fig 12) among other parameters listed. The charging

efficiency of the battery therefore is an important parameter to consider when making decisions on appropriate batteries for a given PV/SAPS.

2.7.1.2 Discharge Characteristics

Battery discharge is the controlled release of the energy stored in the battery during charging half-cycle to meet the requirements of the load imposed on it. The amount of charge that can be drawn from the battery over a given period of time is expressed by the battery capacity which is measured in amp-hours (Ah). In accordance with IEC¹⁰ recommendations (CEI/IEC 60896-11: 2002) the battery capacity is usually given for a reference temperature of either 20 degC or 25degC [57]. Therefore a battery rated 100amp-hours will be expected to supply a current of 5amperes for 20hours. However due to the non-linearity of the reaction kinetics, the same battery when discharged at 20amperes will not yield 5hours but lower, hence the capacity of a battery is always given with reference to a specific discharge time frame, such as 20hours, 100hours etc. The IEC requires discharge capacity tests to be conducted at 10h, 8h, 3h, 1h and 0.25h rates [102]. The discharge current is usually expressed in terms of the battery capacity C; for a 100Ah battery a discharge rate of 1C implies 1x100Amps of current similarly 0.2C implies 0.2x100= 50Amps etc. The relation between the

¹⁰ IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees.

available battery capacity C (amp-hours), the battery run time T (hours), and the discharge current I (amps), is given by the Peukert's Equation:

$$\dots\dots\dots (2)$$

Where n is called the Peukert number which ranges from 1.1 to 1.3, and R is the hour-rate of the battery usually 20hrs for most batteries. Among all battery chemistries, it is more efficient to discharge at lower currents as shown by Figures 13 and 14, regarding the battery's capacity at various discharge rates.

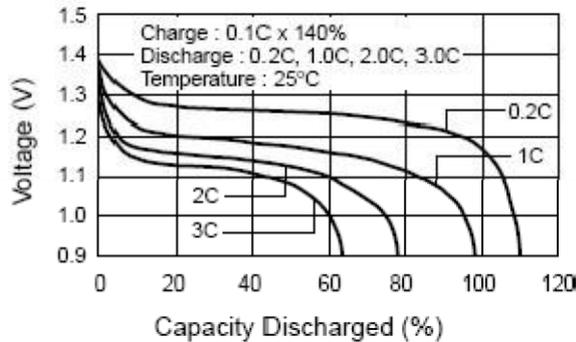


Figure 13: Discharge Characteristics of a Nickel-Cadmium Battery
Effect of discharge current on battery capacity Credit:
GP Batteries International [27]

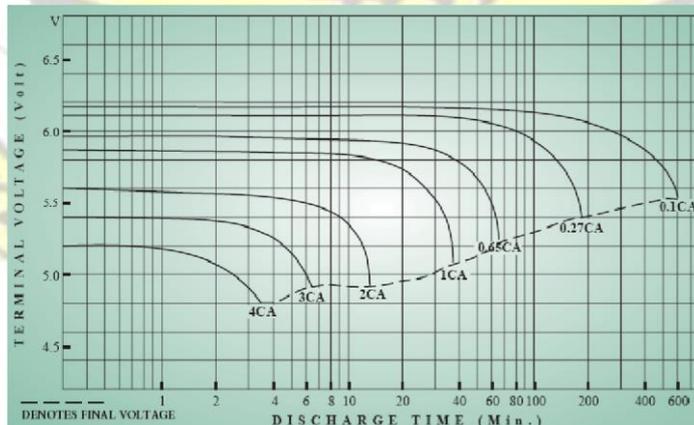


Figure 14: Discharge Characteristics of a 6V Lead-Acid Battery
Effect of discharge current on battery capacity Source [23]

During discharge the cell voltage gradually decreases as a result of increasing internal resistance within the battery. The variation of the voltage with depth of discharge is shown in Fig 15

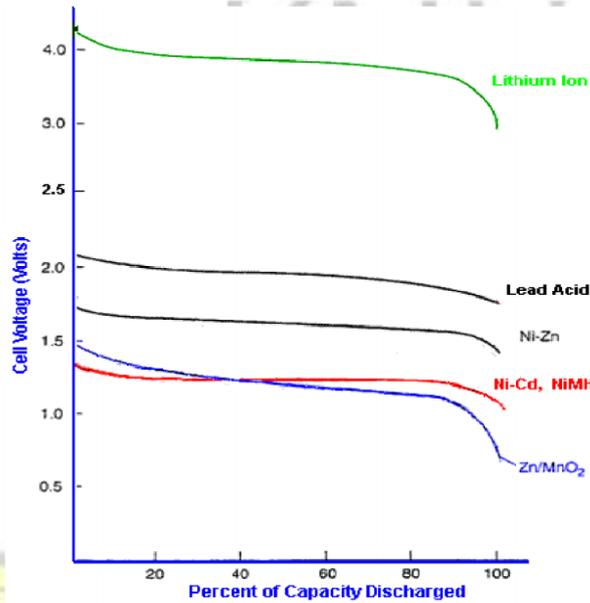


Figure 15: Variation of Cell Voltage with Depth of Discharge [Mpower solutions UK]

The graph in Fig 15 shows typical discharge curves for various cell chemistries discharged at 0.2C rate (and 20degC) with each cell having its own characteristic nominal voltage and discharge slope. Some chemistries such as Lithium Ion have a fairly flat discharge curve while others such as Lead acid have more pronounced slopes. Flat discharge curves are usually desirable since they can supply a fairly constant voltage throughout the discharge half-cycle [52]. On the other hand a curve with a pronounced slope facilitates the estimation of the State of Charge (SOC) of the battery since the cell voltage can be used as a measure of the remaining charge in the cell, though this (the voltage) is very dependent on the discharge current and the internal impedance of the cell. The cell voltage at any instant during operation is also a function of the operating

temperature and the age of the cell. A typical voltage variation chart for various discharge temperatures is shown in Fig. 16.

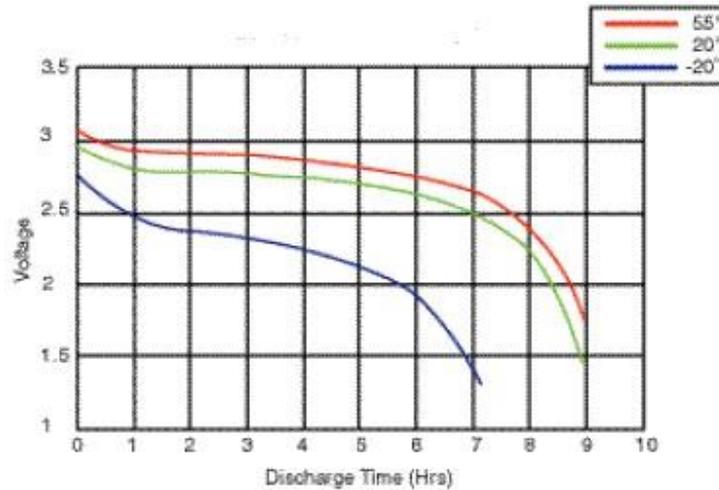


Figure 16: Discharge Characteristics at Different Temperatures
Source: Mpower solutions Ltd

PV charge controllers are usually equipped with a low voltage disconnect (LVD) feature which utilizes the concept of Voltage-SOC relation to protect batteries from being discharged too deeply. This generally affects the battery service life. The power delivered by cells with steep-sloping discharge curve falls quite rapidly during discharge. And this could pose problems for high power applications towards the end of the discharge half-cycle if the system is not carefully designed. As can be seen from Figures 17 and 18, battery performance is strongly influenced by temperature. At very low temperatures the electrolyte freezes and ionic mobility within the electrolyte is severely hampered raising the cells internal resistance and drastically affecting its performance or even causing it to fail. At the other extreme where the battery operates at elevated temperatures the electro-active species become unstable and there could be enough energy to activate secondary and parasitic reactions such as the electrolysis of water. Increasing temperatures reduce gassing voltage; between these two extremes

battery capacity generally improves with increasing temperature, but this happens at the expense of battery life. As shown in Figures 17 and 18, an optimum operating range (usually at ambient temperatures of 20-30degC) for the batteries could be obtained from the manufacturer's data. Variation of battery capacity with discharge rate and time.

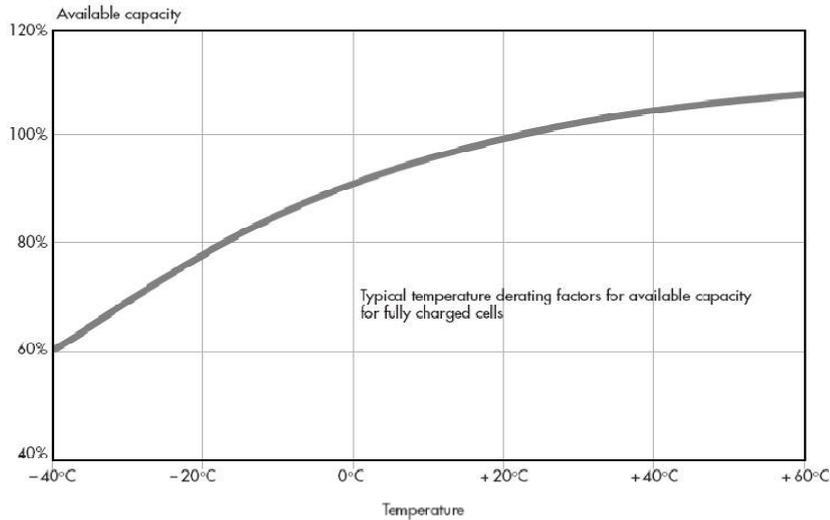


Figure 17: Typical Capacity Variation of a NiCd Battery With Temperature Source [54]

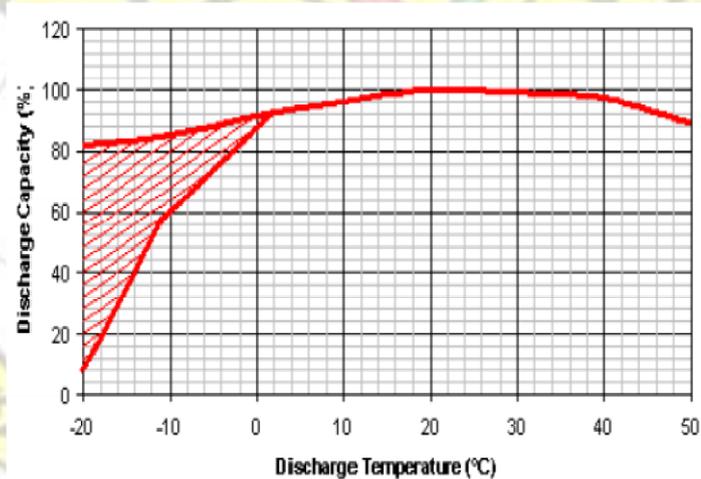


Figure 18: Typical Capacity Variation of a NiMH Battery with Temperature Source: [33]

When batteries are used at elevated temperatures their service life is drastically shortened as shown in Fig 19 below.

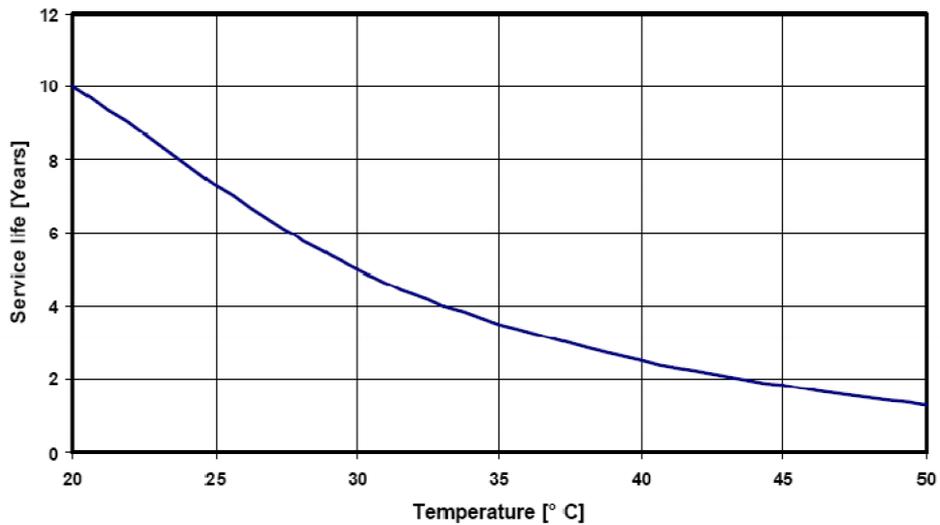


Figure 19: Battery Operating Temperature and its Effect on Service Life for a Gel VRLA Battery
 Credit: Exide Technologies [56]

The only exception to the high temperature deterioration is the high-temperature thermal batteries in which an electrolyte which is solid and inactive at normal ambient temperatures becomes active at high temperatures by the application of heat from an external source to activate and turn it into an electrolyte. These batteries are usually for military applications in ballistic missiles and other weapon systems [55]. Since the environmental (ambient temperature) circumstances in which the batteries will operate may be different from that at which the battery testing and rating has been done, a temperature-correction co-efficient could be applied to reflect the change in battery capacity with temperature variation [53]. Fig 17 shows the variation of battery capacity with temperature for a typical Nickel-Cadmium battery.

2.7.1.3 Storage (Charge retention)

Recalling that the role of the battery within the PV/SAPS is to be a store-house for electric energy, it is important that the battery should be able to retain the electrical energy stored within it for a considerable length of time. Batteries are however known

to exhibit capacity loss while in storage under no-load condition. This self-discharge occurs as a result of small amounts of impurities that are present in the cells; these (the impurities) are sometimes deliberately introduced to enhance some other properties such as mechanical strength and corrosion resistance. The lead acid battery for instance is sometimes alloyed with antimony to enhance its mechanical strength for deep-discharge applications, but this raises the self-discharge rate from about 15% to 2-10% per month under standard storage conditions of 20degC [26, 55]. The self-discharge rate is also enhanced by temperature increases; Fig 20 shows the variation of self-discharge with temperature for a lead-acid battery.

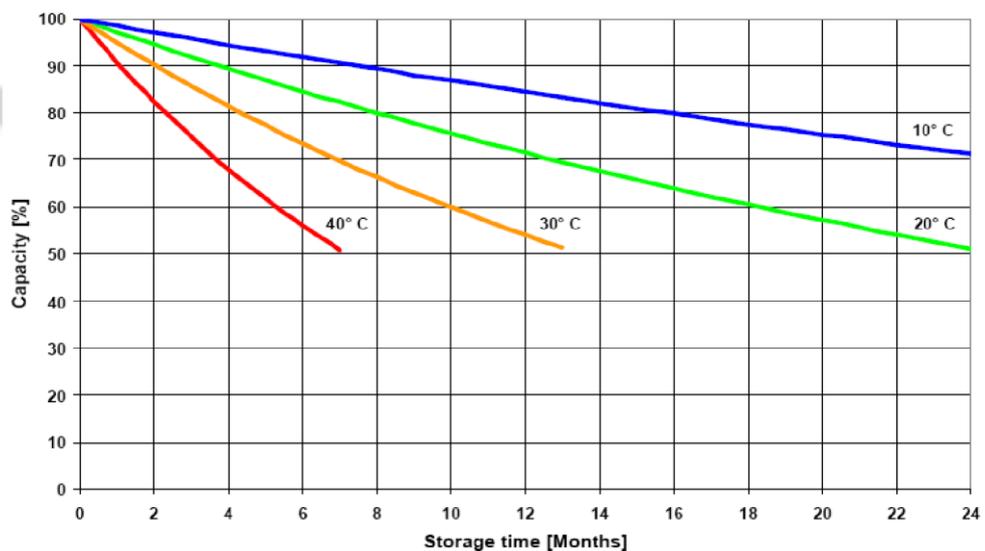


Figure 20: Remaining Battery Capacity Vs. Storage Time at Various Temperatures
Source [56]

2.7.1.4 Cycle Life

Cycle life is the number of charges and discharges that a battery can achieve before the discharge capacity drops to 80% of the nominal capacity at the 3h rate [8, 102].

The cycle life of a battery is intimately connected with:

- Depth of discharge
- The operating ambient temperature
- Discharge rate. [27, 58, 60]

Figure 21 presents the dependence of the cycle life on these factors enumerated.

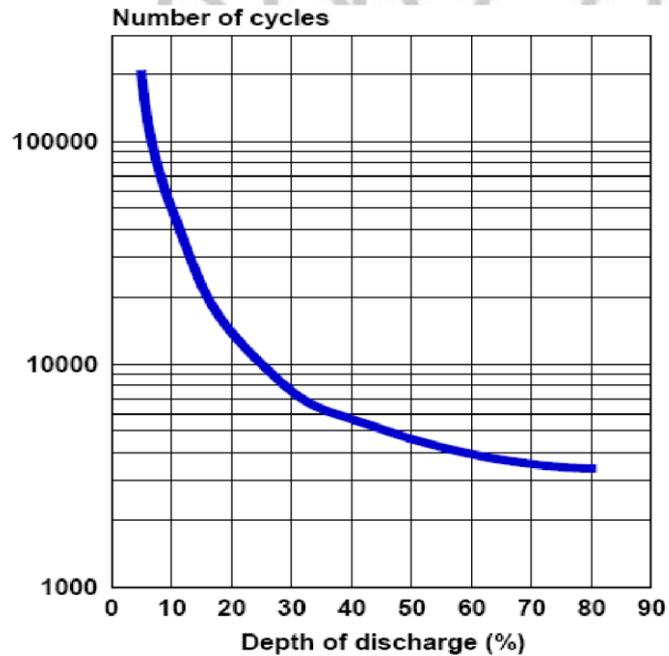


Figure 21: Variation of Cycle Life with Depth of Discharge for a NiCd Battery Source [59]

2.7.2 Economic Assessment

This section of the thesis presents the tools for economic assessment of the electricity storage technologies under review.

2.7.2.1 Life Cycle Cost

Project assessment tasks are usually carried out on the basis of the time value of money.

Some of the most frequently used terms are; present value, future value, discount rate.

An amount P invested at a compound interest rate of r% per annum will yield future value F at the end of year n; the amounts P and F are related by

$$F = P(1+r)^n \dots\dots\dots (3)$$

F, the amount of money at the end of the interest period is called the Future Value of P. On the other hand, if a future payment or income F is known its value in the present, using the equation above is P. P is thus the Present Value of the future payment/income F. In determining the present value of a future investment, the factor r in the equation is usually called the Discount Rate [64]. The discount rate could be nominal in which case it factors in the rate of inflation during the analysis period or real where the rate of inflation is excluded. This is not to say that real discount rates ignore inflation, their use simply eliminates the complexity of accounting for inflation within the present value equation. In this thesis the real discount rate will be used. In dealing with economic assessment of investment alternatives, a number of criteria can be employed to obtain figures of merit, based on which decisions can be made. A number of approaches exist for meeting this task: The Net Present Worth (NPW), Savings/investment ratio, Discounted Payback Period, Equivalent uniform annual cost (EUAC), Benefit/cost ratio (BCR) etc.

This thesis will use the NPW approach to compare the life cycle cost of Nickel Cadmium, Nickel Metal Hydride, Lead Acid and Lithium-Ion batteries, followed by a special focus on lead acid batteries which remain the dominant technology in Ghana and indeed the world over for electricity storage in stand-alone solar photovoltaic applications [9, 10, 20]. The comparative costs of its many variants such as the flooded, the gelled, the AGM as well as the deep cycled or so-called solar batteries shall be

analyzed using market prices from retail outlets, assumed depths of discharge (DOD) and the typical cycle-life information to calculate the number of replacements that have to be made over the life of the system. The present worth of the cost of replacements over the life of the system shall be determined from equation 4

$$NPV = C_0 + C_0 \sum_{n=1}^{11} \frac{1}{(1+r)^n} \dots\dots\dots(4)$$

Where:

PW is the present worth of all cash outflows (expenditure on batteries at the end of the designated years)

Co is the Cost of the battery at the start of the project life

n is the year of battery replacement **r** is the real discount rate

The data will also be used to determine the cost per amp-hour of electricity stored as well as the watt-hour equivalent assuming a system voltage of 12V.

2.7.3 Environmental Assessment

The environmental impact of batteries include the processes involved in the extraction and processing of the relevant materials, production and assembly of components, the service life impacts and recycling or disposal/incineration [70-72] as shown schematically in Fig 22

¹¹ Cash inflow which could come from electricity sales and other benefits associated with the use of renewable energy are not considered in this equation.

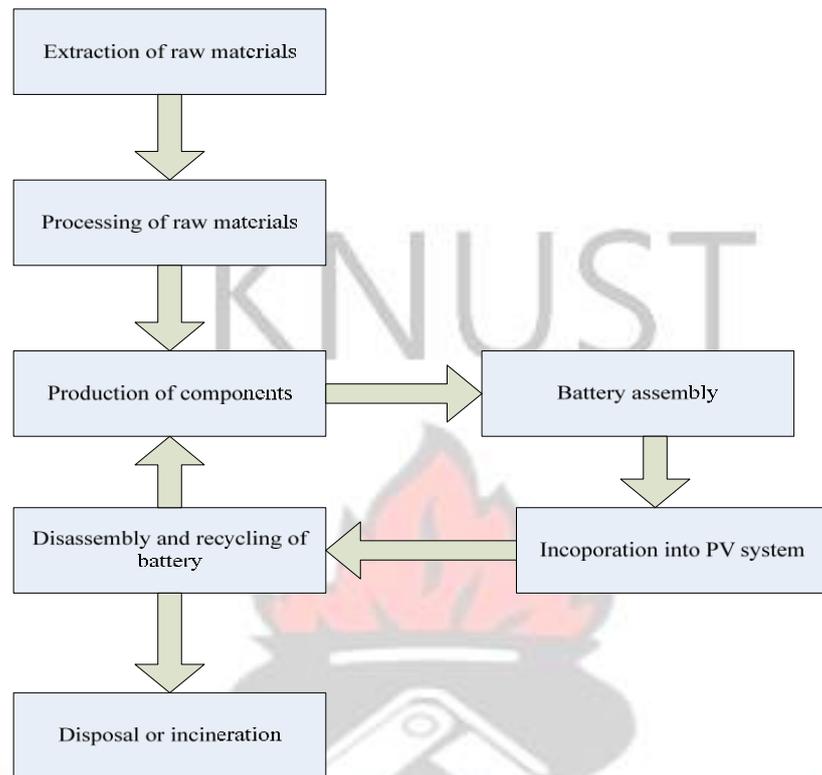


Figure 22: Schematic of a Life Cycle Environmental Impact Assessment

This thesis however limits itself to the effects and impacts batteries tend to have or can have on humans as well as the ecological system during the service as well as the end-of-life. It is however important to note that beside the intrinsic toxicity levels of some of the chemical substances that make up the battery and the dangers associated with the accompanying reactions, the cycle-life risk-exposure depends very much on the consumer's adherence to safety guidelines and the pattern of use [67].

CHAPTER THREE

3. DATA PRESENTATION AND ANALYSIS

This chapter presents the technical performance, economic and environmental data collected for the different batteries under review namely: NiCd, Lead Acid, NiMH and Lithium ion. The data was obtained using the procedures outlined in section 1.3.

3.1 Technical Performance: Data and Analysis

The characteristics compared are; charging, discharging, storage and cycle-life.

3.1.1 Charging

The charging efficiencies (also known as coulombic efficiencies) of the various batteries are given in Table 2 below. This parameter indicates how efficient the charging process is, as some of the electrical energy supplied to the battery during charging is converted to heat and also initiate other parasitic reactions.

Table 2: Typical Coulombic Efficiency of Batteries

Battery Type	Coulombic efficiency (%)
Lead-Acid	90-95
NiMH	70-80
NiCd	70-80
Li-Ion	>94

Source: [40- 42, 85]

3.1.2 Discharging

The major points of interest here are the temperature ranges within which batteries can operate without risk of thermal runaway. As presented in Table 3, all the batteries under study can safely operate over a wide range of temperature. Their optimum operating conditions will however depend on the specifics of design; in the case of lead acid batteries, the optimum is generally agreed to be around 25degC with the useful capacity reducing by about 50% for every 8-10degC rise in temperature [79-81]. Operating temperature range for the various batteries is presented in Table 3.

Table 3: Operating Temperature Range of Batteries

Chemistry	Operating Temperature Range (°C)
Lead-Acid	-40 to +60
NiMH	-20 to +60
NiCd	-40 to +60
Li-Ion	-20 to +60

Source : [79-81]

NiCd batteries stand out with very good discharge characteristics at low temperatures. It for instance delivers about 80% its useful capacity when discharged at -20degC while lead acid battery with immobilized electrolyte will deliver only 60% [82].

3.1.3 Charge Retention

The ability of the batteries to retain the charge that is stored in them was reviewed and the data in Table 4 was obtained; it indicates a very high self-discharge rate for the Nickel based batteries while the lead acid battery has the least rate of self-discharge.

Table 4: Battery Self-Discharge Data

Battery type	Self-discharge rate/month
Lead-Acid	1-5%
Nickel-Cadmium	20-30%
Nickel-Metal-Hydride	25-35%
Lithium Ion	6-9%

Source [80]

3.1.4 Cycle Life

The cycle life is the number of round-trips the battery can make before its capacity falls to 80% of its initial rating. This performance parameter varies for the different batteries and their typical numbers are presented in Table 5 below.

Table 5: Cycle-Life of Various Batteries

Battery Type	Typical Number of Cycles
NiMH	500
NiCd	1500
Lead Acid (SLA)	200-300
Li-Ion	300-500

Source: [61-63, 66]

The data in Table 5 represents average values; the actual cycle life will depend on the design details, quality of materials used but more importantly, on the pattern of use and temperature.

3.2 Economic Performance: Data and Analysis

With prices obtained from local suppliers and from AA Portable Power Corp. [66]; (The detailed price data is available in Appendix C) together with cycle-life information from the technical assessment (section 4.1). The life-cycle cost of storage is determined for each battery technology.

3.2.1 Market Price of Batteries

Battery prices obtained from [66] and processed are presented in Table 6. The unit cost of the batteries was estimated in \$/AH and since they are 12V systems the \$/Watt-hour equivalent was also computed by dividing by 12.

Table 6: Unit cost of Electricity Storage using Various Batteries

Battery Chemistry	Cost Per Amp-Hour (\$/AH)	Cost Per Watt-hour (\$/Wh)
Pb-Acid(SLA)	3.07	0.25
NiCd	16.21	1.35
NiMH	12.53	1.04
Li-Ion	19.40	1.62

The unit cost of storage for a given battery typically decreases with increasing battery capacity as shown in Fig 23 below for the lead acid battery.

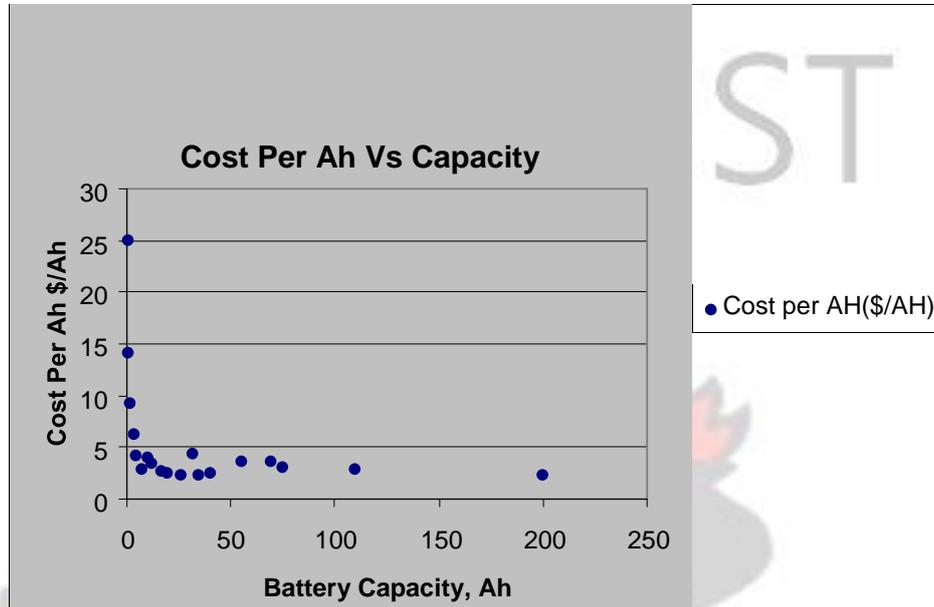


Figure 23: Unit Cost of Storage Vs Battery Capacity for Lead Acid Batteries
Source of data: Appendix C

3.2.2 Comparative Cost of Storage

An 80Wp system, to provide lighting for a rural home with 2days of autonomy was designed with the PVSYST 4.31¹² software. The load profile is given in Table 7. The battery storage for this system is determined to be 53Ah.

Table 7: Daily Load Assessment^a

Equipment	Quantity	Power(W)	Hours of Use (h)	Daily Energy consumption (Wh)
Lighting	3	12	8	288

^a 97% battery efficiency; 94% MPPT regulator efficiency

¹² PVSYST is a design and simulation software for solar photovoltaic systems from the University of Geneva.

Therefore regardless of choice of technology, the battery should meet the above storage requirement for the system. With data from Table 6, the initial cost for the different batteries are shown in Table 8. The initial cost is obtained by multiplying the battery capacity by the cost per Ah.

Table 8: Initial Cost Data for an 80Wp PV System^b

Battery Type	Capacity required (Ah)	Initial Cost(\$)
NiMH	53.0	664.09
NiCd	53.0	859.13
Lead Acid	53.0	162.71
Li-Ion	53.0	1028.20

^b
80% Depth of Discharge

Computation of life-cycle cost is done using the net present worth approach with a discount rate of 12%¹³ and a project life of 20yrs. With the cycle-life data in Table 5, and 2days of system autonomy, if 365days are assumed in a year a theoretical figure of $(365/2) 182.5$ cycles per year is determined. The calendar life of the batteries is then given by $(\text{cycle life})/182.5$ as presented in Table 9.

Table 9: Life (years) of Batteries

Battery Type	Calendar Life(yrs)
<i>NiMH</i>	3
<i>NiCd</i>	8
<i>Lead Acid</i>	2
<i>Li-Ion</i>	3

¹³ This was chosen to reflect an optimistic economic outlook over a 20-year period in which interest rates progressively drop.

Based on the figures from Table 9, the number of replacements needed (over the 20year project life) and the associated years are determined for each of the battery types.

This information becomes the input data into equation 5.

$$\text{---} \dots\dots\dots (5)$$

Using equation (5) for Nickel Metal Hydride, the present worth of investment in batteries at various years during the project is presented in Table 10.

Table 10: Present Worth of Investments in Battery during Service Life

End of yr	0	3	6	9	12	15	18
Present Worth (\$)	664.09	472.09	336.45	239.48	170.46	121.33	86.36

The process is repeated for the remaining batteries and capacities, the results are in Appendix D.

Over the entire project life however the net present value (NPV) is obtained by using equation 3 presented in chapter 2.

The total lifetime throughput is calculated from the daily energy requirement by multiplying it by 7300days (365*20), which is the project life duration. This gives

$$= \left(\frac{\text{---}}{365} \right) 7300 \dots\dots\dots (6)$$

3.2.3 Deep Versus Shallow cycle Lead-Acid Batteries

This section presents the cost and related data on deep-cycle solar batteries (DCSB) and the shallow cycle automotive batteries (SCAB) which are usually employed in local systems. The automotive batteries are discharged to 30% of rated capacity while the deep-cycled solar batteries may go down to 80%. The typical life-time of the shallow-

cycle battery is 2years with the solar batteries going for 5years¹⁴; data for the battery prices was taken from retailers and is available in Table 16.

KNUST



¹⁴ These figures were obtained from personal communication with PV systems design and installation experts and reflect the life of the batteries in normal usage.

Table 11: Battery Price Data in Ghana (collected in June 2008)

SUPPLIER 1: Shallow-Cycle					SUPPLIER 2: Shallow-Cycle				
Capacity (AH)	Price H¢	Wh	GH¢/Ah	GH¢/Wh	Capacity(AH)	Price GH¢	Wh	GH¢/Ah	GH¢/Wh
55	85.9	660	1.56	0.13	45	87.60	540	1.95	0.16
66	110	792	1.67	0.14	50	97.80	600	1.96	0.16
70	110	840	1.57	0.13	62	76.80	744	1.24	0.10
75	120	900	1.60	0.13	65	122.00	780	1.88	0.16
80	140	960	1.75	0.15	66	140.00	792	2.12	0.18
85	140	1020	1.65	0.14	75	163.20	900	2.18	0.18
88	140	1056	1.59	0.13	88	174.00	1056	1.98	0.16
100	150	1200	1.50	0.13	90	174.00	1080	1.93	0.16
120	200	1440	1.67	0.14	100	210.00	1200	2.10	0.18
150	220	1800	1.47	0.12	120	240.00	1440	2.00	0.17
200	250	2400	1.25	0.10	150	319.20	1800	2.13	0.18
		Avg=	1.57	0.13	220	451.20	2640	2.05	0.17
SUPPLIER 3: Shallow-Cycle							Avg=	1.96	0.16
Capacity (Ah)	Price GH¢	Wh	GH¢/Ah	GH¢/Wh	SUPPLIER 4: Shallow-Cycle				
55	88	660	1.60	0.13	Capacity (AH)	Price GH¢	Wh	GH¢/Ah	GH¢/Wh

66	98	792	1.48	0.12	50	80	600	1.60	0.13
100	130	1200	1.30	0.11	66	120	792	1.82	0.15
120	174	1440	1.45	0.12	75	135	900	1.80	0.15

50

150	195	1800	1.30	0.11	88	150	1056	1.70	0.14
		Avg=	1.43	0.12	150	230	1800	1.53	0.13
					120	210	1440	1.75	0.15
							Avg=	1.70	0.14

Table 16 continued:

SUPPLIER 5: Shallow-Cycle					SUPPLIER 6: Deep-Cycle Batteries			
Capacity(Ah)	Price GH¢	Wh	GH¢/Ah	GH¢/Wh	Capacity (Ah)	Price(G H¢)	GH¢/Ah	GH¢/Wh
55	80	660	1.45	0.12	100	307.66	3.08	0.26
75	120	900	1.60	0.13	460	598.24	1.30	0.11
100	130	1200	1.30	0.11	20	64.88	3.24	0.27
150	220	1800	1.47	0.12	100	340.44	3.40	0.28
200	280	2400	1.40	0.12				
		Avg=	1.44	0.12		Avg=	2.76	0.23

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OVERALL AVERAGE			
Cost per Ah, GH¢	=1.62	Cost per Wh, GH¢	=0.135



3.3 Environmental

The components of the various batteries including reacting and non-reacting may have impacts on the environment; which in this case encompasses both the human person his immediate environment and the entire ecosystem. Presented here is a summary of the environmental risks of the various battery systems.

3.3.1 Lead Acid battery

This contains predominantly lead/lead oxide, sulfuric acid with lead sulphate being formed during the discharge reaction; its amount depends on the state of charge of the battery. Lead/ lead compounds form about 65-75% (percentage by weight) of the battery, with the sulfuric acid contributing 14-20% [83]. Lead and its inorganic compound are known to have a number of negative effects on humans. Though it is not absorbed through the skin [83], overexposure can result in nausea, headaches and even chronic health hazards such as damage to kidneys and central nervous system. International Agency for Research on Cancer (IARC) has categorized lead and inorganic lead compounds as a B2 hazard (probable/possible human carcinogen) based on sufficient animal evidence and limited human evidence [83].

3.3.2 Nickel Cadmium Battery

During normal use inhalation is highly unlikely due to the containment of hazardous materials inside the sealed battery case. However, if the batteries are exposed to extreme heat or pressure causing a break in the battery cell case, cadmium fumes may be emitted. Inhalation of cadmium fumes may cause a number of health complications ranging from throat dryness, respiratory irritation, headache, nausea to even death when exposed to high concentrations for an extended period of time (e.g. above 1 to

5mg/m³ during an eight hour period) [84]. Cadmium and nickel have both been identified by the US National Toxicology Program (NTP) as reasonably anticipated to be carcinogens [84]. Nickel is also considered toxic to aquatic organisms and may cause long-term adverse effects in the aquatic environment [72].

3.3.3 Nickel Metal Hydride

Nickel based batteries have two main probable carcinogens Nickel itself and Cadmium. Nickel metal hydride batteries substitute the Cadmium with the metal hydride, which is safer and therefore enhances its environmental and safety credentials. In fact the reason for the development of NiMH is the toxicity of the cadmium component of the NiCd systems.

3.3.4 Lithium Ion Batteries

For the battery cell, chemical materials are stored in a hermetically sealed metal case, designed to withstand temperatures and pressures encountered during normal use. As a result, during normal use, there is no physical danger of ignition or explosion and chemical danger of hazardous materials' leakage [86].

CHAPTER FOUR

4 RESULTS AND DISCUSSION

This Chapter summarizes and discusses that data presented in chapter three.

4.1 Results

4.1.1 Summary of Technical Results

Table 12 below provides a summary of the technical performance parameters of the various batteries under review.

Table 12 Battery Technical Performance Indicators

Battery Type	Charging Efficiency (%)	Discharge Temp Range (°C)	Cycle Life (No of Charge/discharge cycles)	Charge Retention: Self-Discharge Rate/Month (%)
NiCd	70-80	-40 to +60	1500	20-30
NiMH	70-80	-20 to +60	500	25-35
PbA	90-95	-40 to +60	200-300	1-5
Li-Ion	94	-20 to +60	300-500	6-9

4.1.2 Summary of Economic Analysis

Results of the economic comparison of the performance of the batteries using a typical 80Wp system are summarized in Table 13 using initial cost data in Table 8 with replacement years in Table 9 and a 12% discount rate for the 20 year project life.

Table 13: Comparative storage cost for various batteries in an 80Wp system

Battery Type	Initial Cost (\$)	NPV of LCC (\$)	Annualized Cost (\$)	Unit cost of Storage (US\$ cents/Wh) ¹⁵
NiMH	664.09	2090.84	104.54	0.10
NiCd	859.13	1346.26	67.31	0.06
Lead Acid	162.71	719.12	35.95	0.03
Li-Ion	1028.20	3237.22	161.86	0.15

¹⁵ This life-cycle cost (LCC) per Wh is obtained by dividing the LCC by the lifetime throughput which is in this case =288*7300=2102.4kWh

Table 14 below presents the results of a cost comparison between various lead acid batteries when used as electricity storage media in solar home systems: the shallow cycle auto-motive batteries (SCAB) and the deep-cycle solar batteries (DCSB). The SCAB is used with a 30% DOD while the DCSB is drawn to 80% DOD, this assumption accounts for the different battery capacity requirements.

Table 14: Cost Comparisons of Deep and Shallow-cycle Lead Acid Batteries

Battery Type	Initial Cost (GH¢)	LCC (GH¢)	ALCC (GH¢)	Unit Cost (GH¢)
DCSB (66.0Ah)	215	445.5	22.28	0.021
SCSB (176.7Ah)	240	1060.72	53.04	0.05

4.1.3 Summary of Environmental

From the largely qualitative information on the environmental impact of batteries, a comparison is presented in Table 15.

Table 15 Human and Ecological Risk from Batteries

Battery Type	Risk to Human Health	Risk to Ecology	Recyclability in Ghana
NiCd	High	High	Not available
NiMH	Moderate	Moderate	Not available
PbA	High	High	Available (Limited capacity)
Li-Ion	Moderate	Low	Not available

4.2 Discussion

The two Nickel-based batteries have lowest charging efficiency (70-80%) and also the highest self discharge rates (20-30% per month). They however seem to make up for this defect by giving relatively high cycle life: 500 for NiMH and 1500 for NiCd.

For large PV system design, the effect of this self-discharge batteries will have to be accounted for in the design equations. The lead-acid (PbA) and the Li-Ion batteries on the other hand have low self-discharge rates 1-5% and 6-9% respectively. The PbA and Li-Ion batteries also have the highest charging efficiencies: 90-95% and 94% respectively. They however have low cycle life compared to NiCd and NiMH batteries. All the batteries however seem to have a wide range of temperatures within which they can safely operate: -20°C to 60°C.

The Life-Cycle Cost (LCC) of the various batteries indicates a very wide variation: \$719.12-\$3237.22. The lead acid battery stands out as the least-cost option for providing electricity storage in solar home systems. The superiority of the PbA battery may be attributed to a number of factors which include: maturity of design and production technology and the advantage of mass production since they are used extensively in the automobile industry. In comparing the DCSB and the SCAB, Table 14 indicates a significantly lower cost for the DCSB. The absolute figures obtained LCC of GH¢445.5 and GH¢1060.72 for DCSB and SCAB respectively- may be much higher because the original battery pricing data was obtained from small retail shops and the sample space was not wide enough to provide data of high accuracy. The LCC is very dependent on the battery life data which was obtained from a secondary source for this thesis and may need to be experimentally verified. Changes in battery life will have a very significant effect on the eventual life cycle cost.

Results in Table 15 show that the lead acid battery has significant risk to humans if not properly used as prescribed by manufacturers and also to the ecology especially if it is not properly disposed off at the end of its service life. The risk presented by the NiCd battery is also high. There is some limited recycling capacity in Ghana for lead from the lead acid batteries (Pagrik Ghana Limited in Tema). Apart from this there is no known recycling facility for the other substances like the sulfuric acid and the constituent chemicals and components of the other batteries.



CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Based on the objectives and results of this study, the following conclusions can be made:

The commercially available batteries for electricity storage in solar home systems are:

Lead Acid

Nickel Metal Hydride

Nickel Cadmium Lithium-

Ion.

Technically they were all found to be capable of serving as electricity storage systems for solar home systems although Li-Ion and NiMH batteries were found not to be available in capacities that are large enough for most photovoltaic applications, they may however be suitable for lantern systems. The Nickel-based batteries were found to have very high self-discharge rates (20-35%) compared to the others (1-5% for lead acid batteries and 6-9% for Li-Ion), but this is unlikely to have much effect if the system is small and has short days of autonomy. The lead acid battery is the most cost-effective for electricity storage costing 30% (see Table 13) of what it would cost to use the lithium battery. On deep-cycle and automotive batteries, the analysis showed that cost-wise, the former is overwhelmingly superior to the latter. Price data obtained from suppliers indicate an average cost of GH¢ 1.62/Ah (GH¢ 0.135/Wh) for shallow-cycle automotive batteries (SCAB); the figures for deep-cycle solar batteries (DCSB) are GH¢ 2.76 per Ah (GH¢ 0.23/Wh). Life-cycle cost calculations from the data collected showed that shallow cycle automotive batteries SCAB cost at least 140% more than it would actually cost if deep-cycle solar batteries were used. For an 80Wp system the annualized life-cycle cost (ALCC) of electricity storage was GH¢22.28 for DCSBs against GH¢53.04 for SCABs. Environmentally, NiCd batteries are the least attractive, because of the presence of Cadmium which is considered toxic both to humans and the ecosystem. There is no known recycling facility in Ghana for this battery. Lead acid batteries on the other hand, despite their inherent toxicity there is some local recycling capacity (though limited) to ensure that the environmental hazards from Lead is reduced.

5.2 Recommendation

The main recommendations of this thesis are summarized below:

The new and emerging technologies like the NiMH and Li-Ion batteries, though expensive now, should still be studied by local researchers since they have a lot of room for cost reduction which could come from advances in technology or mass production. Deep-cycle solar batteries are more cost effective to use in solar photovoltaic systems than the shallow-cycle automotive batteries, they should therefore be promoted and made readily available for use in solar photovoltaic systems. Well equipped laboratories should be set-up to enable verification of some of the data (like cycle life) on which this thesis bases its conclusions. This should be further researched to obtain empirical data. The variation between cycle-life, depth of discharge and the battery's operating temperature will be useful to study, model and optimize. Future work could look into this.

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APPENDIX A: The Electrochemical Series

Table 16 : The Electrochemical Series

Process	E°/Volts
$\text{Li}^+_{(aq)} + e^- \rightleftharpoons \text{Li}_{(s)}$	-3.03
$\text{K}^+_{(aq)} + e^- \rightleftharpoons \text{K}_{(s)}$	-2.92
$\text{Ca}^{2+}_{(aq)} + 2e^- \rightleftharpoons \text{Ca}_{(s)}$	-2.87
$\text{Na}^+_{(aq)} + e^- \rightleftharpoons \text{Na}_{(s)}$	-2.71
$\text{Mg}^{2+}_{(aq)} + 2e^- \rightleftharpoons \text{Mg}_{(s)}$	-2.37
$\text{Al}^{3+}_{(aq)} + 3e^- \rightleftharpoons \text{Al}_{(s)}$	-1.66
$\text{Zn}^{2+}_{(aq)} + 2e^- \rightleftharpoons \text{Zn}_{(s)}$	-0.76
$\text{Fe}^{2+}_{(aq)} + 2e^- \rightleftharpoons \text{Fe}_{(s)}$	-0.44
$\text{Pb}^{2+}_{(aq)} + 2e^- \rightleftharpoons \text{Pb}_{(s)}$	-0.13
$2\text{H}^+_{(aq)} + 2e^- \rightleftharpoons \text{H}_{2(g)}$	0.00
$\text{Cu}^{2+}_{(aq)} + 2e^- \rightleftharpoons \text{Cu}_{(s)}$	0.34
$\text{Fe}^{3+}_{(aq)} + e^- \rightleftharpoons \text{Fe}^{2+}_{(aq)}$	0.77
$\text{Ag}^+_{(aq)} + e^- \rightleftharpoons \text{Ag}_{(s)}$	0.80
$\text{Cr}_2\text{O}_7^{2-}_{(aq)} + 14\text{H}^+_{(aq)} + 6e^- \rightleftharpoons 2\text{Cr}^{3+}_{(aq)} + 7\text{H}_2\text{O}_{(l)}$	1.33
$\text{Cl}_2(g) + 2e^- \rightleftharpoons 2\text{Cl}^-_{(aq)}$	1.36
$\text{Au}^{3+}_{(aq)} + 3e^- \rightleftharpoons \text{Au}_{(s)}$	1.50

Source : <http://www.chemguide.co.uk/physical/redoxeqia/nonmetal.html#top>

APPENDIX B: Thermodynamics and Electrochemistry-A confluence

The cell potential (EMF) is the driving force behind the electron transfer process. This driving force can be defined in terms of a potential (in volts) between two points in the circuit, where a volt is work per coulomb of charge transferred, in joules.

$$Potential(V) = \frac{Work(J)}{Charge(C)} \dots\dots\dots (7)$$

Thus 1joule of work is produced or required (depending on direction) when transferring 1C of charge between two (2) points in a circuit that differ by 1volt.

This thesis shall adopt the convention of work being +ve when it flows out of the system, current flowing from the cell can do work and hence the cell potential and work have opposite signs.

$$- E = \frac{w}{q} \dots\dots\dots (8)$$

$$w = -(q \times E) \dots\dots\dots (9)$$

From (9) it can be seen that maximum work is obtained at maximum cell potential.

$$W_{max} = q \times E_{max} \dots\dots\dots (10)$$

At constant temperature and pressure the maximum work obtainable is equal to the change in the Gibb's free energy, ΔG [16]

$$W_{max} = -\Delta G \dots\dots\dots (11)$$

Since the processes involve electron transfer the actual charge in coulombs (q) can be found by relating the number of electrons (n) and the Faraday constant F.

$$q = n \times F \dots\dots\dots (12)$$

where $F = 96,486C /mol$

Combining (10), (11) and (12) we obtain:

$$\Delta G = nFE_{\max} \dots\dots\dots (13)$$

The maximum cell potential is therefore directly related to the free energy difference between the reactants and the products.

It can be shown that,

$$\Delta G = \Delta G^\circ + RT \ln Q \dots\dots\dots (14)$$

See [17] for a comprehensive derivation of equation 14

Equation 14 gives the theoretically available energy at any given temperature and concentration of reactant and products. Where Q is the reaction quotient¹⁶

ΔG° is the change in Gibb's free energy at standard conditions, R is the universal gas constant and T is the temperature.

Combining the above equations give:

$$E = E^\circ - \frac{RT}{nF} \ln Q \dots\dots\dots (15)$$

At 25°C this equation simplifies to

$$E = E^\circ - \frac{0.0592}{n} \ln Q \dots\dots\dots (16)$$

¹⁶ Q is the ratio of the product of the concentration of products to the products of the concentration of the reactants in a chemical process.

APPENDIX C1: Battery Price Data

Table 17: Battery Price Data

12V Lead Acid Battery					12V NiMH				
Battery Capacity Ah	Price \$	Energy Wh	Unit Cost \$/Wh	Unit Cost \$/Ah	Battery CapacityAh	Price\$	Energy Wh	Unit Cost \$/Wh	Unit Cost \$/Ah
1.2	17.0	14.4	1.18	14.17					
2.3	21.0	27.6	0.76	9.13	10	120	120	1.00	12.00
3.4	21.0	40.8	0.51	6.18	10	125	120	1.04	12.50
4.5	19.0	54.0	0.35	4.22	10	117	120	0.98	11.70
7.5	21.0	90.0	0.23	2.80	10	100	120	0.83	10.00
10.0	40.0	120.0	0.33	4.00	10	129	120	1.08	12.90
12.0	40.0	144.0	0.28	3.33	13	199	156	1.28	15.31
17.0	46.0	204.0	0.23	2.71	13	180	156	1.15	13.85
20.0	49.0	240.0	0.20	2.45	13	180	156	1.15	13.85
26.0	60.0	312.0	0.19	2.31	13	196	156	1.26	15.08
32.0	140.0	384.0	0.36	4.38	20	270	240	1.13	13.50
35.0	80.0	420.0	0.19	2.29	26	320	312	1.03	12.31
40.0	100.0	480.0	0.21	2.50	40	420	480	0.88	10.50
55.0	199.0	660.0	0.30	3.62	52	496	624	0.79	9.54
70.0	244.5	840.0	0.29	3.49	30	376	360	1.04	12.53
75.0	229.5	900.0	0.26	3.06			Averag=	1.04	12.54
110.0	299.5	1320.0	0.23	2.72					
200.0	450.0	2400.0	0.19	2.25					
		Averag=	0.26	3.07					
12V Lithium-Ion					12V NiCd				
Wh	\$	\$/Wh	\$/Ah		Ah	\$	Wh	\$/W ₁	\$/Ah
77.00	148.00	1.92	23.06		1.00	16.95	12.00	1.41	16.95
168.00	246.00	1.46	17.57						

296.00	396.00	1.34	16.05	1.70	23	20.40	1.13	13.53
133.20	190.00	1.43	17.12	0.70	24	8.40	2.86	34.29
71.00	106.00	1.49	17.92	2.20	29	26.40	1.10	13.18
148.00	199.00	1.34	16.14	4.00	60	48.00	1.25	15.00
77.00	160.00	2.08	24.94	4.00	59	48.00	1.23	14.75
74.00	133.00	1.80	21.57	7.00	96	84.00	1.14	13.71
74.00	125.00	1.69	20.27	2.60	30	31.20	0.96	11.54
	Average=	1.62	19.40	3.00	39	36.00	1.08	13.00
						Average=	1.35	16.22

Source: [66]

APPENDIX C2: Comparing Battery Costs

Table 18: Life-Cycle Cost for 80Wp PV System

Project Life of 20years: : Discount 12%			
12V,53Ah Lead Acid Battery		12V,53Ah NiMH	
End of year	PV (\$)	NiMH	PV (\$)
		End of yr	
0	162.71	0.0	664.09
2	129.71	3.0	472.69
4	103.41	6.0	336.45
6	82.43		
8	65.72	9.0	239.48
10	52.39	12.0	170.46
12	41.76		
14	33.29	15.0	121.33
16	26.54		

		18.0	86.36
18	21.16		
NPV=	719.12	NPV=	2090.84
12V 53Ah Li-Ion		12V 53Ah NiCd	
End of year	PV	End of year	Present worth of Investment in Battery (\$)
0	1028.20	0	859.13
3	731.85	8	346.99
6	520.92	16	140.14
9	370.78	NPV=	1346.26
12	263.91		
15	187.85		
18	133.71		
NPV=	3237.22		

APPENDIX C3: Load Characteristics and Cost for 250Wp and 800Wp Systems

Table 19 Load Characteristics for a 250Wp System

Equipment	Quantity	Power(W)	Hours of Use (h)	Daily Energy Consumption (Wh)
Lighting	4	12	8	384
Television	1	100	4	400
				Total Energy=784Wh, Battery Bank=145Ah

Table 20 Load Characteristics for an 800Wp System

Equipment	Quantity	Power(W)	Hours of Use (h)	Daily Energy Consumption (Wh)
-----------	----------	----------	------------------	-------------------------------

Lighting	4	12	8	384
Television	1	120	6	720
Freezer	1	116	6	696
				Total Energy=2644Wh, Battery Bank=488Ah

Table 21: Cost of Storage Batteries for a 250Wp Solar Home System

Battery type	PW of Battery Investments (\$)	Annualized Cost (\$)	Unit Cost of Storage ¹⁷ (US\$ cents/Wh)
NiMH	5720.23	286.01	0.10
NiCd	3683.17	184.16	0.06
Lead Acid	1967.41	98.37	0.03
Li-Ion	8856.54	442.83	0.15

Table 22: Cost of Storage Batteries for an 800Wp Solar Home System

Battery type	PW of Battery Investments (\$)	Annualized Cost (\$)	Unit Cost of Storage (US\$ cents/Wh)
NiMH	19251.53	962.58	0.10
NiCd	12395.76	619.79	0.06
Lead Acid	6621.35	331.07	0.03
Li-Ion	29806.84	1490.34	0.15

APPENDIX E1: Comparing Cost of SCAB and DCSB

Table 23: NPV of an 80Wp System: Comparing SCAB and DCSB

80Watt System					
Shallow Cycle 180 AH			Deep cycle 66.2AH		
Year	Present Worth		Year	Present Worth	
0	240.00		0	215.00	
2	191.33		5	122.00	
4	152.52		10	69.22	
6	121.59		15	39.28	

¹⁷ The figures in this column do not reflect the decreasing cost of electricity storage as the system and battery capacities increase. This is due to the fact that, battery costs were reduced to a unit amp-hour basis to allow for comparison of batteries like NiMH and Li-Ion that do not have large capacities like 50 and 100 Ah available on the market.

8	96.93		NPV=	445.50
10	77.27		ALCC=	22.28
12	61.60			
14	49.11			
16	39.15			
18	31.21			
NPV=	1060.72			
ALCC=	53.04			
Shallow:: 480AH		250 Watt System Deep:: 181AH		
Year	Present Worth		Year	Present Worth
0	604.00		0	390.00
2	481.51		5	221.30
4	383.85		10	125.57
6	306.01		15	71.25
8	243.95		NPV=	808.12
10	194.47		ALCC=	40.41
12	155.03			
14	123.59			
16	98.53			
18	78.54			
NPV=	2669.47			
ALCC=	133.47			
Shallow::1626.67AH		800Watt System Deep: 610AH		
Year	Present Worth		Year	Present Worth
0	2033.00		0	793.31
2	1620.70		5	450.15
4	1292.01		10	255.42
6	1029.98		15	144.93
8	821.09		NPV=	1643.81
10	654.57		ALCC=	82.19
12	521.82			
14	415.99			
16	331.63			
18	264.37			
NPV=	8985.16			
ALCC=	449.26			

Table 24 Cost Summary for 80Wp, 250Wp and 800Wp Systems: DCSB Vs SCAB

80Wp System			250Wp System		
Lifetime through-put::2102.4kWh			Lifetime through-put::5723.2kWh		
Parameter	DCSB 66.2Ah	SCAB 176.7Ah	Parameter	DCSB (180.0Ah)	SCAB (480.0Ah)
LCC (GH¢)	445.50	1060.72	LCC(GH¢)	808.12	2669.47
ALCC(GH¢)	22.28	53.04	ALCC(GH¢)	40.41	133.47
Unit Cost ¹⁹ GHp/Wh	0.021	0.05	Unit Cost GHp/Wh	0.014	0.046
800Wp System:: Lifetime through-put= 19301.2kWh					
Parameter	DCSB: 610.0 Ah		SCAB 1626.7 Ah		
LCC (GH¢)	1643.81		8985.16		
ALCC (GH¢)	82.19		449.26		
Unit Cost GHp/Wh	0.0085		0.046		



¹⁹ This is calculated by dividing the LCC by the throughput.

APPENDIX E2: The Photovoltaic Cell- Further Description

The basic unit of a solar PV generator is the solar cell. It is made from a semiconductor, mostly silicon (Si) but other materials such as gallium arsenide (GaAs), copper sulphate (Cu₂S), cadmium telluride (CdTe) and copper Indium diselenide (CIS) are also used. Semi-conductors are materials whose electrical conductivity lies between that of conductors and insulators. They have electrical resistivities (ρ) of $10^5 - 10^{-2}$ W-cm [97]. The Si atom has 14 electrons, 4 of which are in the outer orbit as shown in Fig 24, with which it forms covalent bonds within the silicon crystal. In this pure state, the semi-conductor is termed intrinsic.

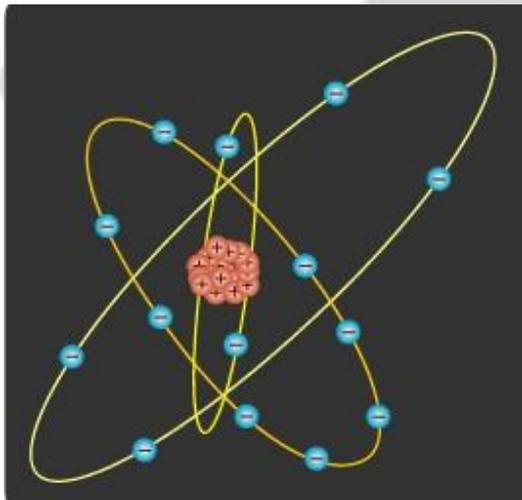


Figure 24: Electronic Configuration of Silicon [98]

It has been known however that, when small amounts of other substances (usually called impurities) are added to the crystal (a process termed doping), the electrical properties change significantly and the result is called extrinsic semi-conductor.

Depending on the nature of the atoms introduced into the structure, the semi-

conductor may be called P-type or N-type. When a pentavalent¹⁸ atom like antimony (Sb) is introduced into the crystal structure of Silicon, it uses 4 (four) of its valence electrons to bond with the tetravalent silicon thus a free electron is made available, this forms an N-type semiconductor as shown in Fig. 25.

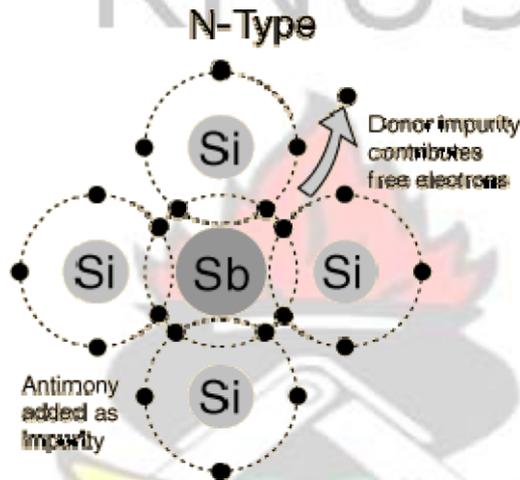


Figure 25: N-Type Semi-conductor

In a similar fashion if the impurity is a trivalent atom such as boron then, the 3 (three) valence electrons in forming covalent bonds with the 4 (four) electrons of silicon will result in the formation of an incomplete bond as shown in Fig. 26. This site to which electrons may migrate is called a **hole**, and is regarded as a positive charge carrier. The semi-conductor doped in this way is termed a P-type semi-conductor.

¹⁸ A pentavalent is an atom that has five electrons in its outermost orbit.

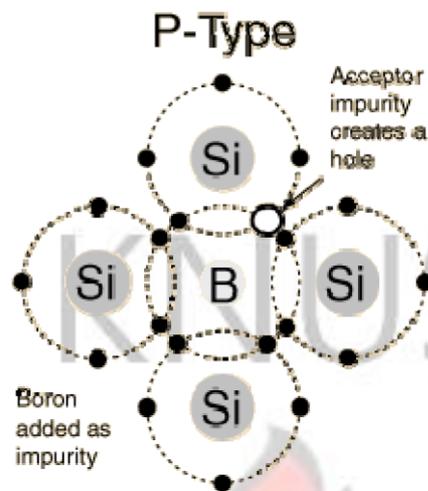


Figure 26:P-type Semi-Conductor

P-N Junction

When these two extrinsic semi-conductors are brought in atomically-close contact, the physical properties at the interface, called *P-N junction*, are very different from that of the bulk material. The term *junction* is a materials science vocabulary generally used for an electrochemical interface between solids. When a p-n junction is formed, some of the free electrons in the n-region diffuse across the junction and combine with holes to form negative ions as shown in Fig 27. In so doing they leave behind positive ions at the donor impurity sites. The buildup of excess positive and negative charges on either side of the junction creates an electric field across the interface; the strength of this field depends on the quantity of dopant in the silicon. At equilibrium, the electric field repels any additional crossover of holes from the p-side or electrons from the n-side. This results in the formation of what is called a depletion

zone at the interface; this is a zone which does not contain any mobile positive or negative charges [99].

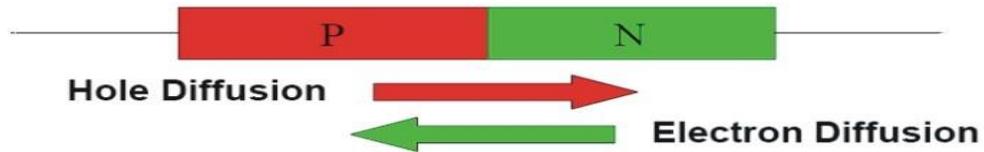


Figure 27: Electron-Hole Diffusion [97]

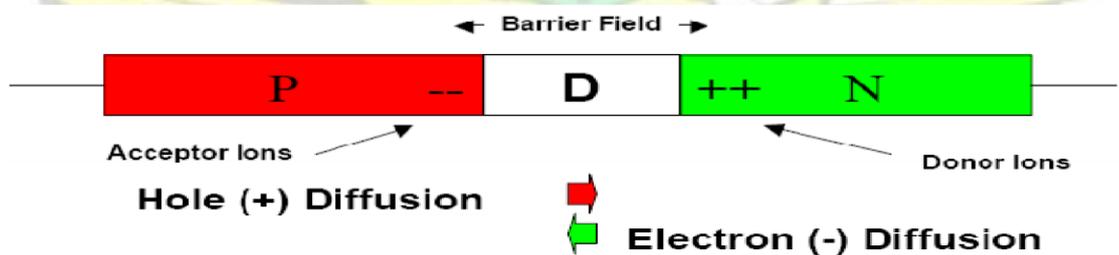


Figure 28: P-N Junction: Showing In-Built Potential [97]

This is sometimes called a solar battery because of its similarity with the electrochemical batteries. For silicon, the EMF of the built-in electric field as shown in Fig 28 has typical values around 0.6-0.7V [96]. When a photon of sufficient energy strikes the extrinsic silicon it knocks out a bound electron thus creating a negative electron and a positive hole. which are separated by the electric field and flows through an external path as shown in Fig. 29. If it weren't for the electric field, the electron and

the hole would attract and recombine. With the electric field, the negative electron is swept towards the n-side and the positive hole goes to the p-side.

This is the source of the electricity of a solar cell.

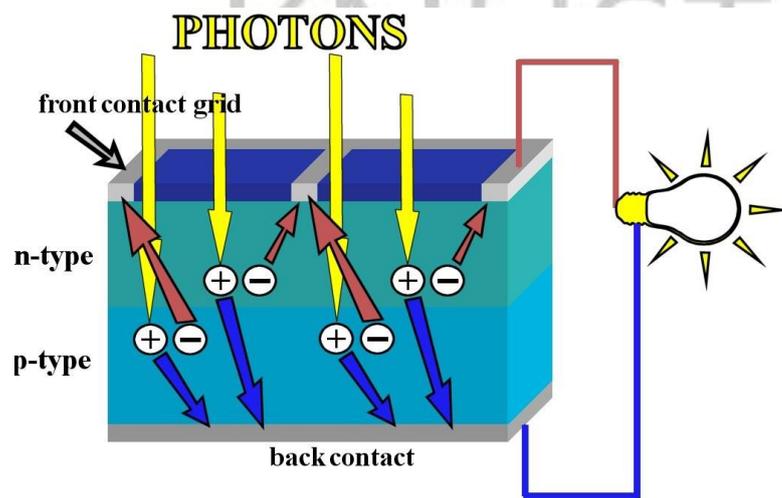


Figure 29: Flow of Electrons in a PV Cell
Source [96]

Silicon is a shiny gray material and can act as a mirror, reflecting more than 30% of the light that shines on it. To improve the conversion efficiency of a solar cell, it is important to minimize the amount of light reflected so that the semiconductor material can capture as much light as possible to use in freeing electrons. Two techniques are commonly used to reduce reflection. The first technique is to coat the top surface with a thin layer of silicon monoxide (SiO). A single layer reduces surface reflection to about 10%, and a second layer can lower the reflection to less than 4% [49]. A second technique is to texture the top surface. Chemical etching creates a pattern of cones and pyramids, which capture light rays that might otherwise be deflected away from the cell. Reflected light is redirected down into the cell, where it has another chance to be absorbed.

Only the absorbed light provides energy to generate electricity. When the radiation possesses energy that exceeds the **work function**, (minimum energy required in freeing an electron from its bond), electrons are dislodged from the material's atoms as shown in Fig 30, allowing them to flow freely under the influence of the electric field. [42].

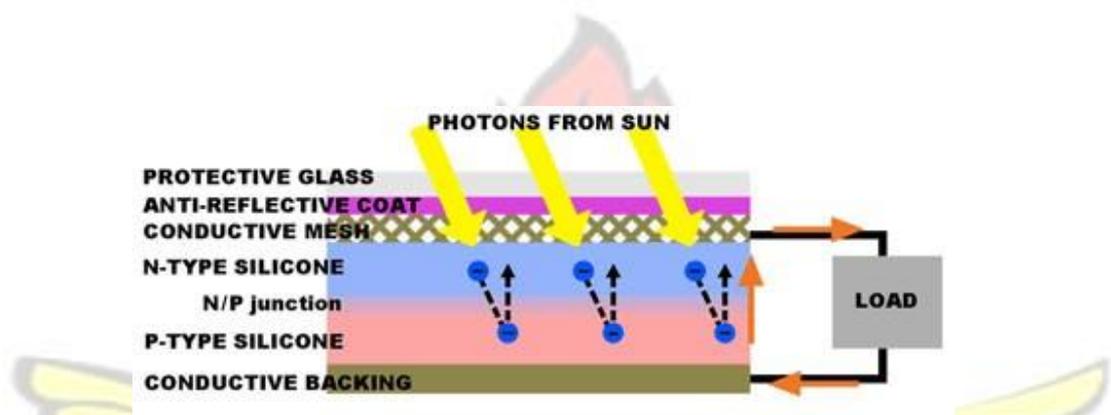


Figure 30: Photons Freeing Electrons from a PV Cell
Credit: Photowatt Technologies [41]

When the electrons leave their position, holes are formed. When many electrons, each carrying a negative charge, travel toward the front surface of the cell, the resulting imbalance of charge between the cell's front and back surfaces creates a voltage potential like the negative and positive terminals of a battery. When the two surfaces are connected through an external load, electricity flows. Commercially available solar cells have typical efficiencies of around 12% [43] although 40.7% has been reported by researchers at Spectrolab Inc.¹⁹[44, 45]. Individual cells can vary in size from about 1cm to about 10cm across. However, one cell only produces 1 or 2 watts, which isn't

¹⁹ Spectrolab Inc. is a subsidiary of aerospace and defense company Boeing and specializes in the manufacture of solar cells for space applications.

enough power for most applications. To increase power output, cells are electrically connected and packaged into a weather-tight module. Modules are usually designed to supply electricity at a certain voltage. Multiple modules can be wired in an array to give the desired power output.

Solar cells are tested at the standard test conditions (STC): Irradiance of 1000W/m^2 , air mass of 1.5 and cell temperature of 25°C . This allows the output of cells to be compared but the normal operating cell temperature (NOCT) gives a better indication of what to expect from the cell under normal operating conditions. The NOCT is typically 25°C above the ambient temperature, depending on cell technology, solar module design and mounting techniques [46]. Solar modules on the market are usually characterized by the short circuit current I_{sc} , open circuit voltage V_{oc} , the maximum power output P_{max} (with its corresponding current and Voltage) as well as the current at NOCT.

The performance of a typical solar module may be specified with the following characteristics:

Short circuit current I_{sc}	4.99A
Open circuit voltage V_{oc}	21.8 V
Max. power output P_{max}	80W
Current at P_{max}	4.67A
Voltage at P_{max}	17.1V
Current at NOCT & 14Volts	4.96A

KNUST



APPENDIX F1: Sensitivity of NPV to Discount Rate

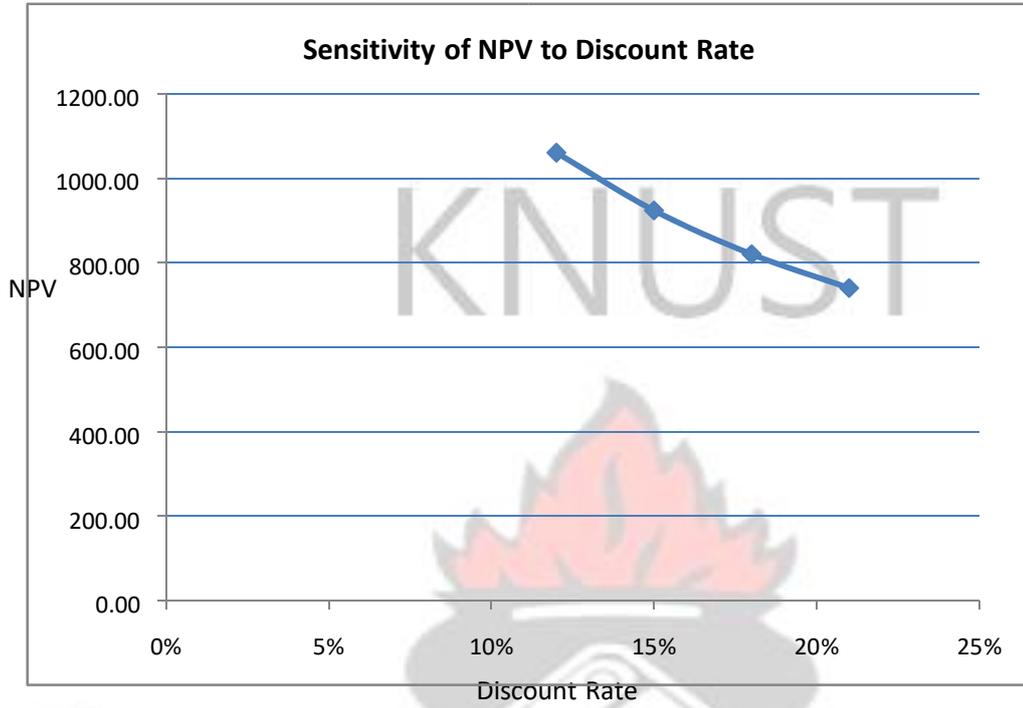


Figure 31: Sensitivity of NPV of SCAB in an 80Wp system

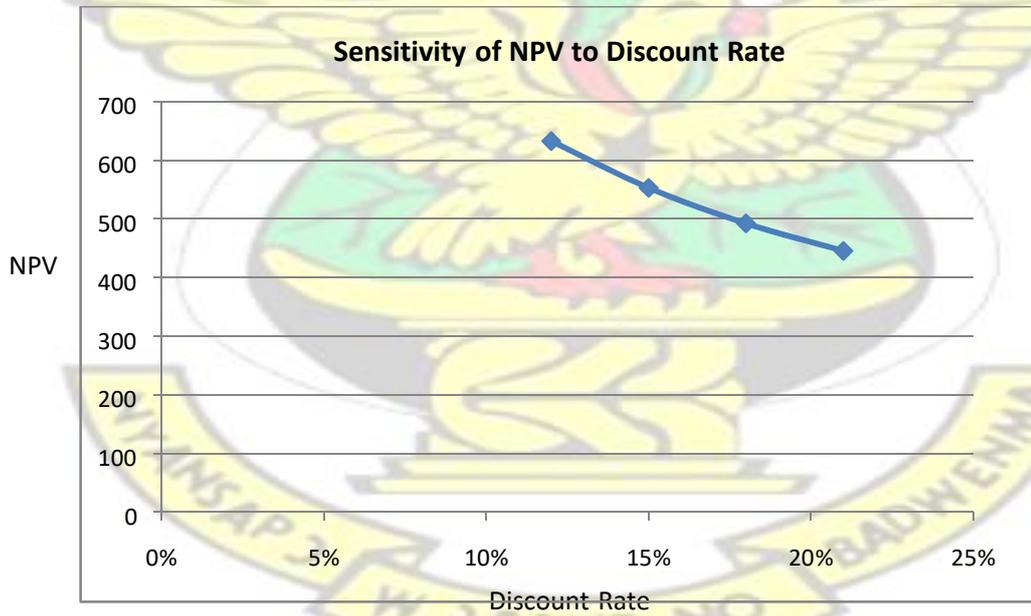


Figure 32 Sensitivity of NPV of DCSB in an 80Wp system

APPENDIX F2: Sample Input and Output Data Using PVSYST

Consumption definition by
 Year
 Seasons
 Months

Week-end use
 Use only during 7 days in a week

Model

Daily consumptions

Number		Power		Mean Daily use		Daily energy
3	Fluorescent lamps	12	W/lamp	8.0	h/day	288 Wh
0	TV / Magnetoscope / PC	40	W/app.	4.0	h/day	0 Wh
0	Domestic appliances	0	W/app.	0.0	h/day	0 Wh
0	Fridge / Deep-freeze			0.60	kWh/day	0 Wh
0	Dish-washer, Cloth-washer			0.00	kWh/day	0 Wh
	Other uses	0	W tot	0.0	h/day	0 Wh
	Stand-by consumers	0	W tot	24h/day		0 Wh

Appliances info Hourly distribution

Total daily energy 288 Wh/day
Total monthly energy 8.6 kWh/month

Back Other profile Cancel Next

Figure 33 Input Data into PVSYST 4.31

Geographical Location and Meteo

Country: Ghana Site: Accra

Meteo file: accra_syn.met : Accra , synthetic hourly data ?

Back Cancel Albedo

Figure 34 Site Information for PVSYST Software

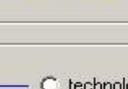
Presizing help

Av. daily needs : Enter accepted LOL % Battery (user) voltage V

0.3 kWh/day Enter requested autonomy day(s) Suggested capacity **53 Ah**
Suggested PV power **77 Wp (nom.)**

Select battery set

Sort Batteries by voltage capacity manufacturer

Batteries in serie  Number of batteries **1** Battery pack voltage **12 V**
 Batteries in parallel  Global capacity **43 Ah**
Stored energy **0.5 kWh**

Select module(s)

Sort modules by: power technology manufacturer

Modules in serie  The PV array power seems to be slightly undersized.
 Modules in parallel  Array voltage at 50°C **14.1 V**
Array current **3.3 A**
Array nom. power (STC) **50 Wp**

Figure 35 Sample Output from PVSYST Software

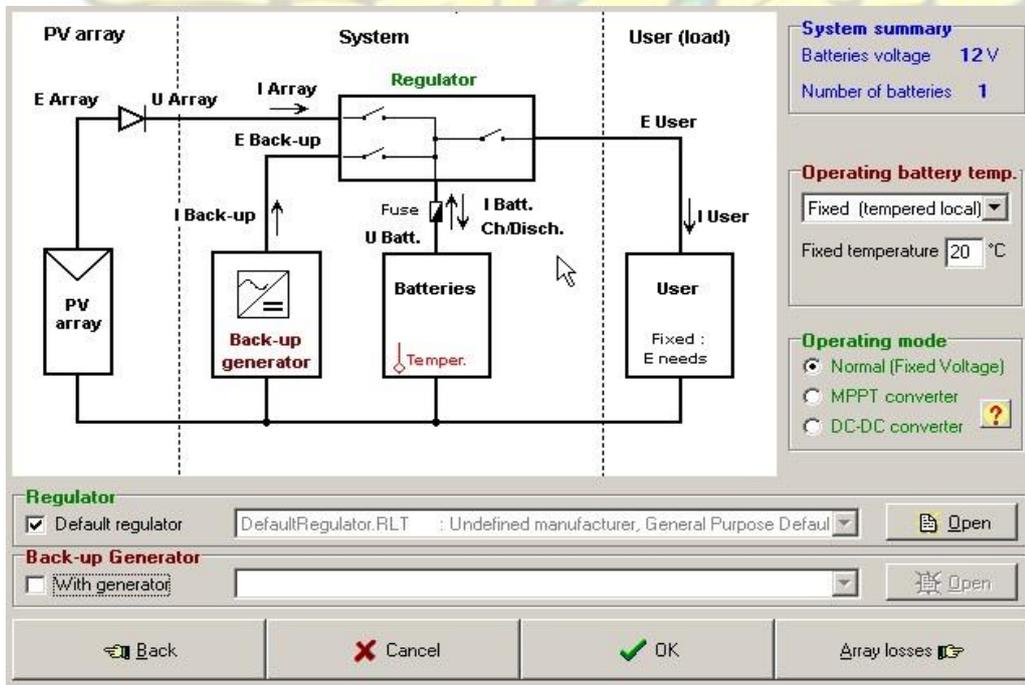


Figure 36 System Schematics from PVSYST