MAKERERE UNIVERSITY

COLLEGE OF ENGINEERING, DESIGN, ART AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

DESIGN OF RELIABLE AND SUSTAINABLE HYBRID SOLAR PV-BIOGAS MICRO-GRID FOR OFF-GRID RURAL COMMUNITIES IN UGANDA

By

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19/U/28377

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A final year project report submitted in partial fulfillment of the requirements for an award of the Degree in Bachelor of Science in Electrical Engineering at Makerere University

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DECLARATION

This report was written by Toolit Martine, a student in the Electrical and Computer Engineering department at Makerere University. It has not been altered or corrected as a result of assessment and it may contain errors and omissions. The views expressed in it together with any recommendation are those of the student.

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APPROVAL

This is to certify that the bearer, TOOLIT MARTINE, carried out his final year project with our supervision fully participating in all works. Therefore, this serves to approve his final year project report for submission to the Department of Electrical and Computer Engineering, College of Engineering Design, Art and Technology, Makerere University.

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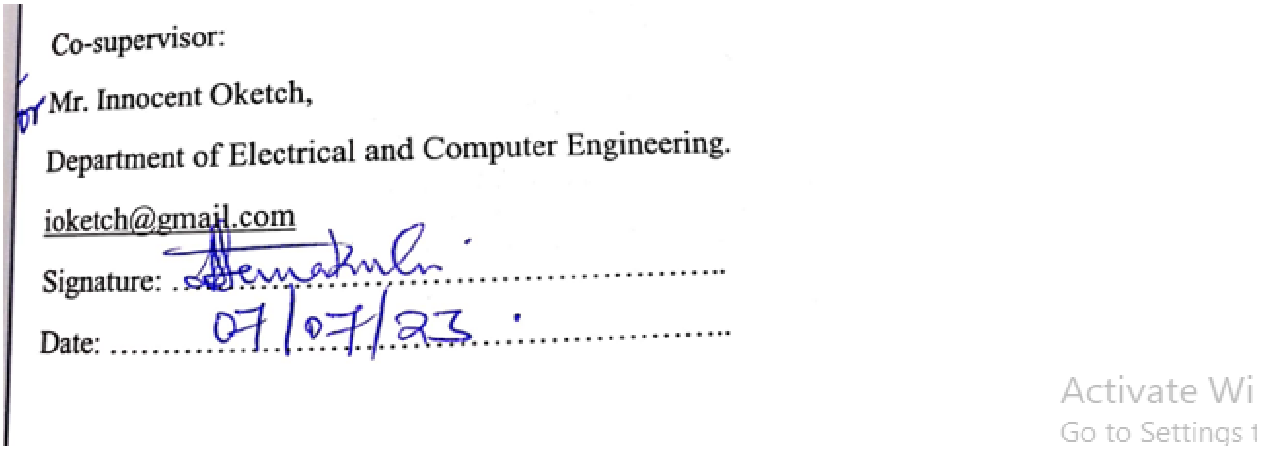

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ABSTRACT

This project aimed to design a reliable and sustainable hybrid solar PV-biogas micro-grid for off-grid rural communities in Uganda. The study used a mixed-methods approach, including a survey of energy demand in the target communities, a review of existing literature on solar PV and biogas systems, and a mathematical design analysis of the proposed microgrid. Technical analysis was then performed to design the hybrid micro-grid system, considering the integration of solar PV and biogas generator.

Study results showed that the energy demand in the target communities was primarily for lighting, maize milling, and small electrical appliances like TV screens, hoofers, shaving machines and charging mobile phones. The proposed microgrid consisted of a solar PV system with a capacity of 5 KWp and a biogas generator of Kw. The solar PV system was designed to meet the energy demand of the community during the day, while the biogas system provided backup energy during periods of low sunlight and night. The study also found that the study results showed that the target communities' energy demand microgrid had significant environmental benefits, including reduced greenhouse gas emissions and improved air quality.

To facilitate the deployment of hybrid solar PV-biogas micro-grids in off-grid rural communities in Uganda, the study proposes several recommendations. Firstly, partnerships should be established between government agencies, non-governmental organizations, and private sector entities to provide technical and financial support. Secondly, awareness campaigns and training programs should be conducted to educate the local community on the benefits and maintenance of the microgrid system. Furthermore, policy framework should be developed to incentive the adoption of renewable energy technologies and promote sustainable rural electrification.

The study concluded that a hybrid solar PV biogas microgrid has a reliable and sustainable solution for off-grid rural communities in Uganda. The study recommended further research to be conducted to optimize the design of the microgrid and explore the potential for scaling up the technology to other communities in Uganda and beyond.

Keywords: ***Renewable energy, Rural electrification, Electricity Generation, Solar Power, Biogas Power, Microgrid, Green Electricity, Green Technology*****.**

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Thank you for all your contributions, dedication, and commitment to this project. Your support has been instrumental in making this project a reality and look forward to working with you to bring our vision to life in case it’s to be implemented.

LIST OF ACRONYMS

AC:	Alternating Current.
CAES:	Compressed Air and Energy Storage.
DC:	Direct Current.
IEA:	International Energy Agency.
LCA:	Life Cycle Assessment.
PV:	Photovoltaic.
SDGs:	Sustainable Development Goals.
SPV:	Solar Photovoltaic
SSA:	Sub-Saharan Africa.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Universal access to electricity powered by renewable energy sources is considered a cornerstone of the transformation of the global energy system [1]. Indeed, reaching universal access to “affordable, reliable, sustainable and modern” energy has been explicitly recognized as a top priority for the international community with the United Nations’ Agenda 2030 in 2015 [2], as the seventh of the 17 Sustainable Development Goals (SDGs). Energy access is recognized to be fundamental for socio-economic development, and SDG 7 is positively related to most of the other SDG’s targets, with synergies outnumbering possible drawbacks [3]. Access should result in the development of productive uses of energy for their transformational impact: in fact, a revision of SDG 7 has been proposed to integrate them, which would increase the interlinkages with other SDGs [4].

So far, there has been significant progress towards the achievement of SDG 7, but there were still 840 million people without access to electricity in 2017, mostly concentrated in the rural areas of sub-Saharan Africa [5]; with current policies and forecasted population growth, it is estimated that more than 600 million people will still have no access to electricity by 2030 [6].

It is estimated that the installation of 210,000 mini-grids will be the cheapest solution for 490 million people to gain access by 2030, also thanks to declining technology costs [7]. Nevertheless, upfront costs are just one of the many barriers currently preventing the widespread development of mini-grids, such as uncertainties and gaps in the regulatory framework, non-cost community's energy demand access to finance, need for capacity building, uncoordinated electrification planning exposure to the risk of main grid arrival, lack of reliable data and the high variability of demand, among others [8] [9] [10].

A framework for rural renewable energy provision has shown that energization options, based on hybrid renewable energy systems and resources, may be the only viable option for rural village energy supply and electrification [11]. This is true for many off-grid rural communities in Africa, where the nature of the population spread has resulted in small isolated villages. Such rural settlements call for smart energy management in stand-alone decentralized off-grid renewable energy systems [12], and zero-net energy based 100% renewable energy systems in community-shared solar power solution configurations [13].

To improve access to electricity, decentralized, solar-based off-grid solutions like Solar Home Systems (SHSs) and rural microgrids have recently seen prolific growth. However, electrical load profiles, usually the first step in determining the electrical sizing of off-grid energy systems, are often non-existent or unreliable, especially when looking at the heart of under-electrified communities.

1.2 PROBLEM STATEMENT

Reaching universal access to electricity by 2030 requires a massive deployment of mini and micro-grids in rural areas of developing countries. Among the many challenges hindering this process are the high uncertainties in assessing demand patterns in rural communities, the costs of field survey campaigns, and the absence of ample and reliable datasets from existing projects. According to the International Energy Agency, in sub-Saharan Africa (SSA), most of the rural electrification is carried out by governments through the extension of the national grid which is technically challenging and expensive to implement due to the inaccessibility and sparseness of most of Sub-Saharan Africa's (SSA) rural areas.

Extending the national grid into off-grid rural areas is often not economically feasible, therefore off-grid systems will be key in seizing the access gap. When dealing with rural electrification plans, the assessment of long-term electricity demand is one of the most critical and complex steps. Indeed, wrong predictions of electricity demand could negatively impact the local socio-economic development and cause an inappropriate sizing of local energy solutions, leading to supply shortages or cost recovery failure.

We seek to address this critical gap by designing a hybrid solar PV-biogas renewable energy solution to meet the energy needs of typical rural communities based on a load profiling survey which shall be carried out to understand the nature of electrical energy consumption and demand in rural areas under various categories that cut across domestic, institutional, commercial and industrial sectors.

1.3 JUSTIFICATION AND RELEVANCE OF THE PROJECT

The availability of sustainable (reliable, affordable, and clean) energy services is critical for economic growth, poverty reduction, as well as the social and cultural transformation of society. Our proposed solution paves the way for the mass establishment of hybrid solar PV and biogas microgrids in all rural parts of Uganda where sufficient biogas feedstock is available.

The design will be used by investors, energy solutions providers, and farmers to set up hybrid solar PV-biogas microgrids with minimized risk and maximized yield. It will save them the research and development burden and enable them to reap the rewards immediately after only incurring the cost of establishment.

Therefore, the proposed solution contributes to Sustainable Development Goal (SDG) 7, which entails access to affordable, reliable, sustainable, and modern energy for all.

1.4. SCOPE OF THE PROJECT

The project will focus on the design only and will not include implementation or construction.

1.5 OBJECTIVES OF THE PROJECT

1.5.1 Main objective

To design a reliable and sustainable hybrid solar PV-biogas microgrid to meet the energy needs of typical off-grid rural communities based on a load profiling survey which shall be carried out to understand the nature of electrical energy consumption and demand in such communities.

1.5.2 Specific objectives

1. To determine the energy needs of a typical off-grid rural community.
2. To identify and select a suitable case study area based on the survey data.
3. To design and simulate a solar PV-biogas hybrid microgrid that can fulfill the energy needs of the selected case study.
4. To assess the reliability and sustainability of the system.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION TO SOLAR ENERGY

Solar energy is one of the most important types of renewable energy. The Sun, our nearest and the biggest star is the biggest source of energy to us. Sun energy or solar energy has been in use since the time human existed on the earth. Solar energy is our essential need and we need it naturally to make our life work properly. Also, we can use solar energy in different methods to get our work done properly.

2.1.1 Getting Electricity from the Sun

When certain semiconducting materials, such as certain kinds of silicon, are exposed to sunlight, they release small amounts of electricity. This process is known as the photoelectric effect. The photoelectric effect refers to the emission, or ejection, of electrons from the surface of a metal in response to light. It is the basic physical process in which a solar electric or photovoltaic (PV) cell converts sunlight to electricity. Sunlight is made up of photons, or particles of solar energy. Photons contain various amounts of energy, corresponding to the different wavelengths of the solar spectrum.

When photons strike a PV cell, they may be reflected or absorbed, or they may pass right through. Only the absorbed photons generate electricity. When this happens, the energy of the photon is transferred to an electron in an atom of the PV cell (which is a semiconductor). With its newfound energy, the electron escapes from its normal position in an atom of the semiconductor material and becomes part of the current in an electrical circuit. By leaving its position, the electron causes a hole to form. Special electrical properties of the PV cell, a built-in electric field, provide the voltage needed to drive the current through an external load (such as a light bulb).

2.2 PHOTOVOLTAIC

2.2.1 Introduction

A solar cell or photovoltaic cell (PV) is a device that converts light into electric current using the photoelectric effect. This is based on the discovery by “Aleixandre-Edmond Becquerel” who noticed that some materials release electrons when hit with rays of photons from light, which produces an electrical current.

2.2.2 The Components of PV Systems

1. **Photovoltaic Solar Cell:** The basic photovoltaic device that is the building block for PV modules.
2. **Module & Module Structure:** A group of PV cells connected in series and /or parallel and encapsulated in an environmentally protective laminate.
3. **Array:** A group of panels that comprises the complete direct current PV generating unit.

4. **Battery:** Batteries accumulate excess energy produced by the PV system and stored it to be used at night or when there is no other input. The battery capacity for holding energy is rated in amp-hours: 1 amp delivered for 1 hour = 1- amp hour.
5 **Battery Charge Controller:** The basic function of a controller is to prevent battery overcharging If batteries are allowed to routinely overcharge, their life expectancy will be dramatically reduced. A controller will sense the battery voltage, and reduce or stop the charging current when the voltage gets high enough. This is especially important with sealed batteries where we cannot replace the water that lost during overcharging. Also, the controller will protect the battery from deep discharging by disconnecting the load.
6 **Inverter:** Inverter converts DC power or direct current produced from the PV array and battery into AC electric power for use in the home, synchronizing with utility power whenever the electrical grid is distributing electricity. Inverters are available in a wide range of wattage capabilities. Efficiencies average about 95% for most models. Figure 2.2 below shows interconnections between the components.

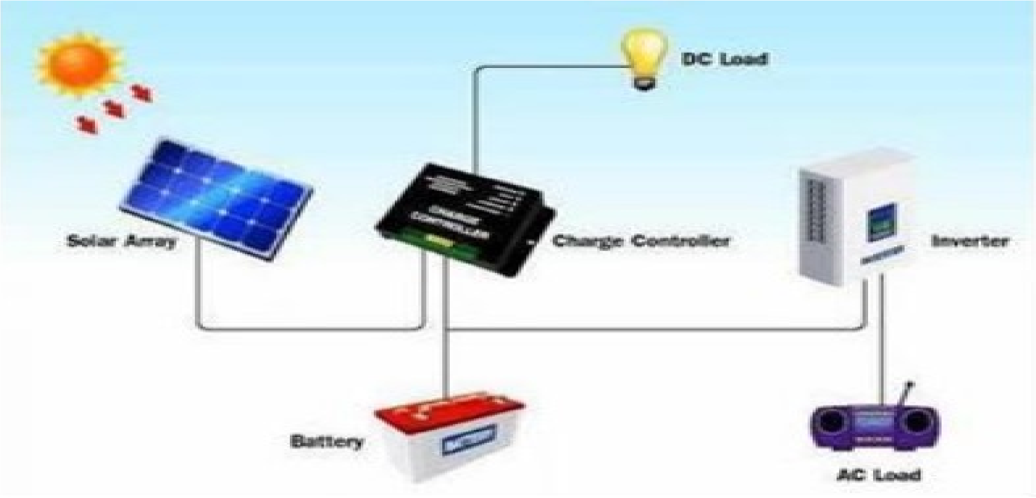


Figure 2.2 Components of the PV system

2.2.3 How Does a Solar PV System Work?

The photoelectric conversion in the PV junction. PV junction (diode) is a boundary between two differently doped semiconductor layers; one is a Type layer (excess holes), and the second one is an N-type (excess electrons). At the boundary between the P and the N area, there is a spontaneous electric field, which affects the generated electrons and holes and determines the direction of the current.

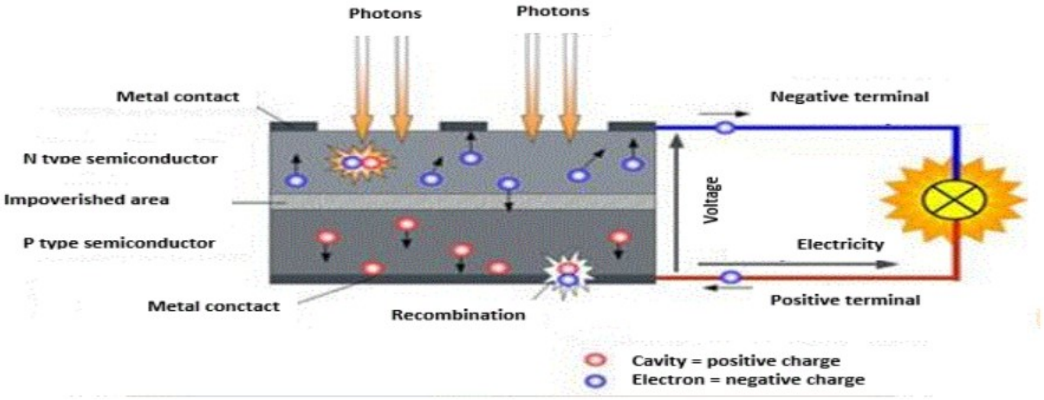


Figure 2.3 Working of Solar PV

2.2.4 Classification of PV Systems

I. **Stand-Alone:** These systems are isolated from the electric distribution grid. Fig. 2.4 describes the most common system configuration. The system described in Fig.2.4 is one of the most complex; and includes all the elements necessary to serve AC appliances in a common household or commercial application.

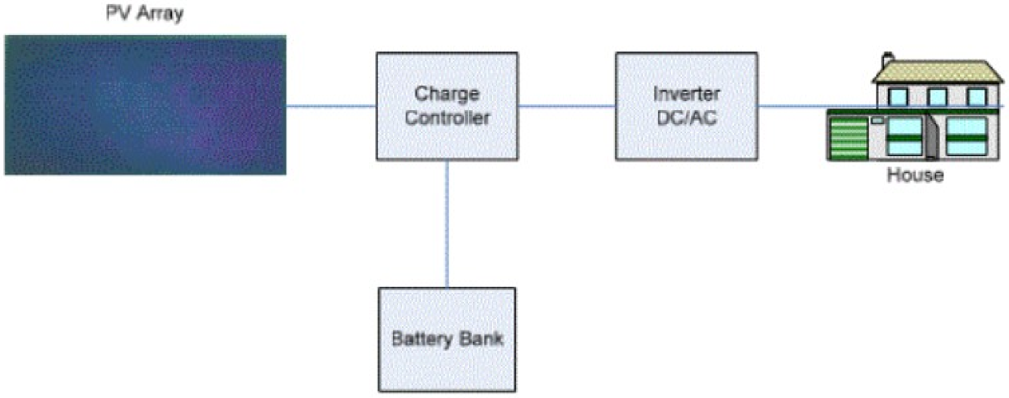


Figure 2.4 Standalone PV system

II. **Grid Connected:** These systems are directly coupled to the electric distribution network and do not require battery storage. Hybrid systems may be possible where battery storage or a generator (or both) can be combined with a grid connection for additional reliability and scheduling flexibility (at additional cost). Most of the installed residential, commercial and central-scale systems use pre-fabricated flat-plate solar modules because they are widely available.

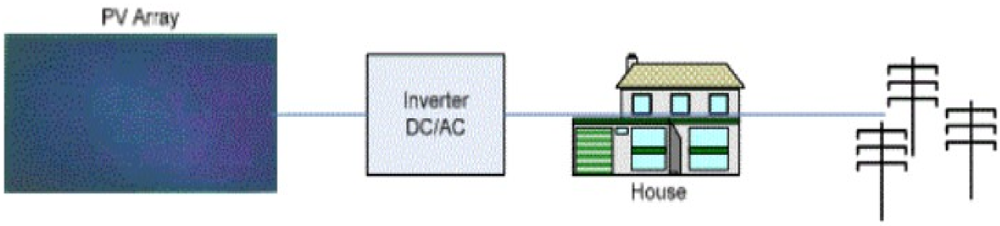


Figure 2.5 Grid-connected PV system

2.2.5 Photovoltaic PV modules

There are three dominating cell technologies:

- **Monocrystalline:** As the name implies, these are cells that are grown from a single crystal. The production methods are difficult and expensive. These tend to be more efficient (more power in less area) and more expensive.
- **Polycrystalline:** The production process allows multiple crystalline structures to develop within the cell. It is easier to implement in a production line. It is relatively cheaper than mono-crystalline at the expense of lower efficiency.
- **Thin-film:** Uses less silicon to develop the cell (hence the name thin film) allowing for cheaper production costs (silicon is in high demand). It tends to be less expensive but has also lower efficiency.

Figure 2.6 Types of PV Panels

2.2.6 Benefits of a photovoltaic system

1. Photovoltaic cells are highly reliable and easy to maintain. PV cells have no moving parts, so visual checks and servicing are enough to keep systems up and running.
2. Solar panels are built to withstand hail impact, high wind, and freeze-thaw cycles. PV systems can produce power in all types of weather. On partly cloudy days, they produce as much as 80% of their potential energy. Even on extremely cloudy days, they can still produce about 25 % of their maximum output.

3. Photovoltaic cells have virtually no environmental impact. PV cells burn no fuel and have no moving parts. They are clean and silent, producing no atmospheric emissions of greenhouse gases that are harmful to the Earth.
4. Photovoltaic cells strengthen our economy and reduce the trade deficit and Using PV cells protects us from fuel price volatility and political instability.
5. . Photovoltaic cells are modular and flexible in terms of size and applications, PV cells can be built to any size in response to the energy needs at hand and they can be enlarged or moved easily.
6. Serves both form and function in a building. State-of-the-art PV modules are available in a variety of colors and styles, allowing designers to use them as aesthetic elements built right into roofs, skylights, awnings, entryways, and facades. Modules can be built to transmit natural light. Mixed with non-trans missive modules, these arrangements create an enjoyable environment inside the building, simultaneously facilitating ventilation and heating.

2.2.7 Disadvantages of Solar PV

1. As in all renewable energy sources, solar energy has intermittency issues; not shining at night but also during the daytime there may be cloudy or rainy weather.
2. Consequently, intermittency and unpredictability of solar energy makes solar energy panels less reliable a solution.
3. Solar energy panels require additional equipment (inverters) to convert direct electricity (DC) to alternating electricity (AC) to be used on the power network.
4. For a continuous supply of electric power, especially for on-grid connections, Photovoltaic panels require not only Inverters but also storage batteries; thus, increasing the investment cost for PV panels considerably.
5. In case of land-mounted PV panel installations, they require relatively large areas for deployment; usually the land space is committed for this purpose for a period of 15-20 years – or even longer.
6. Solar panels efficiency levels are relatively low (between 14% - 25%) compared to the efficiency levels of other renewable energy systems.
7. Though PV panels have no considerable maintenance or operating costs, they are fragile and can be damaged relatively easily; additional insurance costs are therefore of ultimate importance to safeguard a PV investment.

2.3 PV MODELING

2.3.1 Introduction

A photovoltaic system converts sunlight into electricity. The basic device of a photovoltaic system is the photovoltaic cell shown in figure 2.7. Cells may be grouped to form panels or modules. Panels can be grouped to form large photovoltaic arrays. The term array is usually employed to describe a photovoltaic panel (with several cells connected in series and/or parallel) or a group of panels. Most of the time one is interested in modeling photovoltaic panels, which are the commercial photovoltaic devices.

The term array used henceforth means any photovoltaic device composed of several basic cells. The electricity available at the terminals of a photovoltaic array may directly feed small loads such as lighting systems and DC motors. Some applications require electronic converters to process the electricity from the photovoltaic device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid-connected systems and mainly to track the maximum power point (MPP) of the device.

Photovoltaic arrays present a nonlinear I -V characteristic with several parameters that need to be adjusted from experimental data of practical devices. The mathematical model of the photovoltaic array may be useful in the study of the dynamic analysis of converters, in the study of maximum power point tracking (MPPT) algorithms and mainly to simulate the photovoltaic system and its components using circuit simulators.

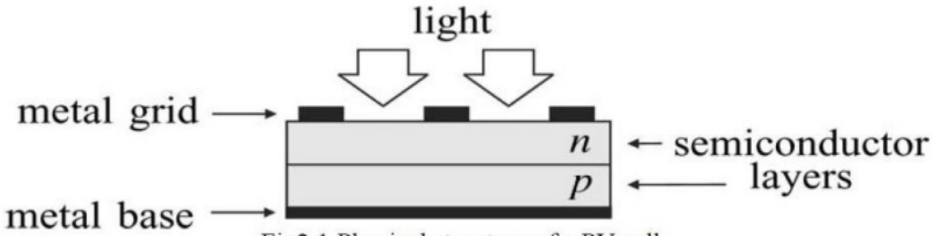


Figure 2.7 Physical Structure of PV Cell

2.3.2 Model of The Photovoltaic Cell

A PV cell is a semiconductor p-n intersection that transforms sunlight to electrical power. To model a solar cell, it is imperative that we assess the effect of different factors on the solar panels and to consider the characteristics given by the manufacturers in the datasheet. It is to be noted that to form a PV module, a set of cells are connected in series or in parallel. To form a PV array, a set of PV modules are connected in series and in parallel. Thus, the mathematical models for the PV array are attained while utilizing the basic description equivalent circuit of the PV cells.

A PV cell is usually embodied by an electrical equivalent of one diode, resistance series Rs and resistance parallel Rp as shown in Figure 2.8.

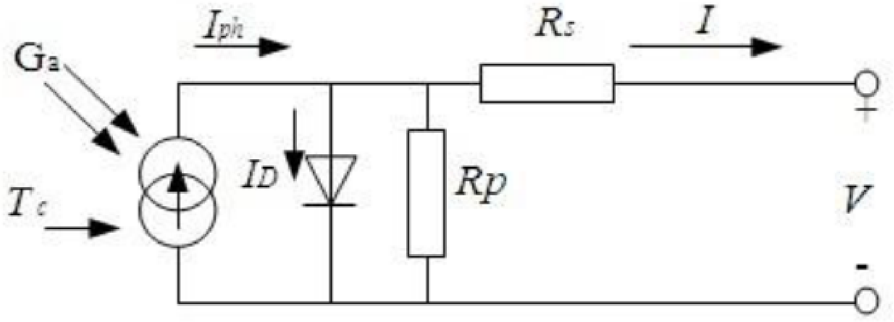


Figure 2.8 Equivalent circuit of solar cell with one diode

From the figure2.8, the different parameters characteristics of the PV cells are:

I_{ph}: currents generated by the solar cells (A), **R**s: resistance series (Ω), **R_p**: resistance parallel (Ω), **G_a**: irradiance from the sunlight (W/m2), **T**: cell temperature (K). Id: diode current (A), **I**: output current of the PV (A), **V**: output voltage of the PV (V).

Manufacturer of the solar module gives the parameters needed to model the solar cells. The data sheet which gives the electrical characteristics is calculated under standard test condition STC when the temperature T is 25°C and the irradiance G is 1000 W/m2. The parameters that can be found inside the datasheet are:

Vop: open circuit voltage, **I**sc: short-circuit current (A), **P**mp: power at the maximum power point, **V**mp: voltage at maximum power point, **I**mp: current at maximum power point.

The solar cell is modeled first, then extends the model to a PV module, and finally models the PV array. From figure2.8, the output current of the PV cell is given in equation 2.1 below:

$$I = I_{ph} - I_d \qquad 2.1$$

Where:

Iph: photon produced by the cell and **I**d: diode current

By Shockley equation, the diode current Id is given by equation 2.2:

$$\boldsymbol{I_d} = \boldsymbol{I_o}(\boldsymbol{e}\,\frac{\mathbf{qVd}}{\mathbf{KT}} - \mathbf{1}) \qquad 2.2$$

Where:

Io: reverse saturation current of diode, **q**: elementary electron charge (1.602x10-19 C), **V_d**: diode voltage, **K**: Boltzmann constant 1.381x10-23 (J/K), **T**: temperature in Kelvin (K).

The relation between voltage and current result by replacing the diode Current is given by equation 2.3.

$$\boldsymbol{I} = \boldsymbol{I_{ph}} - \boldsymbol{I_o}(\boldsymbol{e}\frac{\mathrm{qVd}}{\mathrm{KT}} - \mathbf{1}) \qquad 2.3$$

Where: **V**d is the output voltage of the PV cell. The reverse saturation Io is found by using the above equation. By setting the current I equal to zero and calculating at temperature T1 [14] as shown by equation 2.4.

$$\boldsymbol{I_o}(\boldsymbol{T_1}) = \frac{\mathrm{Iph(T1)}}{(\mathrm{e\ qVoc/KT} - 1)} \qquad 2.4$$

The current generated by the solar cells Iph can be approximated with the short circuit current Isc in [15]. The current generated can be calculated for another irradiance. The standard current, temperature and irradiance from the datasheet are used to determine the current at different condition as shown by equations 2.5 and 2.6.

$$I_{sc} \cong I_p \qquad 2.5$$

$$I_{sc}(T_1) = (\frac{G}{Gnom}) I_{sc}(T_1.nom) \qquad 2.6$$

Where:

Isc (T1): current at temperature T1, **T_1**nom: the temperature of cell from datasheet at STC, **G**nom: irradiance from datasheet at STC.

After calculation, equation 2.7 gives the equation of the PV:

$$I_{ph} - I_o[e\ q(\frac{V+I.Rs}{aKT})\ ] - (\frac{V + I.Rs}{Rs}) \qquad 2.7$$

Where: a is diode quality factor between 1 and 2 and must be estimated. The value of "a" is equal to 1 for ideal diode. V is the cell voltage. For a PV module, the cell voltage is multiplied by the total amount of the cells found within the series. The reverse saturation current I0 depends on the temperature T. It is calculated by the following equation 2.8 [16]:

$$I_o = I_o(T_1)\ (\frac{T}{T1})^{3/n} * e\ [\frac{qVq(T1)}{aK(\frac{1}{T} - \frac{1}{T1})}] \qquad 2.8$$

The value of resistance series Rs is quantified from the slope dV/dI Of the I-V curve at the point open circuit voltage. The equation R is given by equation 2.9 below:

$$R_s = -\frac{dV}{dI} - \frac{aKT/q}{Io * e\ (\frac{qVoc}{aKt})} \qquad 2.9$$

The model is completed by using the following recursive equations to find the currents [14]. The recursive equation is used to calculate the current for a PV cell. It is more convenient to solve numerically. The equation introduces a simplified method to calculate resistance series and neglect the resistance parallel

$$I_{n+1} = I_n - \frac{Iph - In - Io\ [\ e\ {}^\wedge q(\frac{v+In.Rs}{aKt}) - 1\ ]}{-1 - Io((\frac{q.Rs}{aKt})e{}^\wedge q(\frac{v+In.Rs}{aKt})} \qquad 2.10$$

Where: **I_{n+1}**: is the current for one PV cell.

2.3.3 Model of the Photovoltaic module

The following model uses different method to calculate the resistance series and resistance parallel. For example, the s320p36 Ultra is made of36 solar cells (silicon nitride multi crystalline) in series and provides 80Wof nominal maximum power. The maximum power point's voltage is 17.9 V and current delivered at maximum power point is 4.48 A.

The following equation developed in [3] will be used mainly in this report. The model consists of finding the curve characteristic of the PV module from the datasheet. The equation used to calculate the I-V curve is shown by equation 2.11:

$$\boldsymbol{I} = \boldsymbol{I_{ph}} - \boldsymbol{I_o}\,[\boldsymbol{e}\ \boldsymbol{q}(\frac{\mathbf{V + I.Rs}}{\mathbf{NsKTa}}) - \mathbf{1}] - (\frac{\mathbf{V + I.Rs}}{\mathbf{Rp}}) \qquad 2.11$$

Where: **N**s: number of cells in series. The thermal voltage of the module with Ns cells connected in series is defined by equation 2.12.

$$\boldsymbol{V_t} = \frac{\mathbf{NsKT}}{\mathbf{q}} \qquad 2.12$$

The current produced Iph is linearly dependent of the solar radiation and the Temperature as shown by equation 2.13.

$$\boldsymbol{I_{ph}} = \boldsymbol{I_{ph.\,nom}} + \boldsymbol{Ki}\Delta\boldsymbol{T}(\frac{\mathbf{G}}{\mathbf{Gnom}}) \qquad 2.13$$

Where: Ki: temperature coefficient current, ΔT: variation temperature.

The diode saturation current I_0 and the reliance on the temperature can be Seen through equation 2.14 and 2.15 below.

$$\boldsymbol{I_o} = \boldsymbol{I_{o.\,n}}(\frac{\mathbf{T}}{\mathbf{Tnom}})^3\,\boldsymbol{exp}\,[\,(\frac{\mathbf{qEg}}{\mathbf{ak}})(\frac{\mathbf{1}}{\mathbf{Tnom}} - \frac{\mathbf{1}}{\mathbf{T}})] \qquad 2.14$$

$$\boldsymbol{I_{o.\,n}} = \frac{\mathbf{Isc.n}}{\mathbf{exp}\,(\frac{\mathbf{Voc.n}}{\mathbf{aVt.aVt.n}}) - \mathbf{1}} \qquad 2.15$$

The series resistance Rs is calculated by determining the slope dV/dI of the I-V curve at the Voc . By differentiating the equation, Rs become as shown by equation 2.16 below [14].

$$\boldsymbol{R_s} = \frac{\mathbf{dV}}{\mathbf{dI}} - \frac{\frac{\mathbf{nK}T}{\mathbf{q}}}{\mathbf{Io.\ e\ q}(\frac{\mathbf{v+I.Ra}}{\mathbf{aKt}})} \qquad 2.16$$

At the open circuit voltage, voltage V is equal to the open circuit voltage Voc with I equal to zero. The resistance series is shown by equation 2.17:

$$\boldsymbol{R_s} = \frac{\mathbf{dV}}{\mathbf{dI}} - \frac{\frac{\mathbf{nK}T}{\mathbf{q}}}{\mathbf{Io.\ e}\,(\frac{\mathbf{q}Voc}{\mathbf{aKt}})} \qquad 2.17$$

Where: dv/di is slope of the I-V curve at the Voc. In some situations, Rp is neglected.

In [17], Rs and Rp are calculated iteratively. The goal is to find the values of Rs and Rp that makes the mathematical P-V curve coincide with the experimental peak power at the (Vmp, Imp) point.

The value of Rs and Rp are reached when the iteration stopped for Pmax calculated is equal to Pmax estimated.

2.4 PHOTOVOLTAIC OUTPUT CHARACTERISTICS

2.4.1 The I-V and P-V characteristics

Each solar cell has its own voltage- current (V-I) characteristic. Figure2.9 shows the V-I characteristic of a typical photovoltaic cell. The problem with extracting the most possible power from a solar panel is due to nonlinearity of the characteristic curve. The characteristic shows two curves, one shows the behavior of the current with respect to increasing voltage. The other curve is the power voltage curve and is obtained by the equation (P=I*V).

When the P-V curve of the module is observed, one can locate single maximum of power where the solar panel operates at its optimum. In other words, there is a peak power that corresponds to a particular voltage and current. Obtaining this peak power requires that the solar panel operate at or very near the point where the P-V curve is at the maximum. However, the point where the panel will operate will change and deviate from the maximum constantly due to changing ambient conditions such as isolation or temperature levels, which we will discuss further. The result is a need for a system to constantly track the P-V curve to keep the operating point as close to the maximum as much as possible while energy is extracted from the PV array.

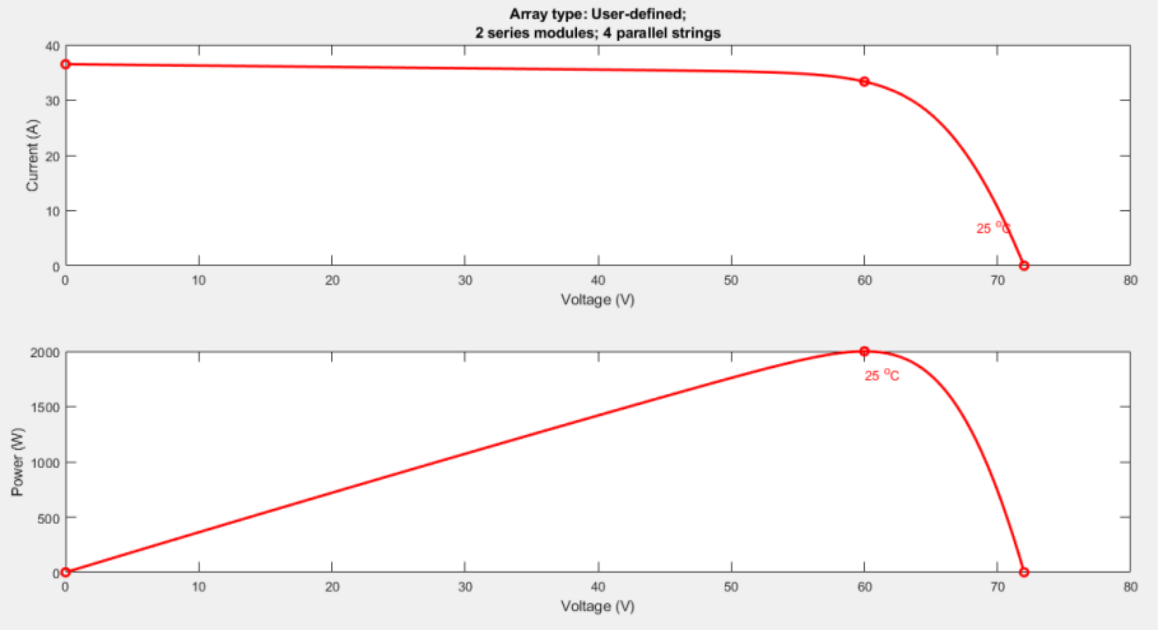


Figure 2.9 Solar Panel V-I Characteristic and power curve

2.4.2 Effects of Irradiance

Solar panels are only as effective as the amount of energy they can produce. Because solar panels rely on conditions that are never constant, the amount of power extracted from a PV module can be very in consistent. Irradiance is an important changing factor for a solar array performance. It is a characteristic that describes the density of radiation incident on a given surface. In terms of PV modules, irradiance describes the amount of solar energy that is absorbed by the array over its area. Irradiance is expressed typically in watts per square meter (W/m2). Given ideal conditions, a solar panel should obtain an irradiance of (100mW/cm2, or 1000W/m2).

Unfortunately, this value that is obtained from a solar panel will vary greatly depending on geographic location, angle of the sun, or the amount of sun that is blocked from the panel because of any present clouds or haze. Although artificial lighting can be used to power a solar panel, PV modules derive most of their energy solely from the energy emitted from the sun. Therefore, changes of irradiance will greatly affect a PV module's performance.

Fig.2.10. shows the effect of irradiance on the output of solar panels. Clearly, a smaller level of irradiance will result in a reduced output. The change in output current is due to the reduced flux of the photons that move within a cell, as we have discussed when observing the operation of a solar cell. We can see that the voltage and open circuit voltage is not substantially affected due to changing levels of irradiance. In fact, the changes made to voltage due to irradiance are often seen as trivial and independent of the changing flux of photons.

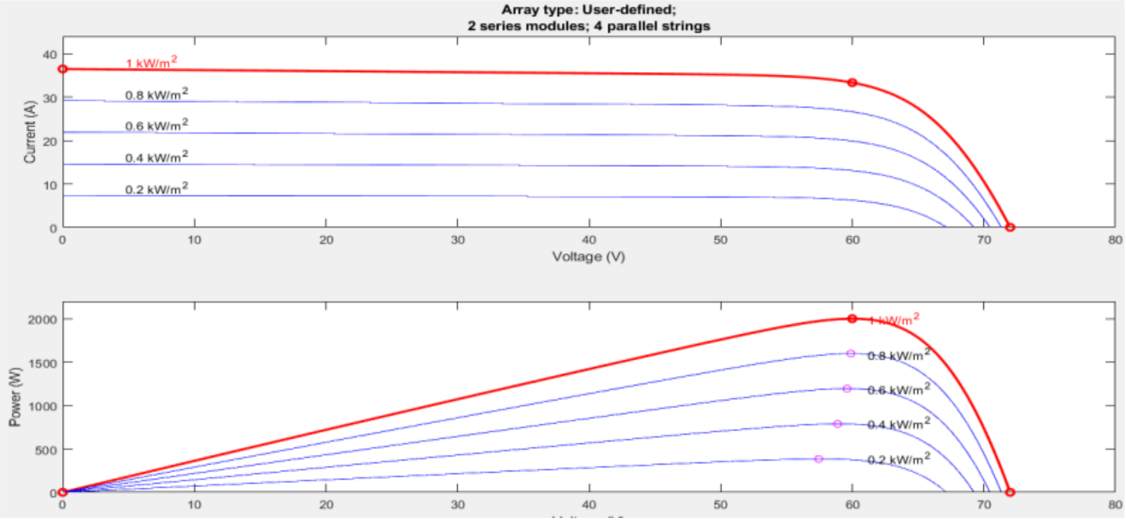


Figure 2.10 I-V and P-V Characteristics of the PV at Various irradiance

2.4.3 Effects of Temperature

A PV module's temperature has a great effect on its performance. Although the temperature is not as an important factor as the duration and intensity of sunlight it is very important to observe that at high temperatures, a PV module's power output is reduced. The temperature of a PV module also affects its efficiency. In general, a crystalline silicon PV module's efficiency will be reduced about 0.5 percent for every degree C increase in temperature.

PV modules are usually rated at module temperatures of 25°C (77°F) and seem to run about 20°Cover the air temperature. This means that on a hot day of 100°F, the module will operate at 120°F, or 50°C, and so will have its power reduced by approximately 12.5%. Fig.2.11.

demonstrates the effect of varying temperature on the output of a solar panel. One can easily see a voltage drop with increasing heat. The effect of varying temperature does not have a very large effect on the current developed.

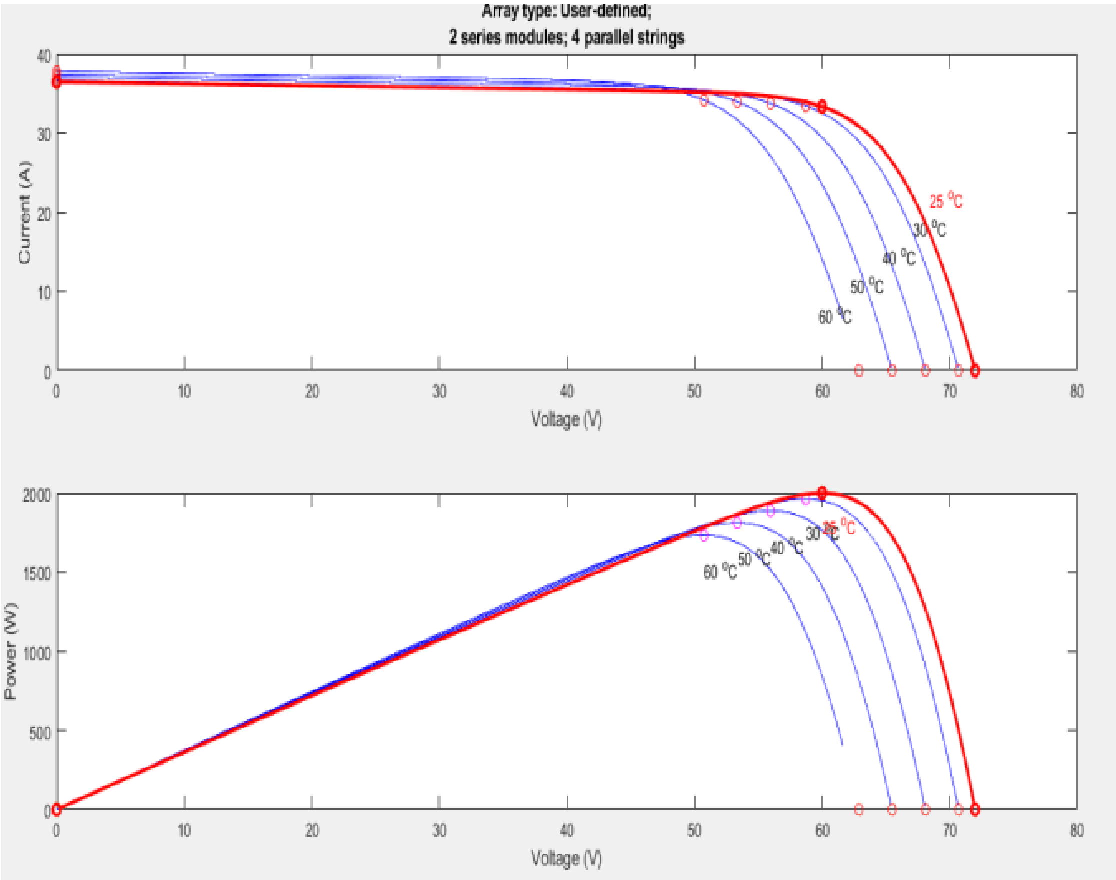


Figure 2.11 Temperature effect on solar panel power and I-V curves

2.5 BATTERIES

2.5.1 Introduction

This section presents a literature review about batteries in PV systems. Batteries experience a wide range of operational conditions in PV applications, including varying rates, of charge and discharge, frequency and depth of discharges, temperature fluctuations, and the methods and limits of charge regulation. These variables make it very difficult to accurately predict battery performance and lifetime in PV systems.

2.5.2 Battery Types and Classifications

Many types and classifications of batteries are manufactured today, each with specific design and performance characteristics suited for particular applications. Each battery type or design has its individual strengths and weaknesses. In PV systems, lead-acid batteries are most common as we said before, due to their wide availability in many sizes, low cost and well understood performance characteristics. In a few critical, low temperature applications nickel cadmium cells are used, but their high initial cost limits their use in most PV systems. There is no “perfect battery” and it is the task of the PV system designer to decide which battery type is most appropriate for each application. In general, electrical storage batteries can be divided into two major categories, primary and secondary batteries.

2.5.2.1 Primary Batteries

Primary batteries can store and deliver electrical energy, but cannot be recharged. Typical carbon-zinc and lithium batteries commonly used in consumer electronic devices are primary batteries. Primary batteries are not used in PV systems because they cannot be recharged.

2.5.2.2 Secondary Batteries

A secondary battery can store and deliver electrical energy, and can be recharged by passing a current through it in an opposite direction to the discharge current. Common lead acid batteries used in automobiles and PV systems and lithium – ion batteries that used in laptops and mobile phones are secondary batteries. Typical lithium-ion batteries are shown in figure 2.12 below.

Figure 2.12 Lithium-ion and lead acid Batteries

I. Lead Acid Batteries

Many types of lead-acid batteries are used in PV systems, each having specific design and performance characteristics. While there are many variations in the design and performance of lead-acid cells, they are often classified in terms of one of the following three categories:

a) **SLI Batteries:** Starting, lighting and ignition (SLI) batteries are a type of lead-acid battery designed primarily for shallow cycle service, most often used to power automobile starters. These batteries have a number of thin positive and negative plates per cell, designed to increase the total plate active surface area. The large number of plates per cell allows the battery to deliver high discharge currents for short periods. While they are not designed for long life under deep cycle service, SLI batteries are sometimes used for PV systems in developing countries where they are the only type of battery locally manufactured. Although not recommended for most PV applications, SLI batteries may provide up to two years of useful service in small stand-alone PV systems where the average daily depth of discharge is limited to 10- 20%, and the maximum allowable depth of discharge is limited to 40-60%.

b) **Motive Power or Traction Batteries:** Motive power or traction batteries are a type of lead acid battery designed for deep discharge cycle service, typically used in electrically operated vehicles and equipment such as golf carts, fork lifts and floor sweepers. These batteries have a fewer number of plates per cell than SLI batteries, however the plates are much thicker and constructed more durably. High content lead antimony grids are primarily used in motive power batteries to enhance deep cycle performance. Traction or motive power batteries are very popular for use in PV systems due to their deep cycle capability, long life, and durability of the design.

c) **Stationary Batteries:** It is commonly used in un-interruptible power supplies (UPS) to provide backup power to computers, telephone equipment, and other critical loads or devices.

Types of lead-acid batteries manufactured:

1. **Flooded cell type battery:** In flooded batteries the electrodes are completely submerged in the electrolyte of flooded batteries to a full state of charge, hydrogen and During charging oxygen gases produced from water by the chemical reaction at negative and positive platepasses out through vents of the battery. This necessitates the periodic water addition to the battery.
2. **Sealed /Gel type battery:** In Gelled batteries The addition of silicon dioxide to the electrolyte forms warm liquid which is added to the battery and become gel after cooling. The hydrogen and oxygen produced during charging process are transported between positive and negative plates through the cracks and voids in the gelled electrolyte during the process of charge and discharge.

   This type of lead acid batteries is suitable for PV applications because of the following reasons:
   - ✓ Easy transportation.
   - ✓ Suitable for remote applications because of less maintenance requirement.
   - ✓ No need for water additions.
3. **Absorbed GLASS MAT [AGM] batteries:** In AGM batteries the glass mats are sandwiched between plates. These glass plates absorb the electrolyte. The oxygen molecules from positive plate moves through the electrolyte in the glass mats and recombine hydrogen at the negative plate to form water used to eliminate acid spilling.

II. Lithium – ion batteries:

The energy density of Li-ion batteries is 3 times that of Pb acid batteries. The cell voltage will be 3.5V, and few cells in series will give the required battery voltage. The lithium electrode reacts with the electrolyte creates a passivation film during every discharge and charge operation. This is compensated by the usage of thick electrodes. Because of this fact the cost of Li-ion battery is higher than NiCd batteries. Extra overcharging damages the battery. It has the following characteristics.

III. Nickel-Cadmium Batteries:

Nickel-cadmium (Ni-Cad) batteries are secondary, or rechargeable batteries, and have several advantages over lead-acid batteries that make them attractive for use in standalone PV systems. These advantages include long life, low maintenance, survivability from excessive discharges, excellent low temperature capacity retention, and non-critical voltage regulation requirements. The main disadvantages of nickel- cadmium batteries are their high cost and limited availability compared to lead-acid designs.

A typical nickel-cadmium battery is shown below. Its cell consists of positive electrodes made from nickel hydroxide (NiO (OH)) and negative electrodes made from cadmium (Cd) and immersed in an alkaline potassium hydroxide (KOH) electrolyte solution. When a nickel-cadmium cell is discharged, the nickel hydroxide changes form (Ni $(OH)_2$) and the cadmium becomes cadmium hydroxide (Cd $(OH)_2$). The concentration of the electrolyte does not change during the reaction so the freezing point stays very low.

Figure 2.13 Nickel-Cadmium Batteries

2.5.3 Factors that affects batteries life time:

1. **Self-discharge**: Disposable batteries typically lose 8 to 20 percent of their original charge per year when stored at room temperature (20–30 °C). This is known as the "self-discharge" rate, and is due to non-current-producing "side" chemical reactions that occur within the cell even when no load is applied. The rate of side reactions is reduced for batteries stored at lower temperatures, although some can be damaged by freezing. Old rechargeable batteries self-discharge more rapidly than disposable alkaline batteries, especially nickel-based batteries; a freshly charged nickel cadmium (NiCd) battery loses 10% of its charge in the first 24 hours, and thereafter discharges at a rate of about 10% a month. However, newer low self-discharge nickel metal hydride (NiMH) batteries and modern lithium designs display a lower self-discharge rate (but still higher than for primary batteries.
2. **Corrosion:** Internal parts may corrode and fail, or the active materials may be slowly converted to inactive forms.
3. **Physical component changes:** The active material on the battery plates changes chemical composition on each charge and discharge cycle; active material may be lost due to physical changes of volume, further limiting the number of times the battery can be recharged. Most nickel-based batteries are partially discharged when purchased, and must be charged before first use. Newer NiMH batteries are ready to be used when purchased, and have only 15% discharge in a year.

Some deterioration occurs on each charge–discharge cycle. Degradation usually occurs because electrolyte migrates away from the electrodes or because active material detaches from the electrodes. Low-capacity NiMH batteries (1,700 – 2,000 mAh) can be charged some 1,000 times, whereas high-capacity NiMH batteries (above 2,500 mAh) last about 500 cycles. NiCd batteries tend to be rated for 1,000 cycles before their internal resistance permanently increases beyond usable values.

4. **Charge/discharge speed**: Fast charging increases component changes, shortening battery lifespan.
5. **Overcharging**: If a charger cannot detect when the battery is fully charged then overcharging is likely, damaging it.
6. **Environmental conditions:** Automotive lead–acid rechargeable batteries must endure stress due to vibration, shock, and temperature range. Because of these stresses and sulfating of their lead plates, few automotive batteries last beyond six years of regular use. Automotive starting batteries have many thin plates to maximize current. In general, the thicker, the plates and the longer life. They are typically discharged only slightly before recharge.
   "Deep-cycle" lead–acid batteries such as those used in electric golf carts have much thicker plates to extend longevity. The main benefit of the lead–acid battery is its low cost; its main drawbacks are large size and weight for a given capacity and voltage. Lead–acid batteries should never be discharged to below 20% of their capacity, because internal resistance will cause heat and damage when they are recharged. Deep-cycle lead–acid systems often use a low-charge warning light or a low-charge power cut-off switch to prevent the type of damage that will shorten the battery's life.
7. **Storage**: Battery life can be extended by storing the batteries at a low temperature, as in a refrigerator or freezer, which slows the side reactions. Such storage can extend the life of alkaline batteries by about 5%; rechargeable batteries can hold their charge much longer, depending upon type. To reach their maximum voltage, batteries must be returned to room temperature; discharging an alkaline battery at 250 mA at 0 °C is only half as efficient as at 20 °C. Alkaline battery manufacturers such as Duracell do not recommend refrigerating batteries.

2.5.4 Deep-cycle battery

A deep-cycle battery is a battery designed to be regularly deeply discharged using most of its capacity. The term is traditionally mainly used for lead–acid batteries in the same form factor as automotive batteries; and contrasted with starter or 'cranking' automotive batteries designed to deliver only a small part of their capacity in a short, high-current burst for cranking the engine.

For lead-acid deep-cycle batteries there is an inverse correlation between the depth of discharge (DOD) of the battery and the number of charge and discharge cycles it can perform; with an average "depth of discharge" of around 50% suggested as the best for storage vs cost.

The structural difference between deep-cycle and cranking lead-acid batteries is in the lead battery plates. Deep cycle battery plates have thicker active plates, with higher-density active paste material and thicker separators. Alloys used for the plates in a deep cycle battery may contain more antimony than that of starting batteries. The thicker battery plates resist corrosion through extended charge and discharge cycles.

Deep-cycle lead-acid batteries generally fall into two distinct categories; flooded (FLA) and valve-regulated lead-acid (VRLA), with the VRLA type further subdivided into two types, Absorbed Glass Mat (AGM) and Gel. The reinforcement of absorbed glass mat separators helps to reduce damage caused by spilling and jolting vibrations. Further, flooded deep-cycle batteries can be divided into subcategories of Tubular-plated or flat plated. The difference generally affects the cycle life and performance of the cell.

2.5.5 DOD and SOC

Depth of Discharge (DOD) is the fraction or percentage of the capacity which has been removed from the fully charged battery. Conversely, the State of Charge (SOC) is the fraction or percentage of the capacity is still available in the battery. It is similar to considering whether a bucket (or drinking glass) is half empty or half full.

The following table 2.1 shows the simple relationship between these two scales:

Table 2.1 The simple relationship between SOC and DOD

SOC%	**DOD %**
100	0
75	25
50	50
25	75
0	100

However, these states of charge/depth of discharge scales are normally referred to the nominal capacity (e.g., the capacity at the 10-hour rate). For lower discharge currents you may see references to a DOD of more than 100%. This simply means that the battery can produce more than 100% of its nominal capacity at discharge rates lower than the nominal rate. The relationship is shown in figure 2.14 below.

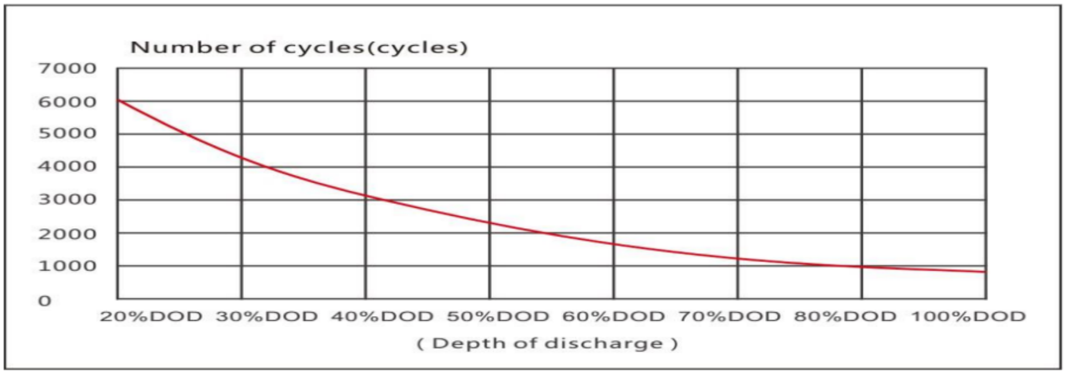


Figure 2.14 DOD and Number of cycles relationship

2.6 INVERTERS

Dc-to-ac converters are known as inverters. The function of an inverter is to change a dc input voltage to a symmetric ac output voltage of desired magnitude and frequency. The output voltage could be fixed or variable at a fixed or variable frequency. A variable output voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand, if the dc input voltage is fixed and it is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by pulse-width modulation (PWM) control within the inverter.

The inverter gain may be defined as the ratio of the ac output voltage to dc input voltage. The output voltage waveforms of ideal inverters should be sinusoidal. However, the waveforms of practical inverters are non-sinusoidal and contain certain harmonics. For low- and medium-power applications, square-wave or quasi-square wave voltages may be acceptable; for high-power applications, low distorted sinusoidal waveforms are required. With the availability of high-speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by switching techniques. Inverters are widely used in industrial applications (e.g., variable-speed ac motor drives, renewable energy, transportation, induction heating, standby power supplies, and uninterruptible power supplies).

The input may be a battery, fuel cell, solar cell, or other dc source. The typical single-phase outputs are (1) 120 V at 60 Hz, (2) 220 V at 50 Hz, and (3) 115 V at 400 Hz. For high-power three phase systems, typical outputs are (1) 220 to 380 V at 50 Hz, (2) 120 to 208 V at 60 Hz, and (3) 115 to 200 V at 400 Hz. Inverters can be broadly classified into two types: (1) single-phase inverters and (2) three-phase inverters. Each type can use controlled turn-on and turn-off devices (e.g., bipolar junction transistors [BJTs], metal oxide field-effect transistors [MOSFETs], insulated-gate bipolar transistors [IGBTs], metal oxide semiconductor-controlled thyristors [MCTs], static induction transistors, [SITs], and gate-turn-off thyristors [GTOs]). These inverters generally use PWM control signals for producing an ac output voltage. An inverter is called a voltage-fed inverter (VFI) if the input voltage remains constant, a current-fed inverter (CFI) if the input current is maintained constant, and a variable dc linked inverter if the input voltage is controllable. If the output voltage or current of the inverter is forced to pass through zero by creating an LC resonant circuit, this type of inverter is called resonant pulse inverter, and it has wide applications in power electronics.

1.7 DC-DC CONVERTERS

1.7.1 Introduction

A dc-dc converter converts directly from dc to dc and is simply known as a dc converter. A dc converter can be considered as dc equivalent to an ac transformer. A dc-dc converter can be used to step down or step up a dc voltage source. Dc converters are widely used for traction motor control in electric automobiles, trolley cars, marine hoists, forklift trucks, and mine haulers. They provide smooth acceleration control, high efficiency, and fast dynamic response.

Dc converters can be used in regenerative braking of dc motors to return energy back into the supply, and this feature results in energy savings for transportation systems with frequent stops. Dc converters are used in dc voltage regulators; and also, are used in conjunction with an inductor, to generate a dc current source, especially for the current source inverter. The dc–dc converters are integral parts of energy conversion in the evolving area of renewable energy technology.

1.7.2 Performance parameters of DC–DC Converters

Both the input and output voltages of a dc–dc converters are dc. This type of converter can produce a fixed or variable dc output voltage from a fixed or variable dc voltage as shown in Figure 2.16a. The output voltage and the input current should ideally be a pure dc, but the output voltage and the input current of a practical dc–dc converter contain harmonics or ripples as shown in Figures 2.16b and c. The converter draws current from the dc source only when the converter connects the load to the supply source and the input current is discontinuous. The dc output power is shown by equation 2.18 below:

$$P_{dc} = I_a V_a \qquad 2.18$$

Where Va and Ia are the average load voltage and load current. The ac output power is shown by equation 2.19:

$$P_{ac} = I_o V_o \qquad 2.19$$

Where Vo and Io are the rms load voltage and load current. The converter efficiency (not the power efficiency) is shown by equation 2.20:

$$\eta_c = \frac{Pdc}{Pa} \qquad 2.20$$

The rms ripple content of the output voltage is shown by equation 2.21.

$$V_r = \sqrt{3Vo^2 + Va^2} \qquad 2.21$$

The rms ripple content of the input current is shown by equation 2.22.

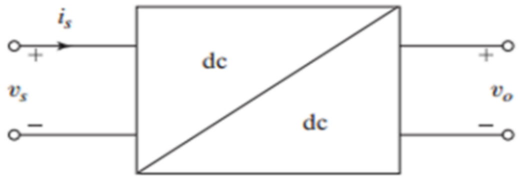
$$I_r = \sqrt{3Ii^{\,2} + Is^2} \qquad 2.22$$

Where Ii and Is are the rms and average values of the dc supply current. The ripple factor of the output voltage is shown by equation 2.23.

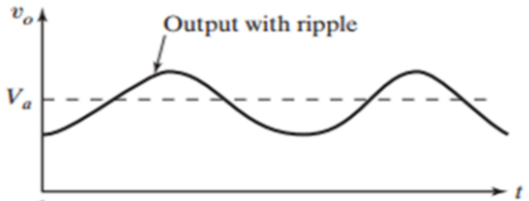
$$R_{Fo} = \sqrt{\mathrm{Vr\ Va}} \qquad 2.23$$

The ripple factor of the input current is shown by equation 2.24

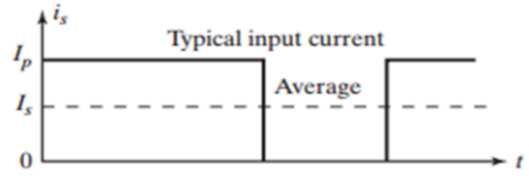
$$R_{Fs} = I_r.I_s \qquad 2.24$$



(a) Block diagram



(b) Output voltage



(c) Input current

Figure 2.15 Input and output relationship of a dc-dc converter

The power efficiency, which is the ratio of the output power to the input power, will depend on the switching losses, which in turn depend on the switching frequency of the converter. The switching frequency f should be high to reduce the values and sizes of capacitances and inductances. The designer has to compromise on these conflicting requirements. In general, fs is higher than the audio frequency of 18 kHz.

1.7.3 Generation of Duty Cycle:

The duty cycle k can be generated by comparing a dc reference signal Vr with a sawtooth carrier signal Vcr. This is shown in Figure 2.17, where Vr is the peak value of Vr, and Vcr is the peak value of Vcr. The reference signal Vr is given by equation 2.25.

$$\mathrm{V}_r = \frac{\mathrm{Vr}}{\mathrm{T}}\,\mathrm{t} \qquad 2.25$$

which must equal to the carrier signal Vcr = Vcr at kT. That is shown by equation 2.26,

$$\mathrm{V}_{cr} = \frac{\mathrm{Vr}}{\mathrm{T}}\,\mathrm{KT} \qquad 2.26$$

which gives the duty cycle k as shown by equation 2.27

$$K = \frac{\mathrm{Vcr}}{\mathrm{Vr}} = \mathrm{M} \qquad 2.27$$

Where M is called the modulation index. By varying the carrier signal Vcr from 0 to Vcr, the duty cycle k can be varied from 0 to 1.

The algorithm to generate the gating signal is as follows:

1. Generate a triangular waveform of period T as the reference signal Vr and a dc carrier signal Vcr.
2. Compare these signals by a comparator to generate the difference Vr - Vcr and then a hard limiter to obtain a square-wave gate pulse of width kT, which must be applied to the switching device through an isolating circuit.
3. Any variation in Vcr varies linearly with the duty cycle k.

1.7.4 Principle of step-up operation:

A converter can be used to step up a dc voltage and an arrangement for step-up operation is shown in Figure5.3, When switch SW is closed for time t1, the inductor current rises and energy is stored in the inductor L. If the switch is opened for time t2, the energy stored in the inductor is transferred to load through diode D1 and the inductor current falls. Assuming a continuous current flow, the waveform for the inductor current is shown in Figure 2.18.

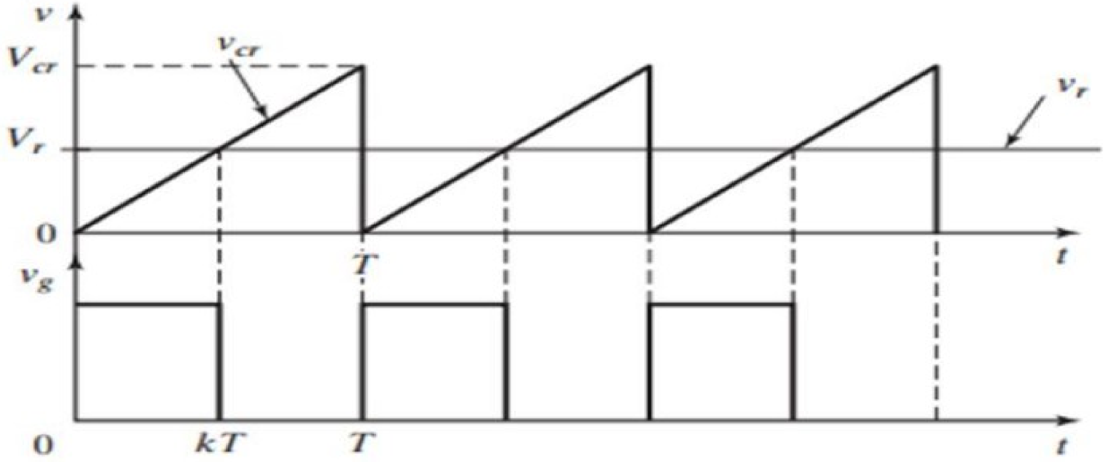


Figure 2.16 Comparing a reference signal with carrier signal

When the converter is turned on, the voltage across the inductor is shown by equation 2.28

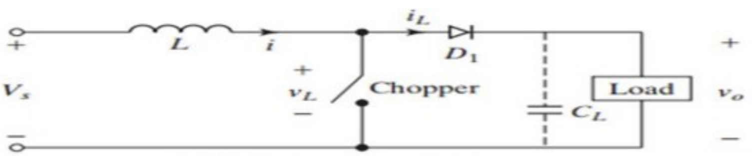
$$v_L = L\,\frac{\mathrm{di}}{\mathrm{dt}} \qquad 2.28$$

and this gives the peak-to-peak ripple current in the inductor as shown by equation 2.29

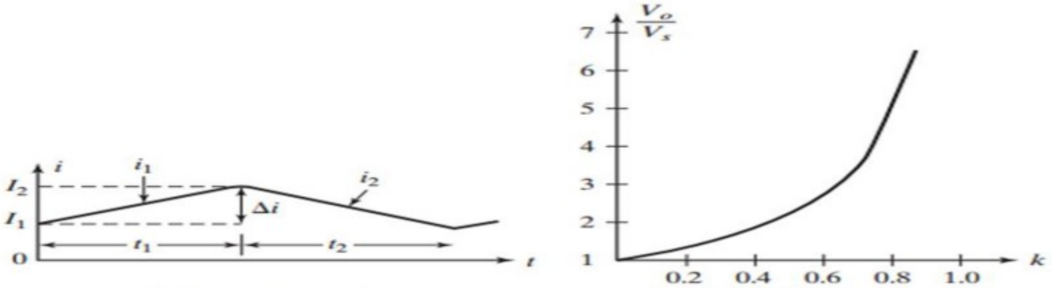
$$\Delta I = \frac{\mathrm{Vs}}{\mathrm{L}} t_1 \qquad 2.29$$

The average output voltage is shown by equation 2.30

$$v_o = V_s\,\frac{1}{1-\mathrm{k}} \qquad 2.30$$



(a) Step-up arrangement



(b) Current waveform (c) Output voltage

Figure 2.17 Arrangement of step-up operation

If a large capacitor CL is connected across the load as shown by dashed lines in Figure 2.18a, the output voltage is continuous and Vo becomes the average value Va. We can notice that the voltage across the load can be stepped up by varying the duty cycle k and the minimum output voltage is Vs when k = 0. However, the converter cannot be switched on continuously such that k = 1. For values of k tending to unity, the output voltage becomes very large and is very sensitive to changes in k, as shown in Figure 5.3c. This principle can be applied to transfer energy from one voltage source to another as shown in Figure 2.19a. The equivalent circuits for the modes of operation are shown in Figure 2.19b and the current waveforms in Figure 2.19c. The inductor current for mode 1 is given by shown by equation 2.31

$$V_S = L\frac{\mathrm{di}}{\mathrm{dt}} \tag{2.31}$$

and is expressed as shown by equation 2.32.

$$i_1(t) = \frac{\mathrm{Vs}}{\mathrm{L}}t + I_1 \tag{2.32}$$

Where I_1 is the initial current for mode 1. During mode 1, the current must rise and the necessary condition, shown by 2.33

$$\frac{\mathrm{di1}}{\mathrm{dt}} > 0 \; or \; Vs > 0 \tag{2.33}$$

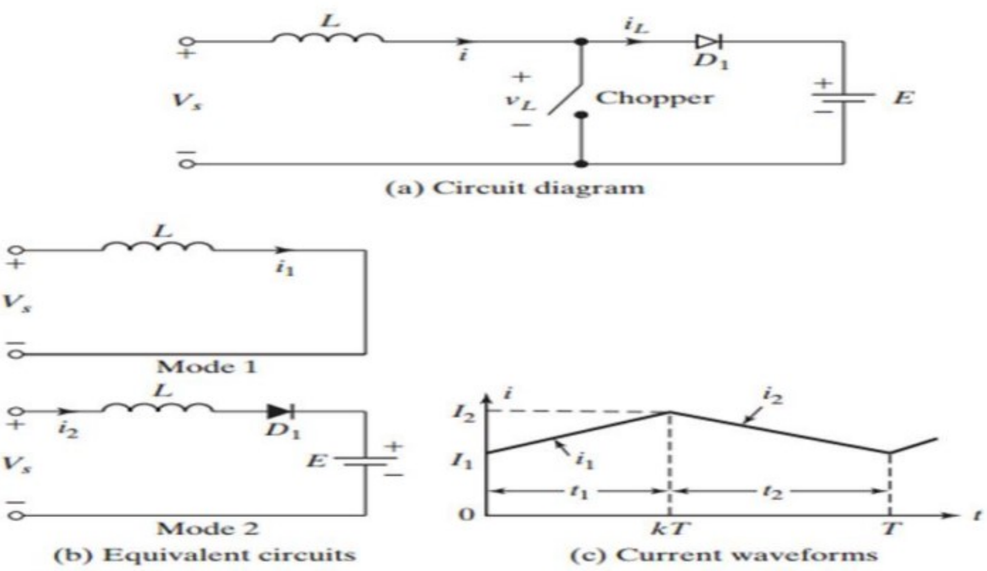


Figure 2.18 Arrangement for transfer of energy

The current for mode 2 is given by 2.35.

$$i_2(t) = \frac{\mathrm{Vs} - \mathrm{E}}{\mathrm{L}} t + I_2 \qquad 2.35$$

Where I2 is the initial current for mode 2. For a stable system, the current must fall and the condition is shown by 2.36.

$$\frac{\mathrm{di2}}{\mathrm{dt}} \; or \; Vs < \mathrm{E} \qquad 2.36$$

1.7.5 Design Boost regulators with selection of L, C for continuous conduction mode

In a boost regulator the output voltage is greater than the input voltage—hence the name “boost.” A boost regulator using a power MOSFET is shown in Figure 2.20a. Transistor M1 acts as a controlled switch and diode Dm is an uncontrolled switch. The circuit in Figure 2.20a is often represented by two switches as shown in Figure 2.20b. The circuit operation can be divided into two modes. Mode 1 begins when transistor.M1 is switched on at t = 0. The input current, which rises, flows through inductor L and transistor Q1. Mode 2 begins when transistor M1 is switched off at t = t1. The current that was flowing through the transistor would now flow through L, C, load, and diode Dm. The inductor current falls until transistor M1 is turned on again in the next cycle. The energy stored in inductor L is transferred to the load. The equivalent circuits for the modes of operation are shown in Figure 2.20c. The waveforms for voltages and currents are shown in Figure 2.20d for continuous load current, assuming that the current rises or falls linearly.

The average output voltage shown by equation 2.37.

$$V_a = V_s \frac{\mathrm{T}}{\mathrm{t2}} = \frac{\mathrm{Vs}}{1 - \mathrm{K}} \qquad 2.37$$

The average input current is shown by equation 2.38.

$$I_s = \frac{\mathrm{Ia}}{1 - \mathrm{k}} \qquad 2.38$$

The peak-to-peak inductor ripple current is shown by equation 2.39

$$\Delta I = \frac{\mathrm{Vs(Va - Vs)}}{\mathrm{fLVa}} \qquad 2.39$$

The peak-to-peak capacitor ripple voltage shown by equation 2.40:

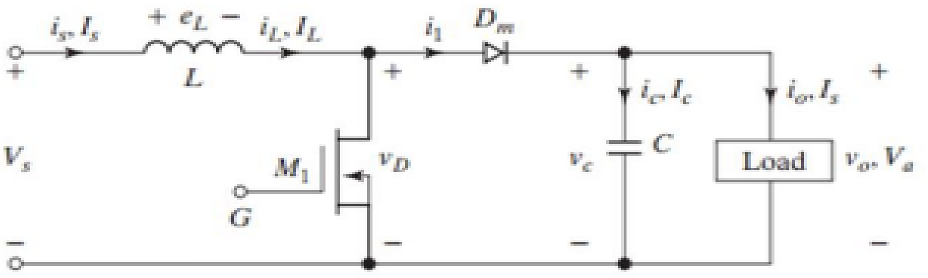
$$\Delta V_c = \frac{\mathrm{IaK}}{\mathrm{fc}} \qquad 2.40$$

Select of critical value of inductor is shown by equation2.41:

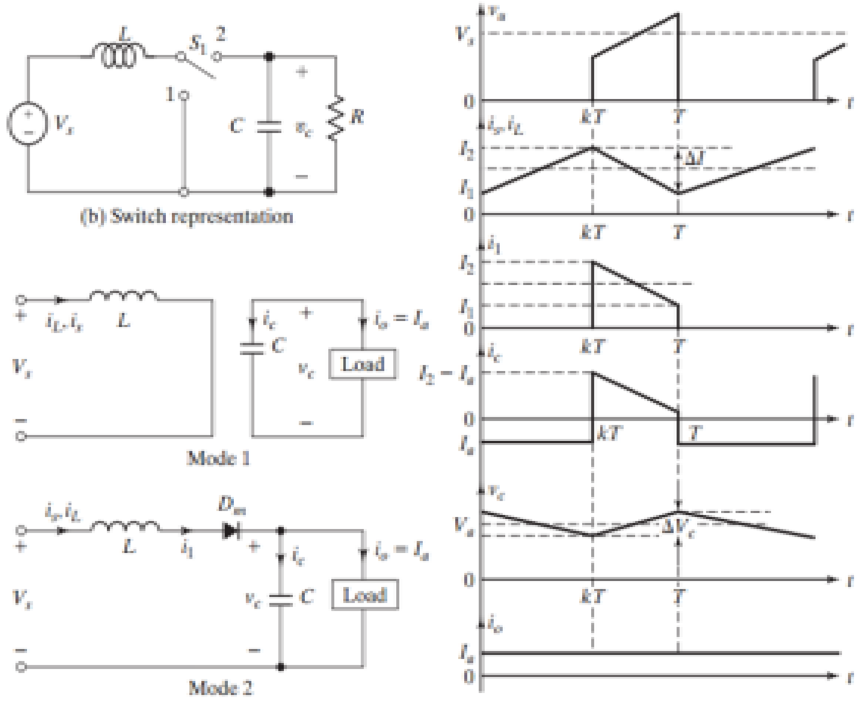
$$L_c = L = \frac{\mathrm{K(1 - K)R}}{\mathrm{2f}} \qquad 2.41$$

Select of critical value of capacitor is shown by equation 2.42:

$$C_c = C = \frac{\mathrm{K}}{\mathrm{2fR}} \qquad 2.42$$



(a) Circuit diagram



(b) Switch representation

(c) Equivalent circuits

(d) Waveforms

Figure 2.29 Boost regulator with continuous iL

1.8 MPPT TECHNIQUES FOR PV PANELS

1.8.1 Introduction

Maximum power is the maximum power available from a PV cell or module and occurs at the maximum power point on I-V curve. It is the product of the PV current (Imp) and the voltage (Vmp). This is referred to as the maximum power point at which the module operates with the maximum efficiency and produces the maximum output power. If a module operates outside its maximum power value, the amount of power delivered is reduced and represents needless energy losses. Thus, this is the desired point of operation for any PV module.

Maximization of power from the solar photovoltaic modules SPV is of special interest as the efficiency of the SPV module is very low. A peak power tracker is used for extracting the maximum power from the SPV module. The present work describes the maximum power point tracker (MPPT) for the SPV module connected to a resistive load through a medicated boost converter.

1.8.2 What is Maximum Power Point Tracking (MPPT)?

Maximum Power Point Tracking, frequently referred to as MPPT, is an electronic system that operates the Photovoltaic (PV) modules in a manner that allows the modules to produce all the power they are capable of. MPPT is not a mechanical tracking system that “physically moves the them point more directly at the sun MPPT is a fully” modules to make electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. Additional power harvested from the modules is then made available as increased battery charge current. MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different.

1.8.3 Reasons of Using MPPT

As we know, the output power of the SPV is affected by the Climatic variations and the load connected to it which is shown in previous sections. So, the maximum output power value of the SPV is changed. The aim of our work is to obtain the maximum output power of the SPV at every climatic condition. A typical solar panel converts only 30 to 40 percent of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel.

According to Maximum Power Transfer theorem, the power output of a circuit I s maximum when the Thevenin impedance of the circuit (source impedance) matches with the load impedance. Hence our problem of tracking the maximum power point reduces to an impedance matching problem when PV is directly coupled with a load, the operating point of PV is dictated by the load (or impedance to be specific).

The impedance of load is shown by equation2.44:

$$\boldsymbol{R_{load}} = \frac{\mathbf{Vo}}{\mathbf{Io}} \tag{2.44}$$

Where: Vo is the output voltage, and Io is the output current. The optimal load for PV is described as shown by equation 2.45:

$$\mathrm{R}_{\boldsymbol{opt}} = \frac{\mathbf{VMPP}}{\mathbf{IMpp}} \tag{2.45}$$

Where: V_{MPP} and I_{MPP} are the voltage and current at the MPP respectively. When the value of R load matches with that of Ropt, the maximum power transfer from PV to the load will occur. These two are, however, independent and rarely matches in practice. The goal of the MPPT is to match the impedance of load to the optimal impedance of PV.

A dc/dc converter (step up / step down) serves the purpose of Transferring maximum power from the solar PV module to the load. A dc/dc converter acts as an interface between the load and the module as it is shown in fig 2.21. The SPV doesn't differ between the converter, inverter or the load.

By changing the duty cycle, the load impedance as seen by the source is varied and matched at the point of the peak power with the source so as to transfer the maximum power which is shown in equation 2.47.

$$P_{in} = P_{out}, \text{ then } \frac{Vin^2}{Rin} = \frac{Vout^2}{Rout} \text{ or } \frac{Vout^2}{Vin} = \frac{Rout}{Ri} \qquad 2.47$$

And since the study is done with boost converter, then shown by equation 2.48

$$\frac{Vout}{Vin} = \frac{1}{1-D} \qquad 2.48$$

$$R_{in} = (1 - D)^2 * R_{out} \qquad 2.49$$

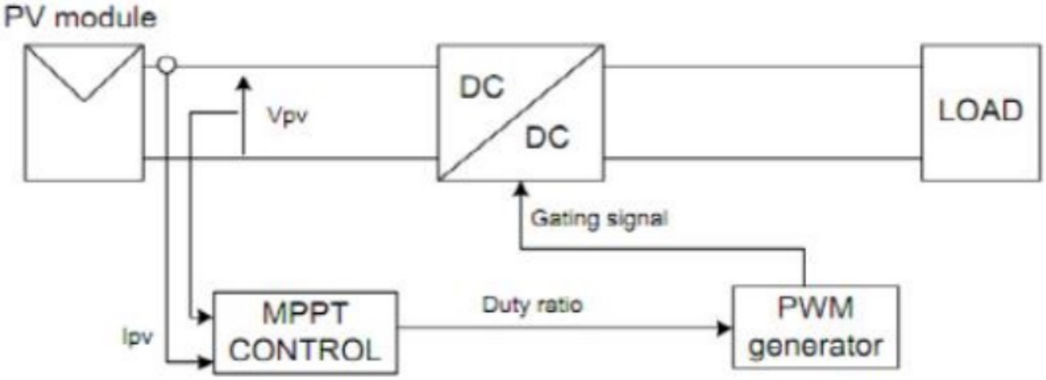


Figure 2.10 Block diagrams of MPPT with P&O

1.8.4 MPPT Techniques

Over the past decades many methods to find the MPP have been developed. These techniques differ in man y aspects such as require d sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/ or temperature change, hardware needed for the implementation or popularity, among others. Some of the most popular MPPT techniques are:

1. Perturb and Observe (hill climbing method).
2. Incremental Conductance method.
3. Fractional open circuit voltage.
4. Fuzzy logic.
5. Load current or load voltage maximization.
6. dP/dV or dP/dI Feedback control.

1.8.5 Incremental Conductance method

The increment al conductance algorithm uses two voltage and current sensors to sense the output voltage and current of the PV array. In incremental conductance method the array terminal voltage is always adjusted according to the MPP voltage it is based on the incremental and instantaneous conductance of the PV module.

Fig. 2.22 shows that the slope of the P-V array power curve is zero at T the MPP, increasing on the left of the MPP and decreasing on the right-hand side of the MPP. The basic equations of this method are as follows.

$$\frac{dI}{dV} = -\frac{I}{V} \quad \text{At MPP}$$
$$\frac{dI}{dV} > -\frac{I}{V} \quad \text{Left of MPP}$$
$$\frac{dI}{dV} < -\frac{I}{V} \quad \text{Right of MPP}$$

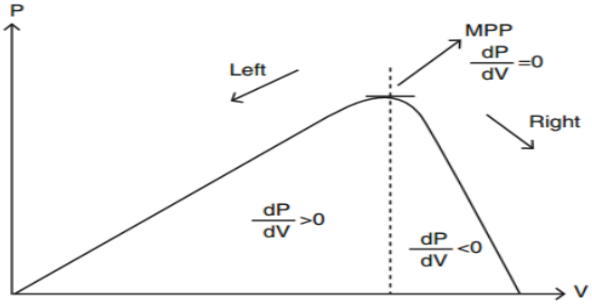


Figure 2.11 Basic idea of incremental conductance method on a P-V curve of solar module

where I and V are P-V array output current and voltage respectively. The left-hand side of equations represents incremental conductance of P-V module and the right-hand side represents the instantaneous conductance. When the ratio of change in output conductance is equal to the negative output conductance, the solar array will operate at the maximum power point. This method exploits the assumption of the ratio of change in output conductance is equal to the negative output Instantaneous conductance. We have equation 2.50

$$P = VI \qquad 2.50$$

Applying the chain rule for the derivative of products yields to equation 2.51

$$\frac{\partial P}{\partial V} = \frac{[\partial(VI)]}{\partial V} \qquad 2.51$$

At MPP, as $\frac{\partial P}{\partial V}$

The above equation could be written in terms of array voltage V and array current I as shown by equation 2.52

$$\frac{\partial P}{\partial V} = -\frac{I}{V} \qquad 2.52$$

The MPPT regulates the PWM control signal of the DC – to – DC boost converter until the condition: $(\partial I/\partial V) + (I/V)$ ¼ 0 is satisfied. In this method the peak power of the module lies at above 98 % of its incremental conductance. The Flow chart of incremental conductance MPPT is shown in Fig. 2.23.

In both P&O and InCond schemes, the speed of occurrence of MPP depends on the size of the increment of the reference voltage. The drawbacks of these techniques are: The first drawback is that they can easily lose track of the MPP if the irradiation changes rapidly. In case of step change they track the MPP very well, because the change is instantaneous and the curve does not keep on changing. However, when the irradiation changes following a slope, the curve in which the algorithms are based changes continuously with the irradiation, as can be seen in Fig. 6.3, so the changes in the voltage and current are not only due to the perturbation of the voltage. As a consequence, it is not possible for the algorithms to determine whether the change in the power is due to its own voltage increment or due to the change in the irradiation.

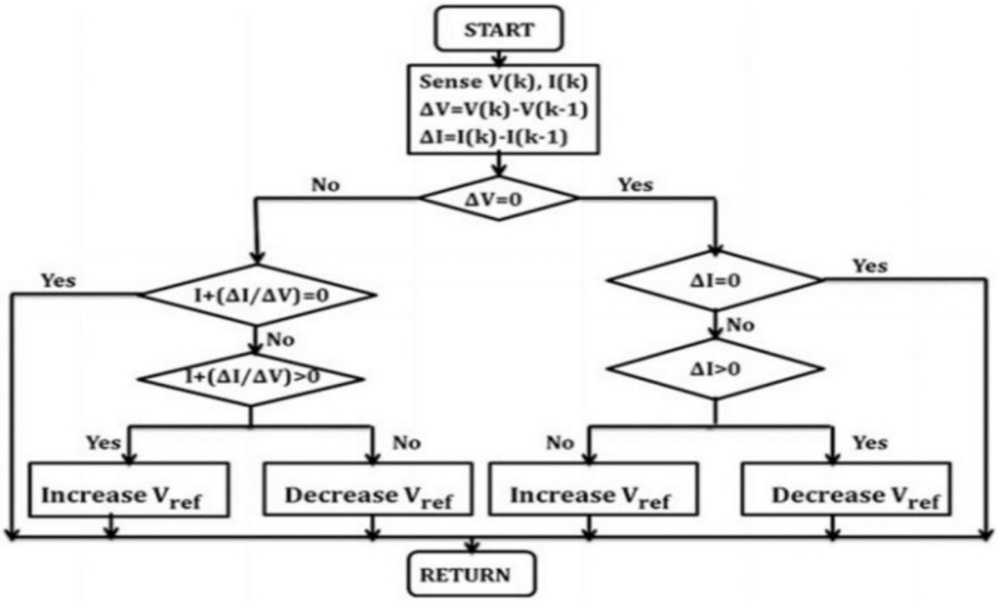


Figure 2.12 Flow chart for incremental conductance algorithm

The other drawback of both methods is the oscillations of the voltage and current around the MPP in the steady state. This is due to the fact that the control is discrete and the voltage and current are not constantly at the MPP but oscillating around it. The size of the oscillations depends on the size of the rate of change of the reference voltage. The greater the oscillation, higher is the amplitude of the oscillations. However, speed of the MPP occurrence also depends on this rate of change and this dependence is inversely proportional to the size of the voltage increments. The traditional solution is a trade-off: if the increment is small the oscillations decrease, then the MPP is reached slowly and vice versa, so a compromise solution has to be found.

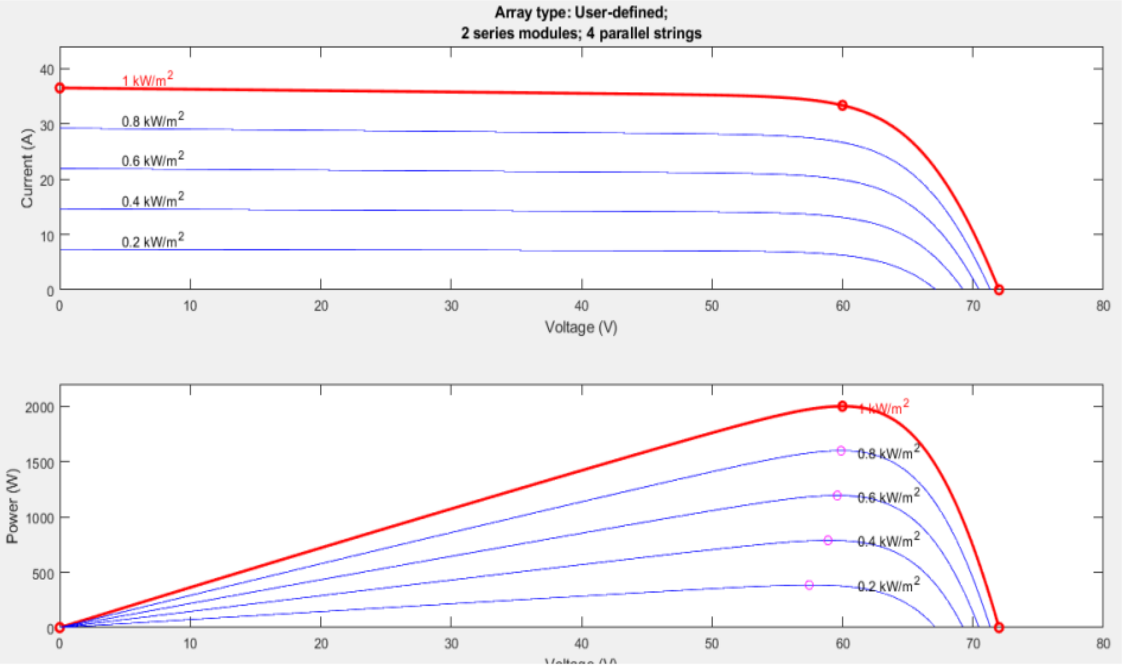


Figure 2.13 P-V and I-V curves depending on the irradiation

1.9 ANAEROBIC DIGESTION

2..9.1 Introduction

Anaerobic Digestion is a biochemical conversion process carried out by various microorganisms in which the biomass organic material is converted into organic acids, which in turn are converted into methane gas (CH4) with carbon dioxide as the other byproduct. The process takes place under very strict anaerobic conditions (no oxygen). The conversion of organic material to CH4 involves a close relationship between four types of bacterial populations with the dynamic balance between the production and utilization of the intermediate products being critical to the overall success of the fermentation. Anaerobic treatment typically removes Chemical Oxygen Demand (COD) by boiling down the organics to methane. Consequently, the COD of the methane produced in an anaerobic system is often tantamount to the number of COD removed. The entire process takes place in four clearly defined process and includes the following four distinct events.

2.9.2 Anaerobic digestion process

1) **Hydrolysis**

   Hydrolysis is the process of converting insoluble complex biomass into soluble compounds by the action of extracellular enzymes of hydrolytic bacteria. These bacteria are the first set of microorganisms that breaks down the biomass into simpler compounds. Carbohydrates, fats and proteins are converted into sugars, fatty acids, and ammonia acids. At the end of hydrolysis process, the complex organics are converted into simpler organics, mostly volatile fatty acids. Hydrolysis is an enzyme-mediated conversion of complex organic compounds (carbohydrates, proteins, and lipids) to simple organics (sugar, amino acids, and peptides). This stage is very important because large organic molecules are simply too large to be directly absorbed and used by microorganisms as a substrate source. The biodegradation is accomplished by certain microorganisms which secrete different types of enzymes, called extracellular enzymes, Theses enzymes break the large, complex, and insoluble organics into small molecules that can be transported into microbial cells and metabolized and are used as a source of energy and nutrition (Adekunle et al., 2015). The rate of decomposition during this stage depends greatly on the nature of the substrate. The transformation of cellulose and hemicellulose generally takes place more slowly than the decomposition of proteins [18] [19].

2) **Acidogenesis**

The second step is the conversion of soluble organics from hydrolysis into short-chain fatty acids and alcohols. Most acids are converted into acetic acid via the step of conversion into acetic acid. Other organic acids are also produced, such as propionic, butyric, valeric and others. At this stage, hydrogen is produced by the fermentation of glucose. The microbes responsible for this process are called "acid formers" and are composed of homoacetogenic bacteria and some facultative bacteria. In this step, acetic acids and water are converted into carbon dioxide and hydrogen.

Acidogenesis is the process in which bacterial fermentation results in the formation of volatile acids. During this stage, the hydrogen producing acetogens convert the volatile acids (longer than two carbons) to acetate and hydrogen. These microorganisms are related and can tolerate a wide range of environmental conditions. This process may be divided into two types: hydrogenation and dehydrogenation. The basic pathway of transformations passes through acetates, CO2, and H2, whereas other acidogenesis products play an insignificant role. Under standard conditions, the presence of hydrogen in solution inhibits oxidation, so that hydrogen bacteria are required to endure the conversion of all acids [18].

3) **Acetogenesis**

This step represents the widespread production of acetic acid by hydrogenation. Acetic acid may also be formed by the dehydrogenation process. During the AD process, acetic acids are the most abundant organic acids produced, among many other fatty acids [18] [20]. The following equations represent the production of acetate by hydrogenation and by dehydrogenation, respectively shown by equation 2.53 and 2.54:

$$2CO_2 + 4\,H_2 \longrightarrow CH_3COOH + 2\,H_2O \qquad 2.53$$

$$CH_3CH_3COOH + 3\,H_2O \longrightarrow CH_3COOH + 3\,H_2 + CO_2 + H_2O \qquad 2.54$$

The simple molecules from acidogenesis are further digested by bacteria called acetogens to produce CO2, hydrogen and acetic acid. Acid forming stage comprises two reactions, fermentation, and acetogenesis reactions. During the fermentation, the soluble organic products of the hydrolysis are transformed into simple organic compounds, mostly volatile (short chain) fatty acids such as propionic, formic, butyric, valericetc, ketones and alcohols. The acetogenesis is completed through carbohydrate fermentation and results in acetate, CO2 and H2, compounds that can be utilized by the methanogens. The presence of hydrogen is of critical importance in acetogenesis of compounds such as propionic & butyric acid. These reactions can only proceed if the concentration of H_2 is very low [21]. Thus, the presence of hydrogen scavenging bacteria is essential to ensure the thermodynamic feasibility of this reaction.

4) **Methanogenesis**

The final step in the AD is the conversion of organic acids into methane by the action of methane-producing microbes. The methanogenesis process is divided into two stages. The first stage is the conversion of acetic acid into methane, which comprises about 70% of the process reactions. The second stage is the conversion of hydrogen into methane utilizing the carbon dioxide produced during the process, which comprises the remaining 30% of the process reactions. The following equations represent acetotrophic coming from acetic acid and hydrogenotrophic coming from H2, respectively.

The main route is the fermentation of the major product of the acid-forming phase, acetic acid, to methane and carbon dioxide. Two-thirds of the total produced methane is derived by converting the acetic acid or by fermentation of the alcohol formed. Whereas the other one third is a result of the reduction of carbon dioxide by hydrogen. The reaction that takes place in the process of CH4 production is called Methanation and can be expressed by the following equations 2.55,2.56,.2.57 and 2.58 [22]:

$CH_3COOH \longrightarrow CH_4 + CO_2$ 2.55

Acetic acid ⟶ Methane + Carbon dioxide

$2CH_3CH_2OH + CO_2 \longrightarrow CH_4 + 2CH_3COOH$ 2.56

Ethanol + Carbon dioxide ⟶ Methane + Acetic acid

$CO_2 + 4H_2 \longrightarrow CH_4 + H_2O$ 2.57

Carbon dioxide + Hydrogen ⟶ Methane + Water

The above equations show that many products, by-products, and intermediate products are produced in the process of digestion of inputs in an anaerobic condition before the final product CH4 is produce [22]. The four stages of the AD process are shown in Figure 2.25.

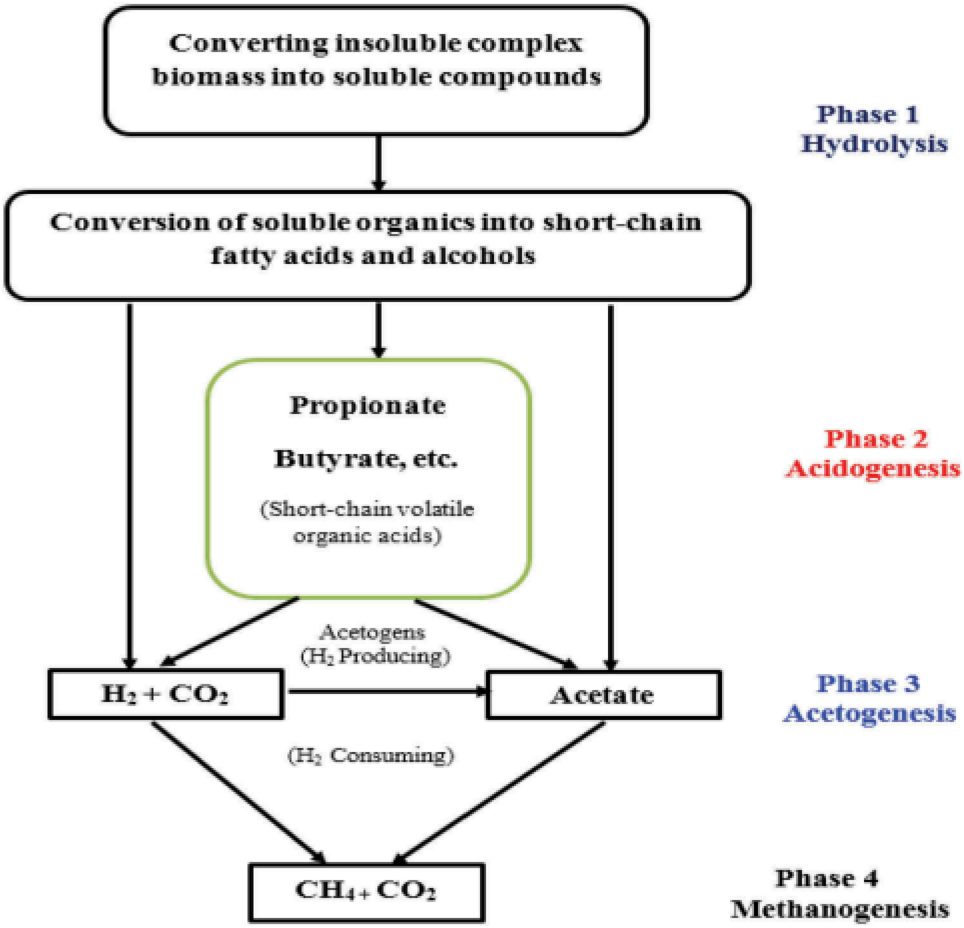


Figure 2.14 A schematic diagram of the four stages of AD process.

1.10 BIOGAS RESOURCES

2.10.1 Introduction

The term “biogas” is commonly used to refer to a gas which has been produced by the biological breakdown of organic matter in the absence of oxygen. Biogas is one of the products formed during the anaerobic digestion process. Biogas is a combination of gases, consisting mostly of methane, produced during the natural decomposition of organic matter in an airtight environment. It is produced by the anaerobic digestion or fermentation of biodegradable materials such as biomass, manure, sewage, waste, green, plant material, and crops. Biogas comprises primarily methane (CH4) and carbon dioxide (CO2) and may have small amounts of hydrogen (H2S), moisture and siloxanes. Typical composition of biogas is as shown in the table below 2.2 [23]:

Table 2.2 Typical composition of biogas

Compound	Chemical formular	Percentage %
Methane	CH_4	50-75
Carbon dioxide	CO_2	25-50
Nitrogen	N_2	0-10
Hydrogen	H_2	0-1
Hydrogen Sulphide	H_2S	0-3
Oxygen	O_2	0-0

Table 2.3 Production of biogas from different types of raw materials

Material	Composition of the gas (percentage)		
	Methane	Carbon dioxide	Hydrogen Sulphide etc.
Cow dung	55-80%	40-45%	Negligible
Night soil	65%	34%	H_2S 0.6% other gases 0.4%

Table 2.4 Composition of biogas produced from cattle dung and night soil

Size of plant (gas production/ day) (m3)	Amount of wet dung required (kg)	No. of animals
2	35-40	2-3
3	45-50	3-4
4	55-60	4-6
6	80-100	6-10
8	120-150	12-15
10	160-200	16-20

2.10.2 Factors for optimum performance

Anaerobic digester is a promising technology for treating waste and producing energy at the same time. Digestion is dependent on several factors for the well-being of a stable digester. Factors such as pH, temperature, organic loading rate, hydraulic retention time and carbon-to-nitrogen (C/N) ratio play a significant role during the bio-degradation of the solid material. There are three temperature regions in which anaerobic digestion can be conducted, pychrophilic (10-20°C), mesophilic (20-45°C) and thermophilic (45-68°C). The most common temperature ranges used to run anaerobic digesters are either mesophilic (with an optimum at 35°C) or thermophilic (with an optimum at 55°C) [24].

1. **Temperature:** Temperature is the most important parameter to be considered in anaerobic digestion. Different species of methogens function optimally in three different temperature ranges 11:45–60°C thermophilic, 20–45°C mesophilic) and below 20°C psychrophilic. The rate of biogas production increase with an increase in temperature. In biogas digestion process, only mesophilic and thermophilic temperature ranges are considered important because anaerobic digestion reaction essentially stops below 10°C11. The bacteria available for digestion process are sensitive to temperature fluctuation, so, it is necessary to maintain a constant temperature. Thermophilic bacteria are more efficient in terms of retention time, loading rate and gas yield, but they need higher heat input and are also sensitive to temperature fluctuations and environmental variables than mesophilic7, 11. Influence of temperature on the rate of anaerobic digestion process is shown in fig.2.26

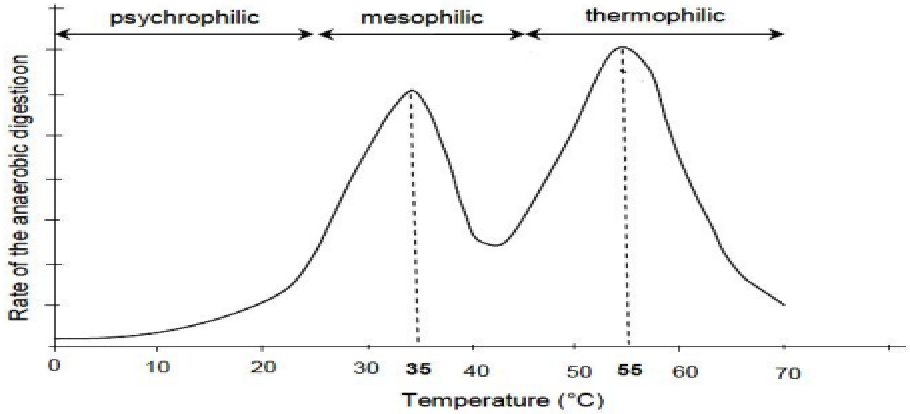


Figure 2.15: Influence of temperature on the rate of anaerobic digestion

2. **Solid to water content:** Water and raw material should be added together to generate slurry with required consistency. Production of biogas is inefficient if the slurry is too dilute or too thick. The optimum solid concentration may vary from 7- 25% depending on the type of raw material used 17. Sewage waste contains very low solid content and so optimum level can be achieved by adding solid matters like crop residues, weed plants etc. Budiyono et al19 experimented the effect of total solid contents (2.6, 4.6, 6.2, 7.4, 9.2, 12.3 and 18.4%. of TS) on biogas yield using cattle manure in a 400 ml batch digester and found that 7.4 and 9.2% of total solids achieved better performance on biogas yield than other total solid percentages.
3. **pH level:** The optimum pH level of the anaerobic digester is at 6.7 to 7.5 20. The pH level will not be constant throughout the process. The volatile fatty acids production rate is much higher than the methane production rate, resulting in pH level below the optimum range and can inhibit methanogens, because they are very sensitive to acid conditions9,11. Reduction in pH can be controlled by the addition of chemicals such as sodium carbonate, sodium bicarbonate, gaseous ammonia, ammonium hydroxide, lime, potassium and sodium hydroxide 9. Sambo et

al21 investigated the effect of pH (4, 7 and 9) using cow dung as feed and reported that pH 7 gives maximum biogas yield followed by 9 and then 4. Sivakumar et al37 studied the biogas potential from spoiled milk and effect of pH investigated by them is shown in fig.2.27.

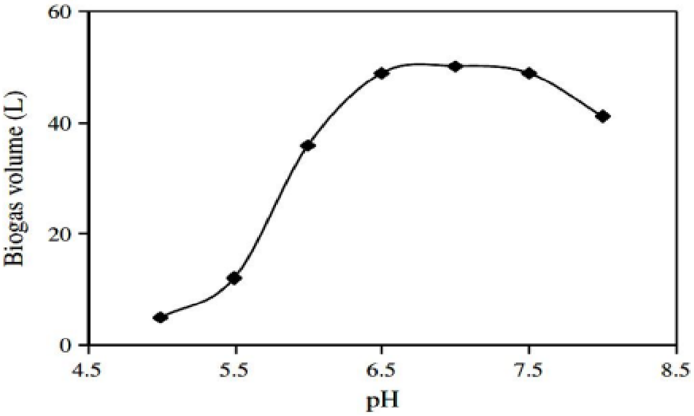


Figure 2.16 Effect of pH anaerobic digestion of spoiled milk

4. **Retention period:** The time period for which the organic material remains inside the digester for biogas generation is known as retention period. The retention period will vary depends on the type of feedstock and the temperature used. Solids retention time (SRT) and hydraulic retention time (HRT) are the two significant retention times in anaerobic digestion process. SRT refers the time that bacteria (solids) remain inside the digester. HRT is commonly used to denote substrate retention time. It is the time spent by the input slurry, inside the digester from the instant of its entry to its exit.
5. **Organic loading rate:** Organic loading rate (OLR) is an important parameter which affects the biogas production in anaerobic digestion, particularly when the digestion takes place in continuous flow mode. OLR is a measure of biological conversion capacity of the anaerobic digestion system. It can be expressed as the amount of raw material (kg of volatile solids) fed to the digester per unit volume per day. Overloading easily affects the digestion process due to accumulation of acids. The optimum loading rate is in between 0.5 kg and 2 kg of total volatile solids per unit volume of the digester per day which can be chosen based on type of raw material, retention time and the process temperature.
6. **C/N ratio:** The relationship between the amount of carbon and nitrogen present in the raw materials is represented by the C/N ratio. The carbon-nitrogen (C/N) ratio is one of the important factors in the production of biogas. The elements of carbon (in the carbohydrates) and nitrogen (in the form of proteins, ammonia nitrates) are the major food for anaerobic bacteria. The consumption of carbon by bacteria is 30 times faster than the nitrogen consumption. Therefore, for optimum rate, the availability of carbon in the substrate should be 20- 30 times higher than nitrogen (i.e., C/N ratio between 20 and 30).

   If the C/N ratio is high, then rapid consumption of nitrogen by methogens takes place and results in lower bio-gas production. Lower C/N ratio leads to ammonia accumulation and pH values exceeding 8.5 which is toxic to methogens. To maintain the optimum C/N ratio in the digester, substrates of high C/N ratio can be co-digested with lower C/N ratio substrates. The effect of C/N ratio of various feeds on biogas production showed that C/N ratio of 26:1 gives maximum biogas yield compared to others. The typical C/N ratios for different organic materials available are shown in table 2.5.

Table 2.5 Typical C/N ratios of different materials

S.N.	Material	N (%)	C/N ratio
1	Cow, buffalo, sheep, pig and horse manure	1.4-3.8	15-40
2	Poultry manure	6.3	5.2
3	Night soil	6	6-10
4	Fish scarps	6.5	5.1
5	Slaughter house waste	7-14	2-4
6	Sawdust	0.1-0.25	200-511
7	Grass clipping and hay	2-4	10-20
8	Bagasse, Wheat and rice straw	0.3-0.5	120-150
9	Corn stalks	0.8	60
10	Kitchen vegetable scraps	3.3	16

7. **Mixing/agitation:** Mixing or agitation is required in the digester to maintain homogeneity and process stability. Mixing helps to combine the fresh incoming material with microorganisms and prevents from thermal stratification and scum formation in the digester. Mixing maintains uniformity in substrate concentration, temperature and other environmental factors. Also, it prevents solid deposition at the bottom of the digester. Mixing can be done either by using mechanical stirrers or by recirculation of the digester slurry using centrifugal pump.

2.10.3 Types of digesters

1. **Plug flow digesters:** This is a type of anaerobic digester that uses a long, narrow horizontal tank in which a material (manure) is added at a constant rate and that force other material to move through the tank and be digested Figure 2.28. Typically, a plug flow digester vessel is five times longer than it is wide, is insulated and heated, and is made or reinforced concrete, steel or fiberglass.

   A plug flow digester has no means of agitation. The term "plug flow" derives from the fact that the manure in principle flows through the digester vessel as a "plug," gradually being pushed toward the outlet as new material is added. In fact, the situation is more complicated and some parts of the manure travel faster than others on their way through the vessel, or may even settle or float and remain in the digester [25]. The main advantage of the plug-flow design is that it is simple and economical to install and operate. However, it is not as efficient or as consistent as the completely mixed design. Plug-flow units are limited to applications with low amounts of sand, dirt, or grit, because these substances will tend to stratify and settle out inside the digester, requiring significant effort to clean out [26]. Complete mix units are more expensive to install and operate than plug flow units, because they require both the capital equipment and the energy for mixing [26].

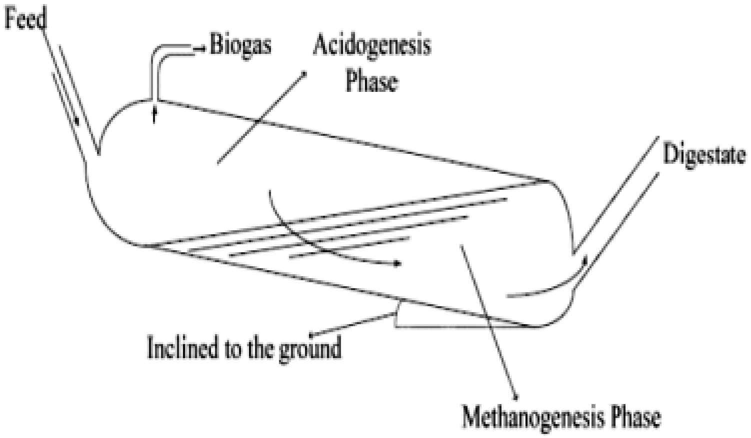


Figure 2.17 Schematic representation of a plug flow digester.

2. **Fixed dome digesters**

   A well and a dome are made out of cement concrete. Fixed dome Chinese model biogas plant (also called drum less digester) was built in China as early as 1936 [27]. Fixed dome digesters are usually built underground [28]. The dome is fixed and hence the name given to this type of plant is fixed dome type of biogas plant. The function of the modified fixed dome digester plant is similar to the floating holder type biogas plant as shown in Figure 2.25, the only difference is the fixed top part of the digester. The used slurry expands and overflows into the overflow tank [29]. Disadvantages of fixed dome digesters are that special sealants are required, high technical skills are required for construction, and gas pressures fluctuate, which causes complication of gas use. The difference between Figure 2.28 and 2.29 is that, in Figure 2.30 the upper part of the digester is fixed, i.e., it does not experience any movement on the upper side when the gas starts to fill up the available empty space as compared to the floating tank type digester.

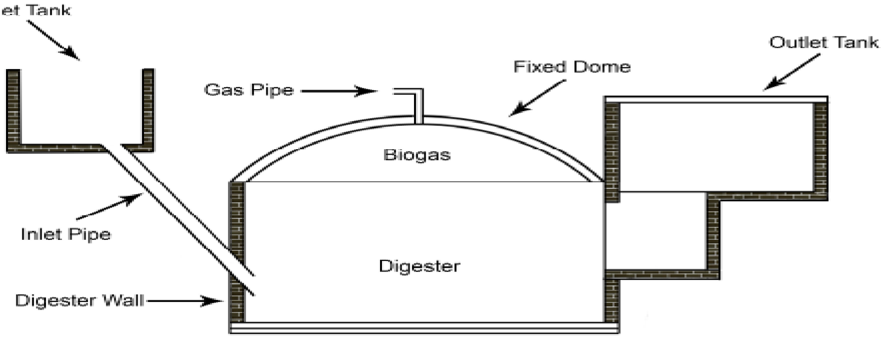


Figure 2.18 Fixed dome digester

3. Floating drum digesters

An experiment on biogas technology in India began in 1937 [14]. In 1956, Jashu Bhai J Patel [30], developed a design of floating drum biogas plant popularly known as Gobar Gas plant. It is divided into two parts. One side has the inlet, from where slurry is fed to the tank as shown in Figure 2.26. The tank has a cylindrical dome made of stainless steel that floats on the slurry and collects the gas generated. Hence the name given to this type of plant is floating gas holder type of biogas plant. The slurry is made to ferment for about 50 days. More gas is made by the bacterial fermentation, leading to the pressure inside the gas collecting dome to increase. The gas can be taken out through an outlet pipe. The decomposed matter expands and overflows into the next small holding tank.

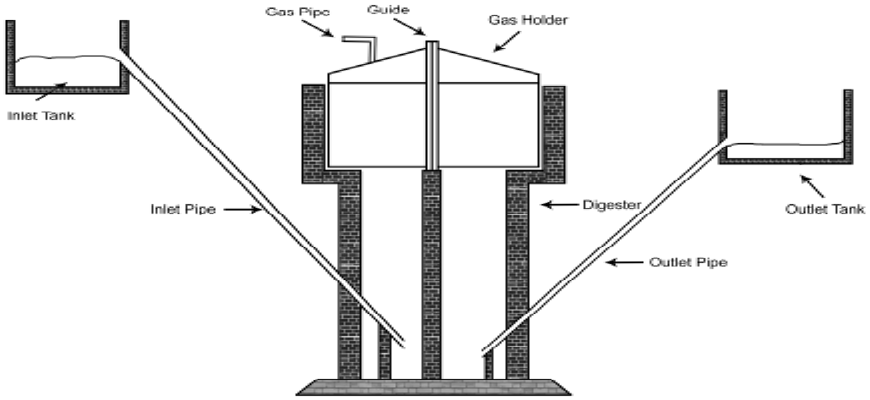


Figure 2.19 Floating drum digester

The shortcomings of these digesters discussed above relative to this research is that the pressure cannot be manipulated or maintained to a specific value for a certain period of time in order to observe the effect it has on the composition of the gas and on the activity of the bacteria. The digester design for this particular research will take into account the accommodation of pressure manipulation.

2.11 SOLAR-BIOGAS HYBRID

2.11.1 Introduction

In power engineering, the term 'Hybrid' describes a combined power and energy storage system. A combination of different complementary energy generation systems based on renewable energy and/or conventional energy is known as Hybrid Power System or Hybrid System. A hybrid energy system usually consists of two or more renewable energy sources combined together to provide increased system efficiency as well as greater balance in energy supply [31]. Components for electricity generation can utilize renewable energy sources like wind turbines, photovoltaic, hydro power, wave power or biomass etc. Furthermore, fossil power plants like diesel generators, gas turbines or fuel cells etc. can be added. In addition, it may include power electronics and electricity storage batteries.

At present electricity generation from solar sources has reached a remarkable efficiency. Electrical energy can be generated in large scale using Solar Thermal Power Plant (STPP) with storage system. It is a fact that STPP cannot operate stably and continuously due to variability of solar irradiation. An optimal operating mode of STPP can be obtained by combining biomass technology with it.

Our proposed hybrid system consists of Solar PV and biogas system. The hybrid system is designed for off grid operation due to the absence of grid electricity. The system consists of PV generators, biogas generator, battery bank, battery charge controller and the load. Here the input from solar is directly fed to the hybrid inverter to the battery bank; whereas the input from biogas is fed to the battery by converting them from AC to DC and direct to load as AC.

The hybrid system in this project is one combining solar PV and biogas with generator and bank of batteries, which are included for backup purposes. Power conditioning units, such as inverters, are also part of the supply system. Hybrid biogas and PV modules, offer greater reliability than any one of them alone because the energy supply does not depend entirely on any one source. For example, on a cloudy stormy day when PV generation is low there's likely enough biogas energy available to make up for the loss in solar electricity and as a result the size of the battery storage can be reduced. Typical components of an hybrid solar PV system consists of the following components.

Charge Controller: A charge controller's job is to regulate the voltage and current coming from and going into battery. So, a charge controller takes the power from somewhere (usually a solar panel installation) and pushes it into the battery at the right levels. It is used to sense when the batteries are fully charged and to stop or decrease the amount of energy flowing from the energy source to the batteries [32]. Discharging a battery, or taking the power out of it, can be controlled by a charge controller, and the point of doing so is to protect the battery. Batteries are not designed to be fully discharged. If we do run our batteries all the way down, it will ruin their life expectancy. So, a charge controller can be used to protect the batteries by sensing when they are full, ½ ways done, and need to be shut off to remain protected.

Inverter: An inverter converts the direct current (dc) electricity from sources such as batteries, or PV modules to alternative current (ac) electricity. The electricity can then be used to operate ac equipment like the ones that are plugged in to most house hold electrical outlets. The normal output ac waveform of inverters is a sine wave with a frequency of 50/60 Hz.

Battery Bank: A good sized, and well maintained, battery bank, is the basis of almost all off grid power generation systems, whether wind power, solar power, or engine driven generators, battery bank is charged to full capacity at least once a week [33].

Rectifier: A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as rectification. Rectifiers have many uses, but are often found serving as components of DC power supplies and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power.

Dump Load: A dump load is a secondary place to put power when the batteries are fully charged. Since the batteries are a sizeable investment in any autonomous power arrangement, they need to be protected from overcharging which will shorten their life span. Simply the dump load takes the power when the charge controller senses that the batteries are full, to protect them. Once the power has been diverted, the dump load uses the power for something productive rather than lose it directly into the ground.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

The proposed hybrid energy system is shown in Figure 3.1. The microgrid consists of a biogas plant, a photovoltaic (PV) system, a battery storage system and an electricity distribution system. The PV system will provide electricity for a variety of uses, and biogas will be used to generate electricity and charge the battery, and fertilizer will be used for agricultural purposes.

3.2 Description of Area

We established the following criteria for area selection, which the chosen area must meet:

- A good population to be served
- Nature of business, the scale of operations, ownership, etc.
- Energy sources of prospective customers
- Electrical Energy consumption by prospective customers
- Available space for a power plant
- Cow dung/biogas feedstock supply availability and costs
- Livestock and agriculture should be main source of income for most of families.

Kalungi B, Mubende district, which is located Gogonya parish, Kitenga sub-county, in the southern part of Buwekura county region of Uganda meets these criteria because there is a large amount of open land around most of the villages. Agriculture and livestock are the main source of income in rural areas. According to the survey we carried out, the selected area's total population was around 2000 people. It has a total number of 500 households and 50 businesses. Number of farms are 140. The power supply is unreliable since the nearest grid access is 20 km away and there are few small-scale solar panels installed by few business people in the area.

The primary source of income is the agriculture and livestock sector. Most households in the rural area have a significant amount of agricultural land and 2–3 livestock assets, such as cows, goats, and pigs. The presence of livestock in large numbers allows the development of biogas plants for power generation and as an alternative for presently used cooking fuels. Micro-grids based on biogas can change people's cooking habits while also contributing to the area's economic development.

3.3 Load assessment Survey

A load assessment survey was carried out. The survey inquired about the size of the household, the variety of electric appliances, their ratings, and the frequency of use. A total of 90 people from two villages Kalungi B and Rwobushomi were interviewed. Interviewees included school teachers, farmers, shop owners, group leaders, counsellors, and chairmen of village councils.

Before performing load profiling, analysis was used for load assessment as domestic, community, and productive use requirements.

The load profiling was done in the following ways, we obtained all appliances in the rural area and their respective ratings including the number of businesses operating them as shown below and we equally inquired about their time of operation from their respective owners. The appliance ratings were multiplied by the number of businesses it is used in and also time of use.

3.4 System Design and Financial Analysis

MATLAB Simulink version R2021a was used in the technical design of the microgrid's electrical system. The power system of the microgrid is composed of the PV system, biogas power plant, inverter, and batteries. We determined the salaries and electricity rates based on the responses of the local population. In order to promote agricultural operations in the area, this research aims to deliver fertilizer at a reduced rate. In this project, to ascertain the model's sustainability, power is provided at a cheap cost, and the revenue is mostly obtained from the sale of fertilizer.

1.5.1 Solar PV Design

Assumptions:

As we assumed the plant for 5 Kw, here we calculated the specific values for 5 kW power plant. But the values can be modified for a larger or smaller scale power plant.

1. The PV panels are 500 W-p each
2. The Operating factor is 75 2.
3. Combined efficiency =.81 3.
4. Running hour= 8 h.
5. Inverter efficiency = .90 5.
6. Depth of discharge= .80 6.
7. Battery voltage= 48V
8. Battery= 200 Ah
9. Inverter= 500 VA
10. Total load= 3000W/3 KW

3.5.1.1 PV panel:

Actual power o/p= 500*0.75 = 375 wp

Power available for the use= 375*0.81 = 303.75 wp

Energy produced by one 500wp panel in 8 hours = (303.75*8) = 2430 Whr

So. PV panel required= 40,000/= 16.46 = **17 panels**

3.5.1.2 Battery Estimation:

Total watt-hour rating = 40,000 / (0.90*0.80*48) = 1,157.41

Battery required= 1,157.41 / 200 = 5.78 = **6 batteries.**

3.5.2 Designing a 5-kw biogas power plant

As we assumed the plant for 5 Kw (5000W), here we calculated the specific values for 5 kw power plant. But the values can be modified for larger or smaller scale power plant.

3.5.2.1 Gas required calculation:

As we know, the average calorific value of biogas is about 21-23.5 MJ/m^3, so that 1 m^3 of biogas corresponds to 0.5-0.6 l diesel fuel or about 6 kWh or 0.16 m^3, for 1Kwh. So, we will need 0.16m^3 per kWh.

Now, we will estimate the required gas for 12 hours. So that, we will have some backup gasses.

So total gas required for 24 hours is, (24*0.16) * 5 = **19.2m^3** of gas

3.5.2.2 No. of animal (cows):

We can use different types of animals for the dung. But here we took the dung of cows as standard. The amount of gas produced from a fresh kg of dung = 40litre/kg Total amount of dung required = 1200litre/40 = 480 kg. So, no of cows required = 480/10 = 48 cows. So, we will need minimum **50 cows.**

3.5.2.3 Digester design:

The digester design should be done very carefully. We will give slurry to the digester not only the dung. So, we need the specific calculation of slurry.

Slurry= dung + water = 480 + 480 = 960kg

Volume of slurry per day = 960 /1090 = **0.88m^3**

Retention period= 25 days

Volume of digester= 0.88 * 25 = 22.01 = **23 m^3**

3.5.2.4 Equation for biogas design:

This the main equation for our thesis works so that we can convert the gas into electricity

1. POWER (the rate of doing WORK) is dependent on TORQUE and RPM.
2. TORQUE and RPM are the measured quantities of engine output.
3. POWER is calculated from torque and RPM, By the following equation:

HP = Torque x RPM ÷ 5252

So, Torque= HP*5252/RPM Again, 1 hp= 746 watt

By Solution, Torque= **17.51N** at 1500 RPM

3.5.3 Plant Design

3.5.3.1 Solar PV MATLAB layout:

For the sake of simplicity of the simulation, here we showed the solar PV layout for 5 KW power supply as a single module as shown in figure 3.2. But it can be modified for any further change of the power.

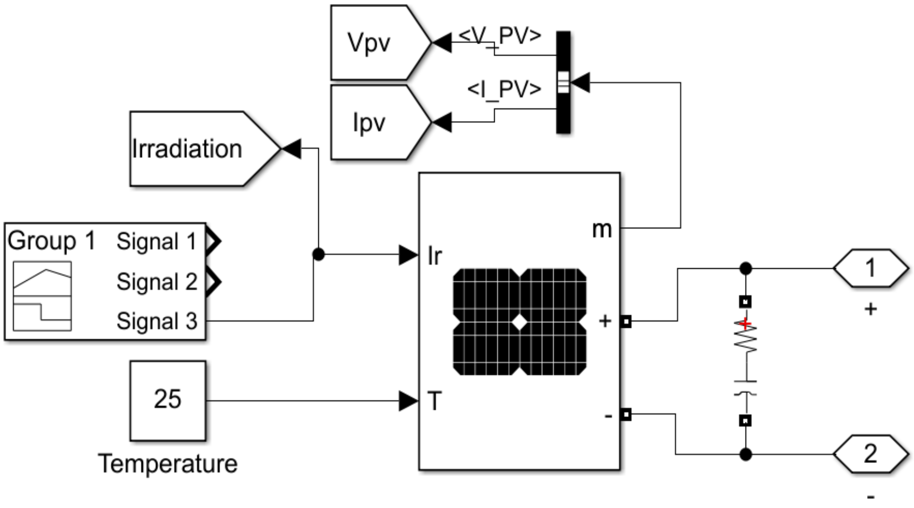


Figure 3.2: Simulink model of the PV Solar panel

1.5.3.2 Battery energy storage layout in Simulink

In the battery design, all six batteries were combined together in a parallel connection and represented by only one battery of 1,200 Ah with 48V as shown in figure 3.3 below

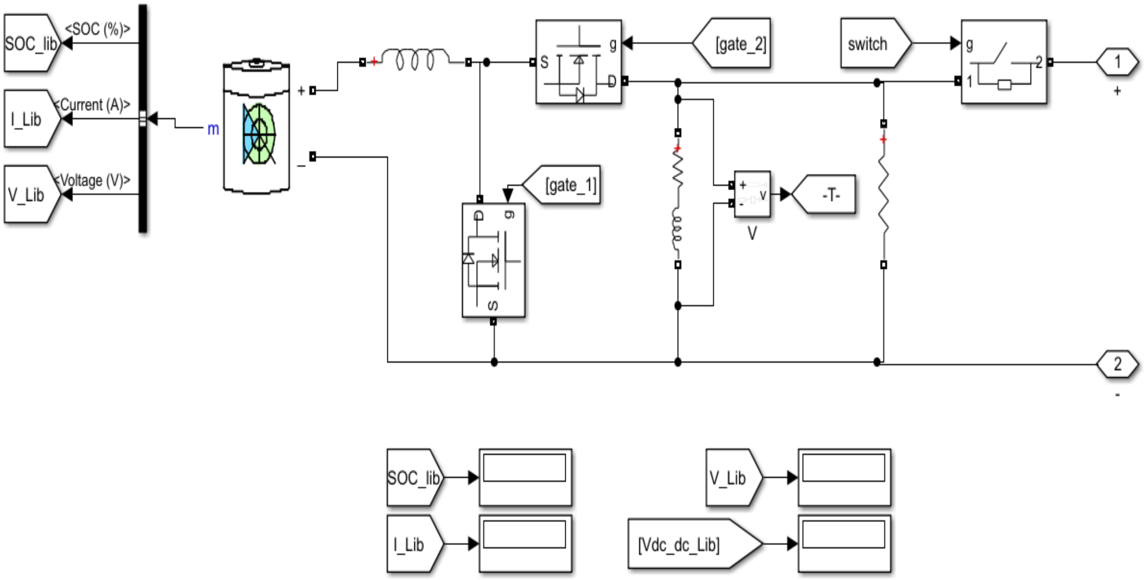


Figure 3.3: Simulink model of the battery system

3.5.3.3 Biogas plant design in Simulink

The biogas power plant is designed in three different vital parts Digester, Engine & generator. In the biogas plant design, our main challenge was to make it variable for any kind of input and output. I.e., the same design will applicable for 5 kW/ 1 MW/ 100 MW and so on. And finally, we found a solution for that design by developing a constant value which will add to the digester design. The value of the constant is 250 and is named as Martine’s constant.

The figure 3.4 below shows the biogas power plant in a block-based design. The constant 50 shows the input of fifty cows, the value 48 represents the output dung from 50 cows which are multiply further by two (2) to make a slurry. To get the real value of the gas for 24 hours which is 19.2 m3, we developed a constant value in the Simulink. The constant value is 250. Then we got the output 19.2 m^3.

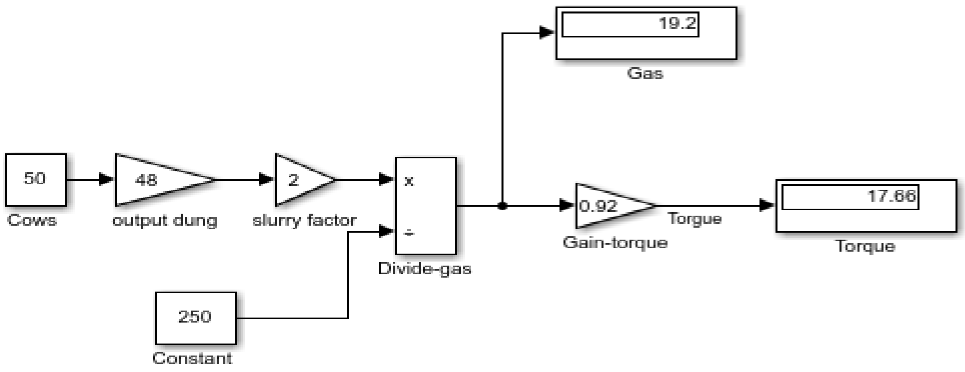


Figure 3.4: Simulink model of the biogas digester

To run the engine, we have to create torque. In Figure 3.5, it is shown that the engine created the desired torque, which is supplied to the generator, and coupled to the engine shaft. The Biogas layout of MATLAB- full Simulink design is shown below;

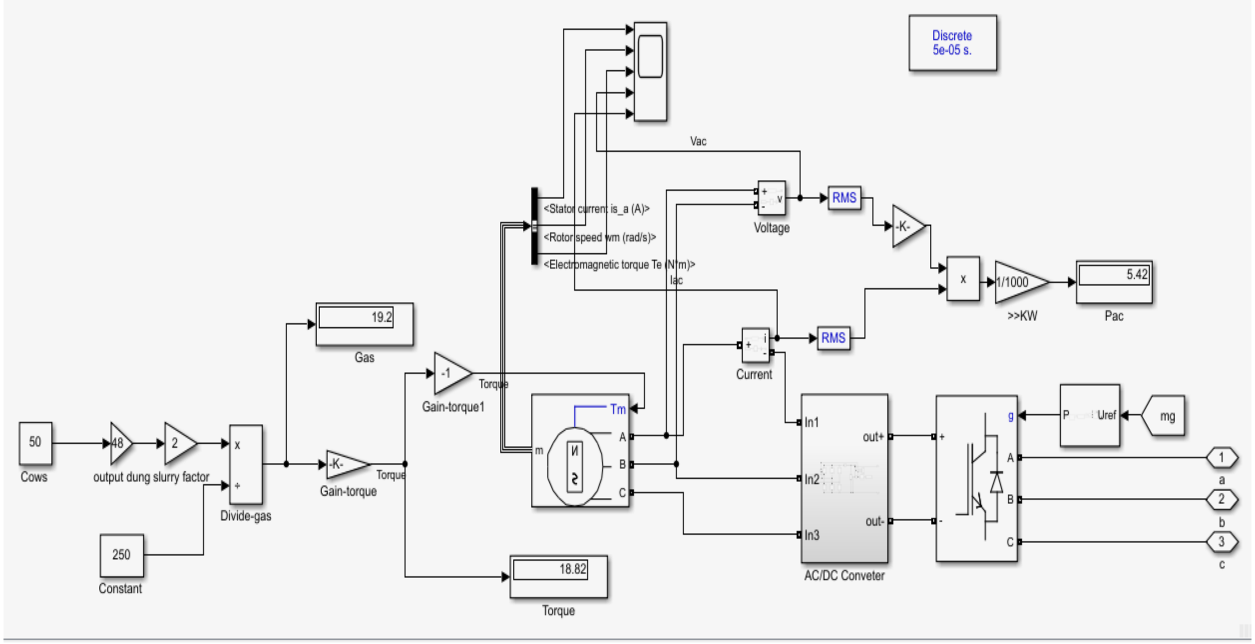


Figure 3.5: Biogas layout of MATLAB- full Simulink design

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Electricity Demand Assessment

For load assessment, we visited two villages, with positive responses from 90 personnel from two different villages. The survey questions included household size, family members, rating, and usage duration of electric appliances. Further, queries related to the day-to-day routine of the local community were included to explore the operational time of electric devices. The typical electric load of community services units is shown in Table 4.1, including schools and health, while the typical electric load for commercial units is shown in Table 4.2

Table 4.1. Community load.

S/N	APPLIANCE	POWER (W)	SALOON (No)	CLINIC (No)	SCHOOL (No)	VIDEO HALL (No)	CASINO (No)	TOTAL No	LOAD (W)
01	Indoor lights	3	3	8	10	2	3	26	78
02	Outdoor lights	3	3	8	10	4	3	28	84
03	Shaving machine	15	3	0	0	0	0	3	45
04	Computers	100	0	0	2	0	0	2	200
05	Screen	60	1	0	0	2	0	3	180
06	Decoders	15	0	0	0	2	0	2	30
07	Printer	200	0	0	2	0	0	2	400
08	Gaming machine	60	0	0	0	0	3	3	180
								TOTAL LOAD	**1,197**

Table 4.2. Productive load.

S//N	APPLIANCE	POWER(W)	SHOPS	BARS (No)	RESTAURANT (No)	TOTAL No	LOAD (W)
01	Indoor lights	3	15	10	5	30	90
02	Outdoor lights	3	30	20	4	54	162
03	Solar Fridge	65	3	2	2	7	455
04	Hoofer	25	5	10	2	17	425
05	Decoders	15	10	10	2	22	330
						TOTAL LOAD	**1,462**

4.2 Load Profiling

According to the survey data, the system's peak demand (3 kW) occurs at 08:00 p.m., with load ranging from 2.7 kW to 2.9 kW at other times. Deferrable loads, such as maize mill motors, were shifted to low-demand time slots, where the time slot is not essential. The mill owner will have complete freedom to run the business at night. Since it is improbable that all users would be using their full capacity at once, installations or networks can be designed with lower load capacities than the simple sum of the expected peak loads. The micro-grid load profiles for 24 hours are shown in Figure 4.1.

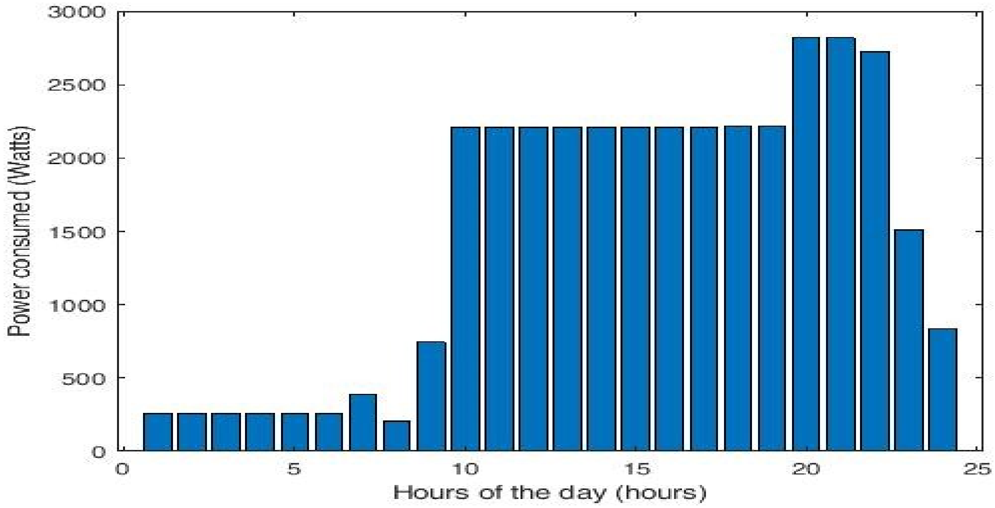


Figure 4.1 Hourly load profile of Kalungi B

We, therefore, assumed that the load would remain constant over the course of the project. Additionally, as the project generates income in case of implementation, the organizing committee may increase its capacity to take on additional loads.

4.3 Initial, Operational, and Periodic Costs

The capital or initial cost includes equipment purchases, such as PV modules, biogas generator, biogas plant, AC/DC hybrid converter, batteries, and different engineering and developmental works. We consulted the local market, online stores, and recent literature to determine the costs. Initial costs are listed in Table 4.1, while Table 4.2 shows an optimized hybrid system's annual operation and maintenance costs, including salaries, generator maintenance, PV system, batteries, and biogas plant. Table 4.3 shows the periodic costs of the system, which occur at the end of the useful life of the equipment.

Multiple online shops, markets, and literature are reviewed for pricing confirmation. Prices for PV and batteries are chosen using the local market and online shops. For the investor price, the same online store's inverter price and local markets were consulted. For batteries, we consulted the Solar

Shop online store. Prices for the anaerobic digestor and biogas generator are taken from existing biogas companies like Biogas Uganda with a 10% price increase to account for inflation.

Table 4.3: Initial Cost Estimates

S/N	ITEM	SPECIFICATION	ESTIMATE (UGX)
01	PV solar panel	500 Wp, 17 pieces, Vmp: 17 V	10,200,000
02	Battery	Lead Acid Battery, 200 AH, 6 pieces	7,500,000
03	Biogas generator	5 kVA with Engine oil, cable, spares	5,000,000
04	Change over switch	2-way, 30A Max.	120,000
05	Hybrid solar inverter	3 kVA max output, Battery-less operation.	3,000,000
06	Electrical installation	PV solar, distribution, prepaid meter, cables, fittings, and Transportation.	5,000,000
07	Circuit breakers	Circuit breaker above 5A, 10 pcs	160,000
08	Prepaid energy meter	Single phase, 10 pieces, 60 A max current.	3,500,000
09	Gas storage bag	20 cubic meters	6,000,000
10	Gas meters and purifiers	diaphragm type, Hydrogen Sulphide, Moisture, and Carbon dioxide scrubbers	5,000,000
11	Biogas Digester	Floating dome type	10,000,000
12	Digester monitoring system	Pressure and Gas flow	500,000
		TOTAL	**53,280,000**

Table 4.4: Annual and Maintenance Cost Estimates

S/N	TYPE	SPECIFICATIONS	COST/MONTH (UGX)	COST/YEAR (UGX)
01	Salaries	1 person, site caretaker.	200,000	2,400,000
02	Maintenance	Repairs and tests	250,000 (quarterly)	1,000,000
03	Land rent	Monthly Payment	150,000	1,800,000
04	Feedstock	Cow dung	500,000	6,000,000
05	Contingencies	3%	-	336,000
			TOTAL	**11,636,000**

Table 4.5: Periodic Cost Estimates

S/N	EQUIPMENT	REPLACEMENT COST % OF INITIAL COSTS	DURATION (YEARS)	COST(UGX)
01	Battery	60	10	4,500,000
02	Biogas generator	70	8	3,500,000
03	Inverter	70	7	2,100,000
			TOTAL	**10,100,000**

The salary and biomass fuel prices are established by the local market, with 10% higher salaries and 10% higher market costs.

There will be no gas connected to consumers for now but it can be considered later under scalability. Meters are connected on the consumer side to read the amount of electricity consumed for communal structures, and commercial buildings. They simply need to draw a connection to their homes, which is outside the scope of this study and is not covered in it.

4.4 System Design and Analysis

A Simulink model for the proposed hybrid solar PV biogas power system is developed. The model consists of solar PV, biogas fueled generator, and battery sub-models connected as shown in figure 4.2 below;

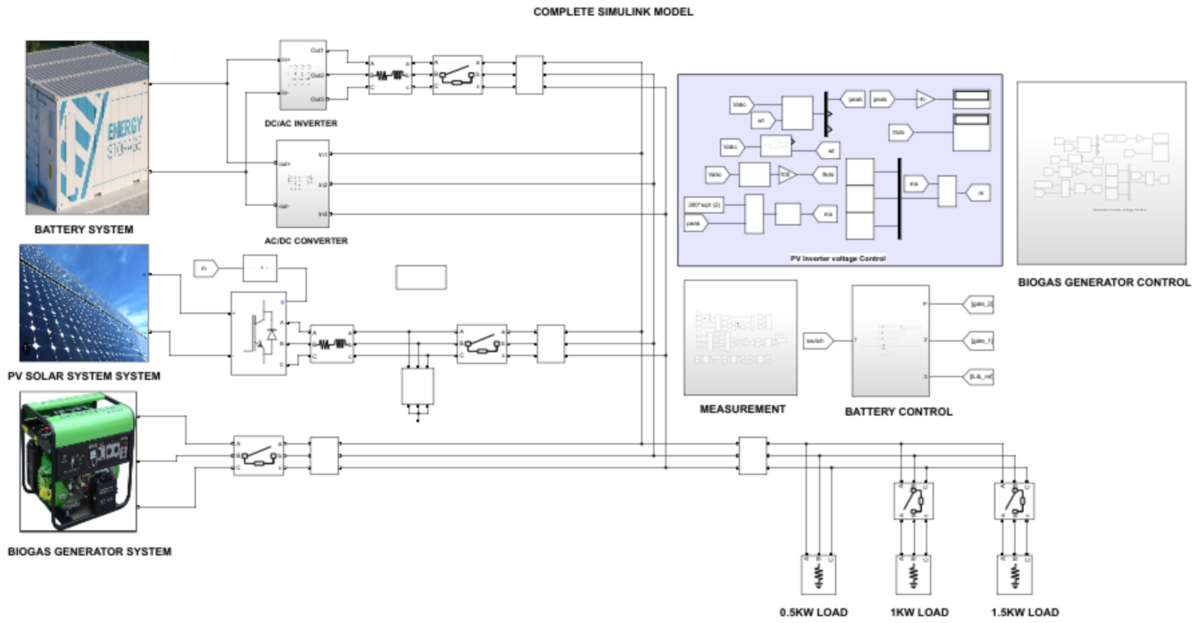


Figure 4.2 Simulink model of the hybrid system

4.5 Financial Analysis

According to Table 4.3, the initial cost of the project is shillings 53.28 million. The annal operational cost shown in Table 4.4 is shillings 11.636 million. Periodic costs of project mentioned in Table 4.5 total 10.1 million for the whole life of project. Each household would pay at 800 shillings for each unit of electricity. Farmers will purchase the fertilizer at 200 per kg. Electricity charges of million will be collected yearly basis for the project, while the annual revenue from fertilizer sales is million.

At the same time, we proposed a high price for the manure to encourage local people's interest in the project, which is essential to its sustainability. The average annual savings of the system is million. Revenue will be mainly collected by selling electricity and fertilizer. Our model has been designed to benefit and develop underprivileged communities unable to access grid electricity.

4.6 Simulation Results

4.6.1 During Sunny Day Mode Behavior of SPV

The performance of SPV is depicted in figure 4.3 and figure 4.4 below. Under sunny day mode the solar irradiance is changed from 0W/m^2 to 500W/m^2 from 7a.m to 8a.m and after that we see that at 11 a.m. the irradiance gradually increased to 1000W/m^2. During the change in solar insolation at 25^{o}C the various parameters such as Vdc mean, Idc, PV power mean are observed. During variable solar irradiance the Vdc is maintained at 200V and the captured power is 4KW under 1000W/m^2 and 2KW during 500W/m^2.

The behavior of the biogas generator and battery is equally observed where the battery comes in during times when the solar PV power is too low to handle the load available and the generator comes in when both the solar PV and battery cannot handle the load. The battery is the immediate backup for the solar PV while the biogas generator comes in as back up for both when they have failed and this often happens in the night hours as seen from the simulation.

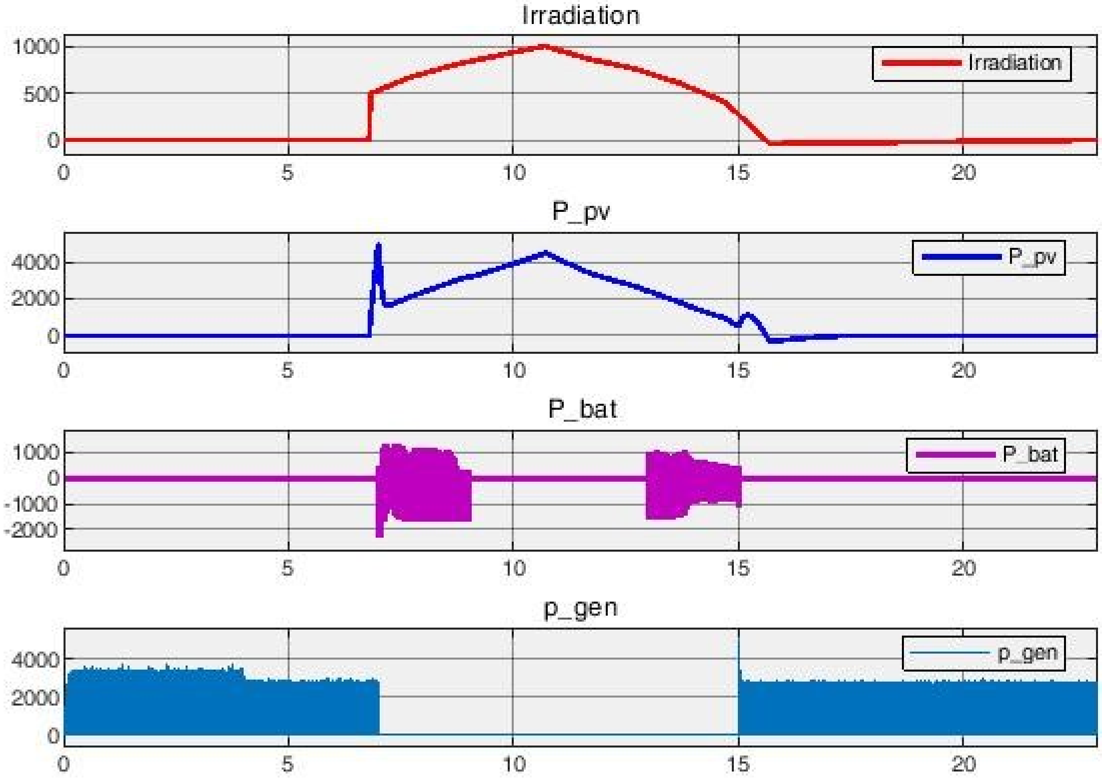


Figure 4.3: Simulation of irradiation and power output versus hours of the day

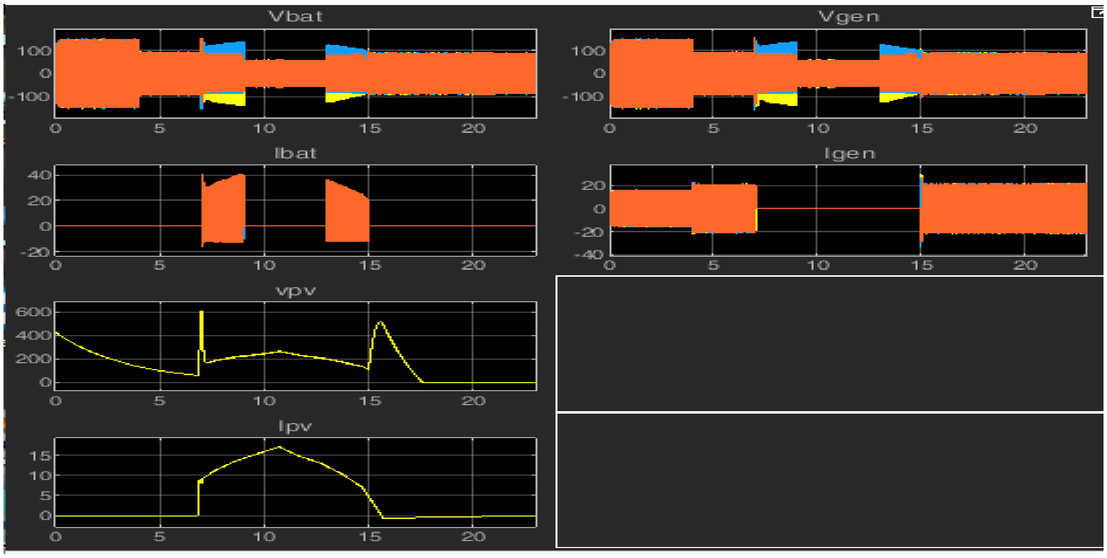


Figure 4.4: Simulation of current and voltage characteristics versus time of the day

4.6.2 During Moderately Cloudy Day Mode Behavior of SPV

The performance of SPV is depicted in figure 4.5 and figure 4.6 below. Under moderately cloudy day mode the solar irradiance is changed from 0W/m^2 to 200W/m^2 from 7a.m to 8a.m and after that we see that at 1 p.m. the irradiance gradually increased to 800W/m^2. During the change in solar insolation at 25ºC the various parameters such as Vdc mean, Idc, PV power mean are observed. During variable solar irradiance the Vdc is maintained at 200V and the captured power is 3KW under 800W/m^2 and 1KW during 200W/m^2.

The behavior of the biogas generator and battery is equally observed where the battery comes in more during times when the solar PV power is too low to handle the load available and the generator comes in longer when both the solar PV and battery cannot handle the load.

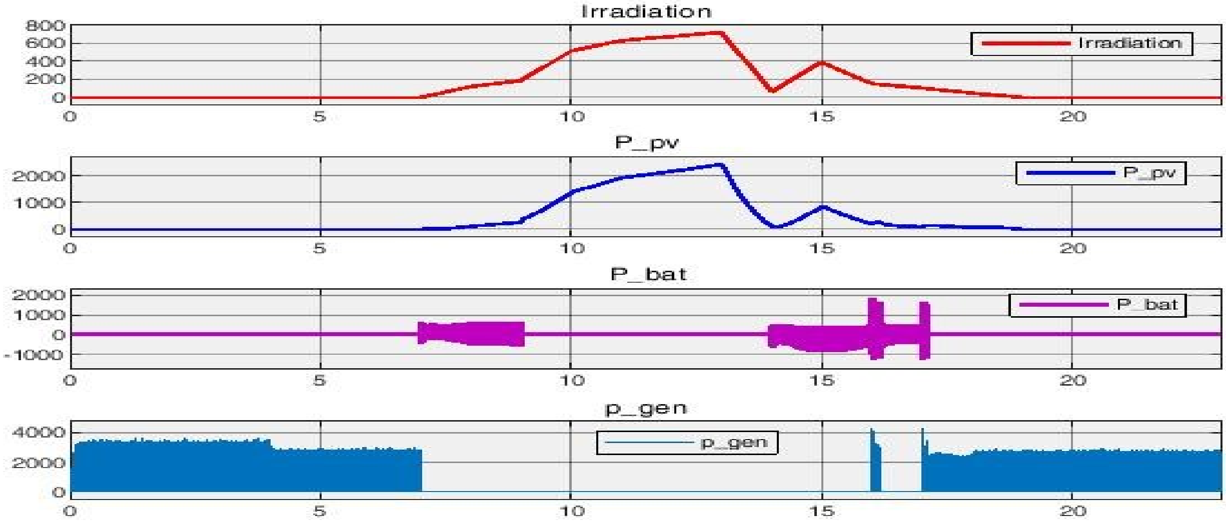


Figure 4.5: Simulation of irradiation and power output versus hours of the day

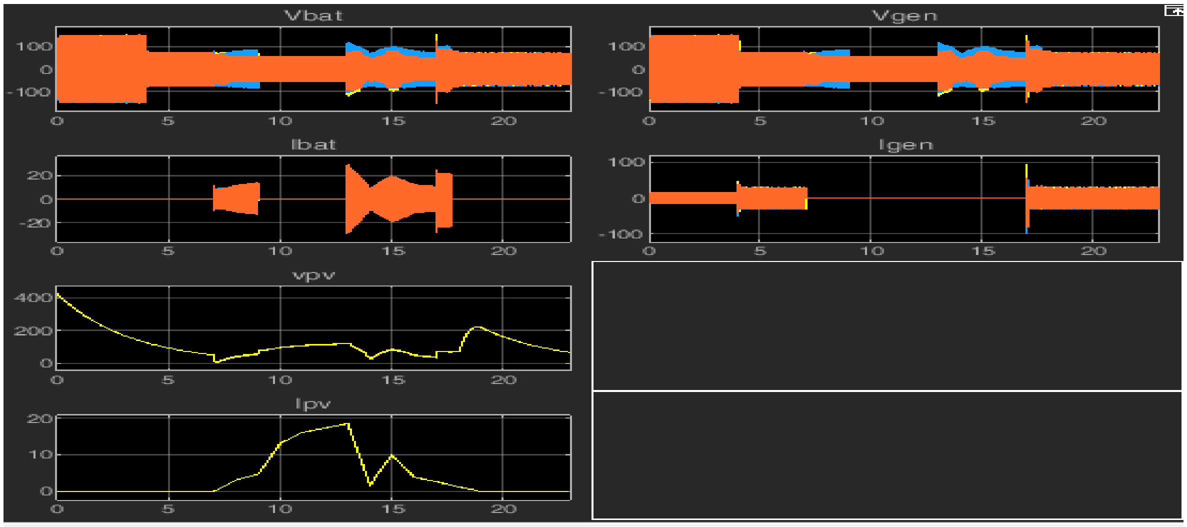


Figure 4.6: Simulation of current and voltage characteristics versus time of the day

4.6.3 During Very Cloudy Day Mode Behavior of SPV

The performance of SPV is depicted in figure 4.7 and figure 4.8 below. Under very cloudy day mode the solar irradiance is changed from 0W/m^2 to 200W/m^2 from 8a.m to 9a.m and after that we see that at 11 p.m. the irradiance gradually increased to 600W/m^2. During the change in solar insolation at 25^{o}C the various parameters such as Vdc mean, Idc, PV power mean are observed.

During variable solar irradiance the Vdc is maintained at 180V and the captured power is 2KW under 800W/m^2 and 0.5KW during 200W/m^2.

The behavior of the biogas generator and battery is equally observed where the battery comes in more frequently during times when the solar PV power is too low to handle the load available and the generator comes for in and stay longest when both the solar PV and battery cannot handle the load.

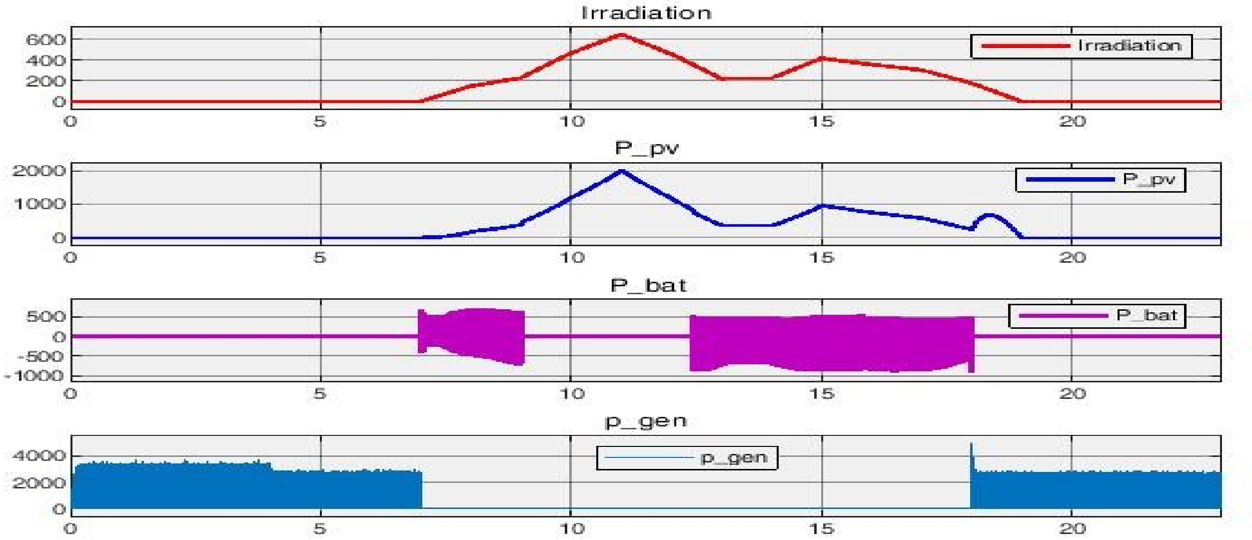


Figure 4.7: Simulation of irradiation and power output versus hours of the day

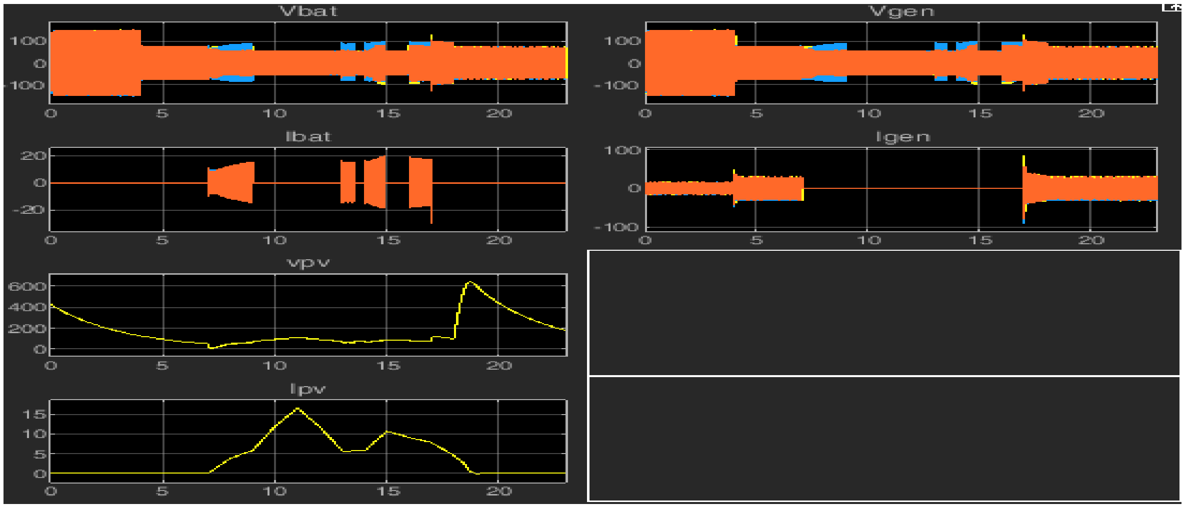


Figure 4.8: Simulation of current and voltage characteristics versus time of the day

4.7 Accessing sustainability and reliability

Reliability and sustainability of the system can vary greatly depending on several factors such as location, the quality of the equipment used, and the maintenance of the system. However, our system has shown that it can be very reliable and sustainable.

4.7.1 Reliability

Our design has an estimated lifespan of 10-20 years. Its reliability is as high as 80-90% though this can be affected by quality of installation and maintenance.

System's availability which is the percentage of time that the system is able to meet the load demand. With our design, the systems availability is as high as 90% since the battery and generator can come in in case of low irradiation or bad weather as seen by the simulation results.

System Capacity: The capacity of the system to meet the energy needs of the community can be analyzed to measure reliability. The system has been designed to have sufficient capacity to meet the energy demands of the community, even during peak demand periods. This was made possible by performing the load profiling and also using higher capacity than the actual peak power demand requirement.

Redundancy/alternate sources: the system can achieve reliability of over 90% this is because of the combination of two independent power sources- solar backed up with the battery energy storage and biogas. When one source is not producing enough power example during the night or cloudy days, or during periods of low cow dung availability, the other source can compensate.

4.7.2 Sustainability

In terms of sustainability, our design is very sustainable since the solar PV system produce electricity from sunlight, which is a renewable resource. The biogas system produces electricity from organic waste, which is also a renewable resource. The percentage of sustainability of the design is equally 80-90%. However practically it may vary due to other factors.

Environmental impact: the sustainability of the system can also be measured in terms of environmental impact. Solar PV systems have low environmental impact as they produce electricity from sunlight which is a renewable and abundant energy resource in Mubende. Biogas system also have a low environmental impact as they produce electricity from organic waste, which is a renewable energy source and helps in waste management. Moreover, the use of biogas system can reduce the emission of greenhouse gases, as the methane that is produced and burned would otherwise be released into the atmosphere. Therefore, making the system highly sustainable.

Resource Availability: The availability of the resources required to operate the system can be analyzed to measure its sustainability. The system was designed to use renewable resources that are abundant in the area, such as solar energy and biogas which are readily available in the area.

Community acceptance: social acceptance is a crucial factor in the successful implementation and operation of the solar PV biogas microgrid. It involves the perception and acceptance of the local community towards the project. The community was engaged in the planning and decision-making process to help the project meet the needs and expectations of the community and to also help build a sense of ownership and responsibility, which can lead to greater support and involvement in the operation and maintenance of the system. A site care taker would also be picked from the community and trained to provide job opportunity for the locals in the community to increase economic benefits and support for the project.

CHAPTER FIVE

CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

5.1 CONCLUSION

This is a study of proposing solar photovoltaic and biogas hybrid system for generation of electricity. In hybrid systems, energy has greater diversity, higher reliability and can be cost effective improving the quality of energy. Hybrid power system aims to increase the system efficiency and increase the use of renewable sources. Hybrid renewable power system is environment friendly too. This hybrid system will independently provide a stable power source from biogas and solar energy. It is seen that biogas is a promising tool for generation of electrical energy. Biogas combined with solar generation brings self-sufficiency and reduction of greenhouse gases and recovers global warming effect. Energy, economy and environment are the three interrelated areas having direct correlation for development of any nation. Per capita energy consumption is an index for development of any nation. Aim of our proposed hybrid renewable energy system is to increase the per capita energy consumption in Kalungi B, Mubende district while keeping environment clean and safe. It can be an excellent, cost effective and also a reliable solution to mitigate the existing power crisis if we can implement this project properly. It has a great impact on improving the socioeconomic condition of rural people as well as will be a good sign of green energy technology.

The proposed microgrid system that is comprised of solar, biogas generator, and battery work efficiently. The proposed system is designed and simulated in MATLAB/Simulink. The characteristics of solar, biogas generator, and batteries are evaluated. Under the islanding mode of operation, the solar and battery along with biogas generator supplies loads.

5.2 LIMITATIONS

- The power generation system proposed here has some limitations also. The battery bank was used for the storage of PV energy. The installation cost of the battery is high. They also have some negative impacts on the environment. When they are out of use, it is very difficult to dispose of them.
- Limitations, such as the sample size that was taken for the geographical scope, and data collection period.
- Simulation results may vary with actual practical/hardware results.
- Biogas generation is an anaerobic reaction process. A fixed temperature should be maintained for proper biogas generation and that is 35-38◦ C. In practice, it is very difficult to maintain this temperature during the wet season. But excess generated energy can be used to heat the digester of biogas plants during that time.
- The most challenging task of biogas generation is the desulphurization process. Sulfur contents from wastes must be separated before being used in the biogas plant. Different containers for keeping different types of waste such as perishable, recyclable, and toxic should be introduced to make this process smooth and easy.

5.3 RECOMMENDATIONS

- Partnerships should be established between government agencies, non-governmental organizations, and private sector entities to provide technical and financial support.
- Further research to address gaps in knowledge and explore opportunities for scaling up the hybrid microgrid model.
- Establish maintenance and training programs: A comprehensive maintenance plan should be developed to ensure the longevity and optimal performance of the microgrid. Regular maintenance activities such as panel cleaning, battery maintenance, and system inspection should be carried out. Additionally, training and capacity-building programs should be provided to local technicians and community members to ensure they have the necessary skills to operate and maintain the system effectively.
- More policy frameworks should be developed to incentive the adoption of renewable energy technologies and promote sustainable rural electrification.

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APPENDIX

FEEDSTOCK SUPPLIER SURVEY QUESTIONNAIRE

Potential supplier details

	QUESTION	**RESPONSE**		
1	Name(s) & phone numbers of contact person/people	**Name**	**Phone number**	
2	Type of supplier	A. Farm B. Restaurant C. School D. Business E. Other (Specify below):		
3	GPS coordinates of premises			
4	Types of feedstocks	A. Animal waste B. Food waste C. Plant waste D. Other (Specify below):		
5	If livestock farm: Number of animals		**Animal**	**Quantity**
		1	Cattle	
		2	Goats	
		3	Pigs	
		4	Sheep	
		6	Other (specify:)	
6	If livestock farm: Type of grazing	A. Zero grazing B. Free range C. Other (Specify below):		
7	If animal waste: Daily quantity of waste		**Animal**	**Quantity**
		1	Cattle	
		2	Goats	
		3	Pigs	
		4	Sheep	
		5	Poultry (specify:)	
		6	Other (specify:)	
8	If food waste: Daily quantity of food waste			

CONSUMER SURVEY QUESTIONNAIRE

Consumer details

	QUESTION	**RESPONSE**		
1	Name(s) & phone numbers of contact persons/people	**Name**	**Gender**	**Phone number**
2	Type of consumer	A. Household B. School C. Business D. Health center E. Farm F. Other (specify below):		
3	If business: Specify the nature of business			
4	The daily average number of people at consumer premises			
5	GPS coordinates of premises			
6	Daily opening time			
7	Daily closing time			
8	Weekend off-time			
9	Space ownership	A. Owner B. Tenant		
10	Number of residents at the premises			
11	Education level of business owner			
12	Monthly Income			

Consumer's energy situation

	QUESTION	**RESPONSE**
1	Grid electricity access	A. Connected B. Not connected but the grid nearby C. No access
2	If not connected: Distance from the grid in km	

3	If the grid is nearby: Amount of money in UGX required for connection					
4	Distance from prospective digester in meters					
5	Status of existing electrical wiring at the premises					
6	Desired additional electrical appliances		**Appliance**	**Purpose**		
		1				
		2				
		3				
7	Electrical appliances		**Appliance**		**Wattage**	**Hours per day**
		1				
		2				
		3				
8	Energy sources currently being used		**Source**	**Purpose**	**Daily quantity**	**Cost**
		1				
		2				
9	Willingness to pay for electrical energy					
10	Price range per unit of electricity consumption is willing to pay					

DEMOGRAPHICS SURVEY QUESTIONNAIRE

Informant details

	QUESTION	RESPONSE
1	Name	
2	Contact	
3	Designation/Occupation	
4	Address	

Area details

	QUESTION	RESPONSE
1	Village	
2	Parish	
3	Sub-county	
4	County	
5	District	
6	Sub-county	
7	Population	
8	Typical economic activities	
9	Number of households	
10	Number of businesses	
11	Number of farms	
12	Typical farming types	
13	Grid electricity access	
14	Dry season times & durations	
15	Wet season times & durations	
16	Number of manufacturers in the area	

17	Typical energy sources used	
18	Number of schools	