MAKERERE UNIVERSITY

COLLEGE OF ENGINEERING, DESIGN, ART AND TECHNOLOGY

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

FINAL YEAR FULL PROJECT REPORT

# TECHNO-ECONOMIC ANALYSIS OF A HYBRID SOLAR PV-WIND SYSTEM POWERING AN OFF-GRID COMMUNITY

**APIO MIRRIAM MERCY 20/U/1280**

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

**JUNE 2024**

# DECLARATION

This is to declare that this report is my original work and has not been previously submitted and approved for the award of a degree by this or any other University. To the best of our (my project partner and I) knowledge with joint efforts, we gathered and compiled information and we believe that this content is original and a true account of the activities we carried out.

Signed:

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Date: 17th JUNE 2024

## APPROVAL

This report has been submitted to the Department of Electrical and Computer Engineering with the approval of the following supervisors.

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I cannot fail to appreciate friends and family who have supported our endeavours with both tangible and intangible support towards this project till completion. I would also like to acknowledge and recognize the support and guidance provided by Mr Paul Asiimwe and my project partner, Mercy Lakareber. Thank you very much and surely the time and effort will not be in vain.

# ABSTRACT

With continuous population increase in the rural communities of Uganda, there has been an increase in demand for electricity to foster socio-economic development. However, access to the national grid has been a challenge for most rural areas in Uganda, hence the need to explore the use of distributed renewable energy sources.

This project report aims at assessing the technical and economic feasibility of implementing a sustainable energy source for electricity generation, by integrating a solar photovoltaic (PV) and wind turbine technologies into a hybrid system powering an off-grid community. In order to implement the hybrid system, a review was carried out on the main components of the systems which include the PV modules, wind turbines, batteries, inverters and the backup generator.

In order to achieve the project objectives, meteorological data was obtained from the NASA POWER website as well as the HOMER Pro software resources tab. Furthermore, field survey of the case study location was carried out to determine the energy demand. The HOMER Pro software was used to carry out the cost and technical analysis.

The last phase of this project involved the design of a low voltage distribution network to carry out power systems analysis using DIgSILENT PowerFactory, with the aim of evaluating the technical performance of the developed solar PV-wind system.

Key words: Renewable energy, hybrid, off-grid community, energy access, HOMER Pro, DIgSILENT

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## LIST OF ACRONYMS

| | |
|---|---|
| **ABC** | Aerial Bundled Cable |
| **AC** | Alternating Current |
| **BOS** | Balance of System |
| **CC** | Cycle Charging |
| **COE** | Cost of Energy |
| **DC** | Direct Current |
| **DIgSILENT** | DIgital SImuLation and Electrical Network calculation program |
| **ESS** | Energy Storage Systems |
| **HAWT** | Horizontal Axis Wind Turbine |
| **HOMER** | Hybrid Optimization of Multiple Energy Resources |
| **HRES** | Hybrid Renewable Energy Sources |
| **LCOE** | Levelized Cost of Energy |
| **LF** | Load Following |
| **Li** | Lithium |
| **Imp** | Maximum current |
| **Isc** | Short Circuit current |
| **MEMD** | Ministry of Energy and Mineral Development |
| **MPPT** | Maximum Power Point Tracker |
| **m/s** | meters per second |
| **MW** | Megawatt |
| **NASA** | National Aeronautics and Space Administration |
| **NDP** | National Development Plan |

| | |
|---|---|
| **NPC** | Net Present Cost |
| **NREL** | National Renewable Energy Laboratory |
| **O&M** | Operation and Maintenance |
| **POWER** | Prediction of Worldwide Energy Resources |
| **PV** | Photovoltaic |
| **REC** | Renewable Energy Conference |
| **SDG** | Sustainable Development Goal |
| **VAWT** | Vertical Axis Wind Turbine |
| $\mathbf{V_{mp}}$ | Maximum Voltage |
| $\mathbf{V_{oc}}$ | Open Circuit Voltage |

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# CHAPTER 1: INTRODUCTION

## 1.1 Background

Africa, just like any other continent in the world has for a long time been greatly dependent on fossil fuel (i.e., natural gas, coal, oil, etc.) as the main source of energy for heat, electricity and transportation making up to about 80% of the continent's energy [1]. This, however, comes at a cost in terms of continued increase in the greenhouse gas emissions that adversely affect the environment, climatic patterns, depletion of these fossil fuel resources as well as posing great health risks [2]. This has resulted in a rapidly increasing demand for renewable energy resources since they provide a great alternative to fossil fuels as a new technology for harnessing energy [3].

In Uganda, approximately 92% of the total energy consumed is from renewable energy sources such as hydro, biomass, wind, geothermal, and solar [4]. These energy sources have been instrumental in electricity generation which is rapidly increasing because of the rapidly growing demands. Electricity generation has notably diversified beyond the use of conventional sources of energy and now includes renewable energy sources as well. However, despite several efforts to increase electrification rates in the country, only 45.22% of Uganda's population had access to electricity by 2021 [5]. Out of this total percentage, electricity accessibility steeply varies between the rural and urban populations of Uganda, with only 10% of Uganda's rural population having electricity access according to the Ministry of Energy and Mineral Development (MEMD) [5].

During the Renewable Energy Conference (REC22) that took place in November 2022 at Kololo Independence Grounds Kampala, MEMD noted that the total installed capacity of electricity generation in Uganda by 2021 stood at 1,346.6 MW, which contributed to only 2% of the total energy consumption. From the statistics collected, the majority is generated from hydro constituting up to 1,072.9 MW, leaving the rest of the renewable energy sources lagging. Thermal generates 101.1 MW, bagasse 111.7 MW, grid-connected solar 60.9 MW and almost none from wind [6]. This indicates that except hydro, other sources of electricity generation in Uganda have not been explicitly explored despite being rich in potential as well as having the added advantages of being environmentally friendly and abundant in nature [7].

In regards to electricity production from renewable energy sources as a whole, a major challenge that arises from the use of these sources is the variability and unpredictability in power output. Electricity from solar is directly generated from the sun's radiation [4,8] and thus greatly affected by any variations in the sun's intensity [9]. Similarly, the average wind speeds in Uganda are not constant and often vary between 4-6 m/s [8]. This poses a great challenge in terms of reliability because of the fluctuations. To ensure the efficiency and reliability of the output while using renewable energy, several technologies are being implemented some of which include the use of Energy Storage Systems (ESS) such as batteries for hours when output is really low [10]. Similarly, there are grid-connected renewable sources to complement the grid power. On the other hand, off-grid stand-alone mini-grids are greatly being utilized to promote rural electrification in hard-to-reach areas [10].

In order for Uganda to advance towards the achievement of Sustainable Development Goal 7 (SDG7) which advocates for access to affordable, reliable, sustainable, and modern clean energy for all by 2030, integration of hybrid renewable energy systems for rural communities in the energy mix will greatly contribute towards this advancement in the energy sector [11]. The hybrid system combines multiple technologies based on renewable sources and/or conventional sources of energy which are clean and, in this case, solar and wind, and also offers improved reliability.

In line with Uganda's Vision 2040, MEMD in 2018 commissioned three small wind-solar mini-grid systems in different locations including; Kacheri Town Council in Kotido District, Lokopol Town Council in Napak District all in Karamoja region, and Lufudu, Namayingo District [12]. These were mainly installed to provide electricity for light and domestic charging to these communities. However, none of these systems are functioning to date due to component failures for example the inverter in one of them got damaged. This therefore calls for the development of more resilient and advanced solar PV-wind hybrid systems that increase reliable electrification of off-grid rural communities.

### 1.2 Problem statement

Electricity extension from the national grid to rural communities is technically challenging and economically not feasible and hence, there's a big gap in electricity distribution to these rural communities.

As a result, most rural communities in Uganda depend on renewable energy sources for electricity generation and access. However, these renewable energy sources face challenges of reliability and sustainability that result into fluctuations of the output power.

## 1.3 Objectives

### Main objective

To evaluate the techno-economic feasibility of a hybrid solar PV – wind system for electricity generation in an off-grid community in Uganda.

### Specific Objectives

i. To determine the energy demands of the case study location through specific site studies and analysis.
ii. To develop a solar PV-wind hybrid system that is able to meet the energy demands of the selected area.
iii. To evaluate the techno-economic performance of the developed solar PV – wind system.

## 1.4 Scope of the project

This project focuses on the design, simulation and analysis only and there is no physical construction of the model.

## 1.5 Justification

According to the national draft energy policy of 2019 [13], it was noted that hydropower predominantly facilitates the renewable energy access for social and productive use on the grid, however, domestic and off-grid agricultural and industrial activities are still primarily powered by biomass and fossil fuels. The use of these energy sources results into grave climate, environment and health issues [14]. Under Uganda's National Development Plan (NDP) III, the aspiration of Agenda 2030 is to achieve universal access to clean energy and electricity and one of the ways this will be possible is through harnessing the potential in renewable energy sources such as hydro, solar, wind, that will increase access to and consumption of clean energy [15].

Statistics has it that about 78% of the electricity currently being tapped is from hydropower which is the major contributor towards the energy sector [16]. Solar energy from the sun is the second largest source of renewable energy that's being harvested for electricity.

In order to cut the use of carbon energy sources while still meeting the ever-increasing energy demands imposed by population increase, integration of an off-grid Hybrid Renewable Energy System (HRES) and in this case, a solar PV-wind system, into the energy mix will increase Uganda's energy security. It is instrumental in increasing electricity access in the rural population, with a reduction of load pressures on the national grid [17].

However, with several attempts by MEMD to adopt to this new technology [12], there are critical issues that are related to both solar and wind depending on their fluctuating sources hence contribution to energy generation made very variable. Furthermore, viability of such projects has not been established and access to an off-grid solar PV-wind hybrid system in these rural communities does not necessarily guarantee good quality of supply and reliability of the system [18].

This project aims at bridging the gap that arises because of the insufficient knowledge about the technical feasibility, economic viability and potential challenges associated with solar PV-wind hybrid systems by conducting a techno-economic feasibility analysis. The findings of this research will contribute valuable insights to the renewable energy sector and informing future policy decisions for potential deployment of efficient and economically viable solar PV-wind hybrid systems.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 INTRODUCTION

### 2.1.1 Introduction to Solar Energy

Solar energy is abundant in nature and available all around the world since it is obtained from the sun directly. This energy can be consumed either as thermal energy or as electricity being used for various purposes [19]. It is also the cleanest renewable energy resource available since it doesn't involve any level of carbon emission. The following subsection captures a review of solar power and its generation.

### 2.1.2 Electricity generation from the sun

Electricity from the sun is generated through a process called photoelectric effect. Photoelectric effect refers to the emission of electrons or other free carriers from a metal surface when light shines on that surface. When photons of light from the sun with a frequency greater than the threshold frequency hit a metal surface, the photons are absorbed and as a result, electrons are dislodged from the metal surface and are now free to move from one point to another [20]. This movement of electrons provides a current path that results into flow of electricity. This current is now transported to different areas for consumption using cables. Figure 1 gives a simple illustration of the photoelectric effect.

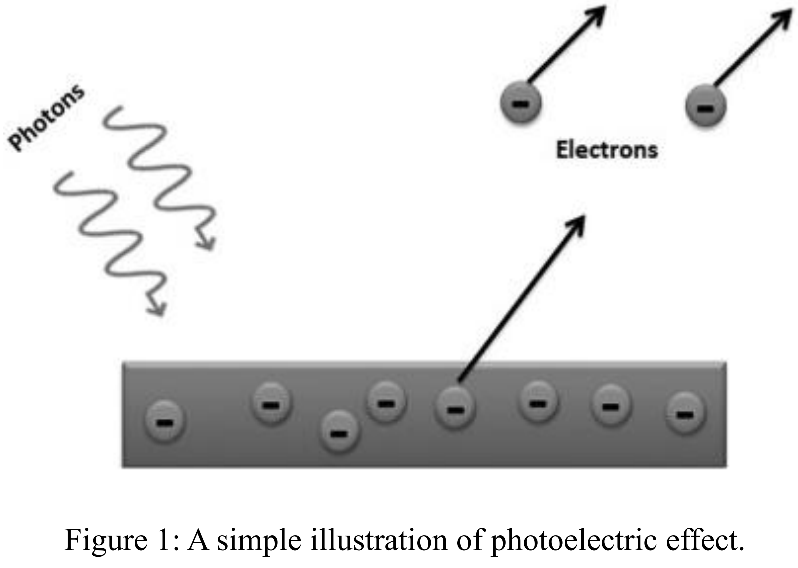


Figure 1: A simple illustration of photoelectric effect.

## 2.2 Photovoltaic

### 2.2.1 Introduction to Photovoltaic

Photovoltaic (PV) solar cells directly convert sunlight into electricity using the photovoltaic effect. A PV system consists of PV cells that are grouped together in series and parallel arrangement to form a PV module. A collection of PV modules put together form a PV array which forms the power-generating unit. The PV modules in the PV array are connected in series arrangement in order to scale up voltage and parallel arrangement in order to scale up current so as to obtain the expected power output levels.

### 2.2.2 Components of PV Systems

The solar PV system consists of several components grouped together in order to be able to output electricity. These components are described briefly below;

1. **Solar cell:** A solar cell is the fundamental building block of the solar module and it is usually made of a semi-conductor material. This is where the light energy is directly converted into electricity by the photoelectric effect.
2. **PV Module:** Solar cells can be arranged together either in series or in parallel and this combination of the solar cells forms what is known as the solar panel or module.
3. **Array:** This is the combination of the solar panels arranged together to generate a required amount of electricity.
4. **Battery:** Batteries store the excess electricity generated from the solar panels that can be used at a time when generation is very minimal for example in the night. Battery capacity to store energy is usually measured in amp-hours.
5. **Charge Controller:** Prevents overcharging and possible undercharging of the battery in order to increase the life expectancy of the batteries. A controller senses the battery voltage and stops charging when voltage becomes too high. It also protects the battery from deep discharging by disconnecting the load automatically.
6. **Inverter:** Converts DC electricity produced by the solar panels into AC electricity which is used by most appliances. Their efficiencies range from about 95% to 98% and this may vary depending on the DC input power and voltage. Conversion of DC electricity to AC electricity from the solar panels synchronizes with the power output from the utility grid hence the solar systems can be grid-tied.

### 2.2.4 Classification of Solar PV System

#### i. Stand-alone/off-grid system

Stand-alone systems are also sometimes known as off-grid systems since they operate independent of the main utility grid. In other words, they are isolated from the electricity distribution grid. Stand-alone systems use batteries to store electrical energy for time when there's minimal output from the generating source. Figure 2 gives a simple outlook of a stand-alone system supplying AC loads in a home.

Figure 2: Stand-alone solar PV system.

#### ii. Grid connected system

This system is connected to the main utility grid and does not necessarily require battery storage. The excess power produced is sold to the utility grid. The net metering system is commonly used and with this, homeowners sell the excess electricity to the grid instead of storing it. Through this, utility companies are able to buy electricity from the different users. Figure 3 shows a schematic of how grid connected systems are set up.

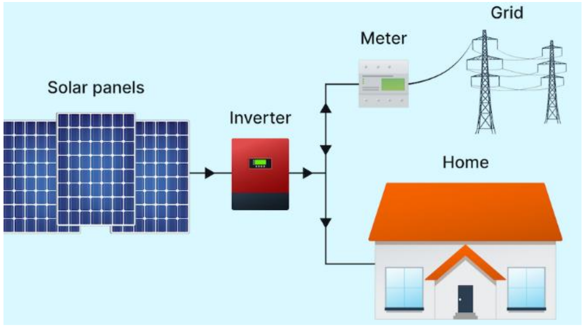


Figure 3: Grid connected solar PV system.

### 2.2.5 Solar PV module cell technologies.

i. **Monocrystalline:** This is made of a single crystal which has a very high purity thus the name monocrystalline and has the highest efficiency. This means that it produces more power over a small area and for this reason, it is the most expensive material for making PV cells.
ii. **Polycrystalline:** This has more than one crystal used in the manufacture of the PV cell and contains a certain percentage of impurities and for this reason it is less efficient and much cheaper compared to the monocrystalline silicon panels.
iii. **Amorphous silicon:** In this case, several layers of photovoltaic material are deposited onto a substrate and their low power outputs limits their use to small applications only. These solar cells also belong to the category of silicon thin-film and the first generation of which the a-Si was produced.

## 2.3 Photovoltaic Output Characteristics

### 2.3.1 The I-V and P-V characteristics

The total energy output of a PV module is given by the product of the output voltage and its operating current. The PV modules don’t produce current at constant voltage because voltage in the module varies at different intervals and as a result variation in power output. The current-voltage graph in Figure 4 describes the performance curve of a PV module and the characteristics described in the following section.

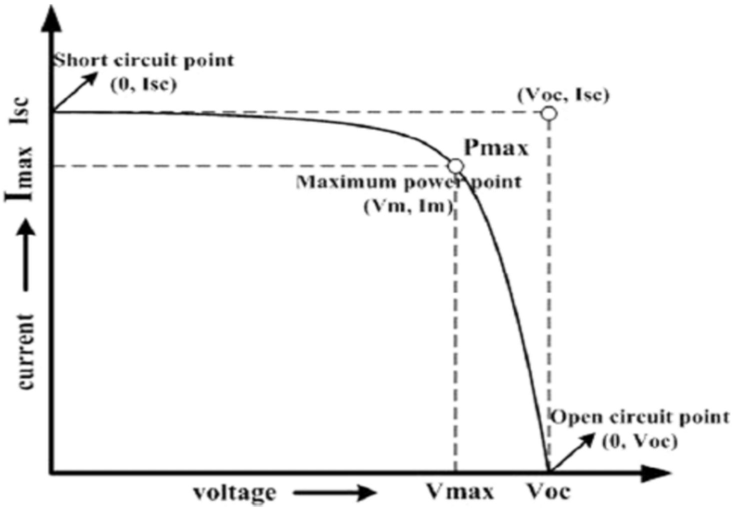


Figure 4: Output characteristics of a solar module

**Maximum Power Point ($P_{max}$)**: The point at which the maximum power output is produced by the module at operating conditions indicated above i.e., $\mathbf{P_{max} = I_{mp} \times V_{mp}}$.

**Open Circuit Voltage ($V_{oc}$)**: The maximum potential voltage achieved when no current is drawn from the module i.e., when there is no current passing through the cell i.e., V (at I=0).

**Short Circuit Current ($I_{sc}$)**: The maximum current output reached by the module under the conditions of a circuit with no resistance. The short circuit current corresponds to the short circuit condition of very low impedance and calculated when the voltage equals 0 i.e., at V=0.

**Maximum power operating current ($I_{mp}$)**: The current for the cell corresponding to the maximum power point on the array's current-voltage (I-V) curve.

**Maximum power voltage ($V_{mp}$)**: The voltage at the maximum power point on the array's current voltage (I-V) curve.

### 2.3.2 Effects of Irradiance

Irradiance is the measure of the intensity of the sunlight being received per unit area which is used in determining the available solar energy. The solar irradiance received by the surface of a solar panel keeps fluctuating because of factors such as particles on the panel, atmospheric weather changes among others. The solar cell current is the most affected by irradiance since its directly proportional to it whereas the voltage is slightly affected and its significance can be ignored. Figure 5 shows the effects of irradiance on the performance of a solar panel.

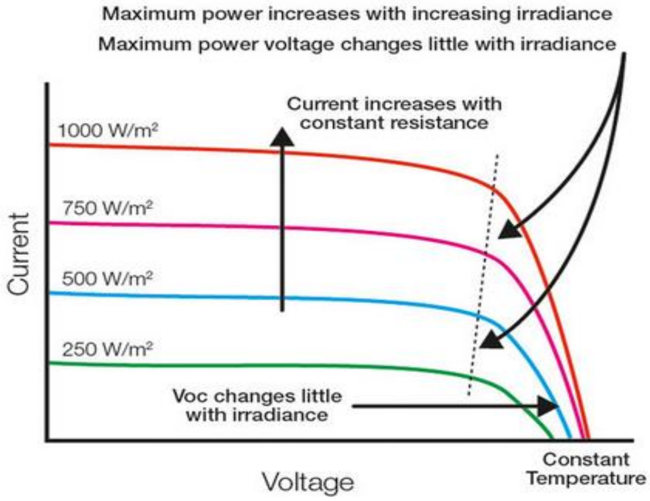


Figure 5. Effects of irradiance on I-V performance

### 2.3.3 Effects of temperature

In photovoltaics, voltage is the most affected by the module temperature. As temperature increases, the $V_{oc}$ of the PV cell decreases and the $I_{sc}$ slightly rises. Both the $V_{oc}$ and the $V_{mp}$ decrease when the module temperature increases. Low cell temperatures, on the other hand, result into higher voltages. In relation to the power, at high temperatures, the power generally drops and at low temperatures, the module produces more power [21]. Figure 6 shows the effect of temperature on the performance of the solar panel.

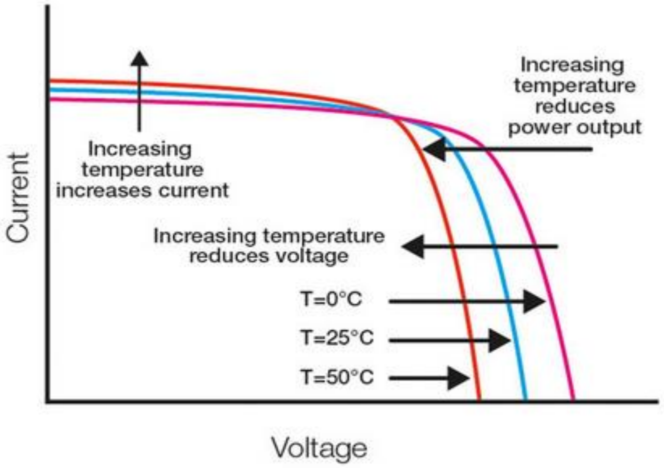


Figure 6: Temperature effect on I-V performance

## 2.4 Batteries

Batteries do store DC power that can be used during the night hours and on days when there's no sunlight. This is a common application in off-grid applications where the excess electricity is stored in the battery banks. During their operation, batteries experience a wide range of conditions in PV applications such as varying rates of charging and discharging, temperature fluctuations, frequency and depths of discharges.

### Battery types and classifications

There are several battery types and classifications that are being manufactured with specific design and performance characteristics suited for particular applications. There are two main battery types when categorized in terms of their rechargeability [22] i.e.;

**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.

**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 used in laptops and mobile phones are secondary batteries and are briefly discussed;

i) **Lead acid batteries**

These are the commonest batteries being used with PV systems and have been used for the longest time. They are widely available in various sizes, relatively cheap in terms of cost and reliable performance. There exist two types of lead acid batteries being manufactured i.e., flooded lead acid batteries and sealed lead acid batteries.

a) **Flooded lead acid batteries:** Here, the electrodes are completely submerged in the liquid electrolyte. These batteries have removeable vent caps that allow for periodic checking of the level and density of the liquid electrolyte and if low, adding of the distilled water. The vent caps also allow escape of the hydrogen when at high charging voltages.
b) **Sealed lead acid batteries:** The electrolyte here is either absorbed into a glass mat or immobilized by making it into a thick gel. The caps are not removeable and include a small valve instead of regular vents to allow escape of the hydrogen. It is not possible to add water into these batteries and they require low maintenance.

ii) **Lithium-ion batteries**

These are a newer technology and less frequently used. The energy density of Li-ion batteries is three times that of the lead acid batteries. They have a longer cycle life and a higher efficiency as well as low maintenance and relatively low self-discharge. However, they’re more expensive and often have several issues with integration of other PV components. They are also non-recyclable and not widely available for use.

## 2.5 Inverters

Inverters convert DC electricity produced by the solar modules into AC electricity that can be used by most of the appliances as well as the electricity grid. Inverters accomplish this by switching the direction of the DC input back and forth rapidly. There are three main types of solar inverters i.e., string inverters, string inverters with power optimizers, and microinverters.

String inverters. These are also known as central inverters and are the simplest type of inverters. They are commonly found in small-scale solar energy systems. With a string inverter, each individual solar panel is wired together into a "string" with another panel, and then multiple strings can be connected to the central inverter.

String inverters with power optimizers**.** These are a step up from the basic string inverter, and use a power optimizer located next to each panel to condition the DC electricity and make it a constant voltage before it's sent down to the main string inverter to be converted into AC electricity.

Microinverters**.** They are the most expensive inverter technology since they offer the highest performance. With microinverters, each individual solar panel has its own small inverter located next to the panel. In this distributed system, microinverters convert DC electricity to AC electricity right on the roof, so they can adapt to more complicated system designs or even roofs with uneven shading where one panel might get more sunlight than the other.

## 2.6 Wind Energy

Wind energy is a clean, renewable and sustainable source of energy that uses wind speeds to produce electricity [23]. Wind arises as a result of the varying heating rates caused by the uneven heating of the earth's surface, which result in pressure and temperature differences that drive air circulation [24]. Since wind flows from regions of high pressure to regions of low pressure, the higher the pressure, the higher the wind speed and hence more wind power generation.

Conversion of wind energy involves an interconnection of components as shown in Figure 7 that operate together to convert the kinetic energy in the wind into mechanical energy and subsequently into electrical energy with the aid of generators [25].

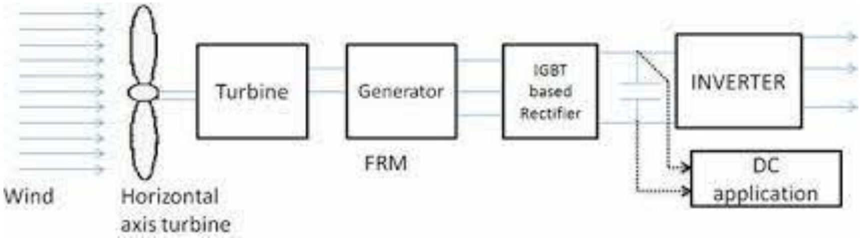


Figure 7: The layout of wind conversion to produce electricity

### 2.6.1 Working Principle of a Wind Energy Conversion System

The wind turbine captures the kinetic energy of the wind and the rotor spins. This rotational motion is then transferred to a generator housed in a nacelle at the top of the tower through the main shaft. The primary shaft is linked to the gearbox, which increases the rotor's rotating speed. The generator converts the mechanical energy into electrical energy through electromagnetic induction.

The power converter converts DC electricity into AC electricity and the step-up transformer increases the voltage of the output power which is used as electricity and fed to the available grid or used for off-grid purposes. The amount of energy in the wind available for utilization by the turbine increases with the cube of the wind speed; therefore a 10% increase in the wind speed results into a 33% increase in the energy being produced [26].

### 2.6.2 Components of a Wind Energy Conversion System

1. **Wind Turbine**

This is the primary device used to convert wind energy into electricity. A wind turbine is essentially a rotor with two to three or more propeller blades mounted on it which are used to harness the wind's energy. When wind flows across the blade, the air pressure on one side of the blade decreases. This difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag causing the rotor to spin [20].

The power generated by the wind turbines is inherently dependent on the wind speed [26]. The theoretical mechanical power extracted from the wind is calculated using the equation (i):

$P = \frac{1}{2}\rho \alpha A_T v^3$ ……………………………………………………...(i)

The electrical power that is obtainable from a wind turbine is given in equation (ii);

$P = (C_p \varepsilon_g \varepsilon_b)12\rho\alpha A_T v^3$ ……………………………………………….(ii)

Where; P: Power in watts
$\rho\alpha$: Air density
$A_T$: Rotor swept area, exposed to the wind ($m^2$)
$C_p$: Coefficient of performance also called power coefficient
$v$: Wind speed in metres per second
$\varepsilon_g$: Generator efficiency
$\varepsilon_b$: Gearbox/bearings efficiency

The wind speed is important for operation of a wind turbine. When the wind speed exceeds the cut-in value, the wind turbine generator starts generating power. If the wind speed exceeds the rated speed of the wind generator, it generates constant output power, and if the wind speed exceeds the cut-out value, the wind turbine generator stops running to protect the generator from being damaged.

There are two main types of wind turbines and these include;

a. Horizontal Axis Wind Turbines (HAWT): These are the most common design of wind turbines with the rotor shaft parallel to the ground and to the wind direction. They have two or three blades and some even have multi-blade propellers facing into the wind as the turbine rotates [24]. They have a high efficiency and are easy to design. Figure 8 shows an example of a horizontal wind turbine.

Figure 8: A horizontal axis wind turbine

b. Vertical Axis Wind Turbines (VAWT)

These were the first type of wind turbines to be developed and they have blades that rotate around a vertical axis, resembling an eggbeater or a giant, vertical pinwheel. It can capture wind from any direction without needing a yaw system hence does not require orientation [24]. The control devices and the generator in this type of wind turbine is located on the ground and thus makes maintenance simple. Figure 9 is an example of a vertical axis wind turbine.

Figure 9: A vertical axis wind turbine

**Main components of a wind turbine**

**Rotor blades:** When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin.

**Gear box:** Transforms the low-speed rotation of the rotor into the high-speed rotation required by the generator to produce electrical energy.

**Hub:** It is part of the turbine's drivetrain, turbine blades fit into the hub that is connected to the turbine's main shaft

**Nacelle:** The nacelle sits on the top of the tower and contains the gearbox, low and high-speed shafts, generator and other critical components.

**Generator:** This is driven by the high-speed shaft. The copper windings turn through a magnetic field in the generator to produce electricity. It converts mechanical energy to electrical energy

Some generators are driven by gearboxes and others are direct-drives where the rotor attaches directly to the generator.

**Yaw system**: The yaw drive rotates the nacelle on upwind turbines to keep them constantly facing the wind when wind direction changes to maximize the effective rotor area and hence power.

**Tower:** A tall, vertical structure that supports the entire weight of the wind turbine, including the nacelle and rotor blades. It provides the necessary height to position the rotor at an optimal elevation for capturing higher wind speeds, as wind velocity generally varies with altitude.

## 2.7 Hybrid renewable energy sources (HRES)

This is a combination of multiple types of renewable energy sources such as solar, wind, biomass, geothermal, hydropower and other auxiliary power components like inverter and battery [27]. A hybrid energy system integrates different energy sources to form a single system such that the weakness of some energy sources is complemented by the strengths of other energy sources.

For instance, a PV hybrid system, wind hybrid system, and PV–wind hybrid systems are employed to meet the load demand. Once the power resources (solar and wind energy) are sufficient, the excess power generated is supplied to the battery until it is fully charged. Thus, the battery comes into play when the renewable energy sources (solar PV, wind etc.) power is not able to satisfy the load demand until the storage is depleted.

### 2.7.1 Solar PV-Wind Hybrid System

A solar PV-wind hybrid system comprises integration of a wind conversion system and a solar photovoltaic system to generate electricity. This integration aims at harnessing renewable energy from the sun and wind with enhanced overall energy production and reliability [26].

In order to evaluate the maximum output from each component of the solar PV–wind hybrid system, the single component is first modelled, thereafter the combination needed to meet the required need, can then be evaluated.

### 2.7.2 Components of a typical Solar PV-Wind Hybrid system

The hybrid system consists of the following main components i.e., PV array, converter, wind turbine, battery storage, AC-DC rectifier, AC load and variable DC load as shown in Figure 10 [28].

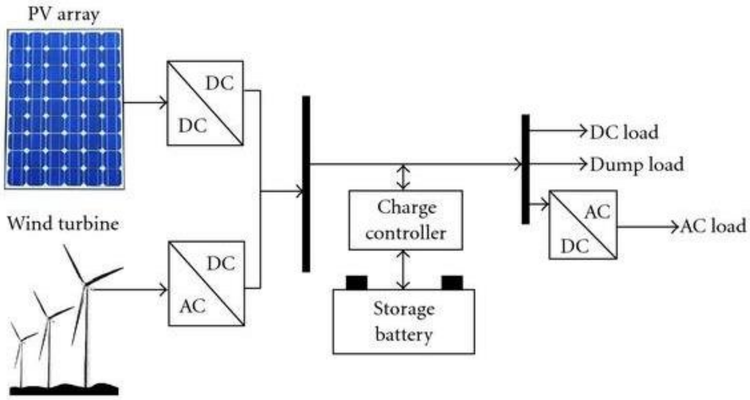


Figure 10: Solar PV-Wind Hybrid system

**PV array:** This is a series and/or parallel combination of solar panels together and in order to provide the required voltage and current under given operating conditions by converting solar energy directly into electricity.

**Wind Turbine Generator:** This uses the kinetic energy of the wind and converts it into electrical energy and the power which is captured at the rotor. The formula for the power produced is given in equation (i).

**Rectifier:** This is an AC/DC converter and it is usually a typical three-phase diode bridge rectifier, the output DC voltage can be obtained from equation (iii) given as;

$$V_{dc} = \frac{3}{\pi} V_{LL}\sqrt{2} \quad \text{(iii)}$$

Where $V_{LL}$ is the AC source line-line RMS voltage

**Boost Converter:** This is also known as the DC/DC converter and it provides a stable voltage for the PV generator to maximize power production of the solar cells. It also provides a connection from the PV generator to the DC bus. DC/DC converter voltage is obtained from equation (iv);

$V_{out} = \frac{V_{in}}{1-D}$…………………………………………………………… (iv)

Where; $V_{out}$: the voltage output

$V_{in}$: the voltage of the PV generator

$D$: Duty cycle

**Inverter:** This converts DC to AC at a desired frequency for a particular load. The DC input to the inverter can be of any form from various sources such as DC output of the variable speed wind power system. This input is switched successively in a given time interval at a given frequency in order to attain the AC output.

### 2.8 Energy Modelling tools

Various energy modelling tools in the form of software tools and programs are available for analysing and designing of renewable energy-based systems. In this project, the HOMER software was used and it is discussed briefly.

#### 2.8.1 HOMER

The Hybrid Optimization for Multiple Electric Renewables (HOMER) is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micro-power systems and to facilitate the comparison of power-generation technologies across a wide range of applications [29]. HOMER is one of the most applied software tools for optimization of hybrid power systems. HOMER performs three principal tasks that i.e., simulation, optimization, and sensitivity analysis summarised in the flow chart in Figure 11.

In Simulation process, HOMER simulates the operation of a system by making energy balance calculations in each time interval of the year. The Optimization process determines the optimal value of the variables over which the system designer has control. Sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control e.g., the average wind speed or the future fuel price.

The optimization process determines a system configuration that achieves the best possible matching between the supply and demand for a given combination of sensitivity variables. The optimal system is that system which satisfies the user-specified constraints at the lowest total net present cost. Finding the optimal system configuration involves deciding on the mix of components that the system should contain, i.e., the size or quantity of each component and the dispatch strategy the system should use [30].

Sensitivity analysis is carried out using sensitivity variables and it reveals how the outputs respond to changes in the inputs. Sensitivity variables are those which the user has no control over and can specify multiple input values. For this study, the sensitivity variables were the diesel costs, the inflation rates and the wind speeds to understand the impact of their variation on the system optimal solution. The values of the variables used in the sensitivity analysis are shown in table 1 below. Each combination of sensitivity variable values defines a distinct sensitivity case and HOMER Pro simulates for all of them and a feasible system is obtained as one capable of meeting the available load demand.

Table 1: Sensitivity variables used in this simulation

| Diesel Fuel Price ($/L) | Expected Inflation (%) | Wind Scaled Average (m/s) |
|---|---|---|
| 1.26 | 3.30 | 2.68 |
| 1.3 | 3.40 | 3.0 |

Figure 11 shows the flow chart of activities followed while modelling the hybrid system on HOMER Pro until the selection of the most optimal system design. The most optimal system in this case must be able to meet the available load requirements as well as minimize the NPC of the entire project.

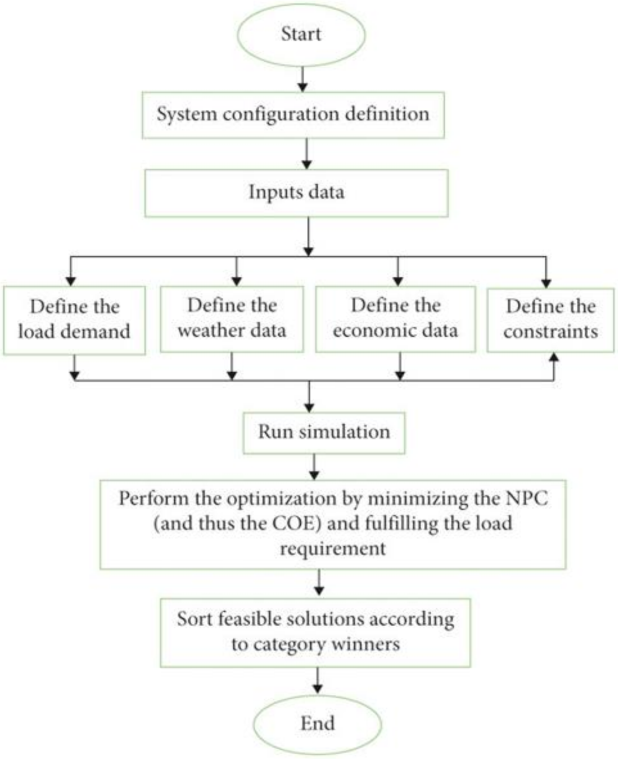


Figure 11: The flowchart for the modelling of the hybrid system on HOMER Pro

**2.8.2 The dispatch strategy**: This is a set of rules used to control the operation of the power generator(s) and the storage bank whenever there is insufficient renewable energy supply to the load. HOMER Pro gives two types of dispatch namely the cycle charging dispatch and load following.

The cycle charging technique is a strategy where the generators operate at full load whenever they are turned on and the excess power produced charges the batteries. On the other hand, the load following technique is a strategy where the generators produce only enough power to meet the load and batteries are charged only with the renewable power sources.

### 2.9 Load Flow Analysis

Load flow analysis is the study of the power system under steady state conditions with the aim of determining voltages, currents, real and reactive power flows in a system under given load conditions [31]. Power flow studies aid in planning ahead and accounting for various adverse situations. Voltage magnitudes and angles at the different busbars in the steady state can be obtained, which is important as the magnitudes of the bus voltages are required to be held within a specific limit. The active and reactive power flow through each line can be obtained after voltage magnitudes and their angels are obtained using load flow.

### 2.9.1 Reasons for performing load flow analysis

- To ensure flow of active and reactive power in all branches of the network
- To analyse the effect of changes of connections and incorporation of new circuits on system loading.
- Analyse the effect of temporary loss of generation and transmission lines on system loading.
- Minimizing of system losses through improvements from change of conductor size and system voltage
- To ensure optimum system operation under given conditions.

### 2.9.2 Classification of buses

There are four quantities specified for each bus and these quantities include; The Voltage Magnitude, Phase angle, Real Power, and Reactive Power. Two of these values are specified while the other two have to be obtained through the solution of the nonlinear equations**.** The buses in the power systems are mainly classified into the following categories:

**Load Bus/PQ bus:** Also known as the PQ bus since the real and reactive power are defined. There are no generators connected to this bus and therefore the generated real and reactive powers are usually zero. The magnitude of voltage and phase angle are not known and only obtained after carrying out the analysis.

**Slack Bus:** Here the specified quantities are voltage magnitude and phase angle. Slack bus is generally a generator bus which is made to take additional active and reactive power to supply the losses caused in the network. This bus is also known as swing bus or reference bus and there is only one of its kind in a given power system.

**Generator Bus:** This is also known as voltage-controlled bus. Here the net active power and the voltage magnitude are known while the reactive power and voltage power angle are not known and not given.

### 2.9.3 Load flow analysis methods

**Gauss Siedel Method:** In this method, it is assumed that all buses other than the swing or slack bus are P-Q or load buses. At slack bus both V and δ are specified and they remain fixed throughout. There are (n – 1) buses where P and Q are given. Initially we assume the magnitudes and angles at these (n–1) buses and update these voltages at every step of iteration [32].

**Newton Raphson Method:** This method needs fewer number of iterations in order to reach convergence and it takes less computer time hence computation cost is less. The N-R method is more accurate and is not affected by factors like slack bus selection, regulating transformers etc. The number of iterations required in this method is almost independent of the system size [32].

**Fast Decoupled Method:** This is a very fast and efficient method of obtaining power flow problem solution. It is an extension of Newton-Raphson method formulated in polar coordinates with certain approximations which result into a fast algorithm for power flow solution.

This method exploits the property of the power system where in MW flow-voltage angle and MVAR flow-voltage magnitude are loosely coupled.

In other words, a small change in the magnitude of the bus voltage does not affect the real power flow at the bus. Similarly, a small change in phase angle of the bus voltage hardly has any effect on reactive power flow. Because of this loose physical interaction between MW and MVAR flows in a power system, the MW- δ and MVAR-V calculations can be decoupled. This decoupling results in a very simple, fast and reliable algorithm [32].

# CHAPTER THREE: METHODOLOGY

## 3. 0 Introduction

This chapter explains various methodologies that were followed in order to meet the objectives of the project. This section covers the data collection of the meteorological data and the energy demand in details and further covers the methods used in the analysis of the results obtained and the conclusions drawn.

## 3.1 Case study area description

Paicho subcounty in Gulu District is located 22.63 km away from Gulu town. The main economic activity carried out in the area is Agriculture. It was established that the area meets the following criteria and conditions;

- A good population being served
- The electrical energy consumption by the prospective customers.
- The energy sources currently being used by the customers.
- Available space for the installation of the hybrid system.
- Average wind speeds and good solar irradiance in the area

Figure 12 below shows a map of Paicho as obtained from Google earth.

Figure 12: The location of Paicho (Source: Google maps)

### 3.2 Load survey

The load survey was carried out in two villages of Paicho subcounty i.e., Corner Ward village and Te-Kibur village. Responses were obtained from 100 respondents using questionnaires and these included consumers such as households, schools, businesses and churches from which the overall energy consumption for the two villages were estimated. The survey majorly focussed on establishing the size of the household/business, the electrical appliances being used, their number, rating and frequency of use.

### 3.3 Resource assessment and data collection

### 3.3.1 Solar resource data

The solar radiation values for Gulu district were obtained from the HOMER Pro software and the annual average was found to be 5.69 kWh/m$^2$/day. The highest daily irradiation during the year is experienced in the month of February which happens to be the hottest months of the year in northern Uganda. The highest clearness index is 0.634 in the month of January and the lowest is 0.517 in the month of July. Figure 13 shows the graphical monthly solar radiation and clearness index for the entire year.

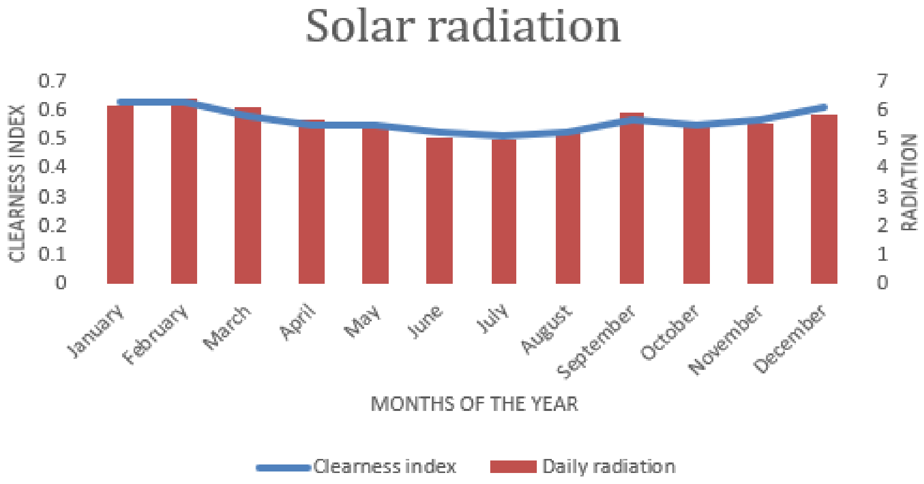


Figure 13: Daily solar radiation for the months of the year

### 3.3.2 Wind resource data

In order to quantify the wind potential in any given area, the wind speeds at certain hub heights are measured and recorded. In this case, the suitable wind speeds were obtained at hub heights of

10 m. It was established that Paicho, located in Gulu district has an average wind speed of 2.69 m/s when measured at hub heights of 10 m as obtained from National Aeronautics Space Administration Prediction of Worldwide Energy Resources (NASA POWER) and is shown in Table 2 and graphically in Figure 14.

Table 2: Monthly wind speeds in Gulu

| Months of the year | Average wind speed m/s |
|---|---|
| January | 3.74 |
| February | 3.87 |
| March | 3.68 |
| April | 2.86 |
| May | 2.03 |
| June | 1.8 |
| July | 1.77 |
| August | 1.84 |
| September | 1.95 |
| October | 2.19 |
| November | 2.91 |
| December | 3.6 |

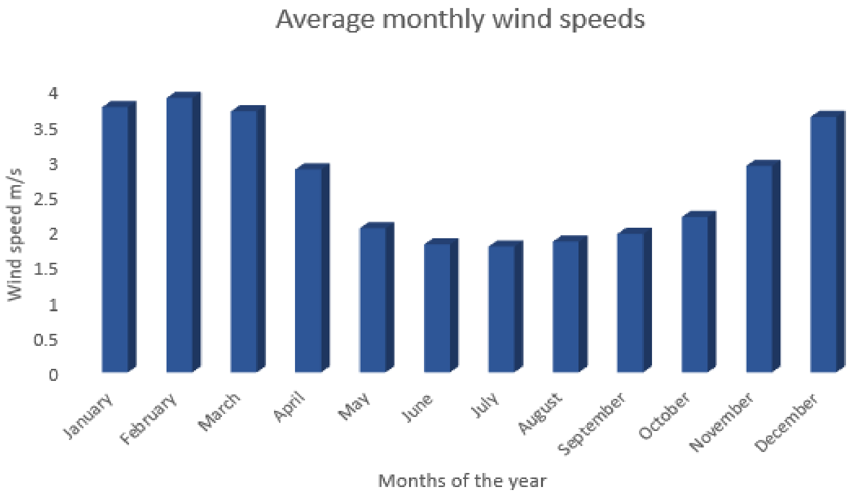


Figure 14: Average wind speeds for the months of the year

### 3.3.3 Ambient temperature

The graph in Figure 15 shows the ambient temperature the area. The ambient temperature exhibits a negative correlation with the solar PV performance as discussed in the literature review in section 2.3.3.

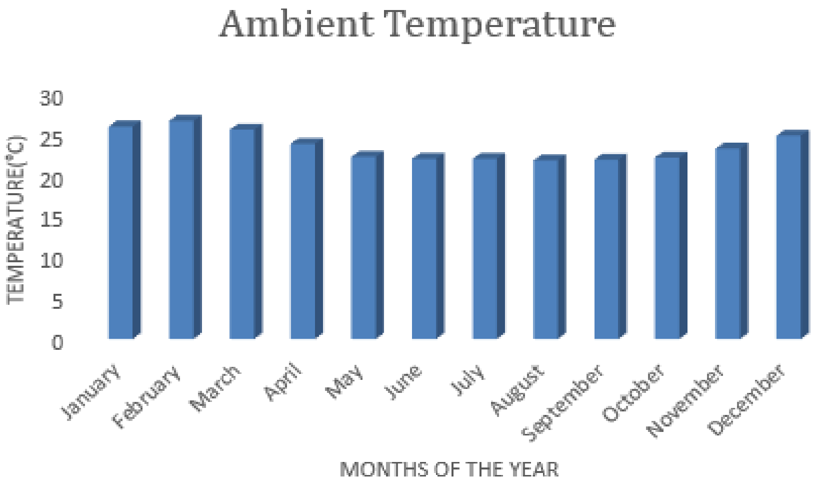


Figure 15: The monthly average ambient temperature

### 3.4 The hybrid components

The hybrid system is made of several electrical components that ensure production, storage and adaptation of electrical energy and these include the battery, the solar panel, the wind turbine, the inverter and other accessory devices. Cost consideration was put into place while choosing these components as well as their capacity and reliability to produce the required output in the long run. Some of the specifications of the different components used in this particular hybrid system are discussed below.

**Photovoltaic Array**: The Canadian Solar MaxPower CS6U-330P panel from the HOMER Pro library which is manufactured by Canadian solar with a lifetime of about 25 years was chosen for this project. The initial cost of the solar panel per kilowatt is given as $500 which also doubles as the replacement cost. Its O & M cost is assumed to be $50.

**Wind Turbine**: The wind turbine used in this study is the Aeolos-V1kW turbine with a hub height of 10m that makes it suitable to generate power at wind speeds obtained at 10m and its lifetime is about 20 years. The initial capital and operation and maintenance costs are $4386.49 and $50 respectively.

**Converter:** The converter model which is used in this setup is the CyboEnergy Off-Grid C1-Mini-1000N selected from the HOMER library. Its inverter efficiency is 96% and lifetime is given as 10 years. The capital and replacement cost of a 1k W converter is $300 and O & M is zero.

**Battery**: The battery which is selected for this hybrid system is a 48V lead acid battery of model BAE SUNDEPOT 48-420 with 327Ah capacity, maximum input current of 138A and state of charge of 50%. The initial cost (which includes cost of installation and power electronics) and replacement cost is taken as $4,339.94 per battery with the same replacement cost and O&M is taken as $500.

**Generator:** The model which is selected from the HOMER library is Generic 25kW Fixed Capacity Genset manufactured by Generic. Its capacity is 25kW and has a minimum load ratio of 25% with a lifetime of 15,000 hours. The capital and replacement cost of this generator is $12,500 and O & M is $0.75/op.hours with fuel cost of $1.26/liter.

### 3.5 Modelling and simulation in DIgSILENT PowerFactory

The hybrid distribution network was modelled as a one bus system consisting of a solar PV array and a static generator which is the wind turbine connected to a bus bar and the AC loads are distributed from the same bus bar along the line.

A new project was created in DIgSILENT PowerFactory software and the system frequency was set to 50 Hz with a line voltage of 415V. The distribution network was modelled starting from the hybrid system, then connected to a bus bar and then to a line. Throughout the network, we used the ABC conductor of cross section area 35 $mm^2$. Table 3 shows the different specifications of the conductor.

The loads were clustered into zones, the distance between these loads were measured and implemented as the distances along the line. With the loads placed at these different distances on the line, the system was simulated.

Table 3: Specifications of the ABC conductor

| **Specification** | **Value** |
|---|---|
| Conductor type | ABC |
| Rated Current (A) | 0.148 kA |
| R+/km | 0.574 **Ω** |
| R0/km | 0 **Ω** |
| X+/km | 0.294 **Ω** |
| X0/km | 0 **Ω** |

Figure 16 shows the model of the distribution line after attaching all loads at their respective locations on the line. This model run a successful load flow in two iterations.

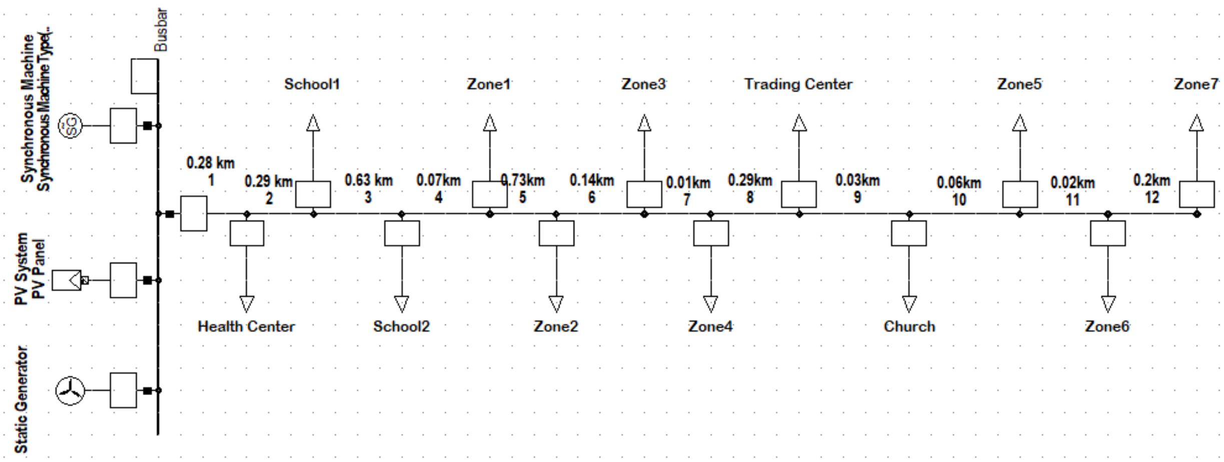
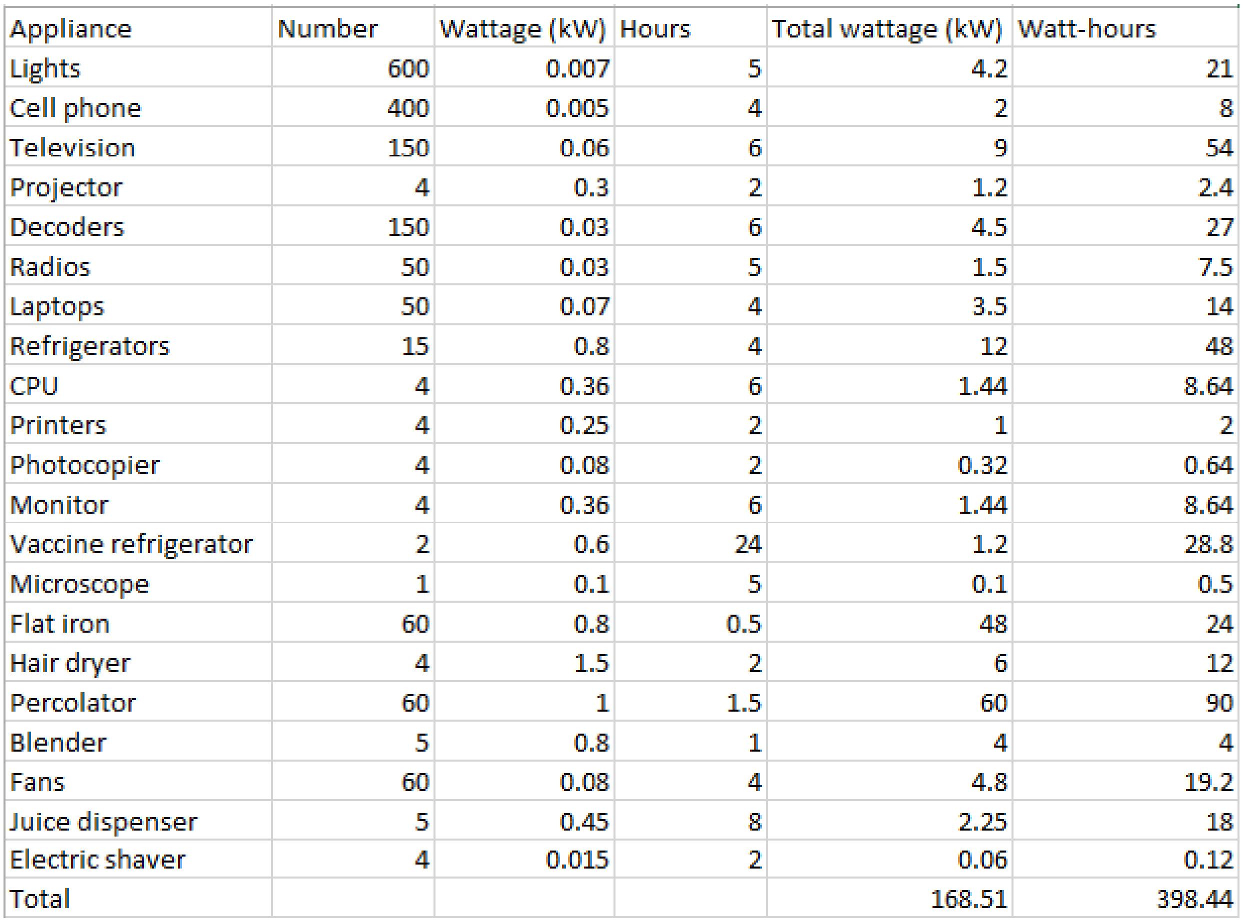


Figure 16: The model of the distribution line

# CHAPTER FOUR: RESULTS AND DISCUSSIONS

## 4. 0 Electricity Demand Assessment

The total energy demand was computed for the various consumers interviewed and these were summed up to obtain the total energy demand of the two villages. The survey questions included household size, 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 table in Figure 17 shows the detailed calculation of the estimated energy consumption as per the survey carried out.



| Appliance | Number | Wattage (kW) | Hours | Total wattage (kW) | Watt-hours |
|---|---|---|---|---|---|
| Lights | 600 | 0.007 | 5 | 4.2 | 21 |
| Cell phone | 400 | 0.005 | 4 | 2 | 8 |
| Television | 150 | 0.06 | 6 | 9 | 54 |
| Projector | 4 | 0.3 | 2 | 1.2 | 2.4 |
| Decoders | 150 | 0.03 | 6 | 4.5 | 27 |
| Radios | 50 | 0.03 | 5 | 1.5 | 7.5 |
| Laptops | 50 | 0.07 | 4 | 3.5 | 14 |
| Refrigerators | 15 | 0.8 | 4 | 12 | 48 |
| CPU | 4 | 0.36 | 6 | 1.44 | 8.64 |
| Printers | 4 | 0.25 | 2 | 1 | 2 |
| Photocopier | 4 | 0.08 | 2 | 0.32 | 0.64 |
| Monitor | 4 | 0.36 | 6 | 1.44 | 8.64 |
| Vaccine refrigerator | 2 | 0.6 | 24 | 1.2 | 28.8 |
| Microscope | 1 | 0.1 | 5 | 0.1 | 0.5 |
| Flat iron | 60 | 0.8 | 0.5 | 48 | 24 |
| Hair dryer | 4 | 1.5 | 2 | 6 | 12 |
| Percolator | 60 | 1 | 1.5 | 60 | 90 |
| Blender | 5 | 0.8 | 1 | 4 | 4 |
| Fans | 60 | 0.08 | 4 | 4.8 | 19.2 |
| Juice dispenser | 5 | 0.45 | 8 | 2.25 | 18 |
| Electric shaver | 4 | 0.015 | 2 | 0.06 | 0.12 |
| Total | | | | 168.51 | 398.44 |

Figure 17: Detailed calculation of the energy consumption

## 4.1 Load profiling

In this community, there are various loads because of the different types of consumers that operate different loads at different time intervals. According to the survey conducted, the peak demand of the area in a day occurred between 1800 hrs and 2200 hrs. Figure 18 shows the daily load profile of the area for 24 hours.

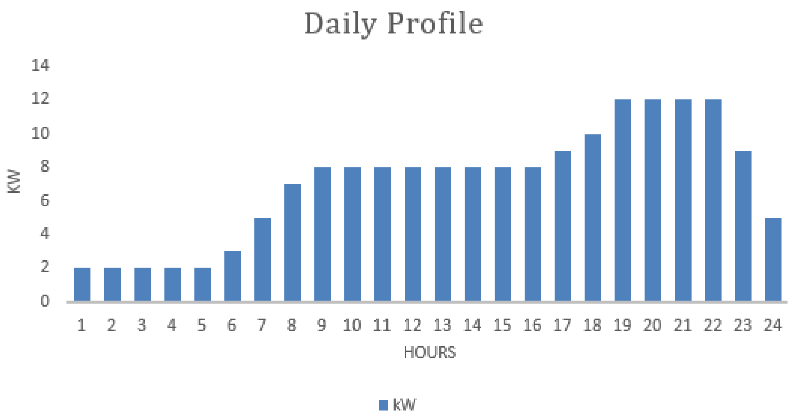


Figure 18: Daily load profile of the area

### 4.2 Simulation of the hybrid in HOMER Pro

Upon selection of the different components of the hybrid system on HOMER Pro and providing the necessary meteorological data for the location, the load demand and the detailed component costs, the simulation of the hybrid system was run to be able to establish the most optimal system. The techno-economic design that was developed and simulated in HOMER Pro software is shown in Figure 19.

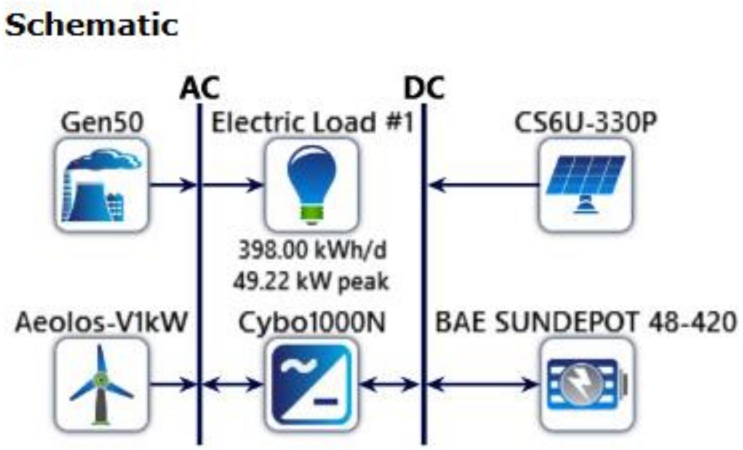
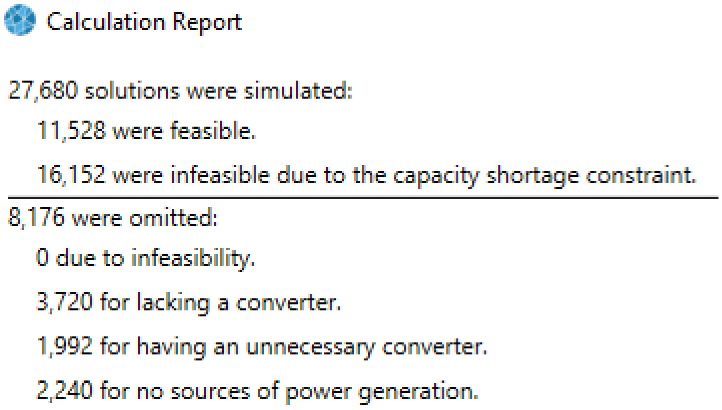


Figure 19: The schematic of the hybrid system

HOMER Pro runs several simulations and gives output of the different possible system configurations and their architecture. In this case, the system ran 27,680 simulations and of which 11,528 were feasible with the rest being infeasible as shown in the calculation report in Figure 20. The infeasibility often arises because HOMER Pro attempts to achieve all possible system configurations with different component combinations.



Calculation Report

27,680 solutions were simulated:
- 11,528 were feasible.
- 16,152 were infeasible due to the capacity shortage constraint.

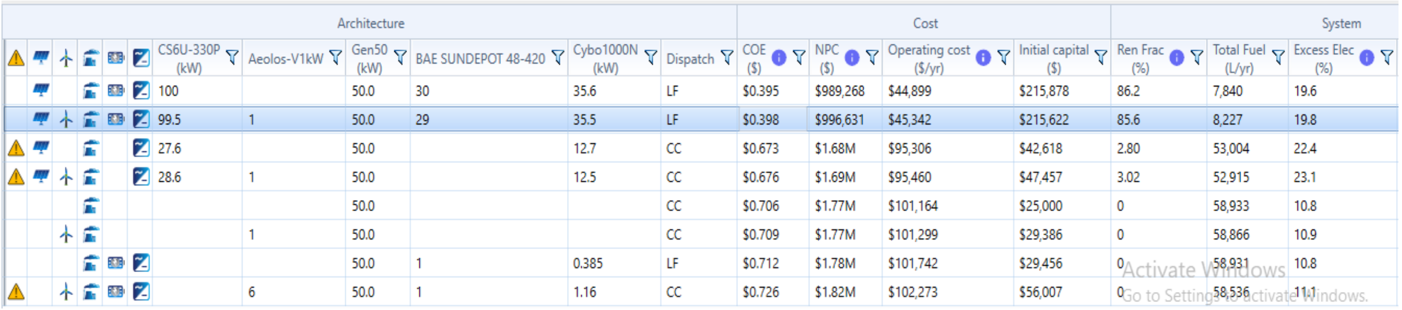
8,176 were omitted:
- 0 due to infeasibility.
- 3,720 for lacking a converter.
- 1,992 for having an unnecessary converter.
- 2,240 for no sources of power generation.

Figure 20: The overall calculation report

### 4.3 Optimization results

During the optimization process, HOMER Pro simulates many different system configurations, discards the infeasible ones (those that do not satisfy the user-specified constraints) and ranks the feasible ones according to total Net Present Cost (NPC) presenting them in ascending order with respect to increasing NPC.

The table in the Figure 21 shows the categorized optimization results list which displays the different system configurations and their various costs.



| Architecture | | | | | | | | | | | | Cost | | | | System | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ⚠ | | | | | | CS6U-330P (kW) | Aeolos-V1kW | Gen50 (kW) | BAE SUNDEPOT 48-420 | Cybo1000N (kW) | Dispatch | COE ($) | NPC ($) | Operating cost ($/yr) | Initial capital ($) | Ren Frac (%) | Total Fuel (L/yr) | Excess Elec (%) |
| | ✓ | | ✓ | ✓ | ✓ | 100 | | 50.0 | 30 | 35.6 | LF | $0.395 | $989,268 | $44,899 | $215,878 | 86.2 | 7,840 | 19.6 |
| | ✓ | ✓ | ✓ | ✓ | ✓ | 99.5 | 1 | 50.0 | 29 | 35.5 | LF | $0.398 | $996,631 | $45,342 | $215,622 | 85.6 | 8,227 | 19.8 |
| ⚠ | ✓ | | ✓ | | ✓ | 27.6 | | 50.0 | | 12.7 | CC | $0.673 | $1.68M | $95,306 | $42,618 | 2.80 | 53,004 | 22.4 |
| ⚠ | ✓ | ✓ | ✓ | | ✓ | 28.6 | 1 | 50.0 | | 12.5 | CC | $0.676 | $1.69M | $95,460 | $47,457 | 3.02 | 52,915 | 23.1 |
| | | | ✓ | | | | | 50.0 | | | CC | $0.706 | $1.77M | $101,164 | $25,000 | 0 | 58,933 | 10.8 |
| | | ✓ | ✓ | | | | 1 | 50.0 | | | CC | $0.709 | $1.77M | $101,299 | $29,386 | 0 | 58,866 | 10.9 |
| | | | ✓ | ✓ | ✓ | | | 50.0 | 1 | 0.385 | LF | $0.712 | $1.78M | $101,742 | $29,456 | 0 | 58,931 | 10.8 |
| ⚠ | | ✓ | ✓ | ✓ | ✓ | | 6 | 50.0 | 1 | 1.16 | CC | $0.726 | $1.82M | $102,273 | $56,007 | 0 | 58,536 | 11.1 |

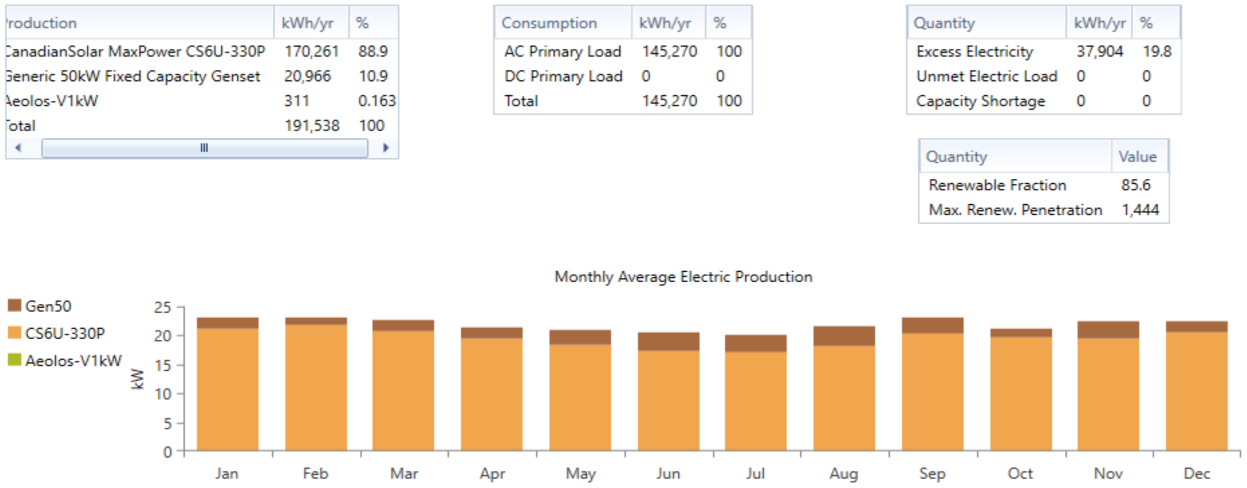
Figure 21: The optimisation results

In the overall list, the top ranked system configuration has the lowest NPC and initial cost but it lacks wind turbines that are an important aspect of the project and therefore this system is eliminated. The highlighted row shows the most optimal system configuration selected for this project containing the following system architecture; 1 wind turbine, 99.5kW solar system, 29 batteries, 50kW generator and 35.5kW converter dispatched using load following strategy with NPC of $996,631 and initial cost of $215,622.

## 4.4 Electrical production

Figure 22 shows the monthly average electric power production from each of the components of the optimal hybrid system selected from above. The highest production from the system is significantly obtained from the solar PV system with minimal production of electricity from the generator that comes into play when there is peak demand from the system. The wind turbines generate the lowest percentage of the total annual energy.

The renewable fraction of the system is 85.6% and 19.8% of the total annual energy generation is excess energy to cater for any variations in the peak demand of the system. The capacity shortage of the system as well as the unmet electric load is zero implying that the system is effectively supplying the demand of the community throughout the year.



| roduction | kWh/yr | % |
|---|---|---|
| anadianSolar MaxPower CS6U-330P | 170,261 | 88.9 |
| eneric 50kW Fixed Capacity Genset | 20,966 | 10.9 |
| eolos-V1kW | 311 | 0.163 |
| otal | 191,538 | 100 |

| Consumption | kWh/yr | % |
|---|---|---|
| AC Primary Load | 145,270 | 100 |
| DC Primary Load | 0 | 0 |
| Total | 145,270 | 100 |

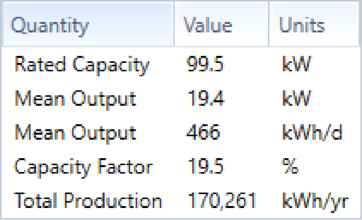
| Quantity | kWh/yr | % |
|---|---|---|
| Excess Electricity | 37,904 | 19.8 |
| Unmet Electric Load | 0 | 0 |
| Capacity Shortage | 0 | 0 |

| Quantity | Value |
|---|---|
| Renewable Fraction | 85.6 |
| Max. Renew. Penetration | 1,444 |

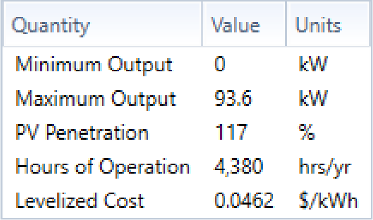
Figure 22: The Electrical energy output for the entire year

### 4.4.1 Performance of the solar PV

The overall solar PV array operated with a capacity factor of 19.5% indicating that its operations were at 19.5% of its maximum potential. Figure 23 shows the performance indicators, power output and daily performance respectively for the PV component of the optimal hybrid system. With an installed capacity of 99.5 kW, the PV array achieved a maximum power output of 93.6 kW and a 0kW minimum output. The LCOE of 0.0462$/kWh is for the installed costs of the PV panels alone without accounting for BOS components.



| Quantity | Value | Units |
|---|---|---|
| Rated Capacity | 99.5 | kW |
| Mean Output | 19.4 | kW |
| Mean Output | 466 | kWh/d |
| Capacity Factor | 19.5 | % |
| Total Production | 170,261 | kWh/yr |



| Quantity | Value | Units |
|---|---|---|
| Minimum Output | 0 | kW |
| Maximum Output | 93.6 | kW |
| PV Penetration | 117 | % |
| Hours of Operation | 4,380 | hrs/yr |
| Levelized Cost | 0.0462 | $/kWh |

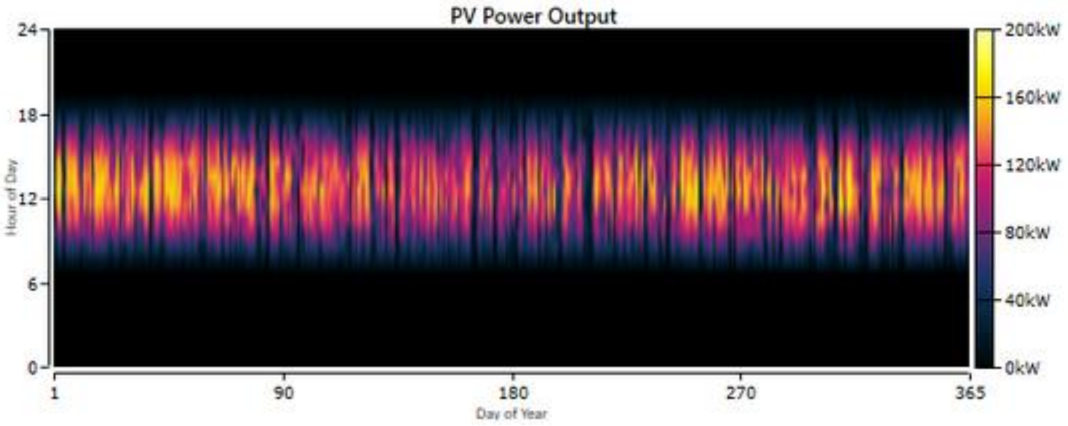


Figure 23: The solar PV output performance

### 4.4.2 Performance of the battery bank

The table in Figure 24 shows a summary of performance indicators for the battery storage of the system. It also shows the graphical variation in state of charge of the battery bank. The system architecture contains 29 batteries, with a string size of 1.00 per battery, and 29 strings in parallel and a bus voltage of 48.00 V. The battery storage has an autonomy of 13.7 hours with a nominal capacity of 455 kWh, a lifetime throughput of 506,050 kWh and expected life time of 7.97 years.

| Quantity | Value | Units |
|---|---|---|
| Batteries | 29.0 | qty. |
| String Size | 1.00 | batteries |
| Strings in Parallel | 29.0 | strings |
| Bus Voltage | 48.0 | V |

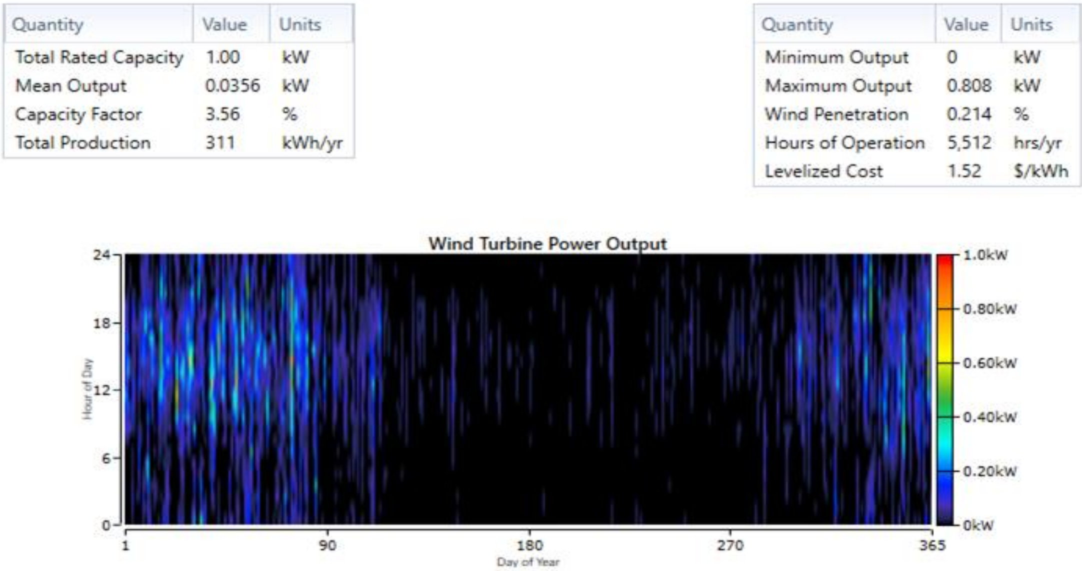
| Quantity | Value | Units |
|---|---|---|
| Autonomy | 13.7 | hr |
| Storage Wear Cost | 0.255 | $/kWh |
| Nominal Capacity | 455 | kWh |
| Usable Nominal Capacity | 228 | kWh |
| Lifetime Throughput | 506,050 | kWh |
| Expected Life | 7.97 | yr |

| Quantity | Value | Units |
|---|---|---|
| Average Energy Cost | 0 | $/kWh |
| Energy In | 64,989 | kWh/yr |
| Energy Out | 61,922 | kWh/yr |
| Storage Depletion | 186 | kWh/yr |
| Losses | 3,254 | kWh/yr |
| Annual Throughput | 63,530 | kWh/yr |

Figure 24: The variation in state of charge of the battery bank

### 4.4.3 Performance of the wind turbines

The wind turbines operated with a capacity factor of 3.56% indicating that its operations were at 3.56% of its maximum potential. Figure 25 shows the performance indicators, power output and daily performance respectively for the wind turbine of the optimal hybrid system.



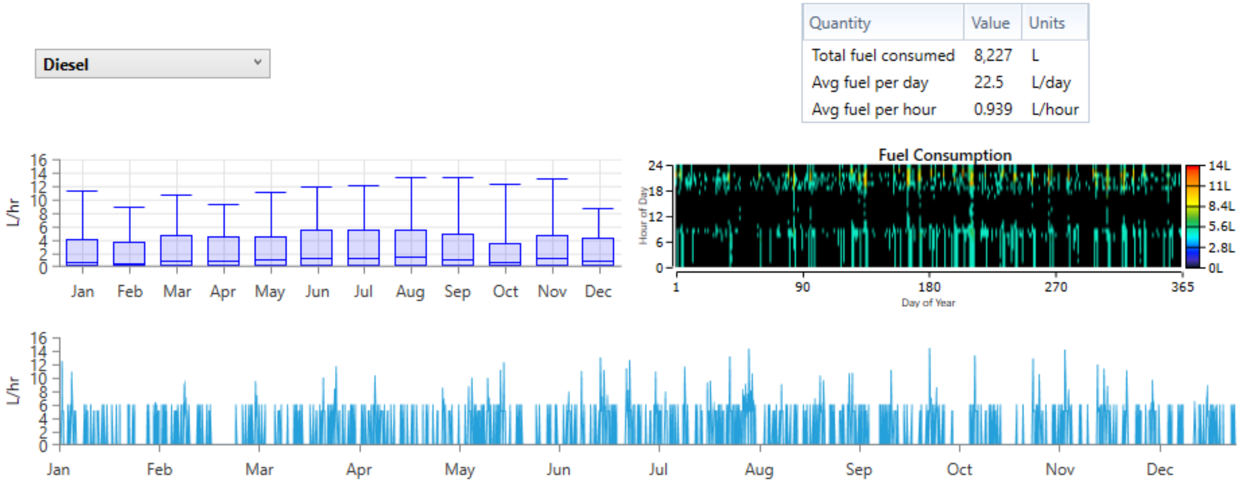
| Quantity | Value | Units |
|---|---|---|
| Total Rated Capacity | 1.00 | kW |
| Mean Output | 0.0356 | kW |
| Capacity Factor | 3.56 | % |
| Total Production | 311 | kWh/yr |

| Quantity | Value | Units |
|---|---|---|
| Minimum Output | 0 | kW |
| Maximum Output | 0.808 | kW |
| Wind Penetration | 0.214 | % |
| Hours of Operation | 5,512 | hrs/yr |
| Levelized Cost | 1.52 | $/kWh |

Figure 25: Performance indicators and daily performance of the wind turbine.

### 4.5 System fuel consumption

The fuel consumption of the system is highly dependent on the number of hours that the given generator, in this case the Generic 50 kW, is operating in order to meet the available demand at a particular time. The generator dispatching strategy used here is the load following criteria since we only need the generator to be operated to produce only the required amount of power to cover the capacity that cannot be supplied from the renewable systems or battery bank to meet the load but not charge the battery system. Figure 26 shows a summary of the system fuel consumption patterns of the system throughout the year basing on generator performance.



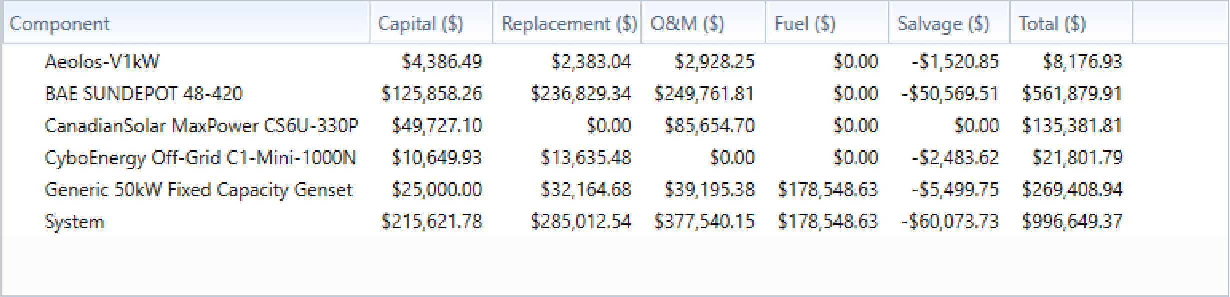
| Quantity | Value | Units |
|---|---|---|
| Total fuel consumed | 8,227 | L |
| Avg fuel per day | 22.5 | L/day |
| Avg fuel per hour | 0.939 | L/hour |

Figure 26: The fuel consumption summary for the generator operation

### 4.6 Economic analysis of the system

Renewable energy systems generally have initial high capital costs because of the costs involved at the instalment stages. HOMER Pro uses the total NPC to represent the lifecycle cost of a system. NPC is the present value of all costs of installing and operating the components over the project lifetime minus the present value of all the revenues earned.

The total NPC condenses all the costs and revenues that occur within the project lifetime into one sum. NPC includes the costs of initial construction, component replacements, maintenance as well as fuel costs. The NPC for the most optimal hybrid system is $996,649.37 as shown in details in Figure 27 and the initial cost of the system is $215,622. Figure 28 shows the cash flow that indicates the revenues, expenditure and the overall return on investment for the entire project lifetime.



| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Aeolos-V1kW | $4,386.49 | $2,383.04 | $2,928.25 | $0.00 | -$1,520.85 | $8,176.93 |
| BAE SUNDEPOT 48-420 | $125,858.26 | $236,829.34 | $249,761.81 | $0.00 | -$50,569.51 | $561,879.91 |
| CanadianSolar MaxPower CS6U-330P | $49,727.10 | $0.00 | $85,654.70 | $0.00 | $0.00 | $135,381.81 |
| CyboEnergy Off-Grid C1-Mini-1000N | $10,649.93 | $13,635.48 | $0.00 | $0.00 | -$2,483.62 | $21,801.79 |
| Generic 50kW Fixed Capacity Genset | $25,000.00 | $32,164.68 | $39,195.38 | $178,548.63 | -$5,499.75 | $269,408.94 |
| System | $215,621.78 | $285,012.54 | $377,540.15 | $178,548.63 | -$60,073.73 | $996,649.37 |

Figure 27: The cost summary for the entire system

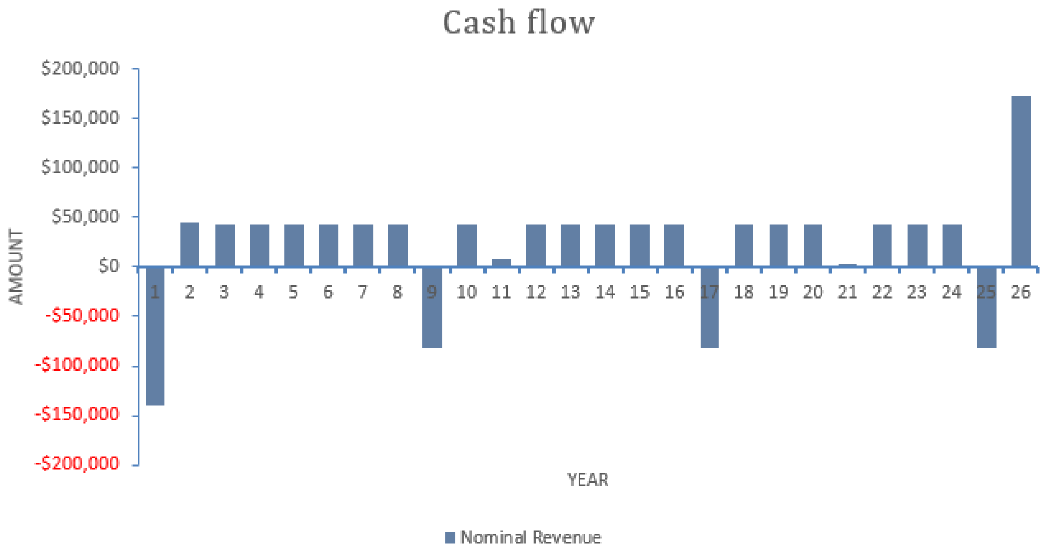


Figure 28: Cash flow of the hybrid system for the entire project lifetime

### 4.7 Impact of diesel fuel price and inflation rate on optimal solution

From Figure 29, it is observed that an increase in diesel price has a significant effect on the NPC of the optimal configuration. From a base price of $ 1.26 /L when the NPC is $ 989,267, the NPC increases almost linearly as a function of the diesel price. At a price of $ 1.30/L, the NPC increases to $ 994,582.

It may be noted that an increase in diesel price can significantly reduce emissions by altering the selection of energy supply options and shifting away from diesel to renewable energy generation. An increase in inflation rate from 3.30% to 3.40 % leads to a decrease of energy cost but results in a total net present cost of $ 997,984.

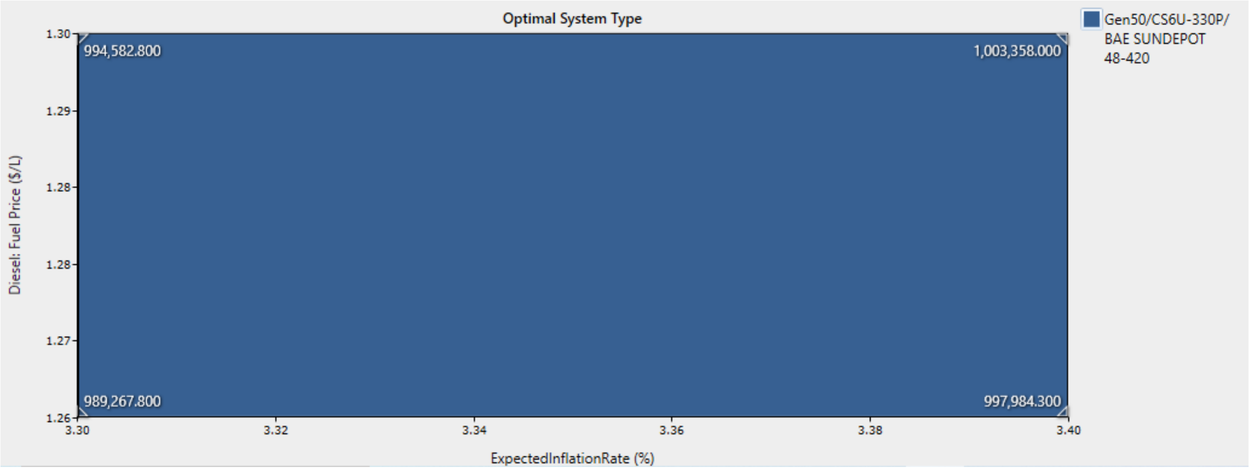


Figure 29: Variation of the Net Present Cost with Diesel Price and Inflation rate

### 4.8 DIgSILENT PowerFactory Simulation

Upon selection of the most optimal hybrid system, we simulated the system in the DIgSILENT PowerFactory as a low voltage distribution network and run a load flow analysis of the system to further analyse the system technically. The load flow successfully executed in two iterations as shown in Figure 30 and Figure 31.

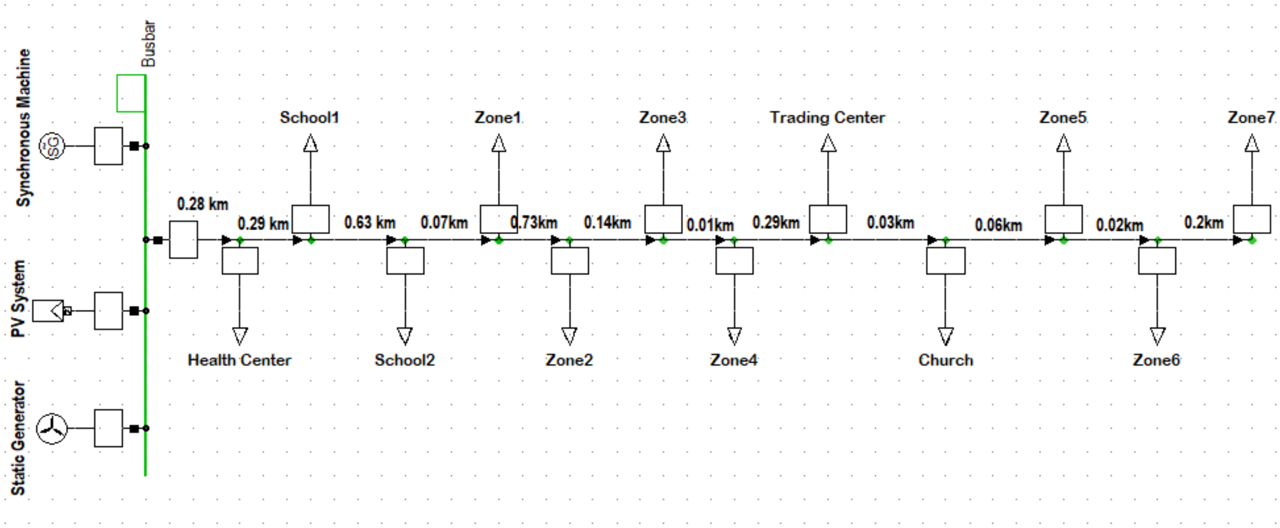
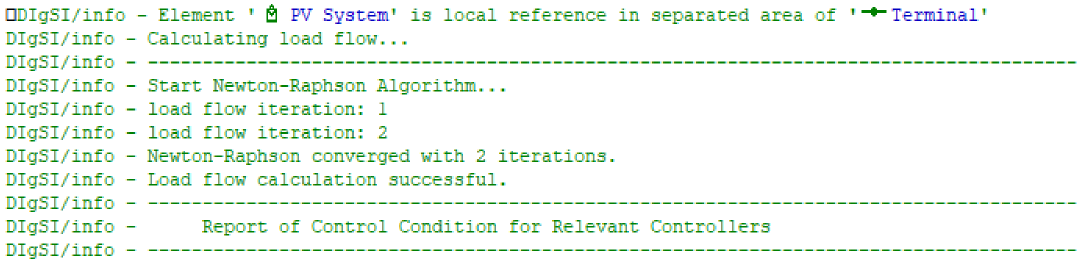


Figure 30: The system after running a load flow analysis



```
□DIgSI/info - Element ' PV System' is local reference in separated area of ' Terminal'
DIgSI/info - Calculating load flow...
DIgSI/info - -------------------------------------------------------------------------------------
DIgSI/info - Start Newton-Raphson Algorithm...
DIgSI/info - load flow iteration: 1
DIgSI/info - load flow iteration: 2
DIgSI/info - Newton-Raphson converged with 2 iterations.
DIgSI/info - Load flow calculation successful.
DIgSI/info - -------------------------------------------------------------------------------------
DIgSI/info -      Report of Control Condition for Relevant Controllers
DIgSI/info - -------------------------------------------------------------------------------------
```

Figure 31: The load flow results

### 4. 8.1 System voltage profiles

Voltage profiles in low voltage distribution networks depend on the power flow and losses along with the network. This is an essential parameter of the power system since a drop in the voltage level leads to a drop in the electrical potential of a circuit while a steep increase in voltage may damage electrical appliances connected in a circuit.

It also aids in evaluation of the voltage levels during steady state analysis ensuring that the voltage drop is within the limits 6% according to the Electricity Regulatory Authority (ERA) [33]. Figure 32 shows the voltage profile for the system as extracted from DIgSILENT Powerfactory software. It is observed that the system operated within the allowable voltage range.

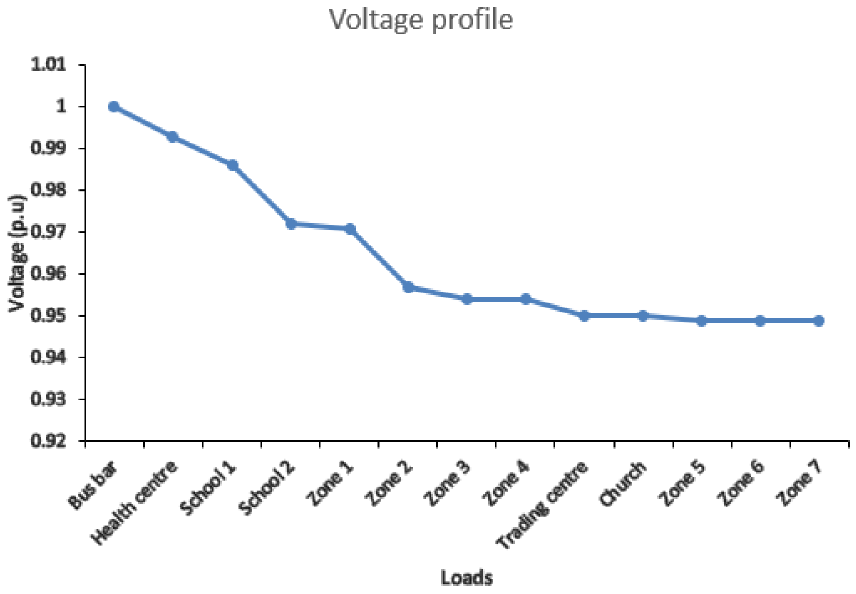
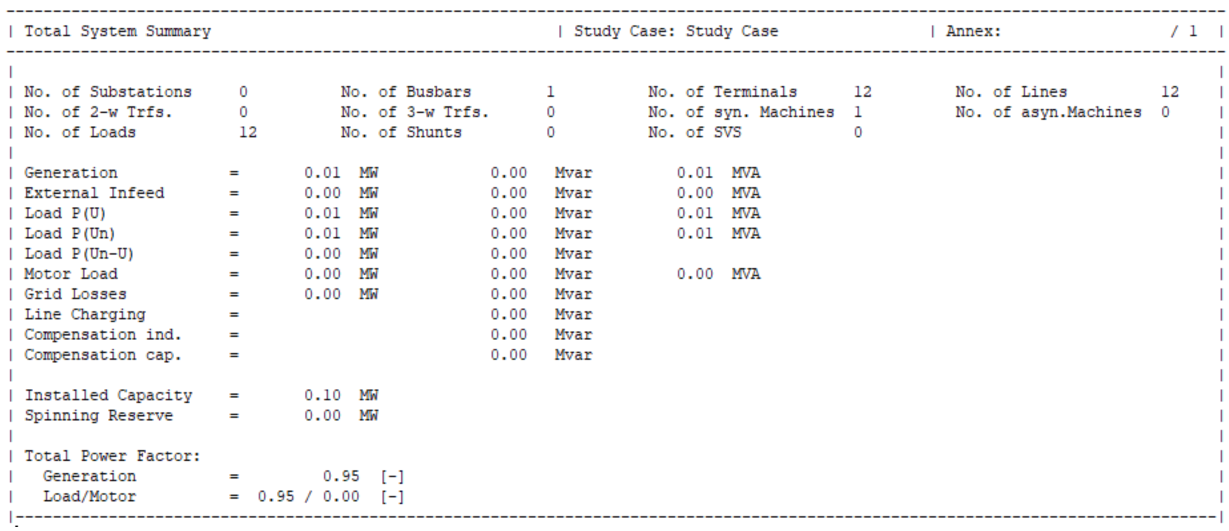


Figure 32: The system voltage profile

### 4.8.2 System losses

The system losses from this network were significantly low and this can be attributed to the fact that the distribution network is operating a short distance thus reduced losses due to transmission effects from point of production to the final consumer.



```
-----------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                    | Study Case: Study Case                | Annex:                 / 1  |
-----------------------------------------------------------------------------------------------------------------------------
|                                                                                                                            |
| No. of Substations     0         No. of Busbars       1         No. of Terminals      12        No. of Lines          12    |
| No. of 2-w Trfs.       0         No. of 3-w Trfs.     0         No. of syn. Machines  1         No. of asyn.Machines  0     |
| No. of Loads          12         No. of Shunts        0         No. of SVS            0                                     |
|                                                                                                                            |
| Generation           =       0.01  MW           0.00   Mvar        0.01  MVA                                               |
| External Infeed      =       0.00  MW           0.00   Mvar        0.00  MVA                                               |
| Load P(U)            =       0.01  MW           0.00   Mvar        0.01  MVA                                               |
| Load P(Un)           =       0.01  MW           0.00   Mvar        0.01  MVA                                               |
| Load P(Un-U)         =       0.00  MW           0.00   Mvar                                                                 |
| Motor Load           =       0.00  MW           0.00   Mvar        0.00  MVA                                               |
| Grid Losses          =       0.00  MW           0.00   Mvar                                                                 |
| Line Charging        =                        0.00   Mvar                                                                 |
| Compensation ind.    =                        0.00   Mvar                                                                 |
| Compensation cap.    =                        0.00   Mvar                                                                 |
|                                                                                                                            |
| Installed Capacity   =       0.10  MW                                                                                     |
| Spinning Reserve     =       0.00  MW                                                                                     |
|                                                                                                                            |
| Total Power Factor:                                                                                                        |
|   Generation         =         0.95  [-]                                                                                   |
|   Load/Motor         =  0.95 / 0.00  [-]                                                                                   |
|----------------------------------------------------------------------------------------------------------------------------|
```

Figure 33: The system losses

# CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusion

This project demonstrated the potential of increasing electricity access in rural communities of Uganda using off-grid hybrid renewable energy systems.

The findings show that the wind energy potential of the study area is considerably lower. Although wind potential may not be sufficient for a large, independent wind system, the analysis showed that if wind is integrated with other energy systems such as PV, diesel generator, and batteries etc., a viable solution can be obtained.

The optimization of different system configurations and a distribution network analysis demonstrated the economic and technical feasibility of implementing a solar PV-hybrid system.

The findings obtained from the entire study can be applied in the design, execution, or development of HRES for any applications in different locations across the country having similar geographical coordinate as the site considered in this study.

## 5.2 Recommendations

The following are recommendations of this research work, that may be useful to researchers and decision makers.

More investment should be put into the study of the potential of hybrid renewable systems in different areas that have renewable energy resources potential.

This study was conducted only in Paicho subcounty, Gulu district, Northern Uganda. Future researches should consider extending such work to other potential sites country wide, so that all the rural communities can benefit from the abundant and free renewable energy resource.

Research should be conducted for the connection of hybrid systems into the existing electricity networks.

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# APPENDIX

## SURVEY QUESTIONNAIRE

### Informant Details

Name: ……………………………………………….

Contact: ……………………………………………….

Occupation: ……………………………………………….

### Section 1: AREA DETAILS

Village: ………………………………………….

Parish: ………………………………………….

Sub-county: ………………………………………….

County: ………………………………………….

District: ………………………………………….

Population: ………………………………………….

Main economic activity: ………………………………………….

Number of households: ………………………………………….

Number of businesses: ………………………………………….

Number of schools: ………………………………………….

Number of health centres: ………………………………………….

Typical energy sources: …………………………………………….

### Section 2: GENERAL INFORMATION

Name of consumer(optional):

………………………………………………………………………………..

Type of consumer:

- ☐ Household
- ☐ School
- ☐ Health centre
- ☐ Business
- ☐ Church
- ☐ Other (please specify): ……………………………………….

How would you describe the size of your household (if household)?

- ☐ Single individual
- ☐ Small family (2-4 members)
- ☐ Large family (5 or more members)

Average monthly income per household.

- ☐ Less than 100,000 shillings.
- ☐ 100,000 shillings to 200,000 shillings.
- ☐ 200,000 shillings to 300,000 shillings.
- ☐ 300,000 shillings to 400,000 shillings.
- ☐ 400,000 shillings.

**Section 3: ELECTRICITY CONSUMPTION AND PREFERENCES**

What electricity sources do you currently use in your household?

- ☐ Grid electricity
- ☐ Solar power
- ☐ Wind power
- ☐ Biomass
- ☐ Other (please specify all): ……………………………………..

What electrical appliances do you currently use? (Specify type, number and rating in watts) How long do these appliances operate in a day? (in hours)

| Type of appliance | Rating of appliance | Number of appliances | Hours per day |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

What time of the day do you use electricity most?

- ☐ Morning (0000 hrs to 0600 hrs)
- ☐ Mid-morning (0700 hrs to 1159 hrs)
- ☐ Afternoon (1200 hrs to 1759 hrs)
- ☐ Evening (1800 hrs to 2300 hrs)

What is the status of your grid electricity access?

- ☐ Connected
- ☐ Not connected but grid nearby
- ☐ No access

How satisfied are you with the reliability of your current electricity source?

- ☐ Very satisfied
- ☐ Satisfied
- ☐ Neutral
- ☐ Dissatisfied
- ☐ Very dissatisfied