SYSTEM SIZING OF SOLAR ENERGY REQUIREMENT FOR AN “ALL-DIRECT CURRENT” STAND-ALONE TELECOMMUNICATION SYSTEM

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A thesis submitted in partial fulfillment of the requirements for the award of the degree of Master of Science (Electronics and Instrumentation) in the School of Pure and Applied Sciences of Kenyatta University

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DECLARATION

This thesis is my original work and has not been presented for the award of a degree or any other award in any other university.

All sources of information have particularly been acknowledged by way of references.

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DEDICATION

This thesis is dedicated to my parents
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<th>Symbol</th>
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<tr>
<td>$P_{a,b}$</td>
<td>Actual Power Discharged Per Battery Bank</td>
</tr>
<tr>
<td>$P_{d}$</td>
<td>Actual Power Produced by the Modules</td>
</tr>
<tr>
<td>$P_{a,m}$</td>
<td>Actual Power Produced Per Module</td>
</tr>
<tr>
<td>A/C</td>
<td>Air Conditioner</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>Ah</td>
<td>Amperes hour</td>
</tr>
<tr>
<td>AS/NZS</td>
<td>Australian and Newzealand Standard</td>
</tr>
<tr>
<td>CdTe</td>
<td>Candinium Terride</td>
</tr>
<tr>
<td>$P_{cr}$</td>
<td>Capacity Power Requirement During Night Time</td>
</tr>
<tr>
<td>CES</td>
<td>Community Energy System</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Conversion Efficiency</td>
</tr>
<tr>
<td>CIGS</td>
<td>Copper-Indium-Gallium-Diselenide</td>
</tr>
<tr>
<td>$\eta_{coul}$</td>
<td>Coulombic Efficiency</td>
</tr>
<tr>
<td>$I_{mp}$</td>
<td>Current at Maximum Power Point</td>
</tr>
<tr>
<td>I-V</td>
<td>Current Versus Voltage</td>
</tr>
<tr>
<td>deg</td>
<td>degree Celsius</td>
</tr>
<tr>
<td>$P_{mod}$</td>
<td>Derated Power Output</td>
</tr>
<tr>
<td>$E_d$</td>
<td>Design Daily Energy</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>$T_{cell, eff}$</td>
<td>Effective Cell Temperature</td>
</tr>
<tr>
<td>FF</td>
<td>Fill Factor</td>
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</table>
GPS  Global Positioning System
Hrs  Hours
HEP  Hydro Electric Power
IES  Individual Energy Systems
\( N_i \)  Initial Number of Modules used in the Actual Experiment
\( P_{in,r} \)  Input Power Requirement Determined by the Load Requirement
IEEE Institute of Electrical and Electronics Engineers
kWh  Kilowatt Hour
LLP  Loss of Load Probability
LPSP  Loss of Power Supply Probability
METEOSAT  Meteorological Satellites
cSi  Monocrystalline Silicon
NREL  National Renewable Energy Laboratory
NiCd  Nickel Cadium
\( V_{dc} \)  Nominal Battery Voltage
\( N_{n,b} \)  Number of Batteries Required to Support Load During Night Time
N  Number of PV Modules
\( N_{m,d} \)  Number of Modules Required During Daytime
\( N_{m,u} \)  Number of Modules Required to Produce Power for Night Time Use
\( V_{oc} \)  Open Circuit Voltage
\( f_o \)  Oversupply Coefficient
PV  Photovoltaic
<table>
<thead>
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<tr>
<td>mSi</td>
<td>Polycrystalline Silicon</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>Power Input</td>
</tr>
<tr>
<td>$W_p$</td>
<td>Power in Watts</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>Short Circuit Current</td>
</tr>
<tr>
<td>$J_{sc}$</td>
<td>Short Circuit Current Density</td>
</tr>
<tr>
<td>G</td>
<td>Solar Irradiation</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Condition</td>
</tr>
<tr>
<td>$P_{u,N}$</td>
<td>The Actual Power Produced by the System Batteries</td>
</tr>
<tr>
<td>$N_{i,m}$</td>
<td>The Actual Total Number of Modules Required to Run the System</td>
</tr>
<tr>
<td>$N_{i,b}$</td>
<td>The Initial Number of Batteries</td>
</tr>
<tr>
<td>MF</td>
<td>The Mismatch Factor Between Rated Power and Actual Power Produced by the Modules</td>
</tr>
<tr>
<td>$N_{b,d}$</td>
<td>The Number of Batteries Required During Daytime</td>
</tr>
<tr>
<td>k</td>
<td>The Scaling Factor</td>
</tr>
<tr>
<td>$T$</td>
<td>Time in Hours to Supply Power to the Load for Night Time</td>
</tr>
<tr>
<td>$N_{i,b}$</td>
<td>Total Number of Batteries Required</td>
</tr>
<tr>
<td>VLA</td>
<td>Vented Lead-Acid</td>
</tr>
<tr>
<td>VA</td>
<td>Volt Ampere</td>
</tr>
<tr>
<td>$V_{ah}$</td>
<td>Voltage Ampere Hours</td>
</tr>
<tr>
<td>$V_{mp}$</td>
<td>Voltage at Maximum Power</td>
</tr>
<tr>
<td>$W/m^2$</td>
<td>Watt per square metre</td>
</tr>
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ABSTRACT

Solar photovoltaic (PV) energy has been widely used for decades especially where connection to a national grid is seldom possible and other sources such as fossil fuel and others are either unavailable or uneconomical. Solar PV energy owing to its free, natural availability and environmental friendliness has found demand for use in industries, homes and institutions. However, very little research has been carried out to precisely establish its effectiveness, reliability and adequacy. In this research work, an investigation to system size a PV telecommunication system was carried out for three consecutive months (June, July and August) considered to be the poorest in terms of irradiance by the Kenya Meteorological Department in the year 2012. The study was based on the power rating of a typical telecommunication system which is 1,222VA. However, the set-up was modeled to a typical telecommunication system by scaling down the actual load by a factor of 16 which gave 76.37VA. A standard stand-alone PV power supply unit to power the simulated telecommunication system was mounted in an open area away from any shading outside the solar energy laboratory of University of Nairobi. Voltage, current and hence the power data were measured daily using a data logger for the three months from the PV power supply unit. The irradiance data was also measured using a pyranometer for the same duration of time as that of voltage and current. The irradiance data collected and power harnessed by the installed PV system varied from month to month with July recording the lowest and August the highest. The highest and lowest irradiance fell on sunny day and cloudy day respectively. The daily average irradiance for June, July and August were 452.40W/m², 422.43W/m² and 510.67W/m² respectively. The corresponding daily average power harnessed from modules for June, July and August were 76.10 VA, 75.37 VA and 85.93 VA respectively. There was a direct correlation between the irradiance and module power output. The irradiance and power harnessed was used to determine the number of modules and batteries required to fully support the Telecommunication PV System. For the month of June the number of modules and batteries were found to be 38, 200W modules and 62, 175Ah batteries. For the month of July they were 38, 200W modules and 62, 175Ah batteries and for the month of August 32, 200W modules and 62, 175Ah batteries respectively. The month that gave the highest number of modules and batteries (poorest month in terms of irradiance and power) was used as reference to size the Telecommunication PV system and in this case it was the month of July. The finding reported in this research work is of great importance to telecommunication companies as it serves as a guide as to the approximate number of modules and batteries that should be put in place to support the PV telecommunication systems. It also forms the basis for sizing, as can be used to scale down other PV systems to be installed in areas whose average irradiance is known.
CHAPTER 1
INTRODUCTION

1.1 Background to study

Renewable energy resources have enormous potential capable of meeting the current global energy demand. These resources can furthermore enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and global atmospheric emissions. They also have the potential to provide commercially attractive options to meet specific needs for energy services particularly in rural areas in developing countries, and offer possibilities for locally manufactured products (Asif and Muneer, 2007). Furthermore, the use of renewable energy resources has been charted specifically in many of the roadmaps of the developed countries.

One of the most promising renewable energy technologies is photovoltaic (PV) technology. PV systems are popularly configured as: stand-alone, grid-connected and hybrid systems. In any PV system, sizing represents an important part of the design, that is the optimal selection of the number of solar modules, the size of the storage battery and the size of the charge controller to be used for certain applications at a particular site is an important task that ensures optimal operational efficiency.

Undoubtedly, the major impediment to a wider market penetration as noted by Haas (1995), is the high initial investment costs of the PV systems. This still remains to be the major impediment even at the present stage of development. However, estimation of the sizing parameters which includes the number of PV-array, useful battery capacity and the rating of the charge controller is very useful to conceive an optimal PV system as well as
conceiving an optimal and economic PV system particularly in isolated sites (remote areas in developing nations, mountainous locations, rural regions, etc.). Most PV systems are installed in remote areas where the irradiance level is high but still are hybrid where grid or diesel is a dominant source to power the telecommunication systems. This leads to under-utilization of solar energy and increased cost of running the system.

1.2 Statement of research problem

Despite the high level of irradiance in remote locations, installed PV system are hybrids which highly depend on diesel gensets. Though these hybrids are interconnected to the PV system, they fail to utilize it effectively since they prioritize on the grid and diesel power leading to solar energy wasted. With proper sizing, the solar energy available is more than enough to purely support the PV telecommunication system in absence of other sources of energy. This would greatly reduce the power wastage and the cost of the established systems.

1.3 Justification and significance of study

The implementation of PV systems which purely operate on solar energy greatly reduces the cost of running the system and also leads to increased efficiency as there is no conversion of power from direct current to alternating current (DC to AC).

1.4 Location of study area

The study was carried out at the Department of physics of the University of Nairobi where there is an established solar energy laboratory. Its geographical coordinates are 1\textdegree.
17° South, 36°49' East. From mid-December to mid-March it is sunny season, mid-March to mid-October it is overcast conditions and from mid-October to mid-December is short rains.

1.5 Research objectives

1.5.1 Main objective
The main objective of this study was to carry out a system sizing for a PV dependent telecommunication system (safaricom booster) using sample radiation and output data for lowest irradiance months of the year and to determine or specify the batteries, solar PV array and the rating of charge controllers.

1.5.2 Specific objectives
(i) To lay up a set-up of standard stand-alone “ALL-DC” telecommunication system by mounting PV system incorporating modules, batteries, charge controller and a simulated telecommunication system as load.

(ii) To collect and study irradiance and power profiles of the mounted system for a period of three months (June, July and August 2012).

(iii) To carry out system sizing and study the reliability of the PV system.
1.6 Rationale

The requirement that any given system dependent on solar energy runs effectively and reliably and that it is economically maintained to meet the demand and sustain the telecommunication system has necessitated the research for system sizing.
CHAPTER 2
LITERATURE REVIEW

2.1 Anatomy of an off-grid stand-alone “ALL-DC” PV system

As the world's telecommunication networks are extended and upgraded, greater focus is placed on the provision of rural communication services, where site access is often difficult, and connection to a central electricity grid is seldom possible. To power the telecom based transmitter system, such as repeater stations located in remote areas, with a high level of solar radiation year-round, and where the cost to extend the power lines is prohibitive, PV technology becomes the most economical option. With the availability of energy-efficient auxiliary system equipment operating on DC voltage, there is no need for a DC to AC converter, thus making an “all-DC” PV system possible.

2.2 Stand-alone PV systems

Power systems which can generate and supply electricity to small isolated communities like rural villages in Kenya, remote areas and mountainous regions, without access to the grid, are differently termed ‘decentralized, autonomous or stand-alone’. These may come as Individual Energy Systems (IES) or Community Energy Systems (CES). Several models have been developed to perform simulation and sizing of PV system using different operation strategies. Klein (1978) estimated and evaluated the excess of energy provided by PV generators using the systems for an installation having a constant load. However the method did not put into consideration that irradiance levels change from time to time depending on the period of the year which in turn affects what is produced by the PV generator. This implies that, the method lacked the basis for sizing as it did not
consider extreme conditions whether it was cloudy or highly illuminated periods of the year which is a very important aspect in sizing. Siegel *et al.* (1981) evaluated the monthly average output, the excess of energy and the storage capacity of the battery in a hybrid system. Bucciareli (1984) estimated the performance of PV system based on the Loss of Load Probability (LLP) technique, defined as the ratio between the energy deficit and the energy demand by the load. These analytical methods are based on past data rather than the current actual measured data. Egido and Lorenzo (1992) reviewed methods for computing the capacity of PV arrays and battery storage and suggested an analytical model based on Loss of Power Supply Probability (LPSP). This method uses computing algorithms that allow the improvement of the precision of the LLP calculation according to the dimension of the PV-array area and the storage capacity. This improves the reliability of the system.

Keller and Affolter (1995) developed a method for determining the optimal solar module area of PV systems in relation to the static inverter. Nevertheless, a detailed evaluation of the sensitivity of a numerical sizing method developed by Notton *et al.* (1996), has shown that the influence of some parameters such as simulation time step, input and output power profile on sizing are key to sensitivity. It is therefore important to have knowledge of the daily profile at least on an hourly basis in order to clearly indicate the trend of power harnessed. Markvart (1996) used the sizing curve to investigate the sizing of PV/wind hybrid systems. The construction of a sizing curve was based on LLP which requires the modeling of PV system operation over a substantial period of time. Time series of solar radiation then cannot come directly from the observation but need to be
reproduced “synthetically” based on an algorithm which is faithful to the solar radiation statistics. However with this method there is a tendency of occurrence of error during the synthetical reproduction based on the algorithms. Shrestha and Goel (1998) demonstrated a method to find the optimal combination of PV array size and battery to meet the refrigeration load, by using statistical models for both solar radiation and the load. The research group had designed a stand-alone PV system based on irradiation derived from meteorological satellite (METEOSAT) images. However, there is great need to rely on very current irradiation data for study purpose rather than past data from database. This does not only ensure reliability but also the accuracy of the PV system. Bhuiyan and Asgar (2003) optimized PV battery system for Dhaka, India with respect to power output for different tilt angles and azimuthal angles for optimum performance of hybrid PV system. This method was found to maximize the harnessed power. However this should be based on poor months in terms of irradiance data measured in order to ensure the reliability of the system being sized. Mellit et al. (2004), presented a simplified methodology for sizing a PV system based on spatial interpolation of optimal sizing. Kaushika et al. (2005) developed a computational scheme for stand-alone PV systems with interconnected arrays. The method did not rely much on measured data but rather on the availability of data from database. For reliability and accuracy the actual data measurement is very important as the available data from database may be misleading.

The studies highlighted above have been mainly for hybrid systems or AC systems. Moreover most of the installed telecom systems use PV/ hybrids for the provision of energy. In this research, the attempt was to provide a comprehensive sizing for a standard
stand-alone PV system that would purely utilize solar energy to run the telecommunication system based on actual measured data study purposes. Data logging for irradiance, current and voltages for modules, batteries and the load was carried out. The information obtained from the logging was used to perform sizing of the telecommunication system which would then form the basis of sizing in other selected areas of similar insolation.
CHAPTER 3
THEORETICAL BACKGROUND

3.1 Module operating characteristics

Module characterization is based on current-voltage (I-V) measurement in the dark and under standardized illumination that simulates the sunlight. The parameters that describe the performance of a module are open circuit voltage ($V_{oc}$), short circuit current density ($J_{sc}$) and fill factor (FF). A typical graph of photovoltaic module and solar cell current against photovoltaic voltage is as shown in Fig. 3.1.

![Fig. 3.1: A typical graph of I-V characteristics of a photovoltaic module.](image)

3.2 Energy conversion efficiency

The energy conversion efficiency is the percentage power converted (absorbed light converted to electrical energy) and collected when a module is connected to an electrical load and is given by Eq. 3.1 (Green, 1992)
\[ \eta = \frac{V_{mp} \times I_{mp}}{P_{in}} \]  

(3.1)

where \( \eta \) is conversion efficiency, \( P_{in} \) is power input, \( V_{mp} \) is voltage at maximum power point and \( I_{mp} \) is current at maximum power point.

### 3.3 Fill factor (FF)

The fill factor defines the overall operation characteristics of solar cells. It is the ratio of maximum power point divided by product of open circuit voltage (\( V_{oc} \)) and short circuit current (\( I_{sc} \)) as shown by Eq. 3.2 (Bazouni, 2009)

\[ FF = \frac{P_{m}}{V_{oc} \times I_{sc}} \]  

(3.2)

where \( FF \) is fill factor, \( P_{m} \) is power at maximum power point, \( V_{oc} \) is the open circuit voltage and \( I_{sc} \) is short circuit current respectively. The short circuit current is directly related to the number of photons absorbed by the semiconductor material and is thus proportional to light intensity.

### 3.4 Estimation of solar irradiation at the site

Solar resources are discussed in terms of solar radiation. Solar radiation can be quantitatively measured by irradiance and irradiation. The term “irradiance” refers to the density of the power that falls on a surface and “irradiation” is the density of the energy that falls on a surface over some period of time such as an hour or a day. In this research
work, the irradiance of the site was measured using a CM3 Pyranometer. Figure 3.2 shows a picture of a CM3 Pyranometer.

![CM3 Pyranometer](image)

**Fig. 3.2:** A picture of a CM3 Pyranometer

### 3.4.1 Solar irradiation on an inclined plane

It is theoretically possible to estimate the solar irradiation on any inclined surface given the solar irradiation on a horizontal plane and the tilt angle (Liu and Jordan, 1960). For practical purposes of designing a solar PV system, estimation of solar irradiation is carried out at the optimum tilt angle, which is the incline that collects most solar irradiation. Calculation of optimal tilt angle as suggested by Chiou and El-Naggar (1986) is given by Eq. 3.3

\[
B_{opt} = \phi \pm 10^\circ
\]  

(3.3)

where \(B_{opt}\) is the optimum tilt angle, \(\phi\) is the latitude of the site (degree) and \(10^\circ\) is the solar angle of declination.
3.5 Effective PV cell temperature

The average effective PV cell temperature at the installation site is calculated using Eq. 3.4 (AS\NZS 4509.2)

\[ T_{\text{cell, eff}} = T_{a, \text{day}} + 25^\circ\text{C} \] (3.4)

where \( T_{\text{cell, eff}} \) is the average effective PV cell temperature, \( T_{a, \text{day}} \) is the average daytime ambient temperature at the site (deg) and 25°C is the module’s temperature rise.

3.6 PV array sizing

The number of PV modules required for the PV array using AS\NZS 4509.2 is given by Eq 3.5

\[ N = \frac{E_d \times f_o}{P_{\text{mod}} \times G \times \eta_{\text{coul}}} \] (3.5)

where \( N \) is the number of PV modules required, \( P_{\text{mod}} \) is the derated power output of the PV module, \( E_d \) is the total design daily energy, \( f_o \) is the oversupply coefficient, \( G \) is the solar irradiation after all factors for example tilt angle and tracking have been captured, \( \eta_{\text{coul}} \) is the coulombic efficiency of the battery. The oversupply coefficient \( f_o \) is a design contingency factor to capture the uncertainty in designing solar power systems where future solar irradiation is not deterministic.
3.7 Types of solar PV modules

PV arrays comprise varying numbers of modules connected together. The modules fall into several categories, including monocrystalline silicon (cSi), polycrystalline silicon (mSi), and thin-film solar cells.

3.7.1 Monocrystalline silicon modules

The monocrystalline modules use the purest form of silicon and typically comprise highly ordered blue-black polygons. They are the most efficient type of PV module in good light, with a conversion efficiency of typically 10-16% but also the most expensive. The energy required to make their embodied energy is greater than other PV types. Life expectancy is typically 25-30 years.

3.7.2 Polycrystalline modules

Polycrystalline silicon modules are made from multicrystalline silicon (mSi), these are cheaper and their embodied energy is less than monocrystalline modules. However, their more disorderly atomic structure means that their energy efficiency is generally slightly lower, at typically 12%. Life expectancy is around 20-25 years. In this research work, polycrystalline type modules were used. Figure 3.3 shows a picture of a polycrystalline silicon type module.
3.7.3 Thin-film modules

Thin-film modules consist of an ultra-thin layer of photosensitive material deposited onto a low-cost backing, such as glass, plastic or stainless steel. The earliest types used a layer of amorphous silicon, but subsequently various different combinations of materials have been employed, with varying degrees of success. For example, thin hybrid silicon cells are a combination of amorphous and microcrystalline cells. Other thin-film technologies are based on semiconductor materials, such as Copper-Indium-Gallium-Diselenide (CIGS). Thin films can be rigid or flexible, and can be produced in various colours, giving great versatility for different applications and sites. They require relatively low amounts of raw materials to manufacture, are suited to automated production, and hence are relatively cheap to make. However, efficiencies are lower (e.g. 4-8%), as is the life expectancy (at 15-20 years). Non-silicon-based thin-film modules, such as those using CdTe and CIGS, have better efficiencies, with some exceeding 10%.
3.8 Batteries

For off-grid, stand-alone solar power systems, batteries provide the backup power needed when sunlight is insufficient, such as during periods of heavy cloud cover and during the night. The battery bank should have a sufficient ampere-hour (Ah) capacity to supply load during the longest expected period with no contribution from the PV array. It has to be a full-size battery bank with a good reserve for five or more days (120 hour).

PV batteries generally have to discharge a smaller current to the load for a longer period (such as all night), while being charged during the day. The batteries must be suitable to withstand the heavy daily cycling required for this application. One cycle is defined as a full charge followed by the discharge. It is usually considered to be discharging from 100% to 20%, which means a “depth of discharge” of 80%. After discharging to 20% capacity, the PV system should be capable of recharging the battery to 100% capacity within 30 days (typical) with the defined peak sun hours per day.

3.8.1 Deep-cycle, lead-acid batteries

Deep-cycle, lead-acid batteries are the type that is commonly used in PV home and industrial systems. Deep cycle batteries are designed to discharge most of their stored energy without damage and then re-charge hundreds or thousands of times while still maintaining long life. Deep-cycle batteries produce less current than a shallow-cycle battery but can produce that amount of current for a much longer period of time. It is common practice for a system to be designed with deep-cycle batteries even though the daily or average discharging amounts to a relatively shallow depth of discharge.
Vented (flooded) lead-acid (VLA) batteries are commonly used in PV systems, because they are more durable in cycling operations than other battery types. VLA batteries provide a long reliable service life of 20 years (minimum), if deployed in a temperature-controlled environment, operated at the manufacturer specified charge voltage, and looked after appropriately by performing routine maintenance. VLA batteries are relatively inexpensive and readily available.

3.9 Charge regulator

Output from the solar modules varies considerably, depending on the prevailing sunlight and temperature conditions. Therefore, it's required to regulate its output by wiring it to the charge controller before it goes on to the battery and loads. Once the batteries are fully charged, the charge controller doesn't let current from the PV modules to flow into them. Similarly, once the batteries have been drained to a certain predetermined level, the charge controller will not allow more current to be drained from the batteries until they have been recharged. The charge controller also eliminates any reverse current flow from the batteries to the solar modules at night. For reliability of a system operation, the controller is arranged in a redundant configuration, providing 100% redundancy. The controller is also built with alarm features to indicate abnormal conditions (e.g., array failure, battery low/high-voltage, circuit breaker trip, equipment overload, module anti-theft alarm, etc.) with provision for annunciating the alarms to a central station. In this research work a solsum type of charge controller was used. Figure 3.4 shows a picture of the Solsum type of charge controller used for the collection of data.
3.10 Array installation

In the northern hemisphere, the sun traces a southerly route due to the earth's inclination to the sun. Therefore, it's important to orient the solar array to the south of locations in such locations (the reverse is true for locations in the southern hemisphere). The solar modules should be oriented to face north at a tilt angle equals to site latitude with respect to horizontal position. Tilt from horizontal is required to achieve a better angle at the sun and help keep the solar modules clean by shedding rain or snow. Fixed arrays are often favored for systems that operate without maintenance or personnel on-site. PV modules are very sensitive to shading. Once a solar cell or a portion of a cell is shaded, it becomes a load and draws power instead of producing it. Thus, PV modules should never be shaded by nearby trees or structures. Installing the solar array in an area with natural ventilation will improve system performance and extend its life. The mounting option must allow for safe maintenance and possible replacement of individual modules.
3.11 Types of solar power system

There are more than four types of photovoltaic solar power installation configurations; this is an overview of some of the most common setups.

3.11.1 Stand-alone system

A stand-alone photovoltaic solar power system provides electricity generated from the array to a point of consumption and is independent of the utility grid. Stand alone systems generally use a battery storage system to provide electricity to the load when the solar array is autonomous and unable to generate power. A more sophisticated stand alone system adds an inverter and ties into the building service panel.

3.11.2 Grid tied system

A grid-tied system is also called a utility interactive system. This type of solar power system operates in tandem with the local utility supplier. It uses an inverter to convert DC power to AC power, ties into the service panel supplying electricity at the point of consumption from the solar array. It also ties into the utility grid and sends electricity back to the utility when the energy produced by the array is not consumed at the point of consumption. The term net-metering is used to describe the offset of electricity used from the grid and the electricity sent back into the grid.

3.11.3 Grid tied with battery backup

Also known as a bimodal system, a grid tied system with battery backup is also a tandem system that can operate as a grid-tied utility interactive PV system as well as a stand-
alone system which can draw power exclusively from the batteries in the case of a blackout, even at night when no electricity can be drawn from the solar array.

In the utility interactive mode, the system can be set up as net-metered using a bidirectional utility meter or dual metered, using two utility meters. One for importing power from the grid and one for exporting electricity generated from the solar back to the utility company. This is a sophisticated system that accounts for autonomy in electricity production, but comes with a higher price tag than stand-alone or simple grid tied systems.

### 3.11.4 Hybrid system

Basic hybrid system is configured as a stand-alone system that uses electricity generated from two different sources. A solar array combined with a wind turbine would be an example of dual energy sources in a hybrid system. Hybrid systems are sophisticated and complex. A standard hybrid system converts power from the energy source from DC to AC using an inverter and ties into the AC electrical panel where the electricity is used at the point of consumption.
3.12 Typical telecommunication transmission system

Table 3.1 shows a typical telecommunication system load (Shanmuga, 2010)

**Table 3.1: Composition of a typical telecommunication transmission system**

<table>
<thead>
<tr>
<th>TELECOMMUNICATION EQUIPMENT</th>
<th>POWER RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telecommunication equipment (Receivers and Transmitters antenna)</td>
<td>520W</td>
</tr>
<tr>
<td>PV charge controller</td>
<td>15W</td>
</tr>
<tr>
<td>DC A/C in equipment room</td>
<td>360 W @ 50% duty cycle</td>
</tr>
<tr>
<td>DC A/C in battery room</td>
<td>216W @ 30% duty cycle</td>
</tr>
<tr>
<td>Exhaust fan in battery room</td>
<td>30W</td>
</tr>
<tr>
<td>PV shelter lighting</td>
<td>60W</td>
</tr>
<tr>
<td>Miscellaneous load (fire alarm system, etc.)</td>
<td>21W</td>
</tr>
<tr>
<td>Total load in watts</td>
<td>1,222W</td>
</tr>
<tr>
<td>Total load in current</td>
<td>25.5A</td>
</tr>
</tbody>
</table>

3.13 Series and parallel connection of modules

Solar cells can be thought of as solar batteries. If solar cells say A, B and C are connected in series, then the current stays the same and the voltage increases. If solar cells A, B and C are connected in parallel, the voltage stays the same, but the current increases. Figure 3.5 and figure 3.6 show a series and parallel connection respectively.
It is known that those solar cells are combined to form a ‘module’ to obtain the voltage and current (and therefore power) desired.
CHAPTER 4
MATERIALS AND METHODS

4.1 Introduction

This chapter presents a detailed description of the experimental set-up and procedures used in this research. The chapter introduces the experimental set-up, simulation of DC telecommunication system, mounting of the standard stand-alone PV system, study of irradiance and power and system sizing, before analysis are discussed.

4.2 Experimental set-up

The set-up was modeled to a typical telecommunication system by scaling down the load. The source of power consisted of three polycrystalline PV modules each rated at 40W<sub>p</sub> and three lead acid batteries each with a capacity of 75Ah. The charge controller was rated 12/24V 10A. The modeled load consisted of DC halogen bulbs totaling to 76.37VA. The measurement unit included a CM3 pyranometer for measurement of irradiance, digital multimeter and a minicube data logger with sixteen channels for current and voltage measurement. Figure 4.1 show the schematic arrangement of a typical PV system used for data collection. The figure have a charge controller in between the PV modules, batteries and Telecom loads.

4.3 Simulation of DC telecommunication system

The study was based on the power rating of a typical telecommunication system which is 1,222VA. However in this study, the rating was scaled by a factor of 16 which gave 76.37VA. Throughout the study, the simulated load was fixed at 76.37VA. The load
comprised of nine halogen bulbs each rated 8.5V connected in series. The input power was from three polycrystalline modules each rated 40W_p and three lead-acid batteries each of capacity 75Ah connected in parallel.

**Fig.4.1:** Schematic arrangement of typical PV system used for data collection.

**4.4 Mounting of the standard stand-alone PV system**

A standard stand-alone PV power supply unit to power a simulated telecommunication system was mounted in an open area away from any shading outside the solar energy laboratory of the University of Nairobi, Kenya. The electrical connections took one week and the measurements started on 1.06.2012 after some trials of the system. The mounted system consisted of a single string of three modules mounted at an optimum tilt angle of $11^0 17'$ and three batteries connected in parallel. The optimal tilt angle was calculated using equation (3.3) discussed in subsection 3.4. Halogen bulbs (load) to utilize the DC electricity generated by the photovoltaic modules during the day and also night was connected to the system. Figure 4.2 (a) shows a picture of a minicube data logger, a pyranometer, lead-acid batteries, a charge controller and a digital multimeter while figure
4.2 (b) shows a picture of the 3 polycrystalline silicon modules used to simulate PV power system for the telecommunication facility.

![Figure 4.2: A picture of a simulated PV system showing (a) lead-acid batteries, charge controller, minicube data logger, digital multimeter and pyranometer and (b) polycrystalline modules.](image)

**Figure 4.2:** A picture of a simulated PV system showing (a) lead-acid batteries, charge controller, minicube data logger, digital multimeter and pyranometer and (b) polycrystalline modules.

### 4.5 Study of irradiance and power

The voltage and current parameters were measured daily at the interfaces 1, 2 and 3 shown in figure 4.1 and at an interval of one minute for three consecutive months (June, July and August 2012) using the data logger. At the first interface, current and voltage generated by the modules was measured. At second interface the measurement of current and voltage from the charge controller into the batteries was done and at the third interface current and voltage to the load was measured. The irradiance of the site was measured using a pyranometer at the same intervals and for the same duration of time as that of current and voltage. To find out the solar potential available at the site of study,
power in VA from current, voltage and irradiance data as measured from the simulated system were computed. The hourly, daily and monthly power and irradiance were tabulated and analyzed and related graphs were plotted showing the diurnal variations for the different times of the months.

4.6 System sizing

The projection based on the study in section 4.5 was carried out to determine the number of modules, batteries and the rating of the charge regulator for the telecommunication system. The sizing was based on poorly illuminated month in terms of irradiance. Thereafter, the month that gave the highest number of modules and batteries (poorest month in terms of irradiance) was chosen to give the actual number of modules, batteries and the rating of the charge controller for the telecommunication PV system.

Projections comprised of both daytime and nighttime load utilities. The Projections parameters used in chapter 5 of this thesis to establish the number of modules, batteries and the rating of charge controller required to fully support the telecommunication system comprised of the following.

\[ N_{m,d} \] number of modules required during daytime.

\[ N_i \] initial number of modules used in the actual experiment.

\[ P_{in,r} \] input power requirement determined by the load requirement.

\[ P_a \] actual power produced by the modules.
\( P_{a,m} \) actual power produced per module.

\( N_{m,n} \) number of modules required to produce power for night time use.

\( MF \) the mismatch factor between rated power and actual power produced by the modules.

\( N_{t,m} \) the actual total number of modules required to run the system.

\( k \) the scaling factor.

\( T \) time in hours to supply power to the load for night time

\( N_{b,d} \) the number of batteries required during daytime.

\( N_{t,b} \) the initial number of batteries.

\( P_{a,b} \) actual power discharged per battery bank.

\( N_{n,b} \) number of batteries required to support load during night time.

\( P_{cr} \) capacity power requirement during night time.

\( P_{a,B} \) the actual power produced by the system batteries.

\( N_{t,b} \) total number of batteries required.

The mathematical models developed for sizing considered only the linear effects.
CHAPTER 5
RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents the results and a detailed discussion of the study. For each month, the graphs showing total daily and monthly irradiance and power harnessed from the modules, the power stored in batteries and power consumed by load were plotted and studied. This was followed by discussion, calculation and analysis.

5.2 Analysis for the month of June 2012

The data for irradiance and calculated power from the modules, to the batteries and to the loads were recorded for the month of June. The results were categorized into daily irradiance, daily power produced by modules, daily power consumed by the loads, daily power to the battery system and monthly total irradiance, monthly total power produced by modules, monthly total power consumed by the loads and total monthly power to the battery system over the entire period of study.

5.2.1 Irradiance versus date for June 2012

Figure 5.1 shows the data of daily averages for solar radiation for the month of June 2012. The 20\textsuperscript{th} day of June was not included in the data and analysis. From figure 5.1, it can be observed that the daily average irradiance varied with the day. The daily average for this month ranged between 178 W/m\textsuperscript{2} and 639.92 W/m\textsuperscript{2} and the monthly average was 452.40 W/m\textsuperscript{2}. The daily variation did not show any particular trend but it generally depicted a random profile. This is expected because the drop in irradiance was mainly.
caused by random overcast by cloud cover. The random profile is also expected because whether it shines the following day or not is a matter of probability. However it can also be noted that the highest irradiance recorded was 639.92 W/m² which is far much lower than the standard test condition (STC). It is expected that the field conditions deviate from the STC but not with such a large percentage. This may imply that the atmosphere was filled with dust, smoke and other fine particles that may have contributed to the overall drop in irradiance by absorbing part of it. It was also observed that in the month of June a sunny day had an average of 600 W/m² while a cloudy day had an average of about 350 W/m² apart from the 22nd and the 24th of June 2012 where the irradiance was below 200 W/m². On these two days the weather was considered poorest and was characterized by cloud cover and rain. As earlier observed the 4th and the 22nd day of June 2012 recorded the highest and lowest irradiance, respectively and hence were used for further analysis in this research work.

**Fig. 5.1:** Average daily irradiance for the month of June 2012.
5.2.2 Summary of daily irradiance and power versus date for June 2012

Figure 5.2 shows data for irradiance, power profiles generated by modules, batteries and load consumption for the month of June 2012. The 20\textsuperscript{th} day of June was not included in the data and analysis. There was a direct relationship between power and irradiance, i.e. as the irradiance changed the module power output also changed thus validating the rate of batteries charging. The load was rated at a constant value of 76.37 VA while the upper and lower thresholds for the battery were 95.23 VA and 73.39 VA, respectively. This implies that values of batteries power below 73.39 VA would set the system to disconnect state and vice versa. The ON and OFF state of the load and the connection and disconnect of batteries was regulated by the charge controller.

![Irradiance and related power profiles for modules, batteries and load for month of June 2012.](image)

**Fig. 5.2:** Irradiance and related power profiles for modules, batteries and load for month of June 2012.

A summary of June irradiance and utilization are provided in Table 5.1
Table 5.1 Summary of monthly totals and average power for modules, batteries power and load consumption for the month of June 2012.

<table>
<thead>
<tr>
<th>MONTH</th>
<th>TOTAL MONTHLY MODULE POWERS(VA)</th>
<th>MONTHLY AVERAGE MODULE POWER(VA)</th>
<th>TOTAL MONTHLY BATTERIES POWER(VA)</th>
<th>MONTHLY AVERAGE BATTERIES POWER(VA)</th>
<th>TOTAL MONTHLY LOAD POWER(VA)</th>
<th>MONTHLY AVERAGE LOAD POWER(VA)</th>
<th>LOAD PERCENTAGE UTILIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUNE</td>
<td>2206.98</td>
<td>76.10</td>
<td>2461.19</td>
<td>84.87</td>
<td>1802.80</td>
<td>62.17</td>
<td>81.40</td>
</tr>
</tbody>
</table>

5.2.3 Analysis for highest irradiance day for June 2012

Figure 5.3 shows the analyses on the 4th day of June 2012 which recorded the highest irradiance level (Marked A in figure 5.1). It shows a relationship between irradiance and module power output, batteries power and power available for the load utilization. The power harnessed was in VA since it was the product of voltage and current for the specified interval of time.

Since the load was set to consume a constant power of 76.37 VA, it can be observed that load percentage utilization during daytime was 100% (plot (d) in figure 5.3). There is a close correlation between irradiance and module power at any particular period of time (plot (a) and (b) in figure 5.3). Charging of the batteries depended on module output power, i.e. during sunny days, due to high irradiance level, the batteries were charged to full capacity and hence were able to sustain the load for some time after irradiance had dropped to 60 W/m² (plots (a), (b) and (d) between 1600Hrs and 1700Hrs in figure 5.3).
This is because the surplus power was stored in the batteries, which is obtained by getting the difference in power between curves (c) and (d) in Figure 5.3 for every hour as shown in table 5.2. Surplus power is the difference between power stored in the batteries and the power consumed by the load when the modules are supplying power (during daytime). Surplus power is therefore stored for use when the modules are not supplying power (after sunset).

**Fig. 5.3**: Profile for Irradiance and related power for modules, batteries and load for a sampled clear day in month of June 2012.

From the table, the time it takes for the stored power to sustain the load without any input of the module is therefore given by Eq.5.1
Table 5.2: Difference between battery capacity and load power per hour for a clear day in June 2012.

<table>
<thead>
<tr>
<th>Time of day</th>
<th>8:00</th>
<th>9:00</th>
<th>10:00</th>
<th>11:00</th>
<th>12:00</th>
<th>13:00</th>
<th>14:00</th>
<th>15:00</th>
<th>16:00</th>
<th>17:00</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>76.99</td>
<td>88.26</td>
<td>94.26</td>
<td>95.23</td>
<td>95.23</td>
<td>94.55</td>
<td>93.56</td>
<td>93.70</td>
<td>90.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stored power</td>
<td>0.62</td>
<td>11.89</td>
<td>17.99</td>
<td>18.96</td>
<td>18.96</td>
<td>18.19</td>
<td>17.19</td>
<td>17.33</td>
<td>13.72</td>
<td></td>
<td>153.81</td>
</tr>
</tbody>
</table>

\[
Time\text{(hours)} = \frac{Total\ stored\ power}{Total\ load\ requirement} = \frac{153.81\ VA}{76.37\ VA} = 2\ hours
\] (5.1)

From the analysis the system would run up to 1900 HRS. Since the system is designed to run for 24 hours it therefore implies that, there is a deficit of about 12 hours where the system remains off. If the system is to run up to around 0900HRS the following morning when the modules start to produce enough power to support the load then an additional number of modules and batteries or a standby source need to be provided.

5.2.4 Analysis for the lowest irradiance day for June 2012

Figure 5.4 shows the analyses of the 22\textsuperscript{nd} day of June 2012 which recorded the lowest irradiance level (Marked B in figure 5.1). It shows the data for irradiance, power profiles for modules, batteries and load consumption for the cloudiest day in the month of June. The standard load percentage utilization for the lowest irradiance day for June was 30\% and the deficit was 70\% during daytime. The load power utilization is 24 hours which
implies that there is a need for a stand-by source to continue supplying the required power. During poor days the irradiance was low and the batteries would start to charge at around mid-morning. As batteries charged the load would start to draw power from them.

**Fig. 5.4:** Profile for Irradiance and related power for modules, batteries and load for a sampled cloudy day in the month of June 2012.

**Table 5.3:** Difference between battery capacity and load power per hour for a cloudy day in June 2012.

<table>
<thead>
<tr>
<th>Time of day</th>
<th>8:00</th>
<th>9:00</th>
<th>10:00</th>
<th>11:00</th>
<th>12:00</th>
<th>13:00</th>
<th>14:00</th>
<th>15:00</th>
<th>16:00</th>
<th>17:00</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>77.46</td>
<td>76.37</td>
<td>76.37</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Load</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stored power</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.09</td>
<td>0.46</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.55</td>
</tr>
</tbody>
</table>

From the table, the time it takes the stored power to sustain the load without any input of the module is therefore given by Eq. 5.2
\[ Time(hours) = \frac{Total\ stored\ power}{Total\ load\ requirement} = \frac{5.07\ VA}{76.37\ VA} \approx 2\ minutes \] (5.2)

From the analysis the system would run up to 1302HRS

5.2.5 Projections for month of June 2012

The analyses below present the number of modules and batteries that would be required by the load for the month of June.

(a) Number of modules projections.

(i). Number of modules for daytime projection

\[ N_{m,d} = N_i + \left( \frac{P_{n,r} - P_a}{P_{a,m}} \right) \times MF \] (5.3)

\[ = 3 + \left( \frac{76.37 - 55.83}{18.61} \right) \times 1.53 \]

\[ \approx 5\ modules\ of\ 40\ watts \]

(ii). Number of modules for night time projection

\[ N_{m,n} = N_i \times \left( \frac{P_{n,r} T}{10P_a} \right) \] (5.4)

\[ = 3 \times \left( \frac{76.37 \times 15}{10 \times 55.83} \right) \]

\[ \approx 7\ modules\ of\ 40W \]
Total number of modules for June 2012

\[ N_{t,m} = (N_{m,d} + N_{m,n}) \times k \]  

\[ = (7 + 5) \times 16 = 192 \]

\[ = \frac{192 \times 40}{200} \approx 40 \text{ Modules of 200W} \]

(b). Number of batteries projections

(i). Number of batteries for daytime projection.

\[ N_{b,d} = N_{d,b} + \left( \frac{P_{m,r} - P_{a,B}}{P_{a,b}} \right) \]  

\[ = 3 + \left( \frac{76.37 - 74.62}{24.8} \right) \]

\[ = 4 \text{ Batteries of 75Ah} \]

(ii). Number of batteries for night time projection.

\[ N_{n,b} = N_{d,b} \times \left( \frac{P_{cr}}{P_{a,B}} \right) \]  

\[ = 3 \times \left( \frac{114.56}{74.62} \right) \]

\[ = 5 \text{ Batteries of 75Ah} \]
Total number of Batteries for June 2012

\[ N_{i,b} = (N_{b,d} + N_{b,n}) \times k \]  

\[ = (4 + 5) \times 16 = 144 \text{ Batteries of 75Ah} \]

\[ = \frac{144 \times 75}{175} \approx 62 \text{ Batteries of 175Ah} \]

5.3 Analysis for the month of July 2012

The data for irradiance and calculated power of the modules, to the batteries and to the loads were recorded for the month of July. The results were categorized into daily irradiance, daily power produced by modules, daily power consumed by the loads, daily power to the battery system and monthly total irradiance, monthly total power produced by modules, monthly total power consumed by the loads, and total monthly power to the battery system over the entire period of study.

5.3.1 Irradiance versus date for the month of July 2012

Figure 5.5 shows the daily average solar radiation for the month of July 2012. The data for 17th and 30th day of July 2012 month was not included in the results and analysis. The irradiance ranged between 148.91 W/m² and 566.8 W/m² and the monthly average as 422.43 W/m². From figure 5.5, it can be observed that the daily average irradiance varied with the day. The daily variation did not show any particular trend but it generally depicted a random profile. This is expected because the drop in irradiance was mainly caused by overcast of cloud cover. The random profile is also expected because whether
it shines the following day or not is a matter of probability. However it can also be noted that the highest irradiance recorded was 566.81 W/m² which is far much lower than the STC. It is expected that the field conditions deviate from the STC but not with such a large percentage. This may imply that the atmosphere was filled with dust, smoke and other fine particles that may have contributed to the overall drop in irradiance. It was also observed that in the month of July a sunny day had an average of 566 W/m² while a cloudy day had an average of about 400 W/m² apart from the 12th day of July where on that day irradiance was below 150 W/m². On this day the weather was considered poorest and was characterized by cloud cover and rain. As earlier observed July the 3rd and the 12th day of July 2012 recorded the highest and lowest irradiance respectively and hence were used for further analysis in this research work.

![Graph: Average daily irradiance for July 2012.](image)

**Fig. 5.5:** Average daily irradiance for July 2012.
5.3.2 Summary of monthly irradiance and power versus date for July 2012

Figure 5.6 shows incident irradiance and related power profiles for modules, batteries and load for the month of July 2012. The data for 17th and 30th day of July 2012 month was not included in the results and analysis. Module output power varied with irradiance. The charging of the batteries depended on module power output and ranged from cut off state to a fully charged capacity. The load was rated at a constant value of 76.37 VA while the upper and lower thresholds for the battery were 95.23 VA and 73.39 VA, respectively. This implies that values of power for batteries below 73.39 VA would set the system to disconnect state and vice versa. The ON and OFF state of the load and the connection and disconnect of batteries was regulated by the charge controller. The monthly load percentage utilization for the month of July was 80.7%.

![Graph showing irradiance and related power for modules, batteries and load for month of July 2012.](image)

**Fig. 5.6:** Irradiance and related power for modules, batteries and load for month of July 2012.

A summary of July irradiance and utilization are given in Table 5.4
Table 5.4: Summary of monthly totals and average power for modules, batteries and load consumption for the month of July 2012.

<table>
<thead>
<tr>
<th>MONTH</th>
<th>TOTAL MONTHLY MODULE POWERS (VA)</th>
<th>MONTHLY AVERAGE MODULE POWER (VA)</th>
<th>TOTAL MONTHLY BATTERIES POWER (VA)</th>
<th>MONTHLY AVERAGE BATTERIES POWER (VA)</th>
<th>TOTAL MONTHLY LOAD POWER (VA)</th>
<th>MONTHLY AVERAGE LOAD POWER (VA)</th>
<th>LOAD PERCENTAGE UTILIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>JULY</td>
<td>2110.31</td>
<td>75.37</td>
<td>2349.76</td>
<td>83.92</td>
<td>1733.78</td>
<td>61.65</td>
<td>80.70</td>
</tr>
</tbody>
</table>

5.3.3 Analysis of highest irradiance day for July 2012

Figure 5.7 shows the analyses of the 3rd day of July 2012 which recorded the highest irradiance level (marked A in figure 5.5). The Figure shows the relationship between irradiance and module power output, batteries power and power available for the load utilization.

**Fig. 5.7:** Profile for Irradiance, and related power for modules, batteries and load for a sampled clear day for July 2012.
Since the load was set to consume a constant power of 76.37 VA, it can be observed that, the load percentage utilization during daytime was 100% (plot (d) in figure 5.7). There is a close correlation between irradiance and module power at any particular period of time (plot (a) and (b) in figure 5.7). Charging of the batteries depended on module output power, i.e. during sunny days, due to high irradiance level the batteries were charged to full capacity and hence were able to sustain the load for some time after irradiance had dropped to 55 W/m² (plots (a), (b) and (d) at 1600Hrs in figure 5.7). This is because the surplus power was stored in the batteries, which is obtained by getting the difference in power between curves (c) and (d) in Figure 5.7 for every hour as shown in table 5.5 below.

**Table 5.5**: Difference between battery capacity and load power per hour for a clear day in July 2012.

<table>
<thead>
<tr>
<th>Time of day</th>
<th>8:00</th>
<th>9:00</th>
<th>10:00</th>
<th>11:00</th>
<th>12:00</th>
<th>13:00</th>
<th>14:00</th>
<th>15:00</th>
<th>16:00</th>
<th>17:00</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>-</td>
<td>85.51</td>
<td>92.06</td>
<td>95.23</td>
<td>95.23</td>
<td>95.23</td>
<td>94.56</td>
<td>93.56</td>
<td>92.70</td>
<td>90.09</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>-</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td></td>
</tr>
<tr>
<td>Stored power</td>
<td>-</td>
<td>9.15</td>
<td>15.69</td>
<td>18.96</td>
<td>18.96</td>
<td>18.96</td>
<td>18.19</td>
<td>17.19</td>
<td>16.33</td>
<td>13.72</td>
<td>146.85</td>
</tr>
</tbody>
</table>

From the table, the time it takes for the stored power to sustain the load without any input from the module is therefore given by Eq.5.9
\[
\text{Time (hours)} = \frac{\text{Total stored power}}{\text{Total load requirement}} = \frac{146.85 \text{ VA}}{76.37 \text{ VA}} \\
\approx 2 \text{ hours}
\] (5.9)

From the analysis the system would run up to 1900 Hrs. Since the system is designed to run for 24 hours it therefore implies that, there is a deficit of about 12 hours where the system remains off. If the system is to run up to around 0900 Hrs the following morning when the modules start to produce enough power to support the load, then an additional number of modules and batteries or a standby source should be availed.

5.3.4 Analysis for the lowest radiance day for July 2012

Figure 5.8 shows the analyses of the 12\textsuperscript{th} day of June 2012 which recorded the lowest irradiance level (marked B in figure 5.5). The figure 5.8 shows data for irradiance, power profiles for modules, battery bank and load consumption for the poorest irradiance day in the month of July 2012.

![Graph showing irradiance and related power for modules, batteries and load](image)

**Fig. 5.8:** Profile for Irradiance and related power for modules, batteries and load for a sampled cloudy day for the month of July 2012.
The irradiance level was low and the module output power could not meet the load power demand at any given time. The standard load percentage utilization was 0%. The load remained off throughout the day meaning if the system was to run for 24 hours then a standby source should be in place throughout for the 24 hours.

### 5.3.5 Projections for month of July 2012

The projections for modules and batteries for the month of July 2012 were carried out using the same procedures used in section 5.2.5 of this thesis. Table 5.6 shows the projected number of modules and batteries both for daytime and night time and for the night time and daytime combined totals for the month of July 2012.

**Table 5.6:** projected number of modules and batteries for July 2012.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected number of 40W modules for daytime</td>
<td>5</td>
</tr>
<tr>
<td>Projected number of 40W modules for night time</td>
<td>7</td>
</tr>
<tr>
<td>Total projected number of 40W modules both for daytime and night time</td>
<td>192</td>
</tr>
<tr>
<td>Total equivalent number to 200W modules both for daytime and night time</td>
<td>40</td>
</tr>
<tr>
<td>Projected number of 75Ah batteries for daytime</td>
<td>4</td>
</tr>
<tr>
<td>Projected number of 75Ah batteries for night time</td>
<td>5</td>
</tr>
<tr>
<td>Total projected number of 75Ah batteries both for daytime and night time</td>
<td>144</td>
</tr>
<tr>
<td>Total equivalent number to 175Ah batteries both for daytime and night time</td>
<td>62</td>
</tr>
</tbody>
</table>
The projected number of modules and batteries for June and July were the same and this was because the two months were within the same range in terms of irradiance and power.

5.4 Analysis for the month of August 2012

The data for irradiance and calculated power of the modules, to the batteries and to the loads were recorded for the month of August. The results were categorized into daily irradiance, daily power produced by modules, daily power consumed by the loads, daily power to the battery system and monthly total irradiance, monthly total power produced by modules, monthly total power consumed by the loads, and total monthly power to the battery system over the entire period of study.

5.4.1 Irradiance versus date for August 2012

Figure 5.9 shows the average daily irradiance for August 2012. The data for 19th and 24th day of August 2012 month was not included in the results and analysis. From figure 5.9, it can be observed that the daily average for irradiance varied from day to day. The daily average irradiance was 510.67 W/m². The daily variation did not show any particular trend but it generally depicted a random profile. This is expected because the drop in irradiance was mainly caused by overcast of cloud cover. The random profile is also expected because whether it shines the following day or not is a matter of probability.
However it can also be noted that the highest irradiance recorded was 689.92 W/m² which is far much lower than the STC. It is expected that the field conditions deviate from the STC but not with such a large percentage. This may imply that the atmosphere was filled with dust, smoke and other fine particles that may have contributed to the overall drop in irradiance. The 1<sup>st</sup> and the 4<sup>th</sup> day of August 2012 recorded the highest and the lowest irradiance and hence were used for further analyses in this research work.

**5.4.2 Summary of monthly irradiance and power versus date for August 2012**

Figure 5.10 shows incident irradiance and related power profiles for modules, batteries and load for the month of August 2012. The data for 19<sup>th</sup> and 24<sup>th</sup> day of August 2012 month was not included in the results and analysis. Module output power varied with irradiance. The charging of the batteries depended on module power output and ranged
from cut off state to a fully charged capacity. The load was rated at a constant value of 76.37 VA while the upper and lower thresholds for the batteries were 95.23 VA and 73.39 VA, respectively. This implies that values of batteries power below 73.39 VA would set the system to disconnect state and vice versa. The ON and OFF state of the load and connection and disconnection of batteries was regulated by the charge controller. The monthly load percentage utilization for August was 84.91%.

![Graph](image)

**Fig. 5.10:** Irradiance and related power for modules, batteries and load for month of August 2012.

A summary of August irradiance and utilization are provided in Table 5.7
Table 5.7: Monthly summary of totals and average power for modules, battery bank and load consumption for the month of August 2012.

<table>
<thead>
<tr>
<th>MONTH</th>
<th>TOTAL MONTHLY MODULE POWERS (VA)</th>
<th>MONTHLY AVERAGE MODULE POWER (VA)</th>
<th>TOTAL MONTHLY BATTERIES POWER (VA)</th>
<th>MONTHLY AVERAGE BATTERIES POWER (VA)</th>
<th>TOTAL MONTHLY LOAD POWER (VA)</th>
<th>MONTHLY AVERAGE LOAD POWER (VA)</th>
<th>LOAD PERCENTAGE UTILIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUGUST</td>
<td>2492.09</td>
<td>85.93</td>
<td>2565.20</td>
<td>88.46</td>
<td>1903.34</td>
<td>65.63</td>
<td>85.94</td>
</tr>
</tbody>
</table>

5.4.3 Analysis of highest irradiance day for August 2012

Figure 5.11 shows the analyses of the 4th day of August 2012 which recorded the highest irradiance level (marked A in figure 5.9). The figure 5.11 shows relationship between irradiance and modules power output, batteries power and power available for the load utilization.

Fig. 5.11: Profile for Irradiance and related power for modules, batteries and load for a sampled clear day for August 2012.
Since the load was set to consume a constant power of 76.37 VA, it can be observed that load percentage utilization during daytime was 100% (plot (d) in figure 5.7). There is a close correlation between irradiance and module power at any particular period of time (plot (a) and (b) in figure 5.7). Charging of the batteries depended on module output power, i.e. during sunny days, due to high irradiance level the batteries were charged to full capacity and hence were able to sustain the load for some time after irradiance had dropped to around 80W/m² (plots (a), (b)and (d) at 1600Hrs in figure 5.11). This is because the surplus power was stored in the batteries, which is obtained by getting the difference in power between curves (c) and (d) in Figure 5.11 for every hour as shown in table 5.8 below.

Table 5.8: Difference between battery capacity and load power per hour for a clear day in August 2012.

<table>
<thead>
<tr>
<th>Time of day</th>
<th>8:00</th>
<th>9:00</th>
<th>10:00</th>
<th>11:00</th>
<th>12:00</th>
<th>13:00</th>
<th>14:00</th>
<th>15:00</th>
<th>16:00</th>
<th>17:00</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>76.92</td>
<td>88.16</td>
<td>94.56</td>
<td>95.23</td>
<td>95.23</td>
<td>94.56</td>
<td>93.56</td>
<td>90.70</td>
<td>88.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
</tr>
<tr>
<td>Stored power</td>
<td>0.55</td>
<td>11.79</td>
<td>18.19</td>
<td>18.86</td>
<td>18.86</td>
<td>18.19</td>
<td>17.19</td>
<td>14.33</td>
<td>11.72</td>
<td></td>
<td>148.54</td>
</tr>
</tbody>
</table>

From the table, the time it takes the stored power to sustain the load without any input of the module is therefore given by Eq. 5.16
From the analysis the system would run up to around 1900 Hrs. Since the system is designed to run for 24 hours it therefore implies that, there is a deficit of about 12 hours where the system remains off. If the system is to run up to around 0900 Hrs the following morning when the modules start to produce enough power to support the load, then an additional number of modules and batteries or a standby source should be availed.

5.4.4 Analysis for lowest irradiance day for August 2012

Figure 5.12 shows the analyses of the 1st day of August 2012 which recorded the lowest irradiance level (Marked B in figure 5.9). The figure 5.12 shows Irradiance and related power parameters in a poorly illuminated day for the month of August 2012. The standard load percentage utilization was 60% implying a deficit of 40% during the day time. The stored power is obtained by getting the difference in power between curves (c) and (d) in Figure 5.12 for every hour as shown in table 5.8.
Fig. 5.12: Profile for Irradiance, and related power for modules, batteries and load for cloudy day for the month of August 2012.

Table 5.9: Difference between batteries capacity and load power per hour for a cloudy day in August 2012.

<table>
<thead>
<tr>
<th>Time of day</th>
<th>8:00</th>
<th>9:00</th>
<th>10:00</th>
<th>11:00</th>
<th>12:00</th>
<th>13:00</th>
<th>14:00</th>
<th>15:00</th>
<th>16:00</th>
<th>17:00</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>-</td>
<td>-</td>
<td>76.64</td>
<td>77.45</td>
<td>77.90</td>
<td>77.05</td>
<td>77.26</td>
<td>76.99</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>-</td>
<td>-</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>76.37</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Stored power</td>
<td>-</td>
<td>-</td>
<td>0.27</td>
<td>1.08</td>
<td>1.53</td>
<td>0.68</td>
<td>0.89</td>
<td>0.62</td>
<td>-</td>
<td>-</td>
<td>5.07</td>
</tr>
</tbody>
</table>

From the table the time it takes the stored power to sustain the load without any input of the module is therefore given by Eq. 5.17

\[
Time (hours) = \frac{\text{Total stored power}}{\text{Total load requirement}} = \frac{5.07 \text{ VA}}{76.37 \text{ VA}} \approx 4 \text{ minutes}
\]
From the analysis the system would run up to 1704 Hrs

5.4.5. Projections for the month of August 2012

The projections for modules and batteries for the month of August 2012 were carried out using the same procedures used in section 5.2.5 of this thesis. Table 5.10 shows the projected number of modules and batteries both for daytime and night time and for the daytime and night time combined totals for the month of August 2012.

**Table 5.10**: Projected number of modules and batteries for August 2012.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected number of 40W modules for daytime</td>
<td>4</td>
</tr>
<tr>
<td>Projected number of 40W modules for night time</td>
<td>6</td>
</tr>
<tr>
<td>Total projected number of 40W modules both for daytime and night time</td>
<td>160</td>
</tr>
<tr>
<td>Total equivalent number to 200W modules both for daytime and night time</td>
<td>32</td>
</tr>
<tr>
<td>Projected number of 75Ah batteries for daytime</td>
<td>4</td>
</tr>
<tr>
<td>Projected number of 75Ah batteries for night time</td>
<td>5</td>
</tr>
<tr>
<td>Total projected number of 75Ah batteries both for daytime and night time</td>
<td>144</td>
</tr>
<tr>
<td>Total equivalent number to 175Ah batteries both for daytime and night time</td>
<td>62</td>
</tr>
</tbody>
</table>

The projected number of modules for August 2012 were less in number than those of June and July and this was because of high irradiance and hence the power received in the month of August.
5.5 Comparison of modules, batteries and load power

Figure 5.13 shows a comparison of power from modules, batteries and load for June, July and August 2012. On average the battery power was higher compared to that of modules and load. This was because the charge controller would cut off to prevent over drain from the batteries unlike for modules. Among the three months, August recorded the highest power followed by June and July respectively and this was as a result of higher irradiance in the month of August.

Fig. 5.13 : Power profiles for Modules, batteries and loads for June, July and August 2012.

The table 5.11 below shows a summary of irradiance, power and projected modules and batteries for June, July and August 2012.
Table 5.11: Summary of irradiance, powers and projections.

<table>
<thead>
<tr>
<th>Averages</th>
<th>June</th>
<th>July</th>
<th>August</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance (W/m²)</td>
<td>452.4</td>
<td>422.43</td>
<td>510.67</td>
</tr>
<tr>
<td>Modules power (VA) for experimental set up</td>
<td>76.10</td>
<td>75.37</td>
<td>85.93</td>
</tr>
<tr>
<td>Batteries power (VA) for experimental set up</td>
<td>84.87</td>
<td>83.92</td>
<td>88.46</td>
</tr>
<tr>
<td>Load power (VA) for experimental set up</td>
<td>62.17</td>
<td>61.65</td>
<td>65.63</td>
</tr>
<tr>
<td>Mismatch factor</td>
<td>1.53</td>
<td>1.37</td>
<td>1.28</td>
</tr>
<tr>
<td>Projected number of modules of 200W for actual telecommunication system</td>
<td>38</td>
<td>38</td>
<td>32</td>
</tr>
<tr>
<td>Projected number of batteries of 175Ah for the actual telecommunication system</td>
<td>62</td>
<td>62</td>
<td>62</td>
</tr>
</tbody>
</table>

From the table the month of June and July were within the same range in terms of irradiance hence required the same number of modules and batteries. The month of August had the highest irradiance implying more power thus had the lowest number of modules required to run the system. The month of July was used to size the system as it was the poorest in terms of irradiance and power. This was because the sizing was based on the poorest month as this ensures the safety and certainty of the system in terms of power supply. The number of modules and batteries gotten are arranged in strings of parallel and series to meet the system voltage and current. In parallel set-up voltage remain constant while current sums up and in a series connection current remains constant while the voltage sums up. Figure 5.14 shows a proposed plan set-up of the
arrangement of modules to yield the required power. The set-up consists of five strings each consisting of eight modules of 200W connected in series. Each module produces 24 volts. So total eight series connected module will produce = 24 × 8 = 192 volts. Total output current from solar photovoltaic structure = 5×5 =25 Amperes. Since the system is 48V, a DC-DC converter is used to convert 192 volts to 48 volts.

The total number of modules gotten in this research work was high since the research was based on poorest months in term of irradiance. This number can reduce for other months on the year which has high irradiance levels. To achieve this, an intelligent system can be incorporated in the system set-up to cut down the number of modules and batteries for the existing system when the irradiance level rises.
Fig. 5.14: Wiring diagram of modules, fuse and controller for the telecommunication system set-up.
5.6 Sizing of Charge Controller

The sizing of the charge controller is based on the size of PV system. Since the total wattage that can be obtained from the 40 modules of 200W is around 8000W then the charge controller should be rated 24V/8000W.
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

This study reports on the findings of the sizing of solar energy, for an “all-direct current” stand-alone telecommunication system. The findings are in terms of the irradiance and power required to fully run and support the telecommunication system smoothly.

The investigation was carried out for three consecutive months of June, July and August 2012. These are considered to be the poorest months by the Kenya Meteorological Department in terms of irradiance (Makokha and Angenyo, 2012). The irradiance and power harnessed varied from month to month with July recording the lowest and August the highest. The highest and lowest irradiance corresponded to sunny day and cloudy day respectively. For the month of June this was 639.92 W/m$^2$ and 178 W/m$^2$, July was 566.81 W/m$^2$ and 148.91 W/m$^2$ and for August was 689.92 W/m$^2$ and 233.91 W/m$^2$, respectively. The daily monthly average irradiance for June, July and August were 452.40 W/m$^2$, 422.43 W/m$^2$ and 510.67 W/m$^2$, respectively. The overall irradiance recorded was below the standard test condition (STC) which is 1000 W/m$^2$. The daily variation of irradiance was unpredictable and whether there were to be sunrise or not was a matter of probability. The corresponding daily monthly average power harnessed from modules for June, July and August were 76.10 VA, 75.37 VA and 85.93 VA, respectively. There was a direct correlation between the irradiance and module power output. The irradiance and power harnessed determined the number of modules and batteries required to fully support the Telecommunication PV System. In June, the number of modules and batteries
were found to be 38, 200W modules and 62, 175Ah batteries. In July they were 38, 200W modules and 62, 175Ah batteries and for August were 32, 200W modules and 62, 175Ah batteries respectively. The month that required the highest number of modules and batteries (poorest month in terms of irradiance and power) was used as reference to size the Telecommunication PV system and in this case it was the month of July (38, 200W modules and 175Ah batteries). The total number of modules for the PV system was taken to be forty modules of 200W for configuration purposes.

The applications adopted in this study was satisfactory in determining the possible size of the PV telecommunication system. The total cost of modules and batteries obtained in this study was approximated to be 3.5 million Kenyan shillings. This implies a high initial cost of investment. However, with proper care and maintenance the system can last for over twenty years without incurring extra cost and therefore compared with other sources such as diesel, fossil and other sources of power which incurs cost regularly it is economical.

6.2 Recommendations

The number of modules, batteries and the rating of the charge controller obtained in this study will be of great use to telecommunication companies and any other institution located within the location of study or an area of similar average irradiance.

The study did not concentrate on maximizing the energy that can be harnessed through orienting the modules at different direction and tilt angles. This can significantly reduce
the number of modules, batteries and rating of the charge controller required and hence the cost. It is, therefore, recommended that further research be done on this.

Within the short span of the time allotted for the project, work could not be extended to whole year. The analyses were done only for the poorest months of the year in terms of the irradiance. So in future there is a need to study solar radiation for other months of the year so that comparisons can be drawn both for the best months and poorest months. Thereafter judgments can be arrived at whether to incorporate a standby source for poorly illuminated months to economize on costs.

Different types of modules have got different energy conversion efficiency. This research work was carried out using polycrystalline modules which has lower energy conversion efficiency than monocrystalline modules. It is therefore recommended further research be carried out using monocrystalline modules and thereafter comparison be done in terms of the performance and cost.
REFERENCES


