SOLAR PV SYSTEM SIZING, PERFORMANCE AND ECONOMIC VIABILITY FOR THE KENYAN DOMESTIC MARKET

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SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

PROJECT REPORT

SOLAR PV SYSTEM SIZING, PERFORMANCE AND ECONOMIC VIABILITY FOR THE KENYAN DOMESTIC MARKET

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Submitted in partial fulfillment for the Degree of Masters of Science in Energy Management

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REGISTRATION NUMBER: F56/86916/2016.

DECLARATION

I declare that this work has not been previously submitted and approved for the award of a degree by this or any other University. To the best of my knowledge and belief, the project report contains no material previously published or written by another person except where due reference is made in the report itself.

SILAS KIGIRA GITHAIGA

Sign: ………………………………

Date: ………………………………

Approval

The project report of Silas Githaiga was reviewed and approved by the following:

Prof. Cyrus Wekesa

Prof. M.K Mangoli

DEDICATION

I dedicate this project to my wife for the active role she has played during the actualization of this dream. God knows that it would not have been possible without her efforts and sacrifice.

ACKNOWLEDGEMENT

First and foremost, I would like to acknowledge the Almighty God for giving me physical and spiritual strength during my studies. I fully comprehend that without Him in my life, I would not be in a position to present this report.

Sincere thanks go to the Chairman of the Department of Mechanical and Manufacturing Engineering and all my lecturers at the University of Nairobi including the supporting staff for the impact they have had in my life and also for providing the conducive and enabling environment for learning

Special appreciation to my supervisors, Prof. Cyrus Wekesa and Prof. M.K. Mangoli, for the critical comments and valuable advice that guided me immensely throughout my project work and also in the lectures they undertook with me during the course.

Finally, I extend my appreciation to my family, classmates and friends for the support they offered me during my stay at the University.

ABSTRACT

Electricity in Kenya is sold and distributed by a monopoly, Kenya Power Company Ltd, and the latest data shows an estimated 4.9 million customers served by the company. Of the country's estimated 40 million people, 70% live in rural areas and 90% of this group does not have access to mains electricity. This group relies entirely on wood based fuels for their daily needs with petroleum products accounting for a very small fraction of their energy needs. In 2019, the domestic electricity tariff stands at KShs. 22.84 per kWh and could increase in future.

Kenya has vast solar energy resources with some of the highest average annual solar insolation levels in the world of about 4 to 6 kWh per square meter. However, solar power only accounts for a very small fraction of the total electric power consumed in the country annually. In fact, there is little previous research assessing the viability of solar PV power for powering Kenyan residential homes. The main objective of this project is to investigate the viability of solar PV power compared with grid-derived power for domestic applications. The specific objectives are: Sizing of solar PV system for different categories of domestic loads, perform economic analysis of the solar PV system and perform sensitivity analysis to show the trends for other consumers who fall within the range.

To facilitate the realization of the study objectives, the domestic load was divided into three main classes based on data from the utility company. The first class was the major electrical load consumer (an average of over 1000 kWh in a month), intermediate electrical load consumer (an average of 500 - 600 kWh in a month), and minor electrical load consumer (less than 100 kWh per month).

Economic analysis shows that the major electrical load consumer enjoys the best return on investment with a net present value of KSHs. 4,823,717, a levelized cost of energy of

KSHs 12.31 per kWh and a simple payback period of about 3.44 years. For the intermediate electrical load consumer, the net present value of KShs. 1,367,806, a levelized cost of energy of KShs. 16.97 per kWh and a simple payback period of about 4.25 years. Both categories when put into context show potential viability in actual practice and are recommended for adoption by consumers.

The third class of electrical load consumers was the minor electrical load consumers. Financial analysis of this group shows that the project as designed and laid out is not financially viable in the long term and the financial gains of substituting mains electricity with solar PV power are not sufficient to make the project attractive to potential investors.

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LIST OF ABBREVIATIONS

PV	Photovoltaic
V	Voltage
I	Current
P	Power
Amps	Amperes
kWh	Kilowatt-hour
KShs.	Kenya shillings
T	Temperature
t	Time
kWp	Kilowatt-peak
MWp	Megawatt-peak
DC	Direct current
AC	Alternating current
NPV	Net present value
IRR	Internal rate of return
TCO	Total cost of ownership
r.p.m	Revolutions per minute
Am	After midnight
Pm	Past midday
LCoE	Levelized cost of energy

CHAPTER 1

INTRODUCTION

1.1 Background of study

Kenya is a third world country that has set out ambitious targets that are projected to transform the country into a middle income country by the year 2030. These plans and targets are set out in a draft called 'Vision 2030'. Among the key factors that are projected to play a key role in attaining these objectives is energy sufficiency.

The energy situation in Kenya has seen a significant shift in the past 30 years. Although wood-based fuels are still the most commonly used type of fuels, petroleum products and mains electricity are the dominant fuels used in the commercial sector. Other than the commercial sector, the other main sectors in the Kenyan economy include transport, residential and the manufacturing sector. Petroleum products and mains electricity are and will continue to dominate the energy sector in Kenya for the foreseeable future.

Electricity in Kenya is sold and distributed by a monopoly; the Kenya Power and Lighting Company. The government of Kenya is the majority shareholder in the firm. The company buys bulk electricity from both local and regional electricity producers with KenGen, a state owned electricity producing company accounting for about 70% of the total electricity sold in the country. As of 2016, the company had about 4.9 million customers. This represents about 32% of the population. [1]. Of the country's 40 million people, 70% of the population lives in the rural areas and 90% of this group does not have access to mains electricity. This group relies entirely on wood based fuels for their daily needs with petroleum products accounting for a very small fraction of their energy needs. [2].

Kenya has an ambitious target of having an installed capacity of 5,000 MW by the year 2022 to meet the country's power demands. The realization of such a dream requires massive input in exploration and research on new methods of powering the country.

Electricity production in Kenya is dominated by hydroelectric power and fossil fuels which account for more than 80% of the country's annual electric power production. Electricity production using hydroelectric sources is very unreliable in Kenya due to fluctuating water levels in the dams caused by unpredictable weather patterns in the country. Although the use of fossil fuels to produce power is rather predictable, high costs associated with this source are prohibitive. The result is fluctuating electricity prices in the country which are increasing by the day.

In 2018, electricity prices stand at KSHs. 22.84 per Kilowatt hour for the domestic tariff. With no reprieve in sight, these prices are expected to stay true or increase in the future [3].

This has led to the country being actively engaged in the exploration of new sources of energy for the country. Of the new sources of power being harnessed, geothermal power has been the most successful. Wind power has also been tapped with multimillion projects set-up in Ngong' and Turkana.

Despite the massive investments in increasing the energy production in the country, the effects of these projects have largely not changed the situation affecting the cost of electricity for the domestic market.

For the country to find a solution that is satisfying to both investors and consumers in the long terms, it is evident that the domestic market requires the adoption of cheap, readily available energy sources.

1.2 Solar power

Solar power is energy from the sun. It can either be direct or indirect. Most of the sources of energy known to man are indirect sources of solar energy stored in them. For instance, energy in foodstuffs and wood comes from the sun through photosynthesis; the movement of air masses (causing waves in oceans) and the evaporation of water to form rainfall which accumulates in rivers are also powered by the sun. Therefore hydroelectric and wind power are forms of indirect solar energy [4].

Direct solar power has been used extensively for thousands of years by mankind to warm their bodies, dry foodstuffs and heat water for various purposes. However, recent advancements in technology have led to the use of direct solar power to produce electricity.

The photovoltaic effect is a phenomena that is used to produce direct current from sun light using special structures called solar cells. Each solar cell is capable of producing direct current and a series connection of numerous solar cells is able to produce a substantial amount of electric power which can be put into use.

Kenya has vast resources of direct solar power. The country receives among the highest annual insolation levels in the world of about 4-6 kWh per square meter [5].

1.3 Solar PV power-Mains electricity hybrid

With enormous potential in Kenya, solar PV power is a viable option for powering Kenyan residential homes. A stand-alone solar PV system if well designed and installed can be able to meet the daily electricity requirements for the average domestic power demand in Kenya.

The purpose of this paper is to show how solar PV power can be used to reduce and/or eliminate the cost of mains electricity for the Kenyan domestic market. Due to the irregularities experienced due to the unpredictability of solar energy, mains electricity is kept as a back-up for when solar power fails.

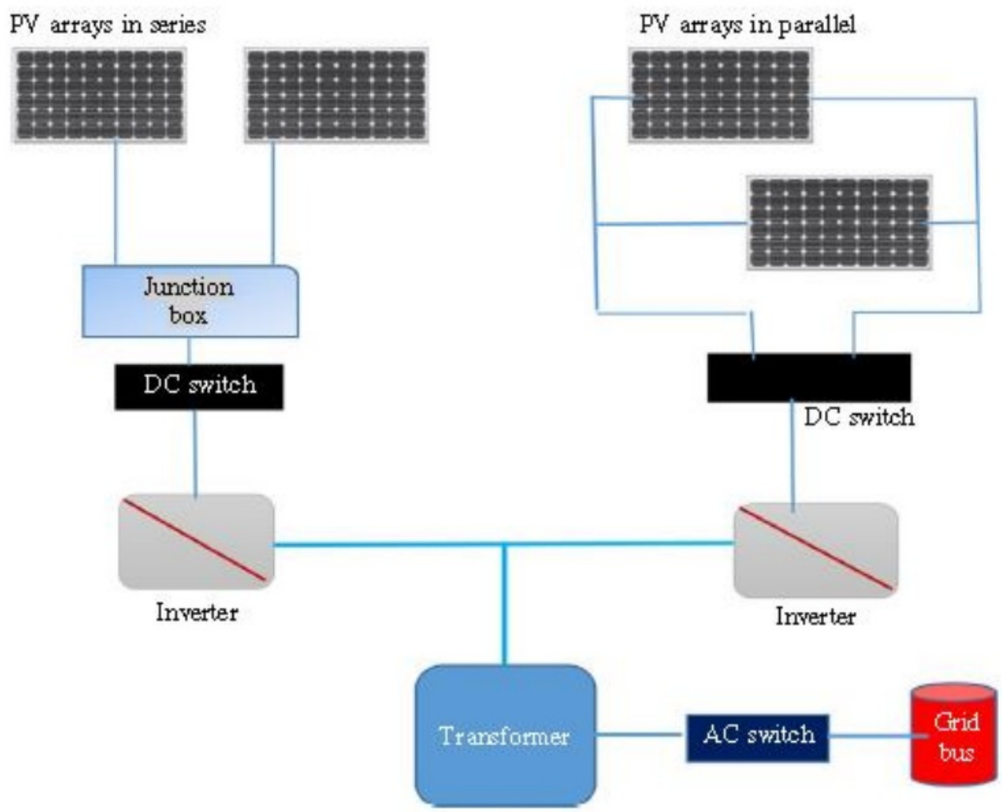

Figure 1.1 Grid connected solar PV system (4)

The figure 1.1 above shows a typical grid connected system with the two basic solar PV panels connections; series and parallel configurations.

1.4 Problem statement

Electricity consumers in Kenya– domestic, commercial and even industrial – have raised complains over a very long period of time regarding the cost as well as the reliability of electrical power/energy delivered by Kenya Power [6]. Indeed, a significant number of these customers have invested in own distributed generation, mostly using solar energy, to address their concerns. However, no systematic and documented study has been done to establish the viability of solar power compared to power from the grid.

Kenya boasts of among the highest average insolation levels in the world of about 4-6 kWh per square meter [5]. A properly designed solar PV system is more than capable of meeting the energy demand for the average middle income household in Kenya.

This study seeks to address this matter and to show how a properly designed and installed solar PV system can be used to meet the daily energy demands for domestic applications in Kenya and consequently make recommendations on the economic viability of the project for large scale rollout in the country.

Solar PV power is used as the primary source of electricity for the home but due to the reliance of solar power to prevailing weather conditions, it is prone to power drops and sometimes complete power outage when there is no sufficient sunlight. To prevent inconveniencing the home when there are power drops from the solar PV system, mains electricity is used as a stand-by system that will be used as cover for when the solar PV system fails.

1.5 Main objective

The main objective of this project is to investigate the economic viability of solar PV power for domestic applications with a view to reducing and/or eliminating the use of mains electricity. However, mains electricity is used as a standby system for when the solar PV system fails.

1.5.1 Specific objectives

i. Size a solar PV system for different categories of domestic load
ii. Perform economic analysis of the solar PV system, hence make recommendations on the suitability of the system for large-scale rollout in Kenya.
iii. Perform sensitivity analysis to show trends for other consumers who fall within the study range

1.6 Scope and limitations

1.6.1 Scope

i. Study and review of existing literature on solar PV power system sizing and execution
ii. Description of a power storage system that can be used to store energy from the solar PV system.
iii. Estimation of the economic relationship between the costs of executing the hybrid system compared to savings realized and hence make recommendations on the economic viability of the system.

1.6.2 Limitations

The main aim of this project is to show how solar PV power can be used to supplement and hence reduce cost of electricity for domestic applications in Kenya. The scope of the project covers three classes of domestic consumers – a major electricity consumer who consumes in excess of 1000 kWh per month, an intermediary consumer who consumes an average of 600 kWh per month and a small scale consumer who consumes less than 100 kWh per month.

Also, all calculations are made based on an AC load. An inverter is used to convert all DC energy derived from the solar PV system into AC.

CHAPTER 2

LITERATURE REVIEW

2.1 Solar Energy

Solar power is the conversion of sunlight into electricity either directly using the photovoltaic effect or indirectly using concentrated solar collectors which use lenses or mirrors and tracking systems to focus on a large area of sunlight into a small beam [4]. Solar energy has seen phenomenal growth in recent years due to technological improvements and new innovations in the field.

People have harnessed solar energy for centuries for many different uses. As early as the7th century, people used simple magnifying glasses to concentrate the light of the sun into beams so hot that they would cause wood to catch fire. Others used solar heat to dry foodstuffs and to keep warm.

But it is not until a century ago in France that a scientist used solar heat from a solar collector to make steam to drive a steam engine that solar energy was seriously considered as an important source of energy and in 1954, photovoltaic technology was born in the united states when Daryl Chapin, Calvin Fuller and Gerald Dawson developed the silicon photovoltaic cell at Bell labs. This was the first solar cell capable of converting enough of the suns energy into power to run every day electrical equipment [7].

Solar energy has experienced an impressive technological shift. While early solar technologies consisted of small scale photovoltaic cells, recent technologies are represented by solar concentrated power and also large-scale PV systems that feed into electricity grids.

The cost of solar energy technologies have dropped substantially over the last 30 years. For instance, the cost of high power band solar modules has decreased from about $27000/KW in 1982 to about $4000/KW in 2006; the installed cost of a PV system decreased from $16000/KW in 1992 to around $6000/KW in 2008 [8]. This has led to widespread use of solar power in applications which include heating (hot water, building heat, cooking), electrical generation (photovoltaic, heat engines) and desalination of sea water.

2.1.1 Photovoltaic effect

A solar cell (photovoltaic cell) is a device that converts light into electrical current using the photovoltaic effect. Solar cells produce direct current whose intensity fluctuates depending on the sunlight's intensity. For use it usually requires inverters to convert the current to AC [4]. multiple solar cells are connected inside modules and the modules are wired together to form arrays then tied to an inverter which produces power at the desired voltage as AC at the desired frequency/phase [4].

Batteries are usually added as backups to store excess electricity.

Advantages of solar energy

1. Solar energy is pollution free during use, production and wastes and emissions are manageable using existing pollution control methods.
2. Solar electric generation is economically competitive where grid connection or fuel transport is difficult, costly or impossible e.g. satellites, rockets, ocean vessels etc.
3. Solar electric generation is cost effective compared to other forms of electricity sources.

4. Operating costs are very low when compared to existing power technologies as only the initial capital cost is required with minimal maintenance.
5. Solar power can be used in remote areas without electricity.
6. Solar energy is infinite i.e. it does not get depleted.
7. Solar energy is free.

Disadvantages of solar energy

1. It requires a relatively large capital investment.
2. To get enough energy for larger application, a large number of photovoltaic cells are needed.
3. Solar cells produce DC which must be converted to AC and the conversion results in 4-12% loss in power.
4. Solar energy can only be harnessed during the day.

2.2 Solar Power System

A solar power system is a complete, fully integrated solar power supply designed for site loads. Each solar power system provides safe and reliable power generation without the need and expense of installing utility power.

A solar power system is the one which can be conveniently installed and transported. It also has the perfect characteristics of self-control, self-protection, needing no attention, compact structure, elegant outline and convenience for use [4].

Parts of a solar power system

- Solar panel

A solar panel is a collection of solar cells. Although each solar cell provides a relatively small amount of power, many solar cell spread over a large area can provide enough power to be useful. To get the most power, solar panels have to be pointed directly at the sun. Solar panels need surface area and more exposure means more electricity can be converted from light energy.

- Controller

The controller regulates the AC and DC output to charge the batteries. The controller will charge the battery unit until it becomes fully charged. When the battery is full, the controller will be in floating charge state.

- Battery

They are used to store energy for use at a later time like during the night or on a cloudy day.

- Inverting function

It is used to convert DC to AC and is mainly applied for isolated solar power systems.

2.2.1 Working of a solar power system

Solar PV modules collect the suns energy and convert it into direct current. Photovoltaic technology directly converts sunlight into electrical energy using semiconductor PV cells. PV or solar cells are composed of semiconductor materials e.g. silicon, single-crystalline thin films and polycrystalline thin films. A key feature of solar cells is the built in electric field formed due to the differing semiconductor materials placed in contact with each other within the cell. One semiconductor is n-type that has an abundance of electrons which have a negative charge, while the other semiconductor is p-type that has an abundance of ‘holes’ with a positive electrical charge. Although both semiconductors are neutral overall, when placed in contact with each other a p-n junction is formed creating an electric field. It is this electric field that facilitates the flow of current [9].

The PV effect is the process through which a solar cell is able to convert sunlight which is made of photons into electrical energy [9]. The amount of electricity produced s directly proportional to the intensity of sunlight. A DC to AC grid-tied inverter converts the electricity from DC to AC for use in a home basis.

The electrical output from PV modules must be controlled and sometimes modified. PV modules are commonly available unregulated thus the inclusion of controllers and battery charge controllers which regulate the charge and discharge cycles of batteries. The PV system charges batteries (during day time).

The batteries in a grid-tied system act as power stores by accepting excess power that is produced and allowing it to be used when the PV system does not produce electricity(nighttime) or produces less power(cloudy weather).

2.3 Solar PV system sizing

Solar PV system sizing refers to a system used as a basis to design an electrical PV system. It helps to establish the size and rating of the major devices that will be used to achieve the objective performance.

Sizing an electrical PV system depends majorly on the functional requirements required.

2.3.1 Utility-interactive system (without battery)

They provide electrical power to supplement another source of power already installed and running in a facility. Breakdown of the system does not result in total loss of electrical loads.

The sizing of an interactive PV system will involve the following key steps:

- Determining the maximum PV system power output

  This is done by determining the total expected power output at any given time by considering the efficiency of the PV module, the available area and the available budget.

- Selecting an inverter that has an 80%-90% of the PV array peak output rated power
- Estimating the amount of power the PV array is expected to produce under normal weather conditions

The specifics of the inverter are critical when sizing an interactive PV system. The inverter voltage requirement will determine the number of PV panels that will be used.

2.3.2 Stand-alone systems

The system is designed to meet a specific electrical load requirement. Breakdown of the PV system will result in complete power loss and possible stoppage of work.

2.3.2.1 Sizing of stand-alone PV systems

Sizing of stand-alone PV systems involves a critical balancing act between the electrical energy demand and supply.

Since the stand-alone PV system works independently, it must be able to meet the peak power requirements under worst case scenarios.

A key part of a stand-alone PV system is an energy storage component usually a battery. The battery stores energy from the solar PV panel and provides the electrical load required at all times.

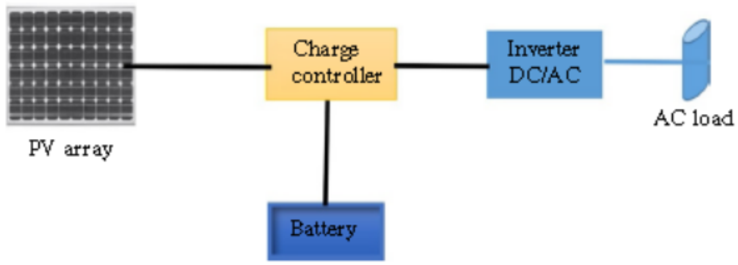

Figure 2.1 Stand-alone solar PV system (5)

The figure 2.2 above shows the layout of the stand-alone system proposed in this paper.

The sizing of the stand-alone PV system involves the following steps:

- Determining the average electrical load requirements
- Conducting a thorough study of the average weather patterns of the target area and knowing the highest and lowest average monthly insolation levels expected in the target region.
- Size the energy storage unit (battery) to meet the electrical load required.
- Size the PV system to meet the maximum load expected during the period with the least amount of sunlight.

2.4 Load Analysis

The electrical energy requirements are based on the electrical loads in use and their average daily power consumption for each month of the year.

Each electrical load average power requirement, daily duration of use and therefore daily power consumption is tabulated on a spreadsheet.

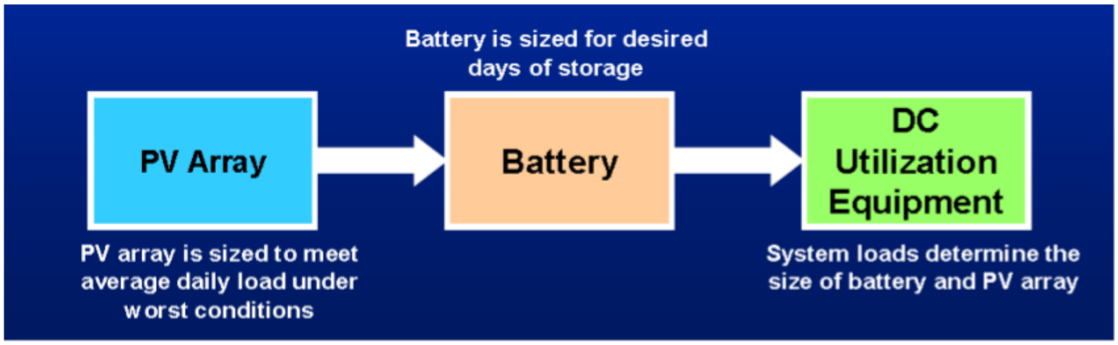

Figure 2.2 Stand-alone PV system design (5)

The figure 2.2 shows the sizing procedures followed when sizing the stand alone system proposed in this paper.

The following steps are important in determining the electrical load requirements.

i. List AC and DC loads separately
ii. Apply inverter efficiencies for AC loads to determine respective DC load requirements.
iii. Daily DC energy requirements are used in sizing of the energy storage and the PV system
iv. The maximum AC load requirement is used to determine the size of inverter to be used

Data collected is then used to identify potential improvements that can be done to increase efficiency and reduce load requirements.

2.5 System design analysis

The design analysis involves establishing a relationship between the average daily electrical load requirements and the average solar insolation levels expected for each month.

The average daily electrical loads for each month are tabulated in a spreadsheet alongside the expected average monthly solar insolation levels. The data is used to determine the month with the highest ratio between the average monthly electrical load and the maximum solar insolation level expected. This is referred to as the critical month. In practice, the critical month is also the month with the highest electrical energy load requirement.

2.6 System availability

This is a statistical parameter that seeks to show the percentage of time that the system can be able to meet the system electrical loads.

2.7 Project evaluation methods

This refers to the tools used to evaluate the financial worthiness of a project and the probability of it surviving in the long term before committing funds to the actualization of the project.

Capital is a scarce resource and the principal responsibility of the management team is to ensure that the organizations funds are channeled towards the projects with the most merit and productivity for the organization. In real life applications, different competing choices exist for consideration by the organization but evaluation of the worthiness of each tells where resources have the greatest chance to reap rewards.

Some of the main considerations made when evaluating the worthiness of a project include:

- Understanding the convolution that comes with the investment

Different types of investments require different types of skills, strategies and techniques in order to optimize operation and returns. The running of a hedge fund requires a different skill-set compared to private equity or venture capital. If you lack the expertise to execute a project, hiring an expert is crucial.

- Ability to handle complex projects

The size and complexity of some projects requires a certain level of ability on the part of the organization. A project may have all the attributes that the organization desires in a project but be too big for the organization. When evaluating which project to undertake, it is important to realize your potential and limits to avoid stoppage halfway during the project.

- Risk/return profile

Every investment is a risk in itself. The risk incurred should always reflect the potential benefits expected. Generally, projects with greater risk have better returns.

Some of the most commonly used project appraisal tools include:

2.7.1 Net present value

The net present value (*NPV*) is used to calculate the net value of future expected cash flows. It is based on assumption that there will be a certain level of consistency in the future cash flows gotten throughout the life of the project. All future cash flows are converted in to their present value using a discounting rate usually unique to a project or an organization (2.1).

$$NPV = [\frac{CF_o}{(1+i)^o} + \frac{CF^1}{(1+i)^1} + \frac{CF^2}{(1+i)^2} + \cdots + \frac{CFn}{(1+i)^N}] \qquad (2.1)$$

Where CF_n is net cash flow during year n, i is the discount rate in per unit and N is the lifetime of the project. Normally, projects with a positive NPV are considered for adoption.

2.7.2 Internal rate of return

It refers to a discounting rate that makes NPV zero. Unlike NPV, the internal rate of return is a measure of the profitability of a project [10]. A project with a higher IRR than the cost of money is attractive to investors.

2.7.3 Payback period

It refers to the period of time taken to recoup the initial capital investment. This method is primarily concerned with recouping the initial capital investment and not the profitability of the venture. Most investors prefer investments with short payback periods.

2.7.4 Levelized cost of energy

The levelized cost of electricity (**LCOE**), also known as Levelized Energy Cost (LEC), is the net present value of the unit-cost of electrical energy over the lifetime of a generating asset. It serves the following key purposes.

- Measures lifetime costs divided by energy production
- Calculates present value of the total cost of building and operating a power plant over an assumed lifetime.
- Allows the comparison of different technologies of unequal life spans, project size, different capital cost, risk, return, and capacities Critical to making an informed decision to proceed with.
- The costs of electricity vary widely according to the ways of its production and distribution.
- There is a great difference between the price of electricity delivered by large, grid-connected power stations (lowest), the price of peak stand-alone power plants and the price of stored electricity in batteries and electro-chemical cells (highest).
- The costs of electricity vary widely according to the ways of its production and distribution.

There is a great difference between the price of electricity delivered by large, grid-connected power stations (lowest), the price of peak stand-alone power plants and the price of stored electricity in batteries and electro-chemical cells (highest).

Consider a loan, amount ***P***, disbursed today for solar PV capital investment. The loan is repaid back in equal annual amounts, ***A***, including interest, at the rate of i, on the loan for a period n (equation 2.2); this simplifies to equation 2.4, from which A is given by equation 2.5.

$$P = [(\frac{1}{(1+i)})A + (\frac{1}{(1+i)^2})A + \cdots + (\frac{1}{(1+i)^N})A] \quad (2.2)$$

$$P = [(\frac{1}{(1+i)}) + (\frac{1}{(1+i)^2}) + \cdots + (\frac{1}{(1+i)^N})]A \quad (2.3)$$

$$P = \left[\frac{(1+i)^N - 1}{(i(1+i)^N]}\right]A \quad (2.4)$$

$$A = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right]P \quad (2.5)$$

The levelized cost of energy is then given by equation 2.6, where P_{rated} refers to plant installed capacity, F_c refers to capacity factor and C_{M+F} refers to annual maintenance and fuel cost.

$$LCoE = \frac{A + C_{M+F}}{(P_{rated})(F_c)(8760)} \quad 2.6$$

2.7.5 Sensitivity analysis

Sensitivity analysis is an investigation that is driven by data. It determines how independent variable of a business can have an impact on the dependent variables. This ultimately leads to change in the output and profitability of the business. The concept of sensitivity analysis is employed to evaluate the overall risk and identify critical factors of the business. By doing so, the business tries to find alternative solutions for different problems [12].

CHAPTER 3

METHODOLOGY

3.1 Introduction

The main objective of this project is to investigate the economic viability of solar PV power for domestic applications with a view to reducing and/or eliminating the use of mains electricity. This chapter seeks to show the methods used to determine the total electrical load that can be taken up by the solar PV system.

3.1.1 Assumptions

System sizing is done based on power consumption from three domestic households with different power consumption rates. The focus group consists of a major domestic consumer, (an average of over 1000 kWh per month), an intermediate domestic consumer, (an average of 600 kWh per month) and a small-scale consumer (less than 100 kWh per month).

An average of 7.1 solar hours per day was used as the daily expected solar insolation levels for all customers.

3.2 Determination of electrical load

The total electrical load of each focus group is determined by adding up the ideal power consumption rate of each electrical component in the household multiplied by the average duration of use. Since it is not practical to accurately determine the total electrical load for each household, an additional 10% of the load determined is added to cover for any additional electrical load that may not be accounted for.

3.3 System design

The power system is equipped with an intelligent inverter that is able to do two main functions:

i. Convert the DC load from the solar PV system into AC

ii. The inverter function is able to detect when power from the solar PV system is unable to meet the load from either household and automatically switches the system to mains electricity.

Due to irregularities in weather patterns and reliability issues from mains electricity, the battery unit is sized so that it is able to take up the load from either household for 6 hours when fully charged when power from the two sources is unavailable.

Water pumping is done during the day when power from the solar PV module is sufficient to charge the battery unit and also power the pumping module.

However, water heating is not possible using the battery unit and any water heating loads are taken up by the grid. Thus, when sizing the solar PV system, power used to heat water is not accounted for.

3.4 Project flow chart

The project methodology is summarized in a flowchart figure 3.1. The flowchart explains how a customer is selected depending on their monthly electrical load consumption. Suitable PV system functions are selected and a combination of the same is used to determine the net present value of the system. If the projected NPV is positive, the project is deemed viable and if the NPV is negative, the project is deemed not viable.

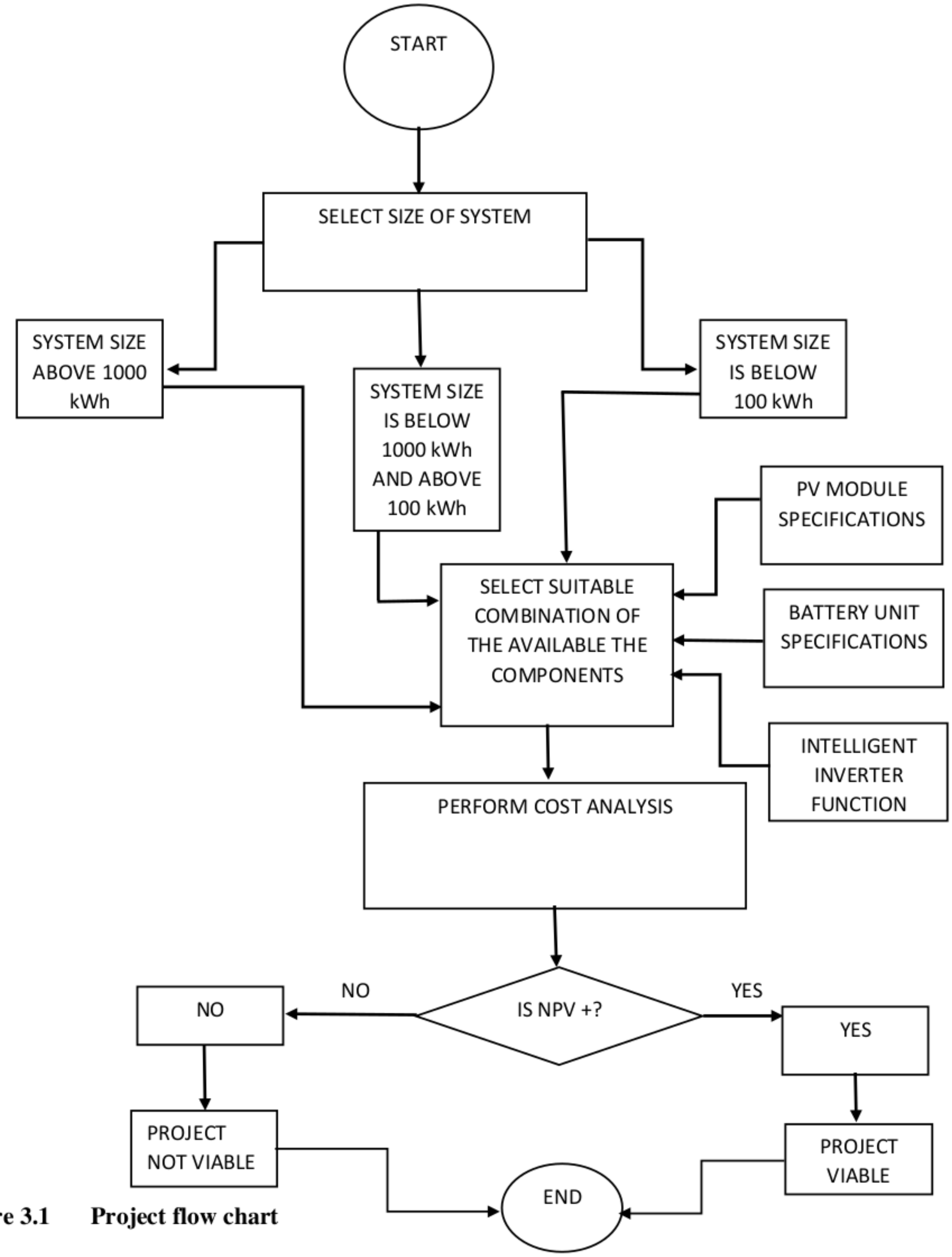

Figure 3.1 Project flow chart

CHAPTER 4

RESEARCH RESULTS, ANALYSIS AND DISCUSSIONS

4.1 Introduction

This chapter examines how the system developed using the methods described in chapter three accomplishes the expected results of the research report. The chapter is divided into the following key sections:

i. Determine the electrical power consumption of three classes of electrical consumers in Kenya hence determine the electrical load that can be substituted by the solar PV system.

ii. Sizing of a power storage system that is used to store power tapped by the solar PV system via an intelligent inverter function

iii. Determine the average monthly electrical power savings expected due to the use of the solar power-mains electricity hybrid system.

iv. Determine the total cost of developing and executing the solar PV power-mains electricity hybrid system.

v. Establish an economic relationship between the amount of power saved (hence money) and the total cost of installing and executing the hybrid system.

4.1.1 Assumptions

A constant cost of electricity of **KSHs. 22.84 per kWh** is assumed for the domestic load. The cost of solar PV panels is calculated using an industry constant of **KSHs. 75 per watt**.

The system is modelled to work in average Kenyan weather conditions and patterns. Based on data from the meteorological department from previous years, it was assumed that the solar PV system would be able to produce sufficient power to cover for all load requirements in the household for the months of January, February, March, September, October, November and December where an average of 9 solar hours is projected.

For the other months of the year, it was assumed that power from the solar PV system would only cover for 50% of the load requirements with the rest being taken care of by power from the grid.

4.2 Determination of the electrical load

The total monthly electrical consumption of the three domestic consumers was done based on the electrical components that they currently poses in their households. The following tables show the electrical equipment found in these households, their power rating and duration of use per day.

The electrical equipment are divided into two classes, major electrical consumers e.g. refrigerators, pumps, heaters, etc. and minor electrical consumers e.g. entertainment systems, lighting, phone chargers etc.

In cases where the minor consumers make-up very little of the monthly electrical consumption, they are grouped together as others.

System sizing is done based on power consumption from three domestic households with different power consumption rates. The focus group consists of a major domestic consumer, (an average of over 1000 kWh per month), an intermediate domestic consumer, (an average of 600 kWh per month) and a small-scale consumer (less than 100 kWh per month).

4.3 Case 1: Major Domestic Electrical Load Consumer

4.3.1 Electrical Appliances

The following tables show the electrical equipment and associated ratings in the households of major domestic consumers.

Table 4.1: Major electrical power consuming appliances

Component	Number of components	Power rating (Kw)	Duration of use per day (hours)	Daily power consumption (kWh)	Monthly power consumption (kWh)
Fridge	1	0.165	24	3.96	118.8
Freezer	1	0.225	24	5.4	162
Oven	1	8.75	1	8.75	262.5
Washing machine	1	0.8	3	2.4	72
Clothes dryer	1	3	1	3	90
Air conditioner	5	0.2	12	12	360
Water pump	1	0.75	1	0.75	22.5
Water heater	5	4	1	20	600
Vacuum cleaner	1	1.1	1	1.1	33
Total (kWh)					**1,720.8**

The table 4.1 shows total electrical load consumption per month is approximately **1,720.8 kWh** from the major electrical appliances in the household. However, power from the PV system cannot run the water heaters in the household, therefore, the load from the water heaters is not put into consideration when sizing the solar PV system.

Table 4.2 The lighting system

Bulb location	**Number of components**	**Power consumption plus ballast (watts)**	**Duration of use (hours)**		**Total power consumption per month(watt hours)**
Living room	10	50	12		180,000
Bedroom	5	15	2		4,500
Perimeter	2	150	12		108,000
Total					**217.5 kWh**

The table 4.2 shows total electrical consumption from the lighting system per month is

217.5 kWh.

Table 4.3 The entertainment system

Component	Number of components	Power consumption (watts)	Duration of use (hours) per day	Total power consumption per month (watt hours)
Desktops	2	50	4	12,000
Laptops	5	40	14	84,000
DVD player	1	25	8	6,000
Digital set top box	1	10	14	4,200
Gaming console	1	100	4	12,000
LED TV	1	80	14	33,600
Total				**151.8 kWh**

90

The table 4.3 shows total energy consumption by the entertainment system per month is given by **151.8 kWh.**

Total electrical energy consumed in the household per month is given by:

151.8 + 217.5 + 1720.8 = **2,090.1 kWh.**

A 10% allowance is given for other electrical components that are in the house but are not documented.

Therefore, total electrical load = 2090.1 + 209 = **2,299 kWh.**

Total electrical load that can be substituted by solar PV system is given by:

2299 – 600 = **1,699 kWh**

4.3.2 Sizing of the solar PV system

The first step involves the design of the power storage unit. The power storage was accomplished by the use of 24V, 100Ah, Lithium accumulators.

Total power consumed per month ***=1,699 kWh***

Daily power consumption = $P = \frac{1699}{30}$ =***56.63 kWh***

Average solar hours per day = 7.1 hours

Maximum power demand = $\frac{56.63}{7.1}$ = ***7.97kW.***

Therefore, the total electrical power load for the home is a maximum supply of **7.97 kW**. This is the peak maximum AC load required in the household at any particular time.

4.3.3 Inverter function

Due to irregularities experienced in supply of power from the solar PV system due to fluctuations in weather patterns, mains electricity is used as a backup for when power from the solar PV system is unable to meet the maximum load from the subject household. An automatic switching system is necessary to ensure that the switch from one power source to the other is swift and causes minimal interruptions on the daily routines of the occupants of the household.

An intelligent, hybrid inverter was used to accomplish the automatic switching system. In addition to converting the DC load from the solar PV system and the power storage unit, it is also enabled to detect when the DC load falls below a set threshold and disengages the solar PV system supply and automatically engages supply from the grid.

The inverter chosen for this case is the R&D 5-8kW pure sine-wave hybrid inverter with the following key specifications.

Table 4.3 Inverter function specifications

Rated power (kW)	5kW -8Kw	
Output power factor	1	
Working mode	Grid -tied mode/anti-flow back can be set	
PV input	Max input voltage	150 V dc
	Optimum operating voltage 65-120 V dc	
	Max charging current	72A - 82A
	Recommended max PV power	5000W - 8000W
AC input	Input voltage range	Single phase 230 V +/- 15%
	Rated frequency	50/60 Hz
	Power factor	0.98
	Max charging current	60A - 72A
Inverter	Inverter voltage	230V (220/240V can be set)
	Min efficiency	85%
	Wave	Pure sine wave
Battery management	Battery setting	Battery number can be set

The inverter works on the following key thresholds:

i. When power from the PV system is sufficient, the system charges the battery first and the excess power takes up the load

ii. When power from the PV system is insufficient, but power form the battery is sufficient, “energy generating priority mode”, the battery takes up the load. The battery is in discharging mode.

iii. When power from the PV system is insufficient, “energy saving priority mode”, any power derived from the PV system is exclusively used to charge the battery while the grid takes up the load.

iv. When grid is not present, the battery and PV system take up the load.

4.3.4 Battery sizing

Daily power consumption is given by:

1699/30 = **56.63 kWh**

Power conversion by the inverter is done at a minimum efficiency of 85%.

Therefore, maximum power required from the battery unit at any instance is given by:

$$Power\ stored\ in\ batteries = \frac{56.63x100}{85} = \mathbf{66.6\ kWh}$$

Assuming a nominal battery voltage of 24 volts, a 6 hours autonomy period and a 0.5 battery discharge allowance, the battery unit size in Ah is given by:

$$\frac{(66.6\ x\ 1000\ x\ 0.25)}{0.5\ x\ 24} = \mathbf{1{,}387.5\ Ah.}$$

This is the maximum load that will be drawn from the battery for a period of 6 hours to cover for when there is a black out and also absence of solar PV power.

The battery unit was accomplished using 24V, 100 Ah lithium batteries.

Power (P) = current x voltage

Total number of 24 V, 100 Ah batteries required is given by:

$$\frac{1387.5}{100} = 13.875$$

Approximately, **14 batteries** are required.

4.3.5 Solar PV system sizing

Assuming a 15% loss in power due to cabling and battery losses, the maximum power requirement from the solar PV system is given by:

$$7.97\ x\frac{115}{100} = \mathbf{9.38\ kW}$$

4.3.6 Water pumping

Pumps require a higher starting current than the battery system can be able to provide at any instance. Therefore, power used to pump water is derived directly from the PV module during the day when output from the PV module exceeds the amount required to charge the battery. Water is pumped into overhead tanks that store the solar power as potential energy that can be used when direct solar power is unavailable.

4.3.7 Electrical power savings

On average, the household consumes a total amount of power equal to **1,699 kWh** per month.

Total electrical power savings for the year are given by:

$$(1699x7) + (0.5x1699x5) = \mathbf{16{,}140.5\ kWh}$$

Total cost of power savings per year is given by,

$$16140.5x22.84 = \textbf{KSHs. 368,649}$$

Therefore, an average of **KSHs. 368,649** is saved per year due to the use of the solar power-mains electricity hybrid system.

4.3.8 Cost of the hybrid system

The following data shows the cost of each component used to accomplish the solar power-mains electricity hybrid system and its local cost.

Table 4.4 Cost of components

Component	Cost Per Unit (KSHs)	Cost Of Components (KSHs)
Solar PV panels	75 per watt	75 x 9380 = 703500
Battery	20,000 each	20,000 x 14 = 280,000
Intelligent inverter	168,000 each	168,000 x 1 = 168,000
Miscellaneous	10% of total	1,151,500 x 0.1 = 115,150
Total		1,266,650

The total cost of installing and executing the hybrid system was **KSHs. 1,266,650.**

4.3.9 Financial analysis of the project

The following table shows the expected cash flows for a projected lifetime of 20 years.

Assumptions

i. The cost of electricity is taken as KSHs. 22.84 with a 5% increase due to inflation.

ii. The cost of installing the system is a one-off investment. However, a 2% fee is added progressively to cover for maintenance costs.

iii. Batteries used cannot be effective for 20 years, therefore, they will require replacing every 7 years. Capital costs include an additional KSHs.560, 000 to cover for replacement.

Table 4.5 Projected cash flows

YEAR	ELECRICITY PRODUCTION (kWh)	ELECTRICITY PRICE (KSHs.)	SAVINGS (KSHs.)	INSTALLATION COST (O&M) (KSHs.)
0	0.00	22.84	0.00	1,826,650.00
1	16140.5	22.84	368,649.02	25,333.00
2	16140.5	23.98	387,081.47	25,839.66
3	16140.5	25.18	406,435.54	26,356.45
4	16140.5	26.44	426,757.32	26,883.58
5	16140.5	27.76	448,095.19	27,421.25
6	16140.5	29.15	470,499.95	27,969.68
7	16140.5	30.61	494,024.94	28,529.07
8	16140.5	32.14	518,726.19	29,099.65
9	16140.5	33.75	544,662.50	29,681.65
10	16140.5	35.43	571,895.63	30,275.28
11	16140.5	37.20	600,490.41	30,880.79
12	16140.5	39.06	630,514.93	31,498.40
13	16140.5	41.02	662,040.67	32,128.37
14	16140.5	43.07	695,142.71	32,770.94
15	16140.5	45.22	729,899.84	33,426.36
16	16140.5	47.48	766,394.84	34,094.88
17	16140.5	49.86	804,714.58	34,776.78
18	16140.5	52.35	844,950.31	35,472.32
19	16140.5	54.97	887,197.82	36,181.76
20	16140.5	57.72	931,557.71	36,905.40

The following table shows the discounted cash flows expected for a projected lifetime of 20 years. A 5% discounting rate is used derived from the expected inflation rate in the country for the next five years.

Table 4.6 Discounted cash flows

YEAR	CASH INFLOWS (AVOIDED EXPENDITURE)	CASH OUTFLOWS	DISCOUNTED CASH FLOWS
0	**0.00**	**0.00**	**0.00**
1	368,649.02	25,333.00	326,967.64
2	387,081.47	25,839.66	327,656.97
3	406,435.54	26,356.45	328,326.61
4	426,757.32	26,883.58	328,977.12
5	448,095.19	27,421.25	329,609.03
6	470,499.95	27,969.68	330,222.90
7	494,024.94	28,529.07	330,819.23
8	518,726.19	29,099.65	331,398.51
9	544,662.50	29,681.65	331,961.25
10	571,895.63	30,275.28	332,507.91
11	600,490.41	30,880.79	333,038.95
12	630,514.93	31,498.40	333,554.82
13	662,040.67	32,128.37	334,055.94
14	695,142.71	32,770.94	334,542.75
15	729,899.84	33,426.36	335,015.66
16	766,394.84	34,094.88	335,475.05
17	804,714.58	34,776.78	335,921.31
18	844,950.31	35,472.32	336,354.82
19	887,197.82	36,181.76	336,775.95
20	931,557.71	36,905.40	337,185.05
TOTAL DICOUNTED CASHFLOWS			6,650,367.47
NET PRESENT VALUE			4,823,717.47

A projected NPV of **KSHs. 4,823,717.47**for the project is derived.

4.3.10 Payback period

The projected payback period for the project is given by:

$$\frac{cost\ of\ hybrid\ system}{annual\ savings}$$

$$\frac{1,266,650.00}{368,649} = 3.44 \text{ years}$$

The project has a simple payback period of approximately **3.44 years.**

4.4 Case 2: Intermediate Domestic Electrical Load Consumer

4.4.1 Major electrical appliances

The following table represents the major electrical consumers in this household.

Table 4.7 Major electrical consumers for the intermediate electrical power consumer

Component	Number of components	Power rating (Kw)	Duration of use per day (hours)	Daily power consumption (kWh)	Monthly power consumption (kWh)
Fridge	1	0.12	24	2.88	86.4
Oven	1	6.45	<1	6.45	193.5
Water heater	2	3	1	6	180
Water pump	1	0.25	1	0.25	7.5
Microwave	1	0.9	<1	0.9	27
Electric iron	1	1.2	<1	1.2	36
Total					**529.9**

The total electrical load in the household from major electrical consumers is **529.9 kWh**.

As stated previously, power from the PV system is not used to run the water heaters.

4.4.2 Minor electrical Appliances

The minor electrical consumers in the household comprise of lighting appliances and the entertainment in the house.

Lighting system

The lighting system is comprised of the following components.

Table 4.8 The lighting system

Bulb location	Number of components	Power consumption plus ballast (watts)	Duration of use (hours)	Total power consumption per month(watt hours)
Living room	2	15	12	10,800
Bedroom	4	15	2	3,600
Perimeter	1	150	12	54,000
Total				**59.4 kWh**

Total electrical consumption by the lighting system is given by **59.4 kWh**

Entertainment system

Table 4.9 The entertainment system

Component	**Number of components**	**Power consumption (watts)**	**Duration of use (hours) per day**	**Total power consumption per month (watt hours)**
Desktops	1	50	2	3,000
Laptops	1	60	8	14,400
Digital set top box	1	20	14	8,400
LED TV	1	80	14	33,600
Total				**59.4 kWh**

Total power consumed by the entertainment system is given by **59.4 kWh**

Average electrical consumption in the household per month is given by:

59.4 + 59.4 + 529.9 = **648.7 kWh**

An allowance of 10% of the approximated electrical load is given for other electrical consumers in the house that may not be documented.

Total electrical consumption in the household per month is given by:

648.7 + 64.87 = **713.57 kWh**

Total electrical load that can be substituted by the solar PV system is given by:

713.57 – 180 = **533.57 kWh**

4.4.3 Sizing of the solar PV system

The power storage unit was also accomplished using 24V, 100Ah lead acid accumulators.

Total power consumed per month =***533.57 kWh***

Daily power consumption = $P = \frac{533.57}{30}$ =***17.8kWh***

Average solar hours per day = 7.1 hours

Maximum power demand = $\frac{17.8}{7.1}$= ***2.5kW.***

Therefore, the total electrical power load for the home is a maximum supply of **2.5 kW**. This is the peak maximum AC load required in the household at any particular time.

4.4.4 Inverter function

A similar inverter function to the one used for the major domestic load consumer was chosen. The inverter chosen for this role is the R&D 1-3 kW pure sine wave hybrid inverter. The inverter works to convert DC power from the solar PV module into AC power for use in the household. It is also responsible for switching the system from grid power to solar PV power and vice versa.

4.4.5 Battery sizing

Daily power consumption is given by:

533.57 /30 = ***17.8* kWh**

Power conversion by the inverter is done at a minimum efficiency of 85%.

Therefore, maximum power required from the battery unit at any instance is given by:

$$\textit{Power stored in batteries} = \frac{17.8x100}{85} = \mathbf{20.94}\ \boldsymbol{kWh}$$

Assuming a nominal battery voltage of 24 volts, a 6 hours autonomy period and a 0.5 battery discharge allowance, the battery unit size in Ah is given by:

$$\frac{(20.94\ x\ 1000\ x\ 0.25)}{(0.5\ x\ 24)}$$

$$= \mathbf{436.3\ Ah.}$$

This is the maximum load that will be drawn from the battery for a period of 6 hours to cover for when there is a black out and also absence of solar PV power.

The battery unit was accomplished using 24V, 100 Ah lithium batteries.

Power (P) = current x voltage

Total number of 24 V, 100 Ah batteries required is given by:

$$\frac{436.3}{100} = 4.36$$

Approximately, **5** batteries are required.

4.4.6 Solar PV system sizing

The maximum power requirement from the solar PV system is **2.94 kW** to cover for a 15% deficit due to power losses which include cabling and battery losses.

4.4.7 Water pumping

Power used to pump water is derived directly from the PV module during the day when output from the PV module exceeds the amount required to charge the battery. Water is pumped into overhead tanks that store the solar power as potential energy that can be used when direct solar power is unavailable.

4.4.8 Electrical power savings

On average, the household consumes a total amount of power equal to **533.57 kWh** per month.

Total electrical power savings for the year are given by:

$(533.57\ x7) + (0.5x533.57\ x5)$ = **5068.9 kWh**

Total cost of power savings per year is given by,

$5068.9\ x22.84$ =**KSHs. 115,774**

4.4.9 Cost of the hybrid system

The following data shows the cost of each component used to accomplish the solar power-mains electricity hybrid system and its local cost.

Table 4.10 Cost of components

Component	Cost Per Unit (KSHs)	Cost Of Components (KSHs)
Solar PV panels	75 per watt	75 x 2940 =220500
Battery	20,000 each	20,000 x 5 = 100,000
Intelligent inverter	128,000 each	128,000 x 1 = 128,000
Miscellaneous expenses	10% of the total cost	448,000 x 0.1 = 44,850
Total		**492,850**

The total cost of installing and executing the hybrid system was **KSHs. 492,850.**

4.4.10 Financial analysis of the project

Assumptions

i. The cost of electricity is taken as KSHs. 22.84 with a 5% increase due to inflation.

ii. The cost of installing the system is a one-off investment. However, a 2% fee is added progressively to cover for maintenance costs.

iii. Batteries used cannot be effective for 20 years, therefore, they will require replacing every 7 years. Installation cost includes an extra KSHs. 200,000 for replacement.

Table 4.11 Cash flows

YEAR	ELECRICITY PRODUCTION (kWh)	ELECTRICITY PRICE	SAVINGS (KSHs.)	INSTALLATION COST (O&M) (KSHs.)
0	0.00	22.84	0.00	692,850.00
1	5068.9	22.84	115,773.68	9,857.00
2	5068.9	23.98	121,562.36	10,054.14
3	5068.9	25.18	127,640.48	10,255.22
4	5068.9	26.44	134,022.50	10,460.33
5	5068.9	27.76	140,723.63	10,669.53
6	5068.9	29.15	147,759.81	10,882.92
7	5068.9	30.61	155,147.80	11,100.58
8	5068.9	32.14	162,905.19	11,322.59
9	5068.9	33.75	171,050.45	11,549.05
10	5068.9	35.43	179,602.97	11,780.03
11	5068.9	37.20	188,583.12	12,015.63
12	5068.9	39.06	198,012.27	12,255.94
13	5068.9	41.02	207,912.89	12,501.06
14	5068.9	43.07	218,308.53	12,751.08
15	5068.9	45.22	229,223.96	13,006.10
16	5068.9	47.48	240,685.16	13,266.22
17	5068.9	49.86	252,719.42	13,531.55
18	5068.9	52.35	265,355.39	13,802.18
19	5068.9	54.97	278,623.16	14,078.22
20	5068.9	57.72	292,554.31	14,359.79

The following table shows the discounted cash flows expected for a projected lifetime of 20 years. A 5% discounting rate is used derived from the expected inflation rate in the country for the next five years.

Table 4.12 Discounted cash flows

YEAR	CASH INFLOWS (AVOIDED EXPENDITURE)	CASH OUTFLOWS	DISCOUNTED CASH FLOWS
0	**0.00**	**0.00**	**0.00**
1	115,773.68	9,857.00	100,873.02
2	121,562.36	10,054.14	101,141.24
3	127,640.48	10,255.22	101,401.80
4	134,022.50	10,460.33	101,654.91
5	140,723.63	10,669.53	101,900.78
6	147,759.81	10,882.92	102,139.64
7	155,147.80	11,100.58	102,371.67
8	162,905.19	11,322.59	102,597.07
9	171,050.45	11,549.05	102,816.03
10	179,602.97	11,780.03	103,028.73
11	188,583.12	12,015.63	103,235.35
12	198,012.27	12,255.94	103,436.08
13	207,912.89	12,501.06	103,631.07
14	218,308.53	12,751.08	103,820.48
15	229,223.96	13,006.10	104,004.49
16	240,685.16	13,266.22	104,183.23
17	252,719.42	13,531.55	104,356.87
18	265,355.39	13,802.18	104,525.55
19	278,623.16	14,078.22	104,689.41
20	292,554.31	14,359.79	104,848.59
TOTAL DICOUNTED CASHFLOWS			2,060,656.01
NET PRESENT VALUE			1,367,806.01

The project has a projected NPV of **KSHs. 1,367,806.01**for the projected lifetime.

4.4.11 Payback period

The projected payback period for the project is given by:

$$\frac{\mathbf{492,850}}{\mathbf{115,774}} = 4.25 \text{ years}$$

The project has a payback period of approximately **4.25 years.**

4.5 Case 3: Small Scale Electrical Load Consumer

4.5.1 Electrical appliances

This group is characterized with relatively very low electrical power consumption. The electrical equipment in the household is comprised of only basic modules with very little electric power being used for entertainment.

The following table shows the electrical consumers in the household:

Table 4.13 Electrical appliances

Component	Number of components	Power rating (watts)	Duration of use (hours)	Monthly power consumption (Watt hours)
Living room bulbs	1	15	6	2,700
Bedroom bulbs	2	15	2	1,800
LED TV	1	40	6	7,200
Set top box	1	15	6	2,700
Radio	1	20	8	4,800
Electric iron	1	1200	1	36,000
Total (kWh)				**52.5 kWh**

An Average monthly electrical consumption of **52.5 kWh** is calculated.

An allowance of 10% of the total electrical load is allowed for other electrical equipment that may be used in the household that is not documented.

Average monthly electrical load is given by:

52.5 + 5.25 = **57.75 kWh**

4.5.2 Sizing of the solar PV system

The power storage unit was also accomplished using 12V, 40Ah lead acid accumulators.

*Total power consumed per month =**57.75 kWh***

Daily power consumption = $P = \frac{57.75}{30}$ *=**1.925kWh***

Average solar hours per day = 7.1 hours

Maximum power demand = $\frac{1.925}{7.1}$*= **0.27kW.***

Therefore, the total electrical power load for the home is a maximum supply of 0.27 kW. This is the peak maximum AC load required in the household at any particular time.

4.5.3 Inverter function

The major drawback for this level of electric consumption is the sizing of the inverter. Currently, in the market, the smallest size of inverter available is a 1-3 kW intelligent inverter. The cost of the inverter is so high that it makes the economic considerations for the project appear not feasible for most investors.

A similar inverter function to the one used for the major domestic load consumer. The inverter chosen for this role is the R&D 1-3 kW pure sine wave hybrid inverter. The inverter works to convert DC power from the solar PV module into AC power for use in the household. It is also responsible for switching the system from grid power to solar PV power and vice versa.

4.5.4 Battery sizing

Daily power consumption is given by:

57.75 /30 = ***1.925* kWh**

Power conversion by the inverter is done at a minimum efficiency of 85%.

Therefore, maximum power required from the battery unit at any instance is given by:

$$Power\ stored\ in\ batteries = \frac{1.925x100}{85} = \mathbf{2.26}\ \boldsymbol{kWh}$$

Assuming a nominal battery voltage of 24 volts, a 6 hours autonomy period and a 0.5 battery discharge allowance, the battery unit size in Ah is given by:

(2.26 x 1000 x 0.25) / (0.5 x 24) = **47.18 Ah.**

This is the maximum load that will be drawn from the battery for a period of 6 hours to cover for when there is a black out and also absence of solar PV power.

The battery unit was accomplished using 24 V, 100 Ah lithium batteries.

Power (P) = current x voltage

Total number of 24 V, 100 Ah batteries required is given by:

= 47.18/100

=0.47

Approximately, 1 battery is required.

4.5.5 Solar PV system sizing

The maximum power requirement from the solar PV system is 0.32 kW taking into account a 15% power drop due to losses by the battery and losses due to cabling.

4.5.6 Electrical power savings

On average, the household consumes a total amount of power equal to **57.75 kWh** per month.

Total electrical power savings for the year are given by:

$$(57.75x7) + (0.5x\ 57.75\ x5)$$

=548.6 kWh

Total cost of power savings per year is given by,

$$548.6\ x22.84$$

=KSHs. 12,530.6

Therefore, an average of **KSHs. 12,530.6** is saved per year due to the use of the solar power-mains electricity hybrid system.

4.5.7 Cost of the hybrid system

The following data shows the cost of each component used to accomplish the solar power-mains electricity hybrid system and its local cost.

Table 4.14 Cost of components

Component	Cost Per Unit (KSHs)	Cost Of Components (KSHs)
Solar PV panels	75 per watt	75 x 320 =24,000
Battery	20,000 each	20,000 x 1 = 20,000
Intelligent inverter	128,000 each	128,000 x 1 = 168,000
Miscellaneous expenses	10% of total cost	21,138
Total		**232,123**

4.5.8 Financial analysis of the project

The following table shows the expected cash flows for a projected lifetime of 20 years.

Assumptions

i. The cost of electricity is taken as KSHs. 22.84 with a 5% increase due to inflation.

ii. The cost of installing the system is a one-off investment. However, a 2% fee is added progressively to cover for maintenance costs.

iii. Batteries used cannot be effective for 20 years, therefore, they will require replacing every 7 years, therefore, an extra KSHs. 40,000 is added on the capital cost to cover for replacement.

Table 4.15 Cash flows

YEAR	ELECRICITY PRODUCTION (kWh)	ELECTRICITY PRICE	SAVINGS (KSHs.)	INSTALLATION COST (O&M) (KSHs.)
0	0.00	22.84	0.00	278,800.00
1	548.6	22.84	12,530.02	1,576.00
2	548.6	23.98	13,156.53	1,607.52
3	548.6	25.18	13,814.35	1,639.67
4	548.6	26.44	14,505.07	1,672.46
5	548.6	27.76	15,230.32	1,705.91
6	548.6	29.15	15,991.84	1,740.03
7	548.6	30.61	16,791.43	1,774.83
8	548.6	32.14	17,631.00	1,810.33
9	548.6	33.75	18,512.55	1,846.54
10	548.6	35.43	19,438.18	1,883.47
11	548.6	37.20	20,410.09	1,921.14
12	548.6	39.06	21,430.59	1,959.56
13	548.6	41.02	22,502.12	1,998.75
14	548.6	43.07	23,627.23	2,038.72
15	548.6	45.22	24,808.59	2,079.50
16	548.6	47.48	26,049.02	2,121.09
17	548.6	49.86	27,351.47	2,163.51
18	548.6	52.35	28,719.04	2,206.78
19	548.6	54.97	30,155.00	2,250.92
20	548.6	57.72	31,662.75	2,295.93

The following table shows the discounted cash flows expected for a projected lifetime of 20 years. A 5% discounting rate is used derived from the expected inflation rate in the country for the next five years.

Table 4.16 Discounted cash flows

YEAR	CASH INFLOWS (AVOIDED EXPENDITURE)	CASH OUTFLOWS	DISCOUNTED CASH FLOWS
0	**0.00**	**0.00**	**0.00**
1	12,530.02	1,576.00	10,432.40
2	13,156.53	1,607.52	10,475.29
3	13,814.35	1,639.67	10,516.95
4	14,505.07	1,672.46	10,557.42
5	15,230.32	1,705.91	10,596.73
6	15,991.84	1,740.03	10,634.92
7	16,791.43	1,774.83	10,672.02
8	17,631.00	1,810.33	10,708.05
9	18,512.55	1,846.54	10,743.06
10	19,438.18	1,883.47	10,777.07
11	20,410.09	1,921.14	10,810.11
12	21,430.59	1,959.56	10,842.20
13	22,502.12	1,998.75	10,873.38
14	23,627.23	2,038.72	10,903.66
15	24,808.59	2,079.50	10,933.08
16	26,049.02	2,121.09	10,961.66
17	27,351.47	2,163.51	10,989.42
18	28,719.04	2,206.78	11,016.39
19	30,155.00	2,250.92	11,042.59
20	31,662.75	2,295.93	11,068.04
TOTAL DICOUNTED CASHFLOWS			215,554.45
NET PRESENT VALUE			-63,245.55

The project has a projected NPV of KSHs. -56,797.98 for the projected lifetime.

4.5.9 Payback period

$$\frac{cost\ of\ hybrid\ system}{annual\ savings}$$

$$\frac{206{,}800}{12{,}530.6} = \mathbf{16.5\ years}$$

The project has a payback period of approximately **17 years.**

4.6 Discussion

Financial analysis of the three systems show that the first two categories of consumers are viable and financially attractive. A positive NPV shows that the projects will more than compensate for their initial investment. However, the third project, is not financially viable in the long run and has a negative NPV.

Table 4.18 Levelized cost of energy

Localized cost of energy (LCoE)					
Consumer class	**Amortization (A)**	**Initial investment (P) (KSHs.)**	**PV power rating in kW (*Prated*)**	**Annual maintenance costs (Cm) (KSHs)**	**LCoE (KSHs.)**
Major consumer	202,193.63	1,721,500	9.38	25,333.11	12.31
Intermediate consumer	77,342.15	658,500	2.94	10,054.14	16.97
Minor consumer	31,712.04	270,000	0.3	1,576.00	69.27

Assumptions made when calculating the levelized cost of energy include: Interest rate per year, ***i***, is 10% per annum, Utilization factor **Fc** of 0.2.

Levelized cost of energy for this project shows that the major electrical load consumer category experiences a cheap and viable LCoE of KSHs. 12.31, and the intermediary electrical load consumer category enjoys a unit cost of KSHs. 16.97 which when put into context with the average cost electricity in the country which stands at KSHs. 22.84 per unit (subject to inflation), show viability since the solar PV system is cheaper. The LCoE for the minor electrical load consumer class averages at KSHs. 69.27 which is a lot more than the market rate. This system will struggle in the current market as it is expensive.

Table 4.19 Summary of the analysis of the three categories of consumers

Consumer class	Average electrical load (kWh per month)	Cost of hybrid system (KSHs.)	Projected NPV (KSHs.)	Payback period (years)	LCOE (KSHs/KWh)
Major electrical load consumer	Over 1000	1,161,500.00	4,823.717.47	3.44	12.31
Intermediary electrical load consumer	600	458,500.00	1,367,806.01	4.25	16.97
Minor electrical load consumer	Below 100	198,000.00	-63,245.55	16.5	69.27

A comparison of the payback periods of the three projects further shows an interesting trend between the amount of investment required and the payback period. The higher the investment cost, the shorter period of time it takes to recoup the initial investment back. The same is reflected on analysis of the levelized costs of energy for the three systems where the large systems have a cost per unit which is below the average consumer rate of KSHs. 22.84. Data for the small electrical load consumer shows that the project cost per unit is way above the market rate making the project unattractive.

The data shows that small installations have a long payback period which may prove unattractive for any potential investors. However, for large-scale consumers, the data is very promising and the payback period is very short and attractive.

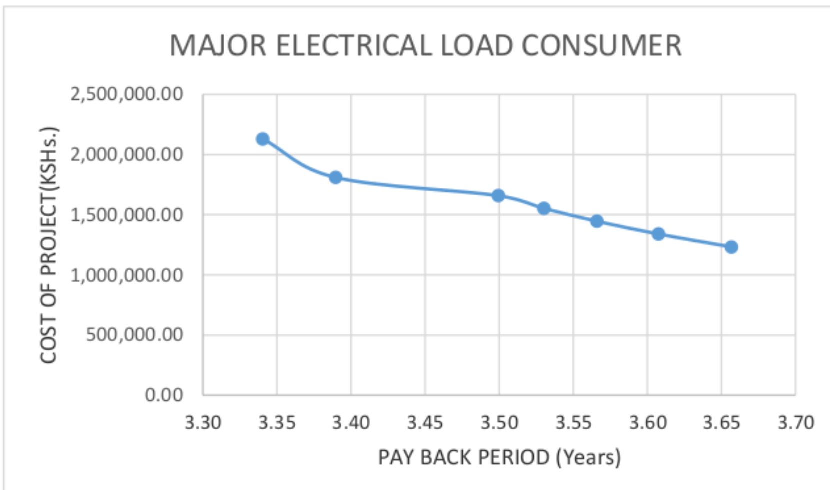

Figure 4.1 Relationship between cost of a solar PV system and payback period (major electrical load consumer)

The data presented in the above graph shows that as the system size for the major electrical load consumer increases, the payback period decreases. However, in this range, the payback period does not go beyond four years making the project highly attractive for customers within this range.

The same is true for the intermediary electrical load consumers. The payback period decreases as the cost of the system increases. The payback period remains attractive at below eight years.

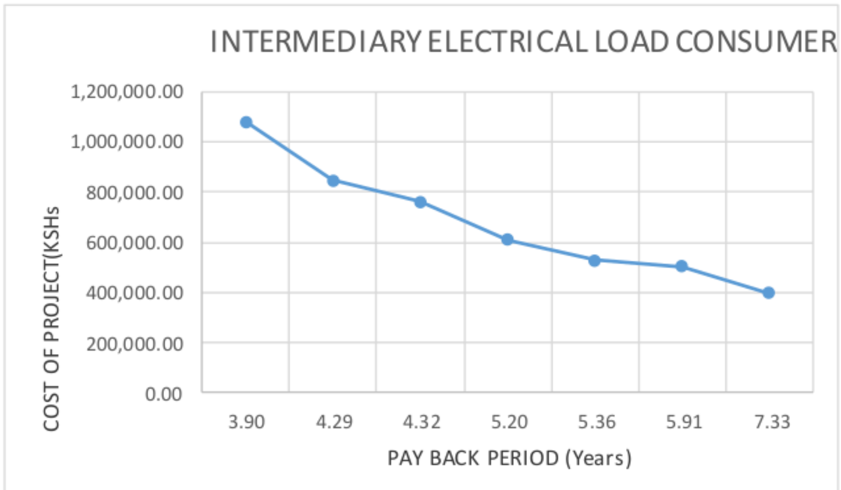

Figure 4.2 Relationship between cost of a solar PV system and payback period (intermediary electrical load consumer)

Analysis of the minor electrical load consumer shows that the payback period is too long making the project unattractive as shown in the graph below.

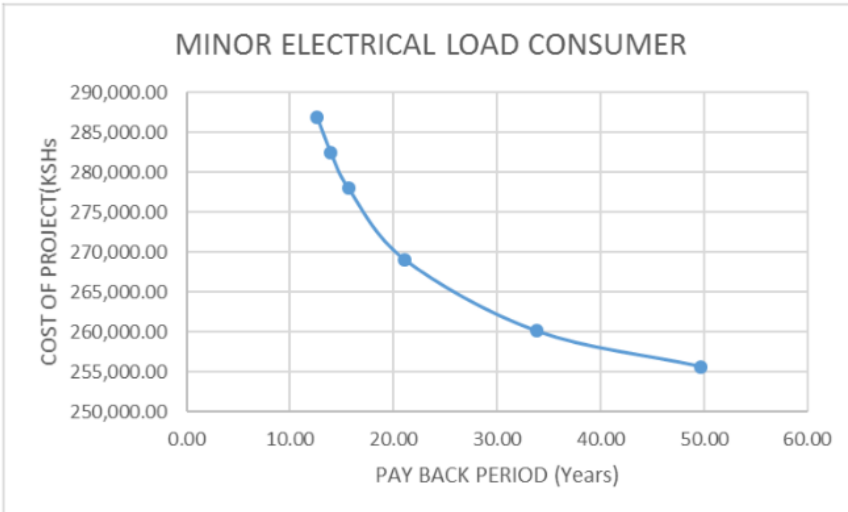

Figure 4.3 Relationship between cost of a solar PV system and payback period (minor electrical load consumer)

With a payback period ranging up to 50 years, data from the minor electrical load consumers shows that the system is not attractive and will struggle to sell.

Also, analyzing the cost per watt of each system reveals an interesting trend. The average cost per watt for the major electrical load consumer is given by:

KSHs. 1,161,500/9380 watts

= KSHs. 123.8

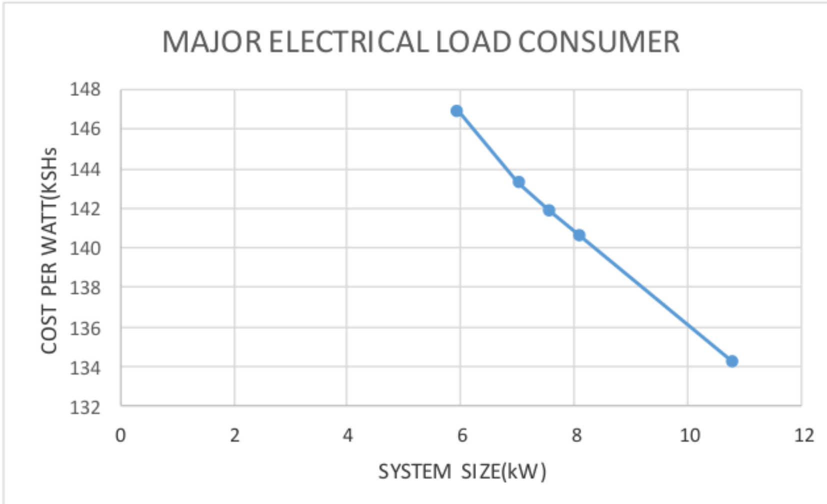

Figure 4.4 Relationship between the size of a solar PV system and the cost per watt (major electrical load consumer)

The cost per watt of the major electrical load category is inversely proportional to the size of the PV system. Bigger systems will have a reduced cost per watt increasing their attractiveness to potential customers.

For the intermediary electrical load consumer, the cost per watt is given by:

KSHs. 458,500/2,940 watts = **KSHs. 155.95**

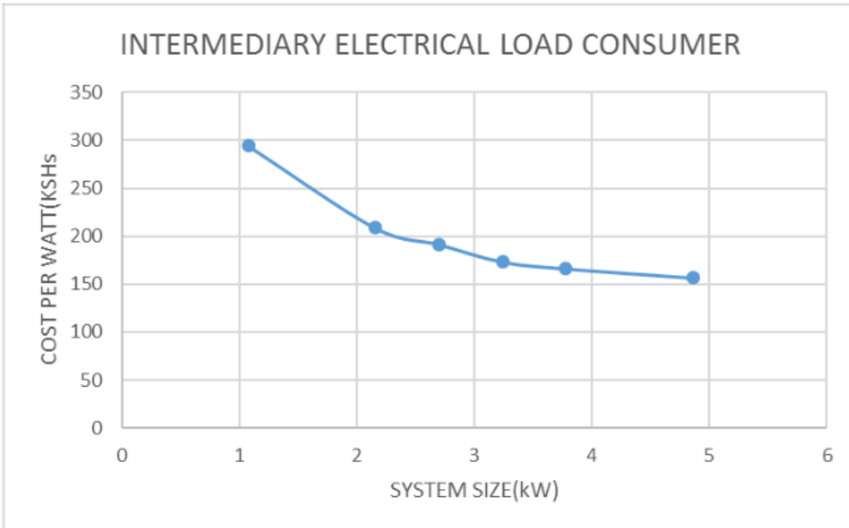

Figure 4.5 Relationship between the size of a solar PV system and the cost per watt (major electrical load consumer)

Data from the intermediary electrical load consumer category shows a lot of similarity with data from the major electrical load consumers. The cost per watt for large systems in this category is lower that small systems.

For the minor electrical consumer, the cost per watt is given by:

KSHs. 198,000/320 watts = **KSHs. 618.75.**

Plotting a graph of system size against cost per watt gives the following graph.

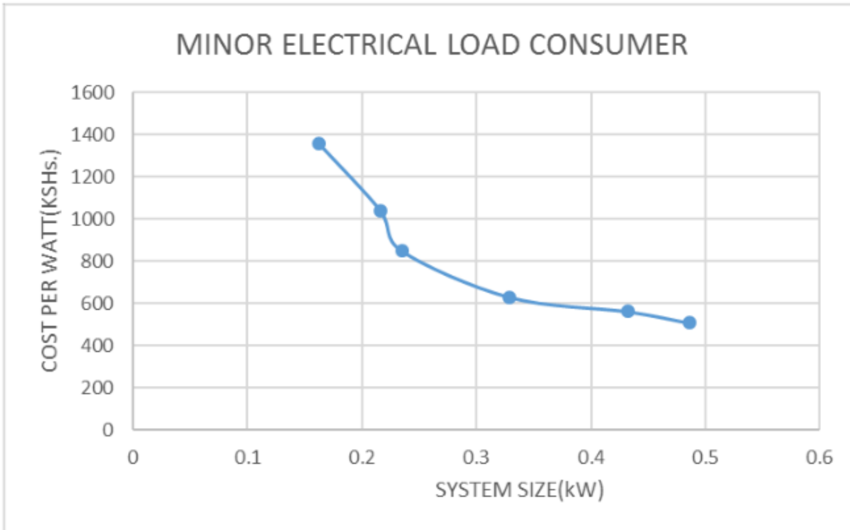

Figure 4.6 Relationsip between the size of a solar PV system and the cost per watt (minor electrical load consumer)

The data shows that the cost per watt is inversely proportional to the size of the system. Small scale systems will attract a higher cost per watt and vice-versa.

4.6.7 Sensitivity analysis

Further analysis of the data to show trends that can be used to predict the worthiness of a project by a customer with consumption data that falls in the range of the study was done. Sensitivity analysis of three main independent variables namely, discounting rate, inflation rate and monthly electrical load consumption were used to determine whether the major financial determinants for the project, i.e. net present value and payback period would be attractive enough to warrant the adoption of a domestic solar PV power system.

Data from consumers who fall in the major electrical load consumer category (above 10000 kWh per month) and intermediary electrical load consumers (between 100 and 999 kWh) is presented in the same graph since they show levels of consistency with each other.

Table 4.20 Monthly electrical load vs. Payback period, NPV

MAJOR ELECTRICAL LOAD CONSUMER		
Monthly electrical load	**Payback period (major)**	**NPV (X 1000,000) (major)**
1000	3.82	2.70
1100	3.66	3.05
1200	3.61	3.34
1300	3.57	3.63
1400	3.53	3.92
1500	3.50	4.21
1600	3.47	4.49
1700	3.39	4.85
1800	3.37	5.14
1900	3.35	5.42
INTERMEDIATE ELECTRICAL LOAD CONSUMER		
Monthly electrical load	**Payback period (intermediary)**	**NPV (X 1000000) (intermediary)**
100	11.58	-0.47
200	7.33	-0.46
300	5.91	0.38
400	5.20	0.80
500	4.77	1.23
600	4.32	1.64
700	4.14	2.07
800	4.00	2.49
900	3.90	2.92
999	3.82	3.34

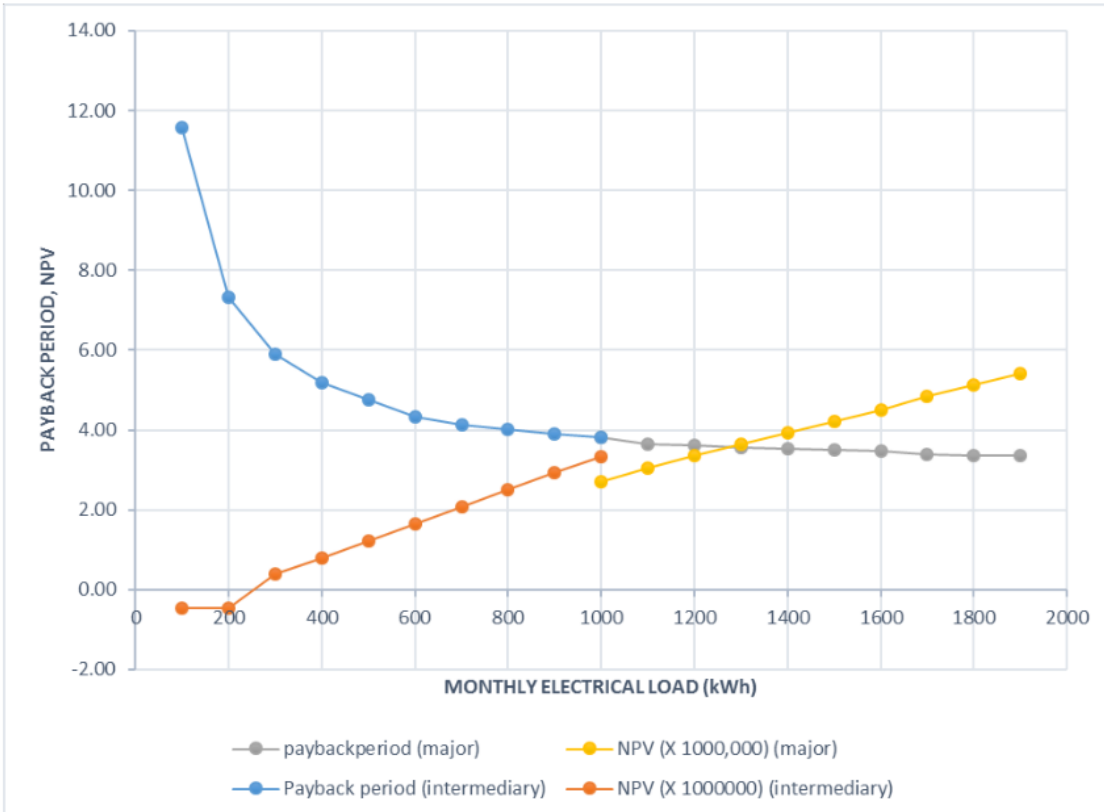

Figure 4.7 Monthly electrical load vs. Payback period, NPV

Analysis shows that increase in the monthly electrical load results in a proportional increase in the net present value for all consumers who fall in this range. Similarly, a corresponding decrease in the average payback period of the project is witnessed.

However, data from consumers who fall under the minor electrical load consumers (between 10 and 99 kWh) is not consistent with the rest and is presented in its own graph.

Table 4.21 Monthly electrical load vs. NPV, payback period (minor consumers)

MINOR ELECTRICAL LOAD CONSUMER		
Monthly electrical load	Payback period (minor)	NPV (X 10000) (minor)
10	97.36	-25.28
20	49.71	-22.12
30	33.82	-18.96
40	25.88	-15.81
50	21.11	-12.65
60	17.94	-9.49
70	15.67	-6.34
80	13.97	-3.18
90	12.64	-0.26
99	11.68	0.28

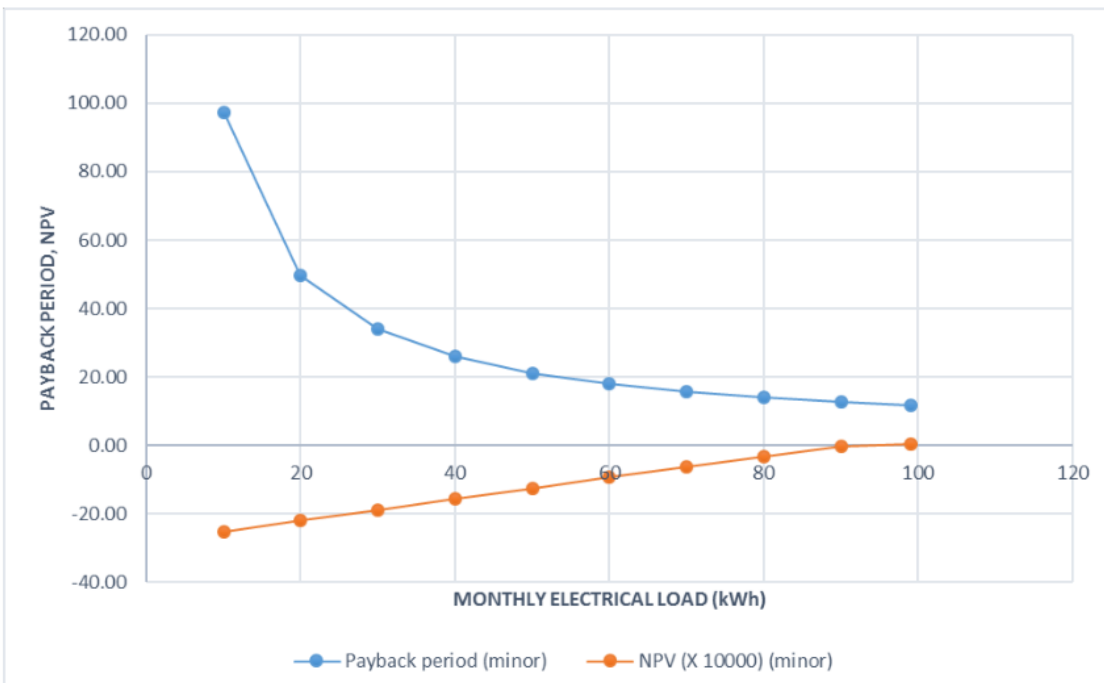

Figure 4.8 Monthly electrical load vs. NPV, payback period (minor consumers)

Analysis shows that change in the monthly electrical load within this range results in very little change in the net present value of the project.

However, there is a considerable decrease in the payback period of the project but does not fall in the industry acceptable region of less than 10 years.

Table 4.22 Figure 4.9 NPV vs. Inflation rate, discounting rate

MAJOR ELECTRICAL LOAD CONSUMER			
Discounting rate	**NPV (discounting rate major)**	**Inflation rate**	**NPV (inflation rate major)**
1%	8,470,528.26	1%	2801814.61
2%	7,354,005.12	2%	3230303.35
3%	6,393,458.42	3%	3709319.15
4%	5,564,203.20	4%	4245367.87
5%	4,845,803.44	5%	4845803.44
6%	4,221,291.79	6%	5518935.87
7%	3,676,540.57	7%	6274152.41
8%	3,199,753.18	8%	7122053.31
9%	2,781,051.77	9%	8074604.03
10%	2,412,142.17	10%	9145305.53
INTERMEDIATE ELECTRICAL LOAD CONSUMER			
Discounting rate	**NPV (discounting rate intermediary)**	**Inflation rate**	**NPV (inflation rate intermediary)**
1%	2420086.759	1%	1313914.709
2%	2079655.438	2%	1542771.131
3%	1786935.113	3%	1800720.42
4%	1534366.554	4%	2091678.498
5%	1315691.784	5%	2420086.759
6%	1125715.221	6%	2790980.36
7%	960111.0735	7%	3210064.94
8%	815267.5929	8%	3683802.778
9%	688160.8139	9%	4219509.447
10%	576251.9086	10%	4825462.186

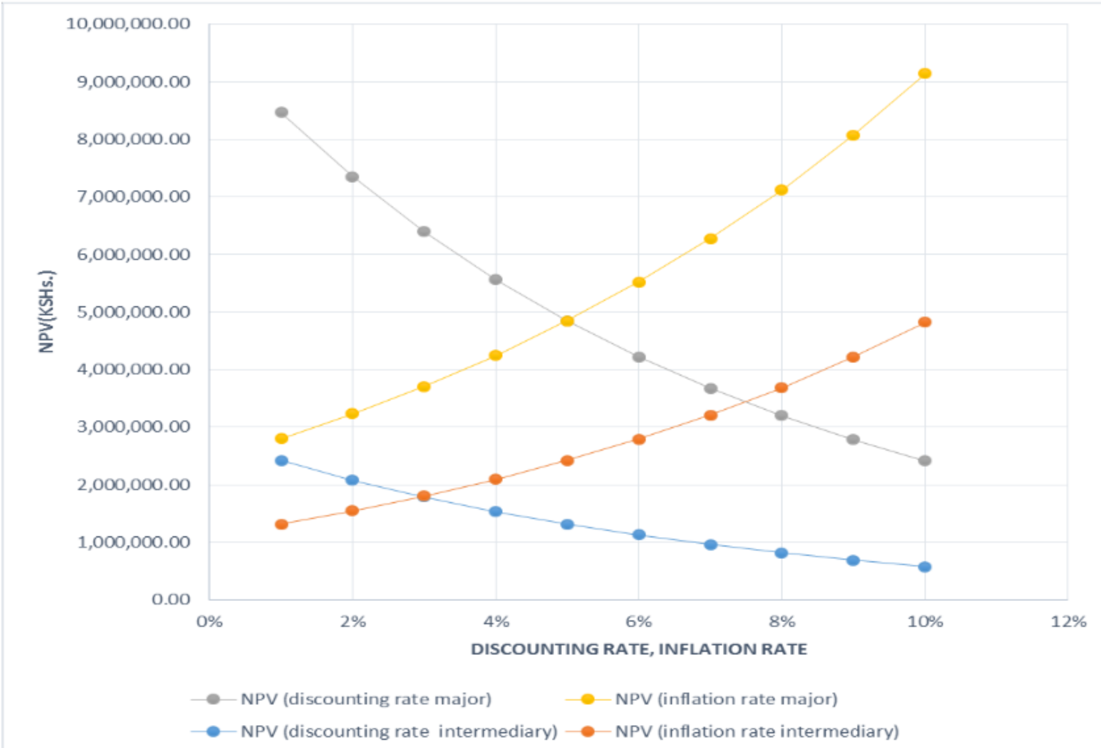

Figure 4.9 NPV vs. Inflation rate, discounting rate

Analysis of how the net present value varies with change in the discounting rate for the major electrical load consumer category shows that as the discounting rate increases, there is a proportional decrease in the net present value of the project. The inflation rate on the other hand has a contrasting effect as it results in an increase in the net present value for every unit increase in the inflation rate.

Table 4.23 NPV vs. discounting rate, inflation rate (minor)

MINOR ELECTRICAL LOAD CONSUMER			
Discounting rate	NPV (discounting rate minor)	Inflation rate	NPV (inflation rate minor)
1%	24634.85439	1%	-95157.26678
2%	-5982.258771	2%	-70372.66679
3%	-32280.21903	3%	-42437.89798
4%	-54946.46386	4%	-10929.0046
5%	-74549.66353	5%	24634.85439
6%	-91561.5872	6%	64798.79727
7%	-106374.7248	7%	110180.5254
8%	-119316.5272	8%	161479.6489
9%	-130660.9442	9%	219488.1502
10%	-140637.7984	10%	285102.1146

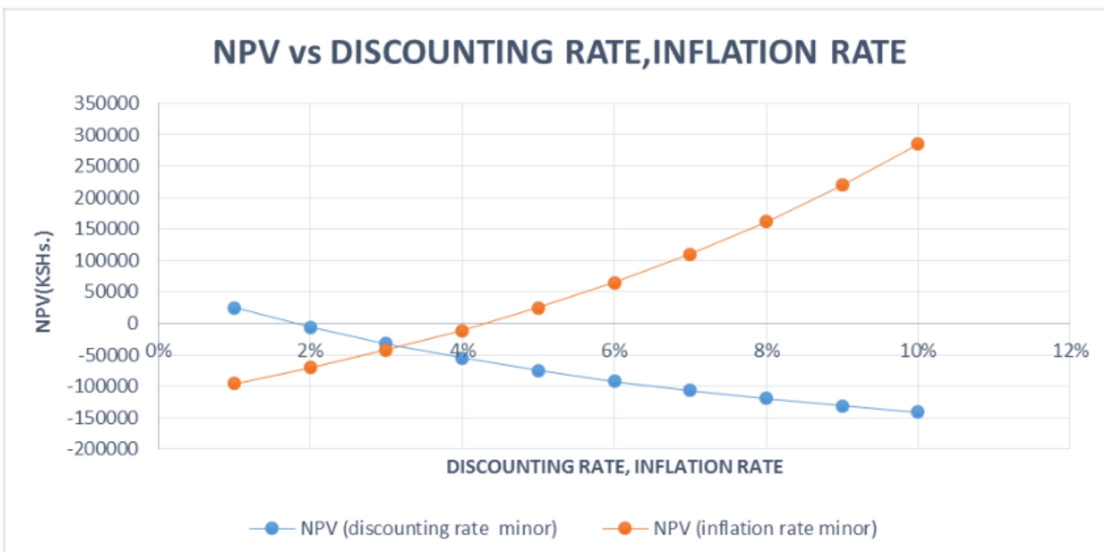

Figure 4.10 NPV vs. discounting rate, inflation rate (minor)

Analysis of consumers who fall under the minor category shows that increase in the discounting rate will result in a decrease in the net present value which is in the negative region making it very unattractive. Increase in the inflation rate results in an increase in the net present value and for figures above 7%, the project starts to show positivity.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSIONS

The research report has conclusively shown that a well designed and implemented solar PV system can be used to substitute and/or eliminate electricity consumption from mains electricity for domestic consumers. With a variety of levels of consumption figures researched on, the results show a considerable level of viability for two classes of consumers with only the minor electrical consumers not showing viability.

The research report was divided into three main classes: the first class was the major electrical load consumer **(an average of over 1000 kWh per month).** The research report shows that this class of consumers will incur the highest cost of installation and execution of the solar PV system but enjoy the best return on investment with a net present value of KSHs**. 4,823,717.47** and a simple payback period of about **3.44 years**. This makes the project attractive financially. The second focus group was the intermediary group of electrical load consumers, **(an average of 600 kWh per month).** This class of consumers enjoy a projected net present value of **KSHs. 1,367,806.01** and a simple payback period of about **4.25 years**. This figures when put in to context show that the project is financially viable.

The third class of electrical load consumers was the minor electrical load consumers who consume an average of **less than 100 kWh per month.** Financial analysis of this group shows that the project as designed and laid out is not financially viable in the long term and the financial gains of substituting mains electricity with solar PV power are not sufficient to make the project attractive to potential investors.

5.2 RECOMMENDATIONS

From the research report, solar PV power is presented as a viable option to replace mains electricity as the primary source of power for domestic consumers. The research report has shown conclusively that this is achievable with long term financial viability for consumers who fall in between the **major electrical load consumers and intermediary electrical load consumers.** The research report recommends that the suggested solar PV system be rolled out in the country as it provides a fresh, economical and innovative way of powering society while reducing overdependence on mains electricity.

However, the research report also shows that for small scale electrical load consumers, the suggested solar PV system is not financially viable and in the long term will not attract any viable savings. This is majorly attributed to the high cost of acquiring and installing the solar PV system. Although the primary cost i.e. the cost of buying the solar PV panels is reasonable, the soft costs i.e. cost of the intelligent inverter, cabling equipment etc. is very high and makes the project too costly. The research report recommends that the solar PV system as suggested should not be rolled out to small scale electrical load consumers.

The research recommends further work to be done on methods that can be implemented to reduce the soft costs associated with the suggested system to make it less costly and more favorable to small scale consumers who attract relatively small savings to make the project viable in the long term. New suggestions on new tools that can be used to substitute the auxiliary parts of the system e.g. the intelligent inverter will lead to lower costs of actualizing the solar PV system and lead to more attractive terms for small scale electrical load consumers.

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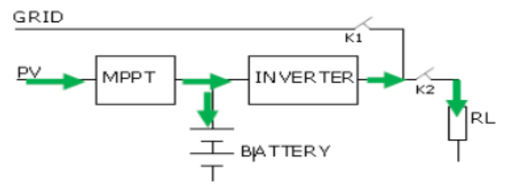
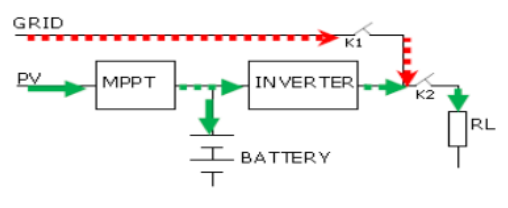
APPENDIX

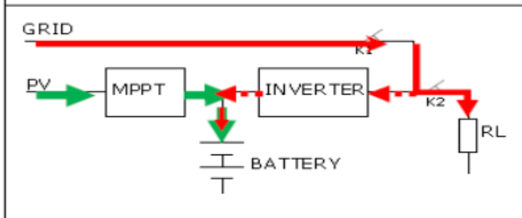
Inverter working principle



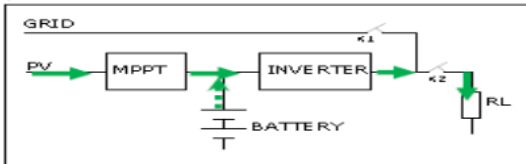
When AC is normal, PV is sufficient, system charge the battery first and excess power takes the load.



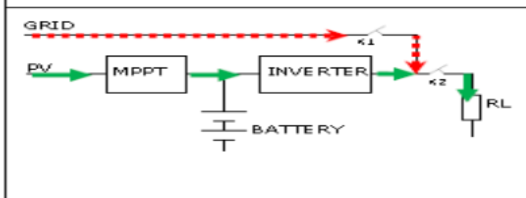
On "Energy Saving Priority" mode: When PV is insufficient, PV charges the battery first, the excess energy will support load together with AC. Inverter and AC power support the load at the same time.



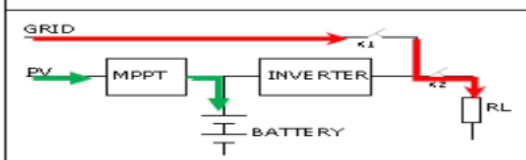
On "Energy Saving Priority" mode: When PV is insufficient and less than the power battery requires, the system turns on AC charger and charge the battery with PV and the load will be supplied by grid.



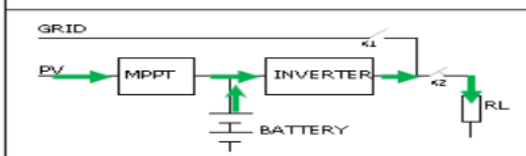
On "Energy Saving Priority" mode: When PV is insufficient and less than the power battery requires, the system turns on AC charger and charge the battery with PV and the load will be supplied by grid.



On" Energy Generating Priority" mode: during the user setting time, when PV is insufficient, and battery discharge to the setting point, the system let PV and AC support the load at the same time. Battery is on the status of being charged.

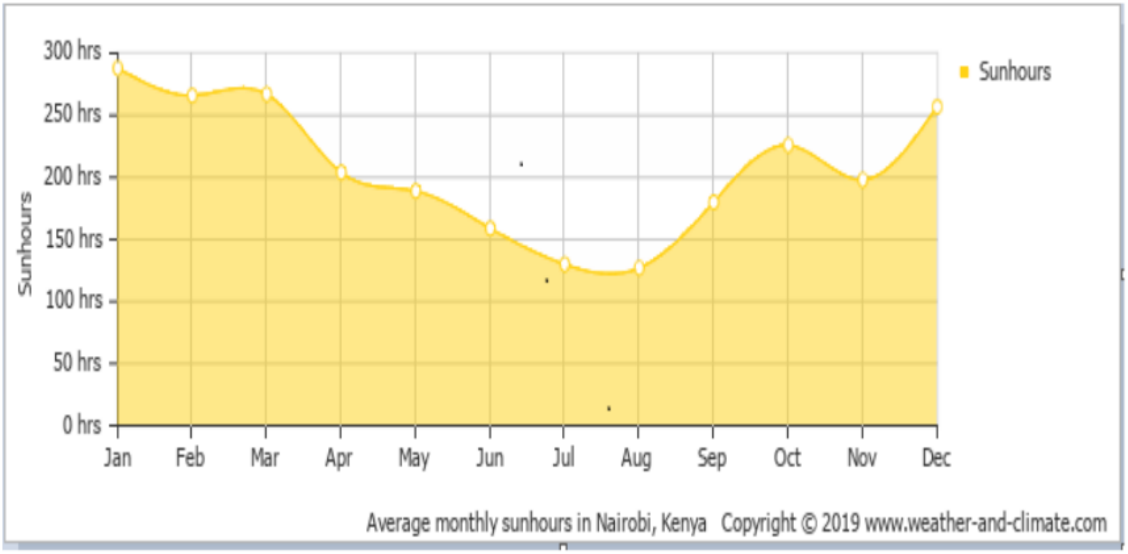


Set the "AC charging close" mode: during the user setting time, system only let PV charge the battery, forbid AC to charge the battery. And load is supported by the AC.



When AC is abnormal, system use PV and battery power to support the load at the same time.

Average sunshine hours in Nairobi



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