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DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

ECONOMIC- ENVIRONMENTAL IMPACTS OF SOLAR PHOTOVOLTAICS USING LIFE CYCLE ASSESSMENT: USING A MULTI-TIER FRAMEWORK

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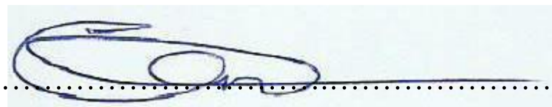
A Research Project Report submitted in partial fulfilment of the Requirements for the award of the Degree of
Master of Science in Energy Management of the University of Nairobi.

NOVEMBER 2020

DECLARATION

I **Celestine Kavindu Philip** declare that this report is my original work, and except where acknowledgements and references are made to previous work, the work has not been submitted for examination in any other University for the award of a degree. No part of this research may be reproduced without the prior permission of the author/University of Nairobi.

Signature:  Date: **18th November, 2020**

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APPROVAL BY SUPERVISORS

We confirm that the Research was carried out under our supervision and has been submitted for examination with our approval as University supervisors.

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ABSTRACT

Since the start of the new millennium, renewable energy technology has been considered harmless, clean and free in nature, on the other hand, non-renewable energy sources are considered as hostile technology. Accessibility of reliable grid electricity to the rural population in Kenya is limited and wanting, this is because population is sparsely distributed and the physical terrain is also at times not friendly to run the electricity poles. Majority of rural households in Kenya therefore do not have access to reliable grid power/electricity. With these challenges the problem to be solved would be to determine whether there are better ways of providing access to electricity to the rural population without relying on the common grid extension. Possible combinations of inventive technologies should be deliberated and be given a chance to prove their value it is on this basis this research was done. Therefore, solar based systems will find dominance due to the terrestrial challenges and the inaccessibility challenges mostly found in rural Kenya.

The main objective of the research project was to investigate and determine the economic and environmental effects of Solar PV using a rural set up as a case study and quantify the same using the Multi-tier framework. The method of executing the research project involved desk reviews, experimental setup and local regulations. The economic tools for determining the economic impacts included the following: Capital Investment, LCC, PBP and ROI while for the quantification of the environmental impact, LCIA technique was applied. The LCCA analysis identified that, comparing solar PVs with grid power supply and diesel generator as a source of energy, Thus the solar PV System LCC is 14.8% of the Diesel generator LCC and variable for the utility LCC. Similarly, a comprehensive LCIA of S, U and G identified the GHG emissions of S to be lower at 5% compared to U and G at 11% and 84% respectively. The major components of the GHG emissions were also identified and quantified according to the power source.

Previous researches on environmental impacts of solar PVs have focused on general GHG emissions in terms of equivalent carbon dioxide emitted and carbon dioxide avoided, this research project focused on the quantification of both the economic and environmental impacts of PV solar systems using life cycle analysis by comparing it to grid power supply (hydro-power) and diesel generator power sources and

determined the actual positive and negative impacts in the life time of a solar system. The environmental effects where categorized into: ecosystem, social and health impacts. There is need to counter relate social, health, ecosystem, emission and resource cost effects of solar PV systems. This will help the government in policy formulation and funding. The major challenges of solar PVs disposal in Kenya were identified as: Limited information and awareness of the e-waste management regulations and weak policies follow-up.

The assessment intended to improve the technical and scientific understanding of solar photovoltaic technologies both positive and negative in rural Kenya and to help support development of effective public policy, regulations and government investment decisions. The study where possible provides information on the relative quantifiable economic and environmental effects of PV solar systems in Kenya which is essential for development of sound energy policies and allocation of funds to strategic research priorities.

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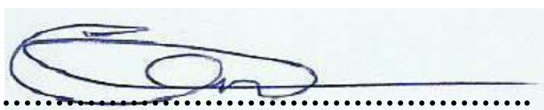

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NOMENCLATURE

BOS: Balance of Systems

CI: Capital Investment

DG: Distributed Generation

FiT: Feed in Tariff

G: Diesel Generator

GHG: Greenhouse Gases

GWP: Global Warming Potential

KCCRS: Kenya's Climate Change Response Strategy

KPLC: Kenya Power and Lighting company

KWh: Kilowatt hour

LCA: Lifecycle Assessment

LCCA: Lifecycle Cost Assessment

LCIA: Lifecycle Impact Assessment

PAYG: PAY as You Go

REA: Rural Electrification Authority

RET: Renewable Energy Technoogy

S: Solar

SET: Solar Energy Technology

SHS: Solar Home Systems

U: Utility

VAT: Value Added Tax

Wp: Watt Peak

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the study

In the recent past, Renewable Energy Technology (RET) has been considered a harmless, free in nature and clean source of electrical energy. On the same argument, Non-Renewable Energy Sources are alleged as the single hostile technology to the environment without centering on the negative effects of Renewable Energy (RE) Sources. It is, therefore, important to assess and evaluate the economic and environmental impacts of RE technologies and decide on the net environmental and economic benefit for their utilization.

Approximately 1.1 billion people which is an equivalent of 80% from Southern of Asia and the Sub-Saharan Africa live in rural or less developed areas [1]. In order to minimize the challenges of electrical energy poverty to the rural population, adoption of alternate sources of electricity is important in accomplishing the Sustainable Development Goal (SDG) by the united nations, reference goal number 7, which is to ensure access to reasonably priced, consistent, maintainable and modern energy for all by 2030. The major challenges in providing electricity to the 1.1 billion people in the remote rural areas are their distance and inaccessibility from the national grid transmission lines, low population, bad terrain, low electricity consumption and relatively low and irregular income compared to urban population. Due to these factor most policy makers and power utility companies often do not give importance to the electrification of the rural population but only considers the urban population and industrial consumers. With these challenges the problem to be solved would be to determine whether there are better ways of providing access to electricity to the rural population without relying on the common grid extension. Possible combinations of inventive technologies should be deliberated and be given a chance to prove their value it is on this basis this research was done. Therefore, solar based systems will find dominance due to the terrestrial challenges and the inaccessibility challenges mostly found in rural Kenya [1].

Availability of solar power can change and improve people's livelihood. People that are unable to afford for the installation and utilization charges of the grid electricity use large sums of their income on purchase of kerosene and diesel for their lamps lighting, stoves cooking purposes, diesel generators and also travel to larger towns for phone (battery) charging. Use of kerosene/diesel as a fuel source has many disadvantages like; air pollution and fire accidents. Availability of solar PV's to families help them save a lot of money for lighting expenses and as well allows ambient environment for reading especially for school going children.

Kenya Power and Lighting Company (KPLC) effective monopoly on electricity made it inefficient and unresponsive to demand and has led to search for alternate sources of energy like solar PV systems. Non-governmental organization (NGOs) have funded projects and introduced photovoltaic technology to rural Kenya and provided empirical evidence of its legitimacy [1]. The average insolation in Kenya is approximately 4.5 $Kwh/m^2/day$ which makes her have a high probability to adoption of solar photovoltaics compared to many other nations [2].

To promote the private sector, the Government of Kenya (GOK) involvement in the PV's has introduced the feed in tariff regulation in the Kenya energy sector. This move seeks to enhance Security of the national energy, entrepreneurship and clean energy connectivity. Devolution and urbanization are key promoters of SET. In the penetration of the solar energy technology in the rural areas international non-governmental organizations have contributed widely to the expansion of the solar market through formation of Sacco's, social enterprise organizations in the distribution of small solar PVs for domestic users on cash and credit terms. Some of this NGO's include: SNV, lighting Africa and GVEP [2].

Factors promoting solar PV adoption in the Kenya market include the following:

(i) Falling global prices of solar products e.g. modules, inverters, batteries and all other solar accessories. This is due to the abolishment of taxes on solar products by the government of Kenya though policy dynamics also poses a challenge.

(ii) Consumer variety: more consumer choices in the market.

(iii) Government support through regulation and policies favoring use of renewable energy especially solar system.

There are several barriers in the adoption of solar photovoltaic systems but the most common barriers in Kenya include the following: Policy barriers, unskilled technicians, socio-technical barriers and economic barriers [2].

1.2 Problem Statement

The energy demand in Kenya is largely increasing than the supply especially in the rural and under developed areas leading to the increased use of alternate sources of energy like solar PV systems. According to Green peace, 2001 there exist an increased market for solar products in Kenya. The current argument is whether there is any significance in adopting to solar technologies. Those who support adoption of solar PV's urge that rural productivity, and income levels can be improved by adoption of the same but critics of solar PV's adoption claim that solar PV's are only affordable by the rural elites but not the rural poor [3].

It is against this background that this research studied and analyzed the use of PV solar panels and their economic-environmental significance in rural Kenya. This project assessed and analyzed the economic-environmental impacts of PV manufacture, installation, use and disposal in a simulated rural set up.

Most forms of distributed generation (DG) is from solar energy. However, there are several policies and strategies that have been implemented to stimulate the market for PV systems with mostly positive results. The existing Solar PVs out in the rural areas are generating enough electricity to operate the most basic domestic appliances this is according to ESDA in 2003 and Jacobson, 2004. One of these strategies and policies is the quantification of the net economic and environmental impacts of such utilization. This formed the basis of the research.

1.3 Research Objectives

1.3.1 Main Objective

The main objective of the project was to investigate and determine the economic and environmental effects of Solar PV using a rural set up as a case study.

1.3.2 Specific Objective

The following specific objectives were addressed so as to achieve the main objective:

(i) To perform an economic impact of solar Photovoltaic based on the multi-tier framework.

(ii) To perform an environmental impact of solar photovoltaic installations.

(iii) To investigate and report the influence of governmental and non-governmental organizations in Photovoltaic solar installation and usage in rural Kenya with respect to environmental and economic aspects.

1.4 Research Questions

(i) What are the positive and negative economic-environmental impacts of Photovoltaic solar installation?

(ii) How does the economic consideration of the multi-tier framework affect the installation and use of PV panels in rural Kenya?

(iii) How does the environmental consideration affect the installation and use of PV panels in rural Kenya?

(iv) To what extent do governmental and non-governmental organizations influence Photovoltaic Solar installation and usage in Kenya?

1.5 Justification of the study

Kenya is heavily reliant on fossil fuels for its energy needs, despite this there still exists electrical energy poverty in the country which results to unreliable supply of electrical energy to majority of its population. This has caused a lot of debate in the past in the following aspects; first, this has meant that with continued economic development from the fossil fuel combustion will continue to bring climate change, GHG emissions and secondly, owing to escalating cost of fuel in the world market, this has had a negative effect on local inflation rates driving up the cost of living as well as the cost of electricity generation and consumption. In all these the rural population has highly been affected by the aforementioned.

Therefore, it has been important to improve on the adoption and utilization of renewable technics with an aim to reduce the over-reliance on fossil fuels hence reducing the negative climatic effects caused by carbon emissions. This research therefore provides quantifiable data to rural residents, government, non-governmental organization, policy and regulation makers on the economic and environmental impacts of using solar PVs as an alternative source of electricity The project determined the net economic and environmental benefits in the use of solar power in rural Kenya. It considered the *lifecycle assessment (LCA)* of both cost and environmental issues of solar home systems from installation to disposal and compared it to the grid power supply costs and diesel generators power supply for domestic consumers in Kenya.

A study on economic impacts of climate change in Kenya conducted by Stockholm Environment Institute (SEI) in 2009 found out that there was a tremendous rise in GHG emissions of approximately 50% over the last decade. This caused the KSCCRS to come up with strategies of promoting clean energy like solar energy.

The U.S Department of Energy in 2006 stated that, solar power is considered one of the most promising sources of renewable energy in the world. Compared to non-renewable sources such as coal, oil and nuclear, some of the advantages of solar energy are as follows:

(i) Photovoltaic cells are modular; there capacity can be expanded with need
(ii) Silent in operation and produce no exhaust.
(iii) Appropriate for inaccessible and remote areas where it is uneconomical to run transmission lines.
(iv) Can be used as backup/standby power during blackouts.
(v) Minimum maintenance.
(vi) Free in nature.
(vii) Environmentally friendly in the utilization stage.

The Kenyan development strategy is based on the vision 2030 which aims at Kenya becoming a middle income and industrialized country. For any country to be industrialized, reliable and affordable source of energy is a driver. Also in line with the vision 2030 and laptop projects in Kenya, most of the schools in rural areas do not have electricity and to power these Schools alternative sources of energy like solar power have to be embraced. Green energy will be important in ensuring that schools get power in a low cost without having to incur daily costs of electricity.

1.6 Scope of the Study

The research determined and analyzed the life cycle environmental and economic impacts of solar photovoltaic in comparison with grid power and diesel generator power source with reference to rural Kenya at household and institutional level. The research was limited to Kenya rural population, governmental and non-governmental impacts, environmental impacts and economic (cost) impacts of solar photovoltaic.

The project assessed the quantifiable environmental impacts of solar PV lifecycle including; manufacture, installation, use and disposal in a simulated rural setup.

The project only assessed, analyzed and quantified the economic (cost) impact of the solar photovoltaic during the usage stage.

1.7 Contribution of the Research Work

Considering previous research work, the results of this research are superior because they major on quantification of the economic and environmental impacts of solar PVs based on consumer levels thus being able to identify the optimum points of operation for consumers. The research also incorporates the component of technical sizing of off-grid systems in order to achieve maximum loading hence improved operating efficiency of the systems. The environmental impacts analysis used in this research identifies the various components of emissions unlike previous researches which only dealt with equivalent carbon dioxide emissions and carbon dioxide avoidance factors.

1.8 Definition of Terms and Concepts

Rural: Remote and less developed areas which are mostly sparsely populated.
Environmental sustainability: Responsible utilization of resources while safeguarding the environment from degradation.

Photovoltaic (PV): It is a method of generating electricity through conversion of solar radiation into a direct current power by use of semiconductors which exhibit the photovoltaic effect. (Photovoltaic Industry Association,2012).

Climate change: It is the permanent variation in climatic conditions which changes either upwards or downwards of the normal.

Rural electrification: Symbolizes the process of connecting rural and remote areas with electrical power.

Greenhouse gases: it refers to a combination of several chemical compounds that are found in the Earth's atmosphere. These are gases which allow sunlight to enter the atmosphere freely. When sunlight strikes the Earth's surface, some of it is reflected back towards space as infrared radiation (heat).

Pollution: It is the adulteration of the environment causing instability and discomfort to the environment (ecosystem).

Poverty: Refers to the inability of the households in accessing key human attributes, including health. They are exposed to greater personal and environmental health risks, are less well nourished, have less information and are less able to access health care.

Grid-connected: This is a power system network integrating transmission line, distribution grids, distributed generators and loads that have connection points called busses.

Off-grid: This type of PV system is used to connect to a battery via charge controller in circumstances where main electricity is not available.

Hybrid system: This type of PV system can be combined with another source of power.

1.9 Report Organization

This report consists of five chapters as explained herein: chapter one provides the introduction in the analysis of economic-environmental impacts of solar PVs considering the systems lifetime. The objectives of the research project, scope, justification for conducting the research and the research contribution are also highlighted.

Chapter two covers theory of the positive and negative impacts of solar PVs based on ecosystem, social and economic aspects.

Chapter three highlights the method used in the research, formulae adequate for addressing the specific objectives and sources of data crucial for accomplishment of the project.

Chapter four presents the results and analysis of the results to achieve the research projects objectives.

Chapter five provides the conclusion and the recommendations for further research.

CHAPTER TWO

ENVIROMENTAL AND ECONOMIC EFFECTS OF SOLAR PV

2.1 Introduction

This chapter focuses on the following major areas: Positive and negative economic and environmental impacts of solar photovoltaics, past researches that have been done relevant to this research on environmental and economic impacts of solar photovoltaic system using lifecycle analysis, Relevant information from the past researches so as to narrow the gaps within the existing literature, methodologies and past findings with the aim of filling them, Quantifiable economic impacts of solar PV systems and General information about PV solar, empirical studies and rural household installation examples from Africa and beyond.

2.2 Economic Effects

2.2.1 Positive

(i) Solar energy source is an inexpensive alternative source of energy which makes electrical energy cost lower hence lowering the cost of production in industries hence stimulating economic growth.

(ii) Connecting solar energy to the power micro-grids in previously unconnected regions improves the economic conditions in such regions.

2.2.2 Negative

(i) For solar farms, large tracts of land are required which lead to an increase in the cost of land for such purposes.

2.3 Health Effects

2.3.1 Positive

(i) Utilization of solar energy as an alternative energy source helps reduce greenhouse gases emission that lead to global warming with the effect of reduction in ozone layer depletion. The ozone layer helps trap UV rays that could cause cancers and thus its conservation is a boost on the health of a population.

(ii) Solar PV panels are silent in operation and are pollution free during the operating phase. these characteristics make the system to be friendly to living organisms hence cause no health repercussions.

(iii) Solar systems do not rely on water resources hence reducing the strain on local water resources and the water available can be used for human healthy survival.

(iv) Properly planned SET systems ensure proper land utilization and minimum risks on the plant and organism health.

2.3.2 Negative

(i) Manufacture of Solar panels and BOS involves use of many toxic materials which are sprayed on the solar cells and can be easily inhaled. The inhalation of these toxic materials which are carcinogenic can lead to health problems.

(ii) Solar farms emit very high temperatures in the zones around them this can result in human beings suffering sunburns.

2.4 Ecosystems Effects

2.4.1 Positive

(i) SETs have reduced greenhouse gases emission hence reduced global warming, the snow on mountain tops and icebergs at sea are being conserved thus preventing rising sea levels that would otherwise submerge sea towns.

(ii) Reduced global warming helps preserve animals and plants while the opposite would lead to death of animals and plants.

(iii) Solar energy use is environmentally friendly as there is no pollution or production of harmful substances or particles that would lead to respiratory diseases.

2.4.2 Negative

(i) Disposal of the toxic substances used in the production of solar cells and associated BOS pose a challenge, if not well-disposed lead to environmental pollution as they are non-biodegradable. To counter this however, solar cells manufacturers are encouraged to recycle these substances to limit environmental pollution.

(ii) Solar farms result in very high temperatures as they concentrate the heat above them in one area and lead to birds burning to death as they pass over them thus leading to the altering of the bird's population and ecosystem.

(iii) The requirement of large tracts of land for installation of solar farms leads to displacement of both human and wildlife populations and thus altering the environment ecosystem. Wildlife especially birds may also leave the region as a survival tactic as more are killed.

(iv) When concentrated solar power systems (thermal solar systems) are used as the source of solar energy, they require large amounts of water for cooling or as the working fluid to produce steam to drive turbines or for washing the reflective surfaces and since they use a large amount of water, this affects the water quality in the environment as it mixes with toxic substances in the solar cells. This is water pollution.

2.5 Social Effects

2.5.1 Positive

(i) For the installation of large solar farms, it results in creation of employment for many people both directly and indirectly i.e. in the solar cells industries as well as at the solar farms themselves. This improves their livelihood and spurs economic growth.

2.5.2 Negative

(i) Solar farms may lead to displacement of people and animals in order to have them effected thus disrupting social order.

2.6 Life Cycle Assessment

Life Cycle Assessment (LCA) is a method used for comparing and analyzing different energy sources economically and environmentally to determine their viability in adoption during their life time (cycle).

LCA has two forms; Life Cycle Cost Analysis (LCCA) for economic effects and Life Cycle Impact Assessment (LCIA) for the environmental effects. These are reviewed and discussed next.

2.6.1 Life Cycle Cost Analysis (LCCA)

Life Cycle Cost Analysis (LCIA) is concerned with the cumulative cost of the PV from manufacture to disposal. Most works in PV analysis have considered the cost aspect. These are found in [5]- [8], among others. In all these works only the efficiency and Energy Payback Time (EPBT) of the PV are addressed.

2.6.2 Life Cycle Impact Analysis (LCIA)

Life Cycle Impact Analysis (LCIA) is a method for determining the environmental features related with the development of a product and its potential effect throughout a products life. It can be used as a tool to detect potential for improvement with the aim to reduce impacts on the environment.

All the research on LCIA has considered only the GHG analysis. These include works in [9] to [11]. However, there are many health and ecosystem factors that need to be put into consideration and have been considered in this research.

2.6.3 LCCA-LCIA

Few works have considered combined Economic and Environmental effects analysis for solar PV. In [4] only the GHG (CO_2) for the LCIA and Energy Pay Back Time (EPBT) for the LCCA were analyzed. Other similar works include [12], [13] and [14]. All these did not consider the other aspects of Environment and Cost. In this project, LCCA, LCIA and LCCA-LCIA approaches in the PV analysis have been done. It is apparent that the economic and environmental effects reviewed in chapter 2 have not been analyzed. The research adopted the LCCA-LCIA Approach to quantify a wide range of economic and environmental aspects of PV use based on technical sizing of the complete system.

2.7 Conclusion

Considering both the advantages and disadvantages of solar economic and environmental impacts, it can be concluded that these renewable energy sources are not free, clean and harmless. This research quantified these effects in comparison with the Kenyan grid system and the diesel generators power supply systems.

CHAPTER THREE

RESEARCH METHODOLOGY

3.0 Introduction

The chapter sets out the various phases followed in completing the study.

3.1 Study Area

The study design focused on a simulated Kenyan rural set up using the multi-tier framework as shown in Table 3.1 [1].

Table 3.1: Multi-Tier Framework for various levels of electricity consumption [1]

	TIER 0	**TIER 1**	**TIER 2**	**TIER 3**	**TIER 4**	**TIER 5**
Tier criteria	Negligible tasks	Task lighting AND phone charging	General lighting, phone charging, television , fan	Tier 2 and any medium-power apparatus	Tier 3 and any high-power apparatus	Tier 2, any very high-power apparatus
Annual consumption (kWh)	Negligible Consumption	≥4.5	≥73	≥365	≥1,250	≥3,000
Daily consumption (Wh)	Negligible Consumption	≥12	≥200	≥1,000	≥3,425	≥8,219

3.2 Data Collection and Analysis

3.2.1 Primary data

Primary data was sourced from first hand sources using the following methods: experiments, real current and local projects and internet survey. It was collected with the research project in mind, directly from primary sources.

3.2.2 Secondary data

Secondary data was obtained from Government publications such as economic surveys, statistical reports, global documentaries, statistical abstracts and development plans among others. The pertinent national Legislation on environment, national regulations and standards, conventions and treaties also formed part of the secondary sources of data that was used in this study.

3.2.3 Data Collection Methods

This research also applied an integrated approach for data collection. The research instruments, used for this study included: direct observation of the PV panels in use, key informants' interviews, simulated experiments and desk reviews.

3.2.4 Data analysis

The research analyzed data by use of qualitative and quantitative methods of data analysis. Qualitative analysis helped to understand the why and how of decision making while quantitative analysis achieved the scientific investigation of the quantitative properties and measurements and their relationship.

3.3 Historical Data

The research also used secondary data on the adoption of solar PV, this was done through review of various documents, example; legislation and policy documents (Energy Act 2012), past studies/researches relating to solar PV, policy briefs and best practices drawn from other jurisdictions. Information gained from primary data was used to argue primary facts.

3.4 Solar PV Experimental Set-Up

The experimental system consists of photovoltaic panels PM/EV simulating the behavior of a photovoltaic generator, a teaching panel for the evaluation of the main operating parameters of the system during the utilization stage that is both the DC and AC electrical parameters, a computerized structure for the analysis of the system's operation by a PC.

The experimental set-up is a representation of a typical stand-alone or off grid power plant with power storage battery and inverter. The Electrical loads connected to study the economic and environmental impacts of solar PV's included the following; lamps or external devices (resistive loads, PC, simulated solar irrigation pump).

The main components of the module are:

(i) A **PV Panel**, composed of two independent modules made in crystal silicon and a supporting structure.

(ii) **A Solar Radiation Sensor**, mounted on the plane of the panel for measurement of the incident solar radiation.

(iii) A **Charge Controller** for optimizing the power flows involving the photovoltaic panel, battery and the inverter.

(iv) A **Battery** for power storage

(v) An **Inverter** for converting DC power to AC power.

(vi) **Electrical Measuring Instruments** (voltmeters, ammeters, power factor meters, frequency meters, a power analyzer.

(vii) A **Synoptic** for condensing the connection modes of the different components of the plant.

(viii) A **Remote Control System** with a PC for displaying and recording the various electrical parameters.

(ix) A **Sun Tracker** (optional).

The solar photovoltaic system consists of a PV panel which collects the solar energy for conversion to electricity. It generates D.C electricity. The D.C electricity is controlled by a charge controller (DC/DC) in order to obtain a regulated DC output to input it to the battery for storage. The DC output from the battery is fed to the inverter to invert it from DC to AC. An optional power meter can be used to record the flow of electricity or the power consumption by the various loads [17].

The actual simulated circuit diagram indicating the positioning of measuring instruments and balance of systems (BOS) for both economic and environmental impact is as shown in Figure 3.1. The simulation system was acquired from **Electronica Venetta**, **Italy** by the **University of Nairobi**, **Electrical and Information Engineering department** and is set in **Power Laboratory AW 108**. The parameter specifications are as shown in Table 3.2.

Table 3.2: Parameter Specification

Parameter	**Value**
Rated power (p max)	115Wp ×2
Maximum power voltage (Vmp)	17.7V
Maximum power current(Imp)	6.5A
Open circuit voltage(Voc)	21.6 V
Short circuit current(Isc)	6.96 A
Tolerance	±5%
Module area:	1m^2×2

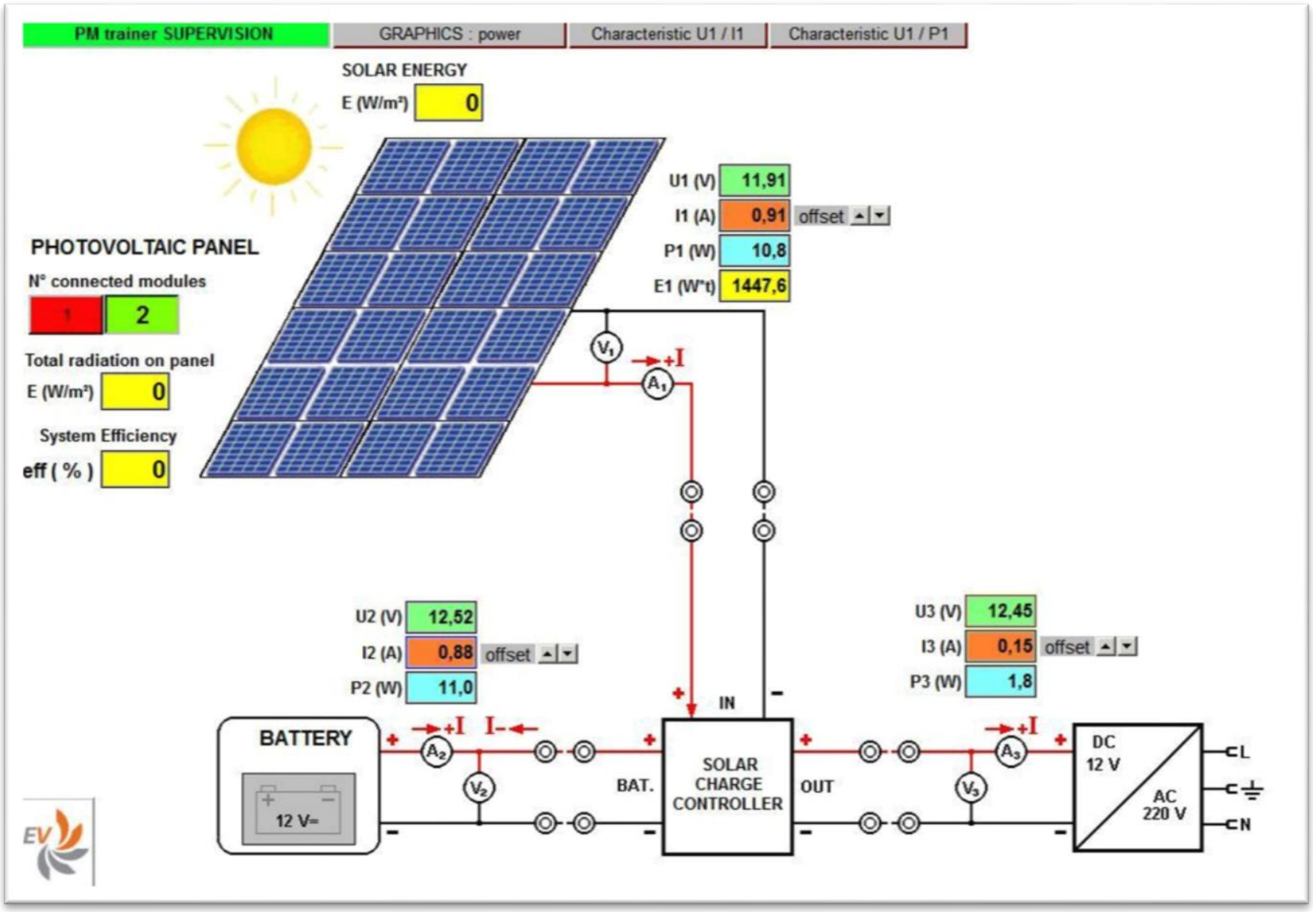

Figure 3.1:Experimental Set for utilization of solar photovoltaic system on a Solar Home System

The simulation of the system was done at the generation and utilization stage whereby a simulated set up of a solar home system for standard rural environment using the multi- tier framework system as shown in Table 3.1 was implemented and compared to a similar utility grid system and a diesel generator power system. The multi-tier framework provided a systematic way of gauging and validating access to electricity and it has five levels of energy access. This research relied on the multi-Tier Framework to categorize consumers and analyze the economic impacts of solar PV.

Task lighting represents small consumers of electricity specifically for minor lighting purposes like reading, cooking, etc. Most rural consumers require electricity for task lighting.

3.5 Tools for LCA

The purpose of these tools is to determine the economic and environmental impacts of solar photovoltaic using a systematic life cycle assessment (LCA).

The standard LCA framework methodology is shown and demonstrated in Figure 2.1. LCA consist of four stages, namely; the definition of the goals and scope, inventory analysis, impact assessment and interpretation of results. In the definition of the goal and scope phase the underlying question (objective) is stated and explained in terms of the system, its boundaries and the definition of a functional unit. In the inventory analysis the flow of contaminants, ingredients and resources are recorded. These basic flows i.e. (contaminants/emissions, (ingredients) resource, consumption, etc. are categorized and accumulated for different economic-environmental problems in cost-impact assessment and finally conclusions are drawn in the interpretation stage [4]

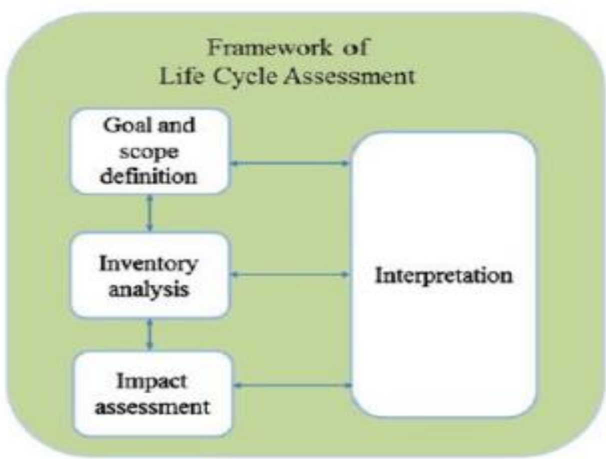

Figure 3.2: Life Cycle Assessment (LCA) [4]

3.6 Economic Analysis

The various tools used for economic analysis can be discussed as follows:

a) Life cycle costing (LCC) for solar PV

The life cycle costing is a technique used to determine the total cost of ownership over the facilities life time.

The solar PV system has 5 major components of cost which include Development / planning (C Dev), PV Panels (C panel), Electrical apparatus (C Elec), Mounting and Civil Works (C Civil) and Operation and Maintenance (C o&m). This can be represented as [15]

$$LCC = C_{Dev} + C_{Panel} + C_{Civil} + C_{Elec} + C_{O\&M} \quad (3.1)$$

For Off-Grid Systems,

$$LCC = C + OM + R \quad (3.1.1)$$

Where:

LCC= lifecycle cost

C = Capital cost

OM = Operation & Maintenance cost

R = Replacement Cost

Each component of LCC has sub-components, these are; development cost which consist of financing costs, legal costs (where applicable), Grid impact study, Environment study and land cost. For the PV module cost it involves the cost of the solar panels, mounting and civil cost Construction site set up, Mounting structure, Commissioning and Module installation. Electrical apparatus costs include; inverter, battery, charge controller, wires and auxiliary. Operations and maintenance costs consists of operations (labor) and maintenance (cleaning and components replacement).

For an off grid system mostly for rural domestic use the cost of the system comprises the sum of the following:

i) Initial investment cost of the PV modules, C_{Bom}

ii) Initial investment cost for balance of systems, C_{Bos}

Assumption

In accordance with other studies the lifetime for the PV project is 25 years, average module price is \$ 0.56/W_P and the capital investment of the system is \$ 1.184/W_P, operation and maintenance cost is 27% of the total capital investment of the system [15].The CBK mean exchange rate as in march 2017 was 102.8482 and is currently being used by the energy utility company. The same will be used for currency conversions for this research.

Therefore;

$$LCC = Capital\ Investment(CI) + C_{O\&M}$$

Where:

$$Capital\ Investment\ = C_{Bom} + C_{BOS} = \ \$\frac{1.184}{W_P} \qquad (3.1.2)$$

b) Simple Payback Period/Payback Period (SPP/PBP)

SPP is calculated as:

$$PBP = \frac{Capital\ Investment}{Annual\ Saving} \qquad (3.2)$$

Where capital investment for solar PV are the cost of the solar panels

And

Annual savings=utility charges for grid power

And

c) Return on Investment (ROI)

$$ROI = \frac{1}{PBP} \qquad (3.3)$$

Where ROI=Return on Investment (Solar PV)

3.7 Validation of Economic Impacts

3.7.1 Tool for Analyzing Grid Power Costs

The tool which will be used to determine the grid power costs is the Kenya Power and Lighting Company (KPLC) billing system [22].

Current Domestic Charging for Grid Power Utilization

Following the review of electricity tariffs by the energy regulatory commission from august 2018, the new tariffs were implemented with effect from 1st November 2018, for both Prepaid and Postpaid customers. The revised tariff rates affect energy consumption charges only and do not affect taxes, levies, Fuel Cost Charges, Forex and Inflation adjustment. The revised tariff affects Domestic Customers and Small Commercial Customers only as shown in Appendices I and II, (Other customer categories like Commercial and Industrial, Street Lighting are unaffected). For Domestic Consumers, the changes are as follows:

(i) **The Domestic Consumer 1** (Lifeline Customers): The consumption band has been adjusted from 0-10 Units to 0-100 units. Energy charge has reduced from Shs.12 per kWh to Shs.10 per kWh for customers whose band was 0-10 units and from Shs.15.8 per kWh to Shs.10 per kwh for customers whose consumption was between 11-100 Units per month [22].

(ii) **The Domestic Consumer 2** (Domestic Ordinary): Consumption band has been set at above 100 units per month. The energy rate applicable remains unchanged at Shs.15.8 per kWh [22].

Life cycle costing of grid power for domestic consumers= connection fee+ (consumption ×utility cost per Kwh) + fixed charges

3.9 Environmental Analysis

In order to determine sustainable development methods, tools, techniques have been developed to measure the environmental impacts of solar PVs. In this determination of the sustainable development LCIA is a valuable tool for evaluating the environmental profile of a product or technology from manufacture to disposal [4]. It helps determine the Carbon Emission Intensity of a technology, in this case the solar photovoltaic technology. The true potential of solar technologies can be determined by comparing it with other energy sources.

LCIA's have been performed by the international reference life cycle dates system (ILCD), impact 2000+, cumulative energy demands (CED), Eco points 97, Eco-indicator 99 and intergovernmental panel on climate change (IDCC) methods.

This research project employed the carbon foot print calculator (an off-line system) in determining the carbon emission/avoidance by various levels of solar PV consumers depending on the physical location and comparing it with grid connected consumers and diesel generator users in the same tier and locality. The researcher used historical data to determine the carbon footprint of various energy consumers in order to determine the carbon emitted in the utilization of solar photovoltaic because most research only seek to determine the carbon dioxide avoided in determining the environmental effects of solar PVs. Similarly, carbon dioxide avoided can be determined as: The product of generated electricity in kwh and CO2 avoidance factor (Kg/kWh). The carbon dioxide avoidance factor varies from one location to another.

3.10 Chapter Conclusion

LCCA and LCIA approaches in PV analysis have been reviewed. It is apparent that the economic and environmental effects reviewed in Chapter 2 have not been fully analyzed. The research adopted the LCCA-LCIA approach to quantify a wide range of economic and environmental aspects of PV use. From the life cycle analysis, the following parameters were determined: standard payback period, the LCC, ROI for solar power systems, grid connected system and diesel generator system customized for a Kenyan rural set up guided by the Multi-Tier framework in order to determine the economic effects of a solar PV system. The research also determined the various GHG and toxic emissions by the aforementioned sources to determine the environmental impacts of solar PVs.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

Results are divided into two categories i.e. economic and environmental analysis.

4.1 Factors Considered in Data Analysis

The factors considered in the determination of the economic and environmental impacts of solar photovoltaic are:

(i) PV Technology (single and multi-crystalline silicon) and alternative available sources of energy for rural population in Kenya i.e. diesel/paraffin and grid power supply (hydro power sources).

(ii) Type of system-roof top.

(iii) The photovoltaic and balance of systems life time-25 years.

(iv) Geographical Location of Installation-Kenya.

(v) Specific maximum power output (Global solar atlas).

(vi) The system performance ratio [30]

(vii) The applicable electricity billing system of the locality (KPLC billing system for domestic consumers)-billing schedule attached in Appendices I and II.

(viii) Standard test conditions-1000W/m².

4.2 Generation and Consumption using Solar PV

A PV system comprising of a model generating plant and variable load consumers was used to determine the system characteristics. The simulation system was specifically used for the domestic consumers in tiers 1, 2 and 3 who according to the Kenyan tariff system belong to consumer category DC1 and DC2, but for larger consumers in tiers 4 and 5 the system electrical characteristics was tabulated mathematically. The purpose of simulating the small consumers was authenticating the operational performance of the larger rated PV system. Several observations were made from the simulation system and are as follows:

(i) Random electrical loading was applied considering a wide range starting from an assumed level of the lowest consumers using the solar lanterns for lighting purposes only e.g. Application of a 3W loads.

(ii) Voltages on the D.C and A.C sides of the system are within the allowable range. The research relied majorly on the A.C side of the distribution.

(iii) Frequency can be considered stable for purely resistive loads but fluctuates with inductive loading e.g. when fluorescent type of lighting is used. This can be noted in the fluctuating frequencies from the simulated data.

(iv) Actual power measured has an allowable slight difference to the expected theoretical power consumption e.g. for a 3w load the power consumed is 5w indicating an increase while for 12w up to 95w load the power consumed shows a decline. The trend between load inserted and the actual power drawn indicates those bigger loads are technically economical.

(v) The operation time is estimated to be 4 hours because Kenya (the study area) lies within the equator and has equal day and night. An assumption is made that majority of the rural population will require power during the night between 7.00 p.m. to 10.00 p.m. (3 hours) and within the day for one hour for other utilization like irrigation and phone charging.

The raw data collected from the simulation of the PV system was recorded as shown in Table 4.1.

Table 4.1: Raw Data for Generation and Consumption of Electricity Using Solar Photovoltaic

Electrical Load Inserted(W)	DC Parameters					AC Parameters					
	V1 (V)	V2 (V)	V3 (V)	I2 (A)	I3 (A)	V (V)	I (A)	P (W)	Freq (Hz)	Power Consumption (wh)	Tier
3	10.5	12.4	12.4	1.3	1.2	220	0.01	5	51.2	20	1
12	10.5	10.3	12.3	2	1.9	222	0.03	10	50.2	40	1
26	10.6	12.2	12.1	3.1	3.0	223	0.09	25	51.2	100	1
35	10.7	12.2	12.0	3.8	3.6	225	0.12	32.5	51.2	130	1
44	10.7	12.2	11.9	4.6	4.3	226	0.16	40	51.2	160	1
48	10.7	12.1	11.9	4.9	4.6	227	0.17	45	51.2	180	1
63	10.7	12.0	11.8	6.1	5.8	225	0.22	60	51.2	240	2
68	10.7	12.0	11.8	6.6	6.2	225.0	0.25	65	51.2	260	2
86	10.7	11.9	11.6	8.2	7.7	228	0.32	81	51.2	324	2
95	10.8	11.9	11.6	9.0	8.5	230	0.35	90	51.2	360	2

In order to determine the daily consumption, the load inserted is multiplied by 4 hours which is the estimated duration of the system operation.

From the raw data represented in Table 4.1 it is observed that there is a variation in the frequency at a load of 12w, this is an indicator of frequency instability (challenge) of solar PV system. The reason for fluctuations in solar PV systems is because when the PV arrays produce more energy than that being consumed especially during the day the battery is fully charged then the frequency at the AC side increases. On the other hand, if the PV arrays produce less energy than what is being consumed the battery provides for the deficit.

4.3 Economic Effects Analysis

4.3.1 LCC Approach for Solar PV

The Capital Investment (CI) was determined based on the load determined using Equation (3.1.2). The multi -Tier framework was used to guide on the choice of these levels. Sample calculation is as shown. (Where Wp represents the watt peak rating of the solar panel).

- CI (0.003Kwp PV)= $= \$\frac{1.184}{W_P} = 1.184 \times 3 = \$3.552$

Further, the LCC was then calculated using Equation (3.1.1). Sample calculations is as shown.

LCC for 0.003Kwp PV = CI+ $C_{O\&M}$

Where

$C_{O\&M}$ = 27% of the total CI of the system [15].

Therefore;

LCC for 0.003Kwp = \$ 3.552 + 0.27(3.552) = \$ 4.51104

- LCC for0.095Kwp PV = CI+ $C_{O\&M}$

These are tabulated as shown in Table 4.2**.**

The LCC's based on the specific load inserted were calculated and indicated as shown in Table 4.2.

Table 4.2: Analysis on LCC and CI Based on Multi-Tier Framework –Based on Load Inserted

Electrical Load Inserted(W)	**Capital invest($)**	**LCC($)**	**Tier**
3	3.552	4.511	1
12	14.208	18.044	1
26	30.784	39.096	1
35	41.44	52.629	1
44	52.096	66.162	1
48	56..832	72.177	1
63	74.592	88.317	2
68	80.512	102.250	2
86	101.824	129.317	2
95	112.48	142.85	2

4.3.1.1 Analysis of LCC and Capital Investment on Multi-Tier Framework Based on System Technical Sizing

Stand-alone PV systems operate reliably and are the best option for many remote applications around the world. Obtaining reliable long-term performance from a PV system requires consistent sizing calculations and knowledge of PV performance, use of good engineering practices when installing equipment and developing and following a complete operation and maintenance plan.

In order to determine accurate economic implications of the PV system, technical considerations of determining the system components specifications were made. This included the following:

(1) Determination of the panel sizes [28, 29]

The most suitable and economic PV panel size was determined by Equation (4.1).

$$panel\ size = \frac{total\ daily\ consumption}{peak\ sunlight\ hours} x1.25 \qquad (4.1)$$

Where:

1.25 is allowance for losses

Peak sun hours=4.3 [5]

For instance, for 1000 watts daily consumption;

$PV\ Panel\ Size = \frac{1000Wh}{4.3\ h} x1.25$ =290.69W =300Wp

(2) Determination of the battery sizes [28].

The appropriate battery capacity for the PV system was derived by Equation (4.2)

$$Battery\ Size = \frac{total\ watthour \times Days\ of\ Autonomy}{x \times y \times battery\ voltage} \qquad (4.2)$$

Where:

X=battery loss (0.85)

Y=depth of discharge (0.6)

Days of autonomy=3 (Kenya standard)

Therefore; for 1,000Wh daily system the battery capacity is calculated as:

$Battery\ Size\ (1{,}000wh) = \frac{1{,}000Wh\ x\ 3}{0.85x0.6x12v}$ =490.19Ah =500Ah

(3) Determination of the inverter sizes [28]

The system inverter sizing was derived from Equation (4.3)

For example, for the 1,000Wh system:

$$Inverter\ Size = \frac{daily\ consumption\ (Wh)}{operation\ period} \times safety\ factor \qquad (4.3)$$

Where:

Safety factor=1.25 <Sf<1.3

For Example, considering 1,000Wh (Tier 3 Base)

Then;

$Inverter\ Size = \frac{1{,}000(Wh)}{4h} \times 1.3$ =325 Watts, 12 V

The recommended system sizes based on the analysis is as shown in Table 4.3. This include the panel, battery and the inverter size. Based on the PV specifications the same data obtained from simulation was used to determine the system CI and LCC using Equation (3.1.2) and the results presented in Table 4.3.

For instance, when a 95w load is inserted on the system for 4 hours its consumption is 95W×4hrs=380Wh. Then to determine the appropriate panel size, battery size and inverter size Equation 4.1, 4.2 and 4.3 are applied.

For example,

$PV\ Panel\ Size(380Wh) = \frac{380Wh}{4.3} \times 1.25$ =110.46Wp =115Wp solar panel

$Battery\ Size\ (380Wh) = \frac{380Wh \times 3}{0.85 \times 0.6 \times 12v}$ =186.275Ah =200Ah, 12 V Battery

$Inverter\ Size\ (380Wh) = \frac{380\ (Wh)}{4h} \times 1.3$ =123.5W,12V =130W, 12V Inverter

Table 4.3: Recommended System Size Based On Data Collected –based on rating

Load (W)	Panel Size(W,V)	Battery Size(V, Ah)	Inverter Size(V,W)	Capital Investment($)	LCC($)
3	3W,6V	12Ah, 6V	5W 6V	3.552	4.511
12	15W,6V	50Ah, 6V	20W, 6V	17.76	22.55
26	30W,12V	55Ah, 12V	35W 12V	35.52	45.1104
35	45W,12V	70Ah, 12V	50W, 12V	53.28	67.6656
44	55W,12V	90Ah, 12V	60W, 12V	65.12	82.7024
48	55.8W,12V	95Ah ,12V	65W, 12V	65.12	82.7024
63	75W,12V	125Ah ,12V	85W, 12V	88.8	112.776
68	80W,12V	135Ah, 12V	90W, 12V	94.72	120.2944
86	100W,12V	170Ah, 12V	115W, 12V	118.4	150.368
95	110W,12V	200Ah, 12V	130W ,12V	130.24	165.408

Considering Table 4.2 which based its evaluation on inserted load only and Table 4.3 whose evaluation of LCC and CI were based on the system proper technical sizing, an average difference of 19% is observed. The reason for the difference is due to under sizing of the load based system which means there is no allowance for an extra loading or expansion of the load being inserted. The major disadvantage of the load sized solar PV system is its rigidness to slight fluctuations to loading. This project considered a properly technically designed solar PV system to determine the economic impacts of solar PVs systems.

Similarly, based on the Multi –Tier Framework, Minimum (base) values on the range of each Tier of the solar PV system were selected and analyzed based on their technical specifications as determined by Equation 4.1, 4.2 and 4.3. The economic parameters of the solar PV system i.e. capital investment and LCC were also determined and recorded as shown in Table 4.4 depending on the PV system (solar panel, battery and the inverter). The purpose of the base analysis is to understand the economic effects of operating at the base (minimum) limits based on the technical aspect of the PV system which could be limited in obtaining the optimum point of operation for PV systems.

It was assumed that whatever was being generated was fully consumed within the day. From the global solar atlas, the specific power output for Makueni County which is estimated as 4.3kWh/kWp per day was used in determining the daily generation and consumption for simulation purposes for each tier. Other specific power outputs for various localities in the world are given in the global solar atlas and range between 4.03 to 5.5 kwh/kWp per day for

Kenya as shown in Figure 4.1. Determination of the daily generation and consumption was determined from Equation (4.4) [29].

$$Daily\ Power\ \ Consumption = panel\ rating(Wp) \times Specific\ Power\ Output \qquad (4.4)$$

According to Table 4.4 the project was guided by the minimum consumption on each Tier.

Table 4.4: Technical and Economic Analysis of the Solar PV using the Multi-Tier Framework

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Tier criteria		Task lighting and phone charging	General lighting, phone charging, television fan	Tier 2 and any medium-power apparatus	Tier 3 and any high-power apparatus	Tier 2 and any very high-power apparatus
Annual consumption (kWh)		≥4.5	≥73	≥365	≥1,250	≥3,000
Daily consumption (Wh)	3w -11.9w	≥12	≥200	≥1,000	≥3,425	≥8,219
Recommended panel size(Wp)	3W,6V	3.5W,12V	60W,12V	300W,12V	1000W,24V	2400W,48V
Recommended battery size	6v,4 Ah	6v,15Ah or 12v, 6Ah	12v,100 Ah	12v,500Ah	24v,850 Ah	48v,1,100 Ah
Recommended inverter size	6v, 5 W	6 V,5, W	12 V,65 W	12V,325 W	24 V,1,200 W	48V,2,700 W
Capital investment($)	3.552	4.144	71.04	355.2	1184	2841.6
LCC($)	4.51104	5.263	90.2208	451.104	1503.68	3608.832

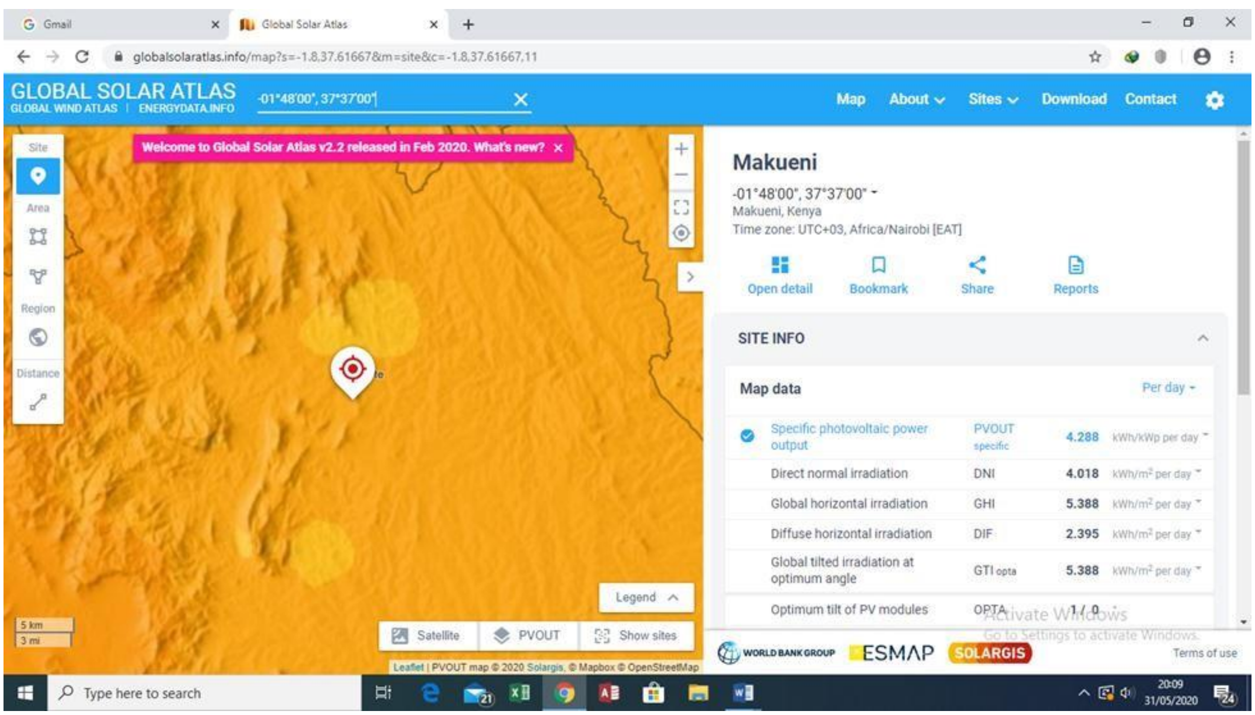

Figure 4.1: Global Solar Atlas [28]

4.3.2 Grid Power Equivalent(s)

The tool used to determine the grid power costs is the Kenya Power and Lighting Company (KPLC) billing system [22]. For the development /construction of the grid power generating plants the consumers are not directly charged therefore the assumption made in this analysis is that the total cost of energy is indicated in the consumer's energy bill. According to the rural electrification authority, it costs approximately Ksh 35,000($330.189) to connect to the national grid. These are relatively high costs that pose a major obstacle to the expansion of electricity connections to low-income households and small businesses, which can therefore benefit from decentralized alternative sources of energy, such as solar. According to the Kenya National Electrification Strategy 2018, out of the 10.8 million households to be electrified, 9.7 are within the 15km of existing grid network while 1.1 million are 15km or further from the main grid and are best served by off-grid [31].

From Appendices I and II the charging method and structure is given and was used to determine the customer energy charge for DC-1 and DC-2 customers. Unit charge for DC-1 is ksh15.08 equivalent to $0.142 and for DC-2 the charge is currently at Ksh 22.09971 ($0.21).

By random sampling the following assumptions were made to determine the cost of utility energy:

i) Consumers P. F's are acceptable and therefore no surcharges by the utility company due to poor power factor.
ii) Average consumption duration is 4 hrs.
iii) Power is majorly required at night in a rural set-up customer class DC-1(<100 units).
iv) Power is required both during the day and at night in a rural set-up customer class DC- 2 (>100 units).
v) Billing cycle is for 30 days.
vi) Utility connection fee for REA is Ksh 35,000 equivalent to $330.189
vii) US Dollar conversion considered at Ksh106 [27].
viii) The duration of study for the grid power is taken as 25 years.

Table 4.5: Components of an Energy Bill for Random Consumers across DC-1 and DC-2 Category

Variable charges	**Pass-Through Charges**
Daily consumption:	FCC(B): Ksh.2.50 Per Kwh
Unit charge:	Forex Adjustment (C): Ksh0.077 Per Kwh
Billing Cycle: 30 Days	Inflation Adjustment (D): Ksh 0.1 per Kwh
Daily charge:	WARMA: Ksh0.0248per Kwh
Monthly charge:	VAT : 16%(A+B+C+D)
Total Monthly consumption(A)	ERC LEVY: Ksh0.03per Kwh
	REP-LEVY: 5%(A)

a) **For daily consumption of 0.012Kwh (Tier 1 minimum) the monthly bill will be:**

Monthly consumption 0.012kwh×30= 0.36 Kwh

Consumption charge: 0.36 kwh× ksh 10/kwh =Ksh3.6

Pass-Through Charges

FCC : Ksh.2.50 per Kwh =ksh2.50/kwh × 0.36 Kwh=ksh0.9

Forex Adjustment : Ksh0.077 per Kwh =ksh 0.077/kwh ×0.36 kwh=ksh 0.02772

Inflation Adjustment :Ksh 0.1 per Kwh=ksh 0.1/kwh × 0.36kwh = ksh 0.036

WARMA :Ksh 0.0248per Kwh =ksh/kwh0.0248 ×0.36kwh = ksh 0.00893

VAT :16% =0.16 (3.6+0.9+0.02772+0.036) = ksh0.73

ERC LEVY :Ksh 0.03 per Kwh=0.03 × 0.36 =ksh 0.0108

REP LEVY : 5% =0.05× ksh3.6 = ksh0.18

Total pass-through charges =ksh1.89345

Total energy charge per month: Total pass-through charges +variable charges=ksh1.89345+Ksh 3.6=ksh5.49345

Total Annual energy cost =(monthly energy cost ×12) +annual connection fee = (5.49345× 12)+ ksh.35,000/25=1,465.9214=$13.829

Life cycle energy consumption charge= annual energy cost ×25 years = ksh5.49345×12×25=Ksh1,648.035

Life cycle cost for grid power= utility connection fee + life cycle energy charge

= ksh 35000 + ksh1,648.035=ksh36,648.035=$345.736

The grid power total costs were calculated based on the minimum Tier consumption levels and random loadings and presented as indicated in Table 4.5 and 4.6 respectively.

4.3.3 Comparison between Solar PV and Grid Power

Considering the recommended technical specifications of the systems, the solar PV LCC and grid system 25-year study (LCC) were compared and the annual savings for the solar PV system determined. The annual saving is defined as the annual cost of grid power because it is a representation of what is saved by using solar PVs in place of grid power. The Minimum values for each tier were put into consideration and analyzed.

Other comparison parameters used to determine the economic effects of solar photovoltaic systems were employed including; PBP and RoI.

(i) Payback Period (PBP)

Payback is the number of years required for the system expenses to balance with the generated income and was determined using Equation 3.2. The PBP for base levels of consumers were determined and presented in Table 4.5.

For example:

$$Payback\ period(4300Wh) = \frac{1503.68}{338.288} \quad =4.445\text{years}$$

From the analysis the PBP achieved by comparing solar PV system to Grid Power Systems varied from 0.3 years for the consumers in tier 0(lowest), 5.7 years for the consumers in Tier 3(medium) and 4.5 years for consumers in tier 5 (highest).as shown in Figure 4.1. This is an indicator that solar photovoltaic systems are economically a viable option for adoption in the less privileged localities in Kenya.

(ii) Return on Investment (RoI)

This is a technique of considering profits in relations to capital invested; a higher rate on investment of an investment refers to a better option. For the base values of each Tier the RoI's were determined by Equation 3.3. and indicated as shown in Table 4.5.

For instance,

1,000Wh, the RoI was determined as:

$$RoI = \frac{1}{4.445} \times 100 = \quad 22.497\%$$

Similarly, for the same specifications considered for the aforementioned RoI for each were determined and the operational trend shown in Figure 4.2. The RoI for the base values of each Tier range from 307%, 17.5% and 21.9% for tier 0, 3 and 5 consumers respectively. This is an indicator that the solar PV projects are viable and more economical for consumers in low ranges (Tiers).

Table 4.5 shows a summary of solar LCC, 25-year study of the grid power system (referred to as the Grid LCC) and the annual savings achieved by solar PV consumers. The analysis only shows the low range values of each Tier of the Multi-Tier Framework System.

Table 4.5: Solar-Grid Power Project PBP Simulation

Solar -Grid Project PBP Simulation							
#	**TIER**	**0**	**1**	**2**	**3**	**4**	**5**
1	**Solar PV size**	3	3.5	60	300	1000	2400
2	**Daily consumption (Wh)**	12.9	15.05	258	1290	4300	10320
3	**Monthly consumption(kWh)**	0.387	0.4515	7.74	38.7	129	309.6
4	**Tariff($/kWh)**	0.142	0.142	0.142	0.142	0.21	0.21
5	**Annual Grid varriable costs($)**	0.659448	0.769356	13.18896	65.9448	325.08	780.192
6	**Annual Grid Total costs($)**	13.867448	13.977356	26.39696	79.1528	338.288	793.4
7	**Solar capital costs($)**	3.552	4.144	71.04	355.2	1184	2841.6
8	**Solar PV LCC ($)-(S)**	4.51104	5.26288	90.2208	451.104	1503.68	3608.832
9	**Grid LCC-25 Year Study-(U)**	346.6862	349.4339	659.924	1978.82	8457.2	19835
10	**Payback period (Years)**	0.32529706	0.376529009	3.41784812	5.699154041	4.444969966	4.548565667
11	**Return on Investment (PV)**	3.07411329	2.655837868	0.29258175	0.175464638	0.224973399	0.219849525

The summary of the economic parameters (LCC, PBP and RoI) for the solar PV system were summarized in Table 4.5. Based on the data in Table 4.5 regarding the economic parameters of the study the following observations were made:

(i) The payback period for small consumers in tier 1,2 and 3 lies between three months to three years which is an indicator that solar PVs for rural population in category DC-1 and DC-2 is a viable option considering a life time of 25 Years. A system is considered viable if the payback period is low compared to the life time of the project. The relationship between payback period and the different tiers is shown in Figure 4.2.

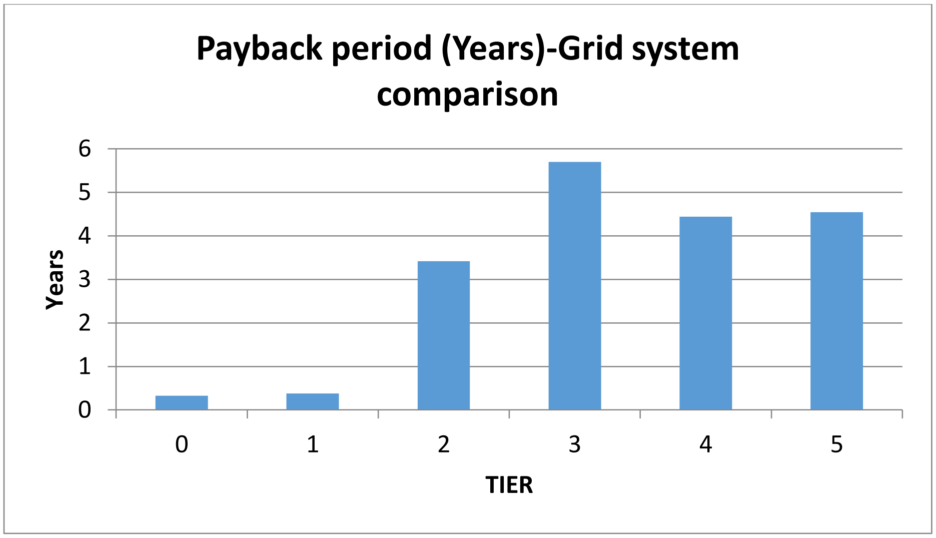

Figure 4.2: Payback Period Trend Compared to Grid System

(ii) The return on investment for DC-1 and DC-2 category of consumers ranges between 307.1%. to 17.555 This is an indicator that economically comparing solar PV system and grid power connection over a period of 25 years solar PVs is a viable option. The interpretation trend of ROI is shown in figure 4.3.

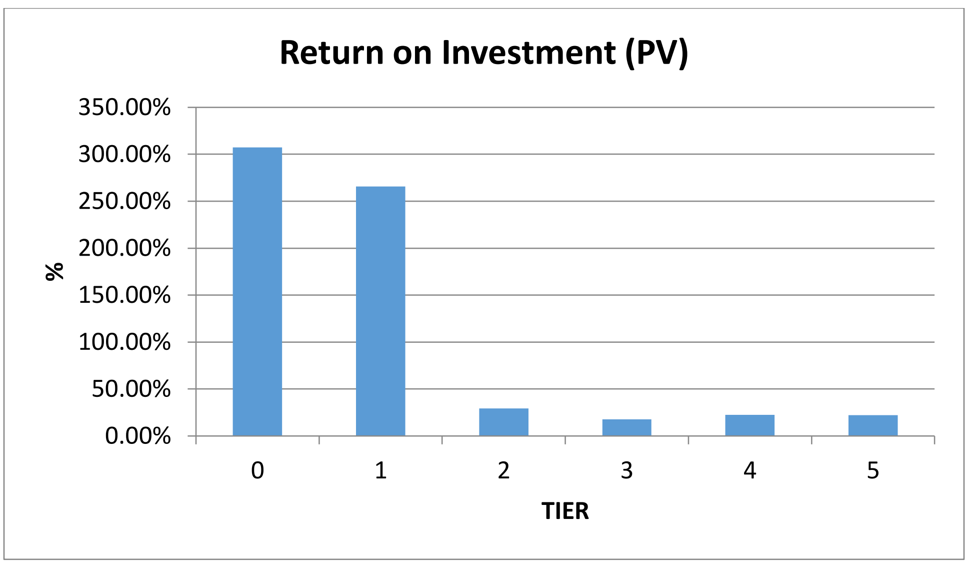

Figure 4.3: Return on Investment -Grid Comparison

(iii)The relationship between the solar panel size and maximum power output (Wp) is a direct proportionality, this implies that an increase in consumer demand increases the Wp rating of the solar panel hence an increase in the ratings and costs of BOS. Figure 4.4 is a representation of this relationship.

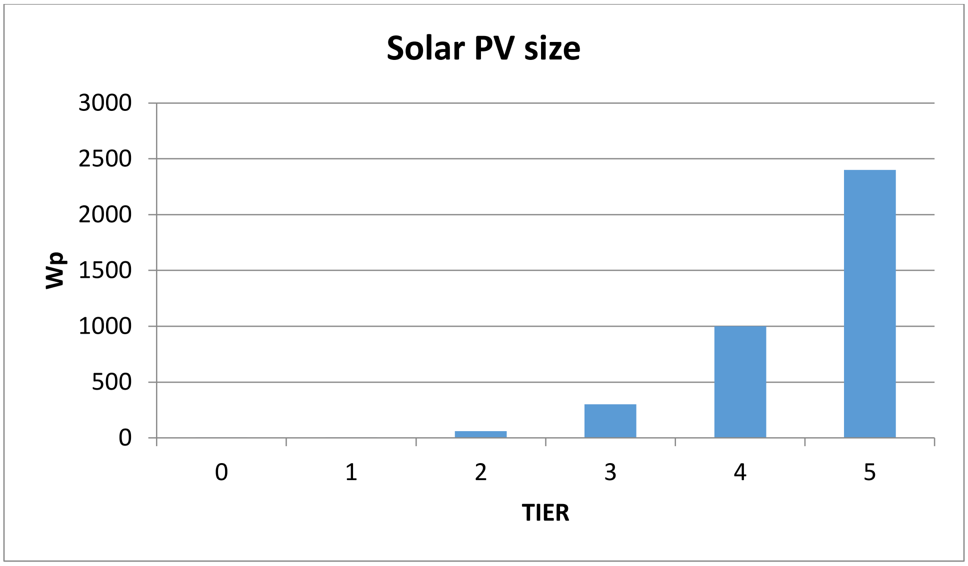

Figure 4.4: Comparison of Solar PV Size and Daily Generation /Consumption

(iv) The capital investment and LCC are directly proportional to the level of consumption(Tier) as represented in Figure 4.5.

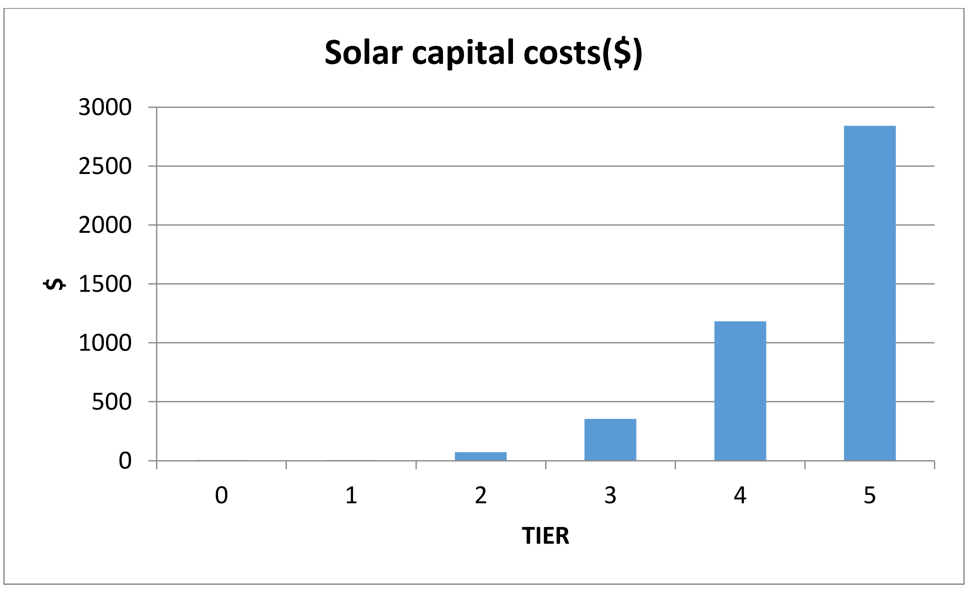

Figure 4.5: Solar Capital Costs

(v) Solar PV systems do not have monthly recurring costs while Grid supply systems have recurring costs (monthly/annual variable costs) which are charged monthly by the utility company. Analysis of the variable costs by the utility company indicates that the larger the consumption the greater the variable costs incurred by grid power consumers as represented in Figure 4.6.

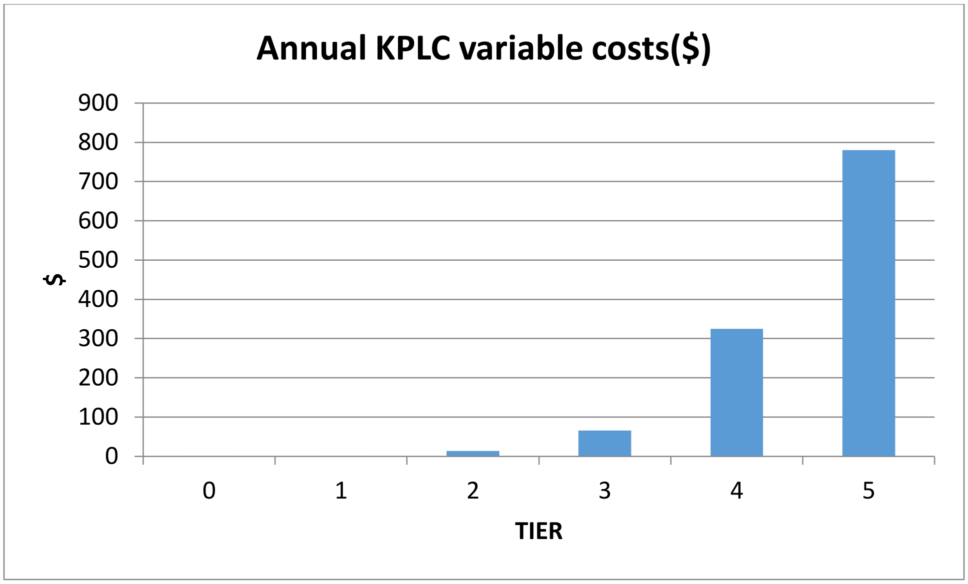

Figure 4.6: Annual Grid Variable Costs

(vi) The annual saving is equivalent to the total utility (U) charges and vary directly to the consumer level.

The connection fee for grid power system estimated as $ 13.21 per year for a 25-year analysis is part of the annual savings enjoyed by solar PV consumers. The connection charges are not favorable for small consumers in Tiers 1 and 2. Of the rural population. The KPLC annual total costs based on each tier is a representation of the annual saving achieved by a solar PV consumer per Tier. It consists of both the variable and fixed charges for grid power. Figure 4.7 is a representation of the annual saving from grid power systems, the trend indicates a direct proportionality between the tier level and the cost of energy. Figure 4.8 represents the time factor of grid consumers considering a 25-year duration.

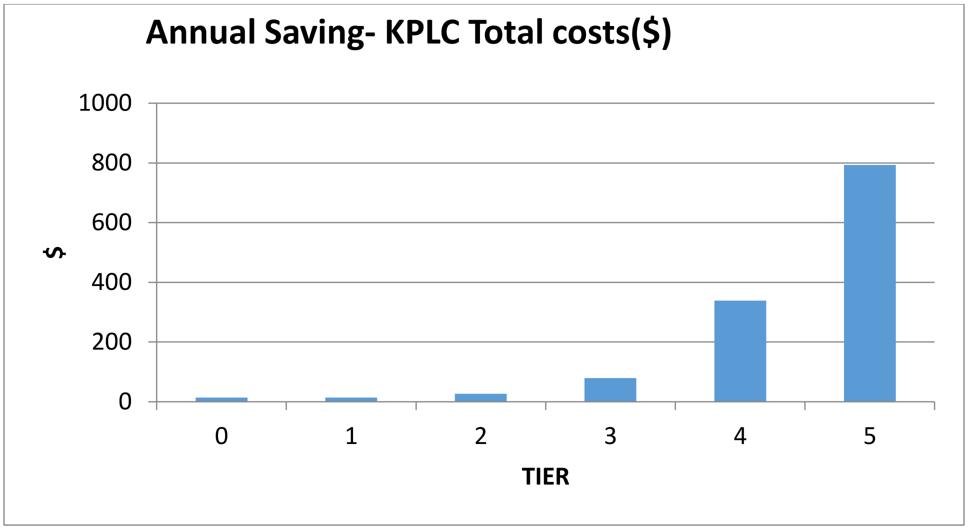

Figure 4.7: Annual Saving Relative To Grid Power

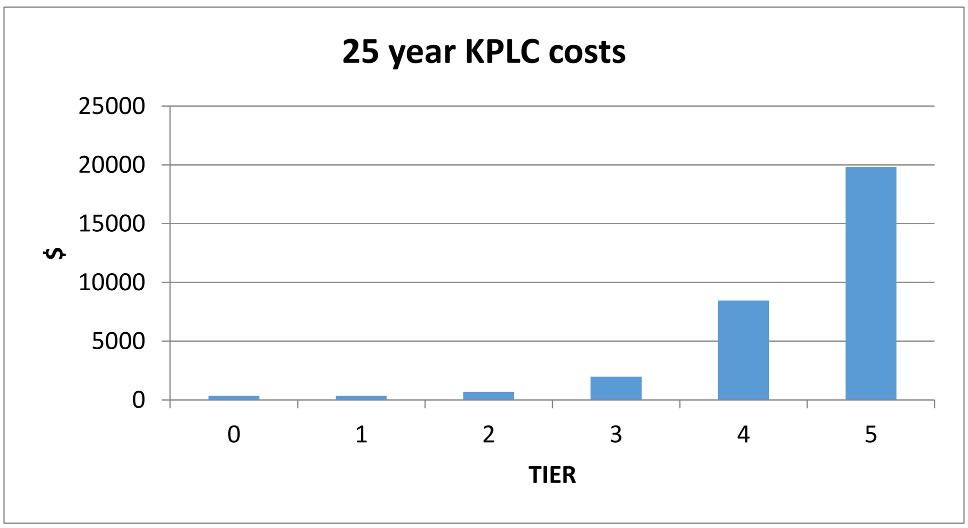

Figure 4.8: Grid Total Costs

Other Observations

Despite the challenge of storage in solar PV systems which can be countered by increasing the size /capacity of the system, grid power systems have a challenge of getting power disconnection in case of delayed or non-payment of the variable costs (monthly power bill).

4.3.3.1 Comparison of Economic Tools for Grid System and Solar PV System Based on a Broad/Expanded Multi-Tier System.

In order to expand and have a wide range of the Multi-Tier Framework several random solar sizes were selected for each Tier as shown in Table 4.6. The purpose of the expanded analysis was to determine the optimum points of operation for the available sources of power (grid and solar PV) for the Kenyan rural population.

Table 4.6: Summary of Economic Parameters Based on the Multi-Tier Framework for Solar PV and Grid Electricity

Solar Project PBP Simulation													
#	TIER	1	1	2	2	3	3	4	4	4	4	5	5
1	Solar PV size	3	30	80	150	300	600	900	1200	1500	1800	2100	2500
2	Daily consp. (Wh)	12.9	129	344	645	1290	2580	3870	5160	6450	7740	9030	10750
3	Monthly consum(kWh)	0.387	3.87	10.32	19.35	38.7	77.4	116.1	154.8	193.5	232.2	270.9	322.5
4	Tariff($/kWh)	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.21	0.21	0.21	0.21	0.21
5	Annl KPLC var costs($)	0.659448	6.59448	17.58528	32.9724	65.9448	131.89	197.8344	390.096	487.62	585.144	682.668	812.7
6	Annual KPLC Total costs($)	13.867448	19.80248	30.79328	46.1804	79.1528	145.098	211.0424	403.304	500.828	598.352	695.876	825.908
7	Solar capital costs($)	3.552	35.52	94.72	177.6	355.2	710.4	1065.6	1420.8	1776	2131.2	2486.4	2960
8	Solar PV LCC ($)-(S)	4.51104	45.1104	120.2944	225.552	451.104	902.208	1353.312	1804.416	2255.52	2706.624	3157.728	3759.2
9	Grid LCC($)-25 Year study-(U)	346.6862	495.062	769.832	1154.51	1978.82	3627.44	5276.06	10082.6	12520.7	14958.8	17396.9	20647.7
10	Payback period (Years)	0.3252971	2.278017703	3.906514668	4.88415	5.699154041	6.21794	6.4125124	4.4740841	4.503582	4.52346445	4.537774	4.5515965
11	Return on Invest (PV)	3.0741133	0.438978151	0.255982656	0.2047439	0.175464638	0.16082	0.1559451	0.2235094	0.222045	0.22106949	0.2203724	0.2197031

From the Tabulations made it is observed that the maximum payback period actually lies in Tier 4 with a solar panel of 1190Wp and a daily consumption of approximately 5.117Kwh with a PBP of 6.5 years. Most domestic consumers in a rural set-up do not operate in this level. This expanded analysis helps to realize a deviation of 10.9% in the PBP compared to the analysis using base value consumers though the economic characteristics remain unchanged.

4.3.4 Diesel Generators Economic Effects Analysis

The average specific fuel consumption in kg/unit for most off-grid diesel generators is 0.29 kg/unit generated [22]. This specific fuel consumption is used in this research to determine the economic parameters of a diesel generator. The average diesel cost in May-June 2020 according to the energy and petroleum regulatory authority (EPRA) was ksh.80.00 and will be used to evaluate the generator running cost within the multi-tier framework as guided by the PV system generation and consumption, the fuel cost fluctuates with the global market prices [25]. The diesel generator initial cost is $1000/Kw including installation cost and the estimated reviving cost is 20% of the total initial cost of the generator and the annual repairs and maintenance for a diesel generator is 5% of the initial capital cost (C) [26**].** Similarly like for solar PVs and grid power by considering the technical specifications the capital investment, total annual energy cost and the life cycle costs were calculated and used in determining the economic impacts of solar photovoltaic.

4.3.4.1 Life Cycle Cost Analysis for Diesel Generator Systems

Considerations for Analysis

i) Off grid generator consumption is 0.29 Litres /unit generated. [22, 24]
ii) Average diesel cost (Ksh. 80.00) $0.755.
iii) $Generator\ Initial\ Price = \$1000/Kw$ (4.5)
iv) Reviving cost =20% of Initial generator cost
v) Operations and maintenance costs =5% of Initial generator cost
vi) To convert the generator rating from Kw to KVA divide Kw rating by 0.8(power factor) for generators.

4.3.4.2 Technical Analysis of the Diesel Generator Rating/Generator Sizing

In order to be able to determine the capital investment for any category of the consumers, it is necessary to evaluate the generator ratings. In determining the generator ratings, the following parameters need to be identified:

i) The actual loads.
ii) Starting current/running current.
iii) Anticipated future load needs.

iv) Nature of the loads (resistive or inductive).

For example:

Considering a system with the following parameters:

Operation period =4hrs.

loading=purely resistive.

running current=starting current.

Anticipated future load needs=25%

In case the system has inductive loads like A.C motors (e.g. water pumps) then, the starting current is usually 2 to 3 times the running current hence the generator size would be greater. To get the appropriate size of a generator supplying an inductive load the normal generator size is multiplied by 3.

For example:

a) Consumers in Tier 1 having a daily consumption of 258Wh, purely resistive load,

Then,

$$Actual\ load = \frac{Consumption(Wh)}{Operation\ time} \quad (4.6)$$

$$= \frac{258\ Wh}{4h}$$

= 64.5 watts

$$Recommended\ generator\ size = actual\ load\ \times safety\ factor \quad (4.7)$$

Where safety factor is equal to 1.25

$$Recommended\ generator\ size = 64.5x1.25$$

=80.625W

= 85W generator at 240 V, 50Hz (not Practical) resistive load

=85×3 =255 W generator at 240 V, 50Hz inductive load

b) Consumers in Tier 2 having a daily consumption of 4300Wh

$$Actual\ load = \frac{Consumption(Wh)}{Operation\ time}$$

$$= \frac{4300Wh}{4h} = 1.075Kw$$

Then,

$$Recommended\ generator\ size = actual\ load\ \times safety\ factor$$

$$= 1075w \times 1.25$$

=1343.75 watts

= 1.4 Kw generator at 240V, 50 Hz for purely resistive load

= 1.4 x 3= 4.2 Kw generator, 240V, 50 Hz for inductive loading.

c) Consumers in Tier 4 having a daily consumption of 10,320Wh

Then,

$$Actual\ load = \frac{Consumption(Wh)}{Operation\ time}$$

$$= \frac{10320Wh}{4h} = 2580W$$

Then,

$$Recommended\ generator\ size = actual\ load\ \times safety\ factor$$

Recommended generator size = actual load ×1.25

=2580W×1.25

=3.225Kw

=3.225Kw generator at 240 V, 50Hz resistive load

=3.225Kw ×3 =9.675KW= 10 Kw generator, 240V, 50Hz

Inductive load

From the generator sizing analysis, it is observed that it is not practical to have diesel generators for consumers in tier 0, tier 1 and lower ranges of tier 2.

4.3.4.3 Economic Analysis of Diesel Generators

After identification of generator sizes, determination of the capital investment and the lifecycle cost was done using Equation (4.5). For example:

For Consumers in Tier 4 having a daily consumption of 4,300Wh

Then,

Generator Initial cost=$1000/Kw x 1.4Kw

=$1400

Total Reviving cost=20% × Generator Initial cost =$1400×0.2 = $280

Total O&M =5%==$1400×0.05 = $70

Generator Capital investment = Generator Initial cost +reviving cost +O&M

=$(1400+280+70) = $1750

Daily fuel consumption = 0.29L/kwh = 0.29 ×4.3=1.247 L

$$Daily\ \ fuel\ Consumption\ cost = Daily\ fuel\ consumption \times unit\ fuel\ cost$$

$Daily\ \ fuel\ Consumption\ cost = 1.247L \times$ $0.755 = $0.941

$$Monthly\ \ fuel\ Consumption\ cost = Daily\ fuel\ consumption\ cost \times 30$$

$Monthly\ \ fuel\ Consumption\ cost = 0.941 \times 30$=$28.23

$Annual\ energy\ cost = Monthly\ \ fuel\ Consumption\ cost \times 12 months$

=$28.23 ×12 =$338.76

$Lifecycle\ cost =$ Generator Capital investment $+$ $(Annual\ energy\ cost \times 25)$

= $1750+ ($338.76×25) =$10,219

Similarly, all the other tiers were analyzed to determine the capital investment, LCC and the annual energy cost of using diesel generators for supplying electrical power for rural population in Kenya. The outcome of the same was compared with the solar power system equivalent(s) as shown in Table 4.7.

Table 4.7: Economic Comparison of Diesel Generator(G) and solar PV (S)

Solar PV/Diesel Generator Simulation							
#	Tier	0	1	2	3	4	5
1	Daily Consumption(Wh)	12.9	15.05	258	1290	4300	10320
2	Monthly Consumption(Wh)	387	451.5	7740	38700	129000	309600
3	Actual Load(W)	3.225	3.7625	64.5	322.5	1075	2580
4	Gen. Size(Kw)	0.00403125	0.0047	0.080625	0.403125	1.34375	3.225
5	Gen. Initial Capital($)	4.03125	4.7031	80.625	403.125	1343.75	3225
6	Reviving &O&M	1.0078125	1.1758	20.15625	100.7813	335.9375	806.25
7	Gen. Capital Invest.($)	5.0390625	5.8789	100.78125	503.9063	1679.688	4031.25
8	Gen. Fuel Consumption(L)	0.003741	0.0044	0.07482	0.3741	1.247	2.9928
9	Gen. Monthly Fuel Con(L)	0.11223	0.1309	2.2446	11.223	37.41	89.784
10	Fuel Cost($)	0.755	0.755	0.755	0.755	0.755	0.755
11	Monthly Fuel Cost($)	0.08473365	0.0989	1.694673	8.473365	28.24455	67.78692
12	Gen. Annual Fuel Cost($)	1.0168038	1.1863	20.336076	101.6804	338.9346	813.44304
13	Gen LCC($)	30.4591575	35.536	609.18315	3045.916	10153.05	24367.326
14	Solar LCC($)	4.51104	5.2629	90.2208	451.104	1503.68	3608.832
15	Gen. Annual Costs($)	1.2183663	1.4214	24.367326	121.8366	406.1221	974.69304
16	PBP(Years)-G comparison	3.702531825	3.7025	3.702531825	3.702532	3.702532	3.702531825
17	RoI	0.270085457	0.2701	0.270085457	0.270085	0.270085	0.270085457

Observations

(i) From the comparison made between the solar PV System and the Diesel Generator the following observations were made:

(ii) The solar PV System LCC is 14.8% of the Diesel generator LCC as represented in Table 4.8.

(iii) The average PBP of solar PV systems in comparison to diesel generators is approximately 3.7years equivalent to 16.67% as shown in Table 4.8 and 4.9.

(iv) The annual savings achieved by a solar PV user are directly proportional to the consumer need.

(v) The major component of the diesel generator costs was identified as the initial generator cost including the installation costs which entails approximately 80% of the capital generator cost as shown in Figure 4.8. From this observation it is evident that for majority of the rural poor population it is difficult to acquire a diesel generator because there are no available diesel generators for lower ratings in the market.

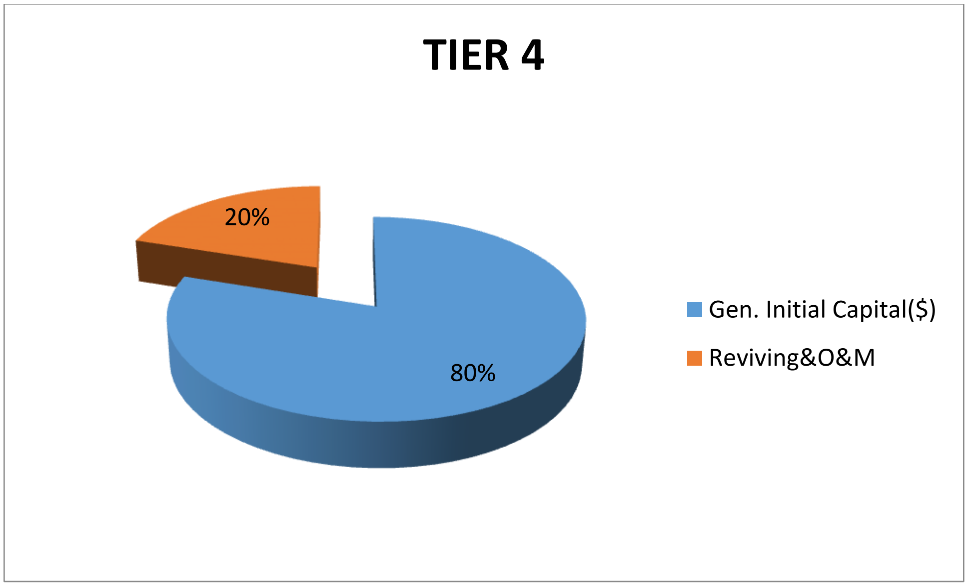

Figure 4.9: Diesel Generator Capital Cost

4.4 Economic Impact comparison of S, U and G based on the Multi-Tier Framework

A detailed comparison on the economic parameters was carried out for the three sources of electrical power (solar photovoltaic systems, grid power systems and diesel generator power systems) for a typical Kenyan rural set-up as indicated in Table 4.8. The relationship between the three sources of electrical power in terms of the economic parameters were compared to determine the impact of solar PV systems as a source of electrical power for the Kenyan rural population. These relationships are illustrated in Figures 4.10, 4.11 and 4.12.

Table 4.8: Economic Impact comparison of S, U and G Based on the Multi-Tier Framework

Solar PV/Diesel Generator/Grid System Simulation							
#	Tier	0	1	2	3	4	5
1	Daily Consumption(Wh)	12.9	15.05	258	1290	4300	10320
2	Gen LCC($)-(G)	30.4591575	35.536	609.18315	3045.916	10153.05	24367.33
3	Solar LCC($)-(S)	4.51104	5.2629	90.2208	451.104	1503.68	3608.832
4	Grid 25 year LCC-(U)	346.6862	349.4339	659.924	1978.82	8457.2	19835
5	Gen. Annual Costs($)	1.2183663	1.4214	24.367326	121.8366	406.1221	974.693
6	Annual Grid Costs($)	13.86745	13.97736	26.39696	79.1528	338.288	793.4
7	PBP (Years)-G. Comparison	3.702531825	3.7025	3.702531825	3.702532	3.702532	3.702532
8	PBP (Years)-U- Comparison	0.325	0.377	3.418	5.699	4.445	4.549
9	RoI (%)-U. Comparison	307.411	265.584	29.258	17.547	22.497	21.985
10	RoI (%)-G. Comparison	27.01	27.01	27.01	27.01	27.01	27.01

The lifecycle costs and the annual savings for the solar photovoltaic system, the diesel generator and 25-year study for grid power systems was done and compared as shown in figure 4.10 and 4.11 respectively. From the LCC trend in figure 4.10 solar PVs have the minimum LCC of approximately $4.5 in comparison to U and G with $347 and $30.5 respectively. This is an indicator that solar PVs are a favorable option for adoption as a source of power in Kenya especially for the rural population.

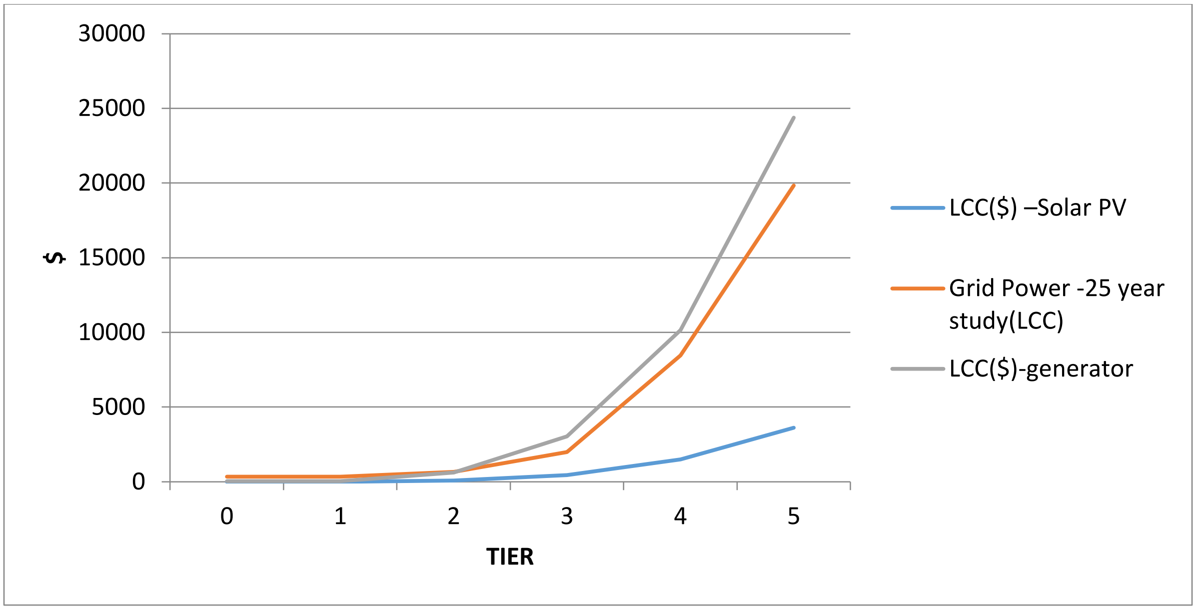

Figure 4.10. Grid-Solar-Diesel Generator LCC Comparison

The annual savings incurred by solar PVs consumers with respect to grid power and diesel generator users is as shown in figure 4.11. The relationship indicates that there is a cost saving for solar PV users.

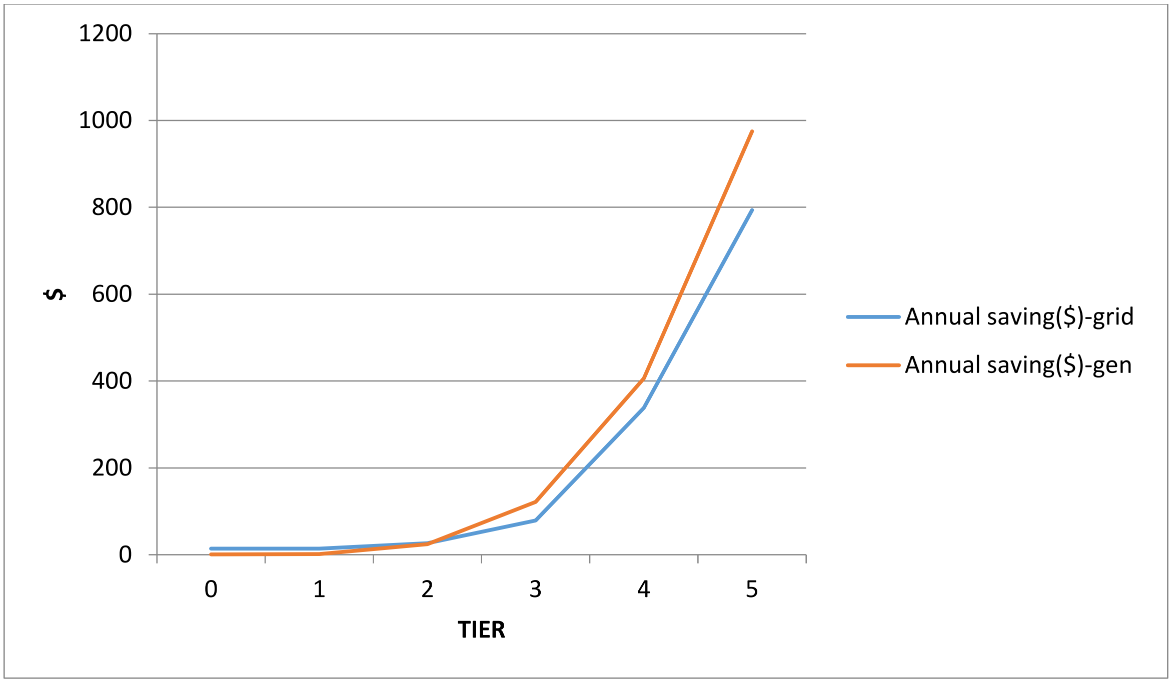

Figure 4.11. Generator and Grid Annual Saving Comparison.

The PBP of solar PVs compared to grid supply and diesel generator systems is as shown in Figure 4.12 and the percentage relationship indicated on Table 4.9.

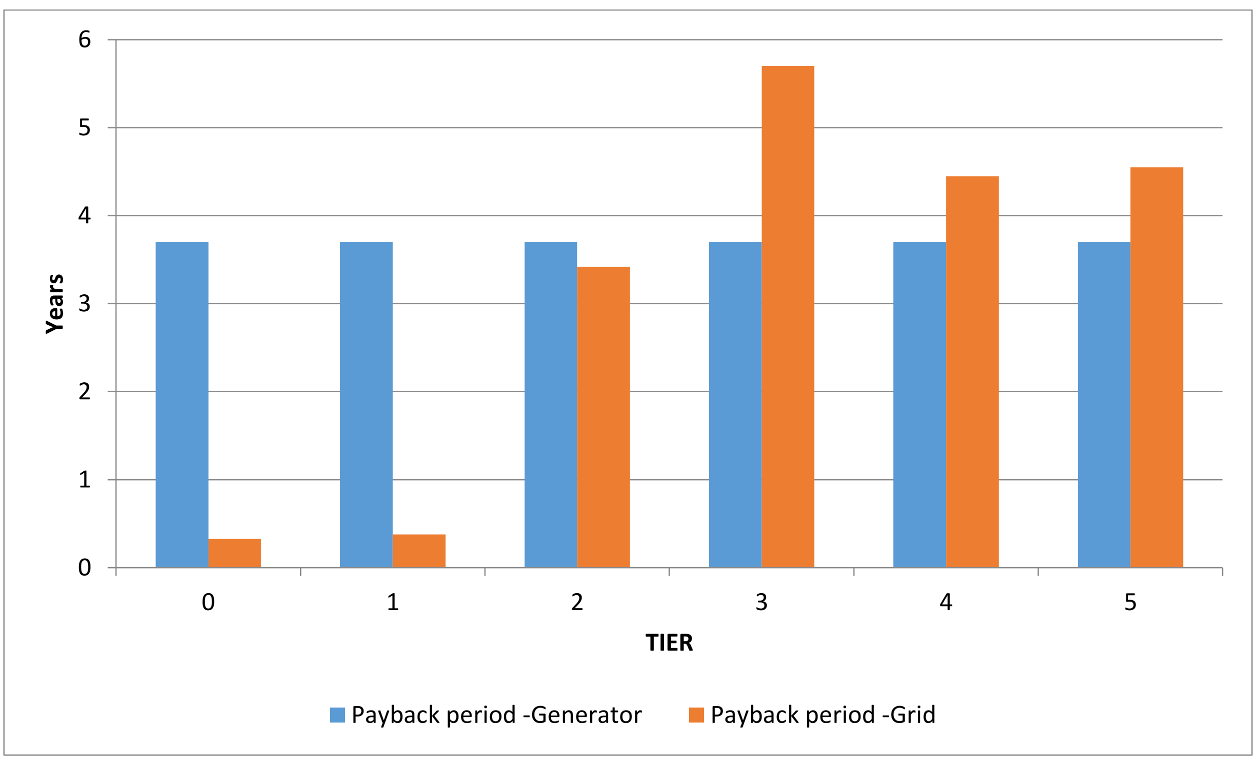

Figure 4.12: Solar PV System PBP

Table 4.9: Percentage Relationship of Solar PBPs

1	PBP-Gen. comparison	16.67%	16.67%	16.67%	16.67%	16.67%	16.67%
2	PBP-Grid comparison	1.73%	2.00%	18.17%	30.29%	23.63%	24.18%

4.4 Summary of Observations/ Conclusion on the Economic Impacts of Solar PV Systems in Kenya

From the economic analysis of the three competing sources of energy for rural population in Kenya it is evident that solar photovoltaic systems are more economical compared to the grid power systems and diesel generators in terms of the following economic parameters:

(i) **Lifecycle Cost**

The data analysis done guided by the multi-tier framework indicate that considering all levels of consumers, solar PVs have the minimum LCC compared to grid power system and diesel generators as a source of power for rural population in Kenya. Thus the solar PV System LCC is 14.8% of the Diesel generator LCC and variable for the utility LCC.

(ii) **Payback Period**

The payback period is determined considering two options i.e. grid power source and diesel generator power source. From the analysis it is noted that for small consumer's category DC-1 and DC-2 grid power serves as a better option compared to diesel generator as a source of power but solar PV systems are the most economical in terms of PBP. The percentage relationship between the PBPs is as represented in Table 4.9.

(iii) **Return on Investment**

A high return on investment means that the investment gains compare favorably to the investment cost. In economic terms, it is one way of considering profits in relations to capital invested. From the analysis done based on the Multi-Tier framework, it is shown that for consumers in Tiers 0, 1, 2 and part of tier 3 which most of the rural population in Kenya lie under have a high return on investment of at least 20%. This is an indicator of the economic superiority of solar PVs systems compared to grid power and diesel generators.

Other Observations

(i) The running cost of the diesel generator system is higher compared to solar PVs and grid power supply due to continuous cost of diesel fuel.

(ii) Available diesel generator capacities are only practical for consumers in tiers 3,4 and 5 only.

(iii)The study analyzed the viability of the options from the following perspective (1) user (2) the energy utility company (KPLC) and (3) the society (Kenya).

(iv)The sensitivity variables for the project are solar radiation and the diesel prices.

(v) The project also considers AC systems as opposed to AC-DC systems or DC systems. The reason for this considerations is because of its compatibility to the Kenyan grid supply and most consumer equipment in the market are A.C.

4.5 Analysis of Environmental Effects

Solar energy is an economically feasible option for power generation as it harnesses the free potential of the sun. However, its integration comes with a few environmental challenges in regards to the following aspects:

1) Use of land resource
2) GHG emissions
3) Disposal of solar panels which contain hazardous materials

In this research, the environmental effects of solar PVs were evaluated by following the two key steps below:

1) Determination of GHG emissions (direct and indirect) from solar PVs, grid power and diesel generators for rural population in Kenya using the Multi-Tier Framework as a guide.
2) Determination of SO_x, NO_x, and particulate matter from the equivalent CO_2 emitted. This is done by matching the consumer level to the GHG emitted and identifying the most appropriate level of operation.

4.5.1 Impact on Use of Land Resource

The scale of integration of solar power generation determines the level of impact that the generation would have on land. For instance, small scale generation is mainly done using solar panels installed on roof tops thus negligible impact on land use. However, large scale generation requires large parcels of land to lay down the panels. The land could have otherwise been used for agricultural purposes or served as habitats for certain wildlife. It is also difficult to have a shared land use model where large scale solar power generation exists unlike for wind power, where the same piece of land can be used for harboring flora and fauna while generation is ongoing. To generate about 1MW of power, 3.5 to 16.5 acres of land is required. The impact on land use can be alleviated by using abandoned pieces of land that have low value, for instance, old mining grounds and brownfields.

4.5.2 GHG Emissions

Carbon footprint refers to the total amount of greenhouse gases produced directly and indirectly to support human activities, usually expressed in equivalent tons of carbon dioxide (CO_2). It is an expression of all emissions of CO_2 (carbon dioxide), which are generated by human activities in a given time frame, usually calculated for the time period of a year. The best technique to understand the environmental impacts of any of the available sources of energy is to calculate the carbon dioxide emissions based on the fuel consumption [36].

Carbon dioxide is referred to as the greenhouse gas causing global warming, other greenhouse gases which might be emitted as a result of human activities include: methane and ozone. These greenhouse gases are normally also taken into account for the carbon footprint. They are converted into the amount of CO_2 that would cause the same effects on global warming and are referred to as equivalent CO_2 amount.

GWP is the warming caused by any GHG as a multiple of warming caused by carbon dioxide of the same mass. According to the international energy agency the relationships of GWP between methane and nitrous oxide is as shown in Table 4.10.

Table 4.10: IEA GHG Emission Factors Database -2019 Edition [36, 37]

GHG Name	Chemical formula	100-year GWP
Carbon dioxide	CO2	1
Methane	CH4	25
Nitrous oxide	N2O	298

Carbon dioxide has a GWP of 1 since it is the baseline unit to which all the other GHG are compared. A GHG with a GWP of 100 means that 1 ton of the gas has CO_2eq of 100 tons. Considering a 100-year GWP for purposes of comparability with international data submission guidelines, the factors from the 4th assessment of the IPCC are used i.e. 1g CH_4 = 25 g CO_2eq and 1g N_2O = 298 g CO_2eq. To convert kg carbon dioxide to kg carbon it is multiplied by a factor 0.27 i.e. 1,000 kg of CO_2 equals 270 kg carbon.

The carbon footprint is a tool used to understand the impact of personal behavior on global warming. Most people would be shocked to realize the amount of CO_2 their daily activities produce. This analysis on the GHG emissions for rural population in Kenya will help create awareness on the individual impact to global warming. It will also help to assist identify the most appropriate/friendly source of power for the rural population in Kenya. Constant monitoring of individual carbon footprint will help the country in minimizing or stopping global warming. An off-line carbon footprint and primary energy consumption calculator (Excel sheet) is attached in appendix 1. This project used an off-line excel carbon footprint and primary energy consumption calculator to check on the carbon footprint of solar PVs, Grid power supply and diesel generators and then compared them to determine the actual environmental effects of solar PVs consumers.

Desk reviews were used in analyzing the environmental effects of solar photovoltaics. GHG emissions for solar photovoltaic systems were compared with other available sources of energy i.e. diesel and hydro power (representing grid power sources). The purpose of selecting hydro power to represent the grid power systems is because it's also a renewable source of power and one of the largest source of power in Kenya. According to the current energy mix in Kenya hydro power represents approximately 29.3% which almost matches the geothermal sources at 29.4% and 25.5% from fossil fuels.

Kenya is among the more virtuous countries in the world environmentally, emitting only 0.03% of the world carbon dioxide poisoning. The energy sector is the third largest contributor for this emissions, this is an indicator that appropriate selection of an appropriate source of energy by considering its environmental effects can reduce this emission further. The study analyzed and compared the carbon footprint of various sources of power and consumers to determine the environmental impacts of adoption of solar photovoltaics.

4.5.2.1 Solar PV GHG Emission

Photovoltaic have been considered as a clean source of renewable energy but considering the holistic lifecycle process involved in material extraction, manufacturing use and disposal of solar PV's the above statement is not true, solar PV's are not emission free. From several reviews Solar PVs in their entire lifecycle has been found to emit between 1g CO_2 – eq/Kwh to 218 g -eq /Kwh and a mean of 49.91 g – eq/Kwh, this project will consider the average CO_2 emission of 49.9 g – eq/Kwh for solar photovoltaics throughout its life time. This is a representation of the amount of GHG's released in gram for every Kwh of electricity that the solar photovoltaic technology provides. [32,42].

The distribution for the life cycle GHG emission emissions of solar PV's consist of direct and indirect emissions and has been found to be distributed as follows [32]:

(i) 71.3% of the total emission are from cultivation and fabrication.
(ii) 19.0% is during construction.
(iii) 13.0% is released during operation. This stage includes maintenance, minor replacements, module cleaning and any other process which occurs when the panel is in use.
(iv) -3.3% is during decomposition/disposal. This is an emission sink considering the recycling of the raw materials. This process involves deconstruction process, disposal, recycling and re-use. The emission breakdown considers this process as a sink of 3.3% of the total emission.

The total emissions consist of direct and indirect emissions. For analysis purposes considered total lifecycle (from manufacturing to disposal) emissions which consist of both indirect and direct emissions and also separately consider the indirect emissions from consumption/operation to disposal.

In the analysis of the environmental impacts in a Kenyan set-up the project will focus on the operation and disposal phases of the solar system life cycle. The reason for focusing on the two stages is because currently Kenya doesn't manufacture solar PVs it only assembles them in Naivasha (Solinc East Africa Ltd). Based on this we therefore find that the indirect emissions solar PVs produce in the Kenya situation comprises of the operation and disposal phases of the solar PVs lifecycle which is 10% of the lifecycle emissions because the recycling stage causes a sink of 3% emission.

(i) Direct Emissions

Direct carbon emissions come from sources that are directly from the site that is producing a product. These emissions can also be referred to as scope 1 and scope 2 emissions.

Scope 1 emissions are emissions that are directly emitted from the site of the process or service. An example for industry would be the emissions related to burning a fuel on site. On the individual level, emissions from diesel combustion on diesel generators or kerosene burning stoves would fall under scope 1. Scope 2 emissions are the other emissions related to purchased electricity, heat, and/or steam used on site.

(ii) Indirect Emission

Indirect carbon emissions are emissions from sources upstream or downstream from the process being studied, also known as scope 3 emissions. Examples of upstream indirect carbon emissions may include any energy used outside of the production facility and Wastes produced outside of the production facility and downstream indirect carbon emissions may include any end-of-life process or treatments, Product and waste transportation and Emissions associated with selling the product.

The total lifecycle GHG emissions from solar PVs can be expressed by Equation (4.8),

$$\text{Total Lifecycle } CO_2 \text{ emitted} = 49.9\text{g/kWh} * \text{consumption(Kwh)} \qquad (4.8)$$

Considering a daily consumption of 4300Wh, for a lifecycle analysis, then;

$$\text{Total } CO_2 \text{emitted daily} = 49.9\text{g/kWh} * 4.3\text{Kwh}$$

$\text{Total } CO_2 \text{emitted daily} = 214.57\text{g } CO_2$

Similarly,

$$\text{Total } CO_2 \text{ emitted annually} = 49.9\text{g/kWh} * 4.3\text{Kwh/day} * (30 * 12)\text{days}$$

$$=77.245\text{kg } CO_2$$

Based on previous specifications/guidelines within the Multi-Tier Framework daily and annual various components of GHG emissions were determined as shown in Table 4.11[32,44]. An excel off-line calculator for the various impact category indicators was utilized as guided by the consumer level and previous published research. The relationship between the various components of the emissions was adopted from previous work [44].

Table 4.11: Lifecycle GHG Emissions for Solar PVs

Carbon Footprint and associated GHGs emissions for Various S Consumers-Lifecycle Analysis							
#	**TIER**	**0**	**1**	**2**	**3**	**4**	**5**
1	Solar PV size	3	3.5	60	300	1000	2400
2	Daily consumption (Wh)	12.9	15.05	258	1290	4300	10320
3	Annual consumption(kWh)	4.644	5.418	92.88	464.4	1548	3715.2
4	Co2 emission factor(g-eq/kWh)	49.9	49.9	49.9	49.9	49.9	49.9
5	Eq.co2 emission(g/kWh)-Daily	0.64371	0.750995	12.8742	64.371	214.57	514.968
6	**Annual eq.Co2 emission(kg/kWh)**	**0.2317356**	**0.270358**	**4.634712**	**23.17356**	**77.2452**	**185.3885**
	Impact category unit for sc-Si [45]						
1	Kg .co2-eq/kWh (Kg)	0.2433456	0.283903	4.866912	24.33456	81.1152	194.6765
2	Kg .CFC11-eq/kWh(Kg)	1.13778E-07	1.33E-07	2.28E-06	1.14E-05	3.79E-05	9.1E-05
3	Kg .NOx-eq/kWh(Kg)	0.00055728	0.00065	0.011146	0.055728	0.18576	0.445824
4	Kg .PM2.5-eq/kWh(Kg)	0.000571212	0.000666	0.011424	0.057121	0.190404	0.45697
5	Kg .SO2-eq/kWh(Kg)	0.001147068	0.001338	0.022941	0.114707	0.382356	0.917654
6	KBq .co-eq/kWh(kBq)	0.0206658	0.02411	0.413316	2.06658	6.8886	16.53264
	Total annual GHG Composition	**0.266287074**	**0.310668**	**5.325741**	**26.62871**	**88.76236**	**213.0297**
	variance(%)	**12.97527262**	**12.97527**	**12.97527**	**12.97527**	**12.97527**	**12.97527**

According to the specified emission distribution the indirect emissions generated through operation and disposal stages in Kenya are derived as shown in Equation (4.9) [32].

$$CO_2 \text{ emitted} = 10\% * 49.9\text{g/kWh} * \text{Kwh} \quad (4.9)$$

Therefore, for every Kwh consumed 4.99g of carbon dioxide is emitted indirectly in Kenya. For example, considering a consumer whose consumption need is in Tier 4 with a daily consumption of 4300Wh then, the carbon dioxide emitted in order for them to consume that power is given by:

$$CO_2 \text{ emitted} = 10\% \ * 49.9\text{g} * 4.3\text{KWh}$$

$$CO_2 \text{ emitted daily} = 21.457\text{g } CO_2$$

$$Annual \text{ CO2 emitted} = 21.457\text{g } CO_2/\text{day} * 30\text{days} * 12$$

$$= 7.725 \ kg \ CO_2$$

Similarly, the same analysis was done for various random consumers within the Multi -Tier Framework as shown in Table 4.12. It is noted that the GHG emissions indirectly emitted in Kenya from solar PV consumers is estimated to be 10% of the total lifecycle GHG emission for solar photovoltaics [32].

Considering the same category of consumers used for economic impacts analysis the daily and annual GHG emissions were calculated using an off-line excel calculator as shown in Appendix III and summarized in Table 4.12 and 4.13.

Table 4.12. Carbon Footprint for Operation and Disposal Stages for Solar PVs Consumers

Carbon Footprint for Various Consumers-Operation and disposal							
#	**TIER**	**0**	**1**	**2**	**3**	**4**	**5**
1	Solar PV size	3	3.5	60	300	1000	2400
2	Daily consumption (Wh)	12.9	15.05	258	1290	4300	10320
3	Annual consumption(kWh)	4.644	5.418	92.88	464.4	1548	3715.2
4	Co2 emission factor(g-eq/kWh)	4.99	4.99	4.99	4.99	4.99	4.99
5	Eq.co2 emission(g)-Daily-(S)	0.064371	0.0751	1.28742	6.4371	21.457	51.4968
6	Annual Co2 emission(kg)-(S)	0.023174	0.027036	0.463471	2.317356	7.72452	18.53885

An expanded category of consumers was also considered as shown in Table 4.13 to countercheck on the trend of GHG emissions. The trend was found to match with the base values consideration.

Table 4.13: Expanded Analysis Based on The Multi-Tier Framework-Operation and Disposal Phases

TIER	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**	**4**	**4**	**5**	**5**
Solar PV size	3	30	80	150	300	600	900	1200	1500	1800	2100	2500
Daily consumption (Wh)	12.9	129	344	645	1290	2580	3870	5160	6450	7740	9030	10750
Annual consumption(kWh)	4.644	46.44	123.84	232.2	464.4	928.8	1393.2	1857.6	2322	2786.4	3250.8	3870
Co2 emission factor(g-eq/kWh)	4.99	4.99	4.99	4.99	4.99	4.99	4.99	4.99	4.99	4.99	4.99	4.99
Eq.co2 emission(g)-Daily	0.064371	0.64371	1.71656	3.21855	6.4371	12.8742	19.3113	25.7484	32.1855	38.6226	45.0597	53.6425
Annual Co2 emission(kg)	0.0231736	0.2317356	0.6179616	1.158678	2.317356	4.634712	6.952068	9.269424	11.58678	13.904136	16.221492	19.3113

4.5.2.2 Hydro Power GHG emission

On the other hand, hydro power generation averagely emits 97g CO_2 eq/Kwh which is higher than PV's, this emission is caused by the rotten organic matter in flooded dams [35,45]. Therefore, to determine the carbon footprint for various consumers of grid power assuming a hydro-power source and based on the Multi-Tier Framework Equation (4.8) is used.

$$\text{Total } CO_2 \text{ emitted} = 97\text{g } CO_2\text{eq/kwh} \quad (4.10)$$

Considering a daily consumption of 4300Wh then the GHG emission would be derived as:

$$\text{Total CO2 emitted} = \frac{97\text{g } CO_2\text{eq}}{\text{kwh}} * 4.3\text{kWh}$$

$$=417.1\text{g } CO_{2\ \text{daily}}$$

Expressing the same in a time frame of one year it will be;

Annual CO2 emitted =417.1 g CO_2 /day ×30 days×12

=150.156kg CO_2

For the same category of consumers used for economic impacts analysis the daily and annual GHG emissions were calculated using an off-line excel sheet calculator as shown in Appendix IV and summarized in Table 4.14. The carbon footprint calculator (excel sheet) provided can be used to calculate the amount of GHG emissions for any category of energy consumer.

Table 4.14: GHG Emissions for Various Grid Consumers

Carbon Footprint for Various grid Consumers-Lifecycle Analysis							
#	**TIER**	**0**	**1**	**2**	**3**	**4**	**5**
1	Solar PV size	3	3.5	60	300	1000	2400
2	Daily consumption (Wh)	12.9	15.05	258	1290	4300	10320
3	Annual consumption(kWh)	4.644	5.418	92.88	464.4	1548	3715.2
4	Co2 emission factor(g-eq/kWh)	97	97	97	97	97	97
5	Eq.co2 emission(g)-Daily(U)	1.2513	1.45985	25.026	125.13	417.1	1001.04
6	Annual Co2 emission(kg)-(U)	0.450468	0.525546	9.00936	45.0468	150.156	360.3744

4.5.2.3 Diesel Generator GHG emissions

Burning of diesel or any other fuels e.g. kerosene, gasoline or petrol produces exhaust gases. Diesel generators are internal combustion engines and produce exhaust like carbon dioxide (CO_2), nitrogen oxides (NO_X) and particulate matter. Diesel exhaust is a group 1 carcinogen which causes lung cancer.

The best way to calculate the carbon dioxide emissions is based on the amount of fuel consumption by the diesel generator. Carbon content of fuels slightly varies, but typically the average carbon content values to estimate CO_2 emissions could be adapted. However, the number of kg of CO_2 produced per liter of fuel consumed by the diesel generator also depends on the characteristics of the diesel generator and the fuel used, and it usually falls in the range of 2.4–2.8 kg/l. Averagely the consumption of one-liter diesel emits around 2.7kg of CO_2 and estimated 0.73 kg of pure carbon [37, 38]. The relationship between the fuel consumption and the generator output in terms of liters is as shown in Table 4.7 in the economic analysis.

The carbon footprint can also be expressed in kg carbon rather than kg carbon dioxide by multiplying with a factor 0.27 (i.e. 1000 kg CO_2 equals 270 kg carbon). The emission factor considered for a diesel generator was 2.7 kg CO_2/kWh.

Several researchers have identified the following relationships in some of the common fuels as shown in Table 4.15.

Table 4.15: Carbon Dioxide Emissions for Common Fuel Types [41, 42]

Fuel type	**Unit (consumed)**	**CO2 emitted per unit (L)**
Petrol	1 Litre	2.3 kg
Gasoline	1 Litre	2.3 kg
Diesel	1 Litre	2.7 kg
Oil (heating)	1 Litre	3 kg

$$\text{Total } CO_2 \text{ emitted} = 2.7\text{ kg } CO_2\text{eq/L} \qquad (4.11)$$

Considering the same category of consumer whose daily energy consumption is 4300Wh and the generator diesel consumption is as shown in Table 4.7 in the economic effects analysis section discussed earlier, the daily and annual emission will be calculated by Equation (4.11)

$$\text{Daily } CO_2 \text{ emitted} = 2.7\text{ kg}\frac{CO_2\text{eq}}{L} * 1.247$$

$$\text{Total } CO_2 \text{ emitted daily} = 3.3669\text{kg } CO_2$$

$$\text{Annual } CO_2 \text{ emitted} = 3.3669\text{kg } CO_{2\ /day} \times 30 \text{ days} \times 12$$

$$= 1{,}212.084\text{kg } CO_2$$

The various GHG emissions for various power consumers using diesel generators were determined by Equation (4.11) and summarized as shown in Table 4.16.an Off-Line excel sheet calculator for the same is attached in Appendix V.

Table 4.16: Diesel Generator GHG Emissions Based On Multi-Tier Framework

Lifecycle Carbon Footprint For Diesel Generator Consumers-Off-Line							
#	Tier	0	1	2	3	4	5
1	Daily power Consumption(Wh)	12.9	15.05	258	1290	4300	10320
2	Annual consumption(kWh)	4.644	5.418	92.88	464.4	1548	3715.2
3	daily generator consumption(L)	0.003741	0.0044	0.07482	0.3741	1.247	2.9928
4	annual generator consumption(L)	1.34676	1.584	26.9352	134.676	448.92	1077.408
3	Co2 emission factor(Kg/L)-diesel	2.7	2.7	2.7	2.7	2.7	2.7
4	Eq.co2 emission(Kg)-daily	0.010101	0.01188	0.202014	1.01007	3.3669	8.08056
5	Annual Co2 emission(kg)	3.636252	4.2768	72.72504	363.6252	1,212.084	2,909.002

Table 4.17 shows the percentage relationship of the components of the exhaust gases from a diesel engine. [39,40]. This percentage relationship will be used in breaking down the GHG emitted from the diesel generator.

Table 4.17: Diesel Generator Exhaust Gas Composition According to Various Sources

	Average Diesel Engine Exhaust Composition[33, 39,40]
Species	**% Mass**
Nitrogen(N2)	75.2%
Oxygen	15%
Carbon dioxide	7.1%
Water	2.6%
Carbon monoxide	0.043%
Nitrogen oxide (Nox)	0.034%
hydrocarbon	0.005%
aldehyde	0.001%
Particulate matter(sulfate +solid substance)	0.008%

From Table 4.17 the components of the GHG can be derived from the equivalent carbon dioxide as shown herein;

Table 4.18: Composition of GHG for Diesel Generators

GHG Composition for Diesel Generator consumers-Off-Line calculator							
#	Tier	0	1	2	3	4	5
1	Daily power Consumption(Wh)	12.9	15.05	258	1290	4300	10320
2	Annual consumption(kWh)	4.644	5.418	92.88	464.4	1548	3715.2
3	daily generator consumption(L)	0.003741	0.0044	0.07482	0.3741	1.247	2.9928
4	annual generator consumption(L)	1.34676	1.584	26.9352	134.676	448.92	1077.408
3	Co2 emission factor(Kg/L)	2.7	2.7	2.7	2.7	2.7	2.7
4	Eq.co2 emission(Kg)-daily	0.0101007	0.01188	0.202014	1.01007	3.3669	8.08056
5	Annual eq.Co2 emission(kg)	3.636252	4.2768	72.72504	363.6252	1212.084	2909.002
	Major GHG Components - G						
	Nitrogen	2.734461504	3.216154	54.68923	273.4462	911.4872	2187.569
	Oxygen	0.5454378	0.64152	10.90876	54.54378	181.8126	436.3502
	Carbon dioxide	0.258173892	0.303653	5.163478	25.81739	86.05796	206.5391
	Water	0.094542552	0.111197	1.890851	9.454255	31.51418	75.63404
	carbon monoxide	0.001563588	0.001839	0.031272	0.156359	0.521196	1.250871
	Nitrogen Oxide	0.001563588	0.001839	0.031272	0.156359	0.521196	1.250871
	Hydro carbon	0.000181813	0.000214	0.003636	0.018181	0.060604	0.14545
	Aldehyde	3.63625E-05	4.28E-05	0.000727	0.003636	0.012121	0.02909
	particulate matter	0.0002909	0.000342	0.005818	0.02909	0.096967	0.23272
	Total GHG Emission(Kg)-eq.co2	3.636252	4.2768	72.72504	363.6252	1212.084	2909.002
	Variance(%)	-2.44257E-14	0	1.95E-14	-1.6E-14	1.88E-14	-1.6E-14

4.6 GHG Emission Comparison Between Solar PVs (S), Grid Power (Hydro Power) (U) And Diesel Generator Power Source (G)

The off-line excel calculator as attached in Appendix VI was used to compare the level of GHG emissions for S, U and G for selected consumers and the following information presented in Table 4.19 was derived.

Table 4.19: GHG Emission Comparison for S, U and G

GHG Emission Comparison for Solar PVs, Hydro Power and Diesel Generators-Off-Line calculator							
#	Tier	0	1	2	3	4	5
1	Daily Power Consumption(Wh)	12.9	15.05	258	1290	4300	10320
2	Annual Power Consumption(kWh)	4.644	5.418	92.88	464.4	1548	3715.2
3	GHG Emission Factor(g/kWh)-S	49.9	49.9	49.9	49.9	49.9	49.9
4	Annual GHG Emissions(Kg)-S	0.231736	0.270358	4.634712	23.17356	77.2452	185.3885
5	GHG Emission Factor(g/kWh)-U	97	97	97	97	97	97
6	Annual GHG Emissions(Kg)- U	0.450468	0.525546	9.00936	45.0468	150.156	360.3744
7	Annual Gen. Consumption(L)-G	1.34676	1.584	26.9352	134.676	448.92	1077.408
8	GHG Emission factor(Kg/L)-G	2.7	2.7	2.7	2.7	2.7	2.7
9	Annual GHG Emissions(Kg)- G	3.636252	4.2768	72.72504	363.6252	1212.084	2909.002
8	GHG Emissions Ratio(S:U:G)	1:1.9:15.7	1:1.9:15.7	1:1.9:15.7	1:1.9:15.7	1:1.9:15.7	1:1.9:15.7
	GHG Emissions by Percentage						
	Solar PV (%)	5.366168	5.329666	5.366168	5.366168	5.366168	5.366168
	Utility(%)	10.43123	10.36027	10.43123	10.43123	10.43123	10.43123
	Diesel Gen.(%)	84.2026	84.31006	84.2026	84.2026	84.2026	84.2026

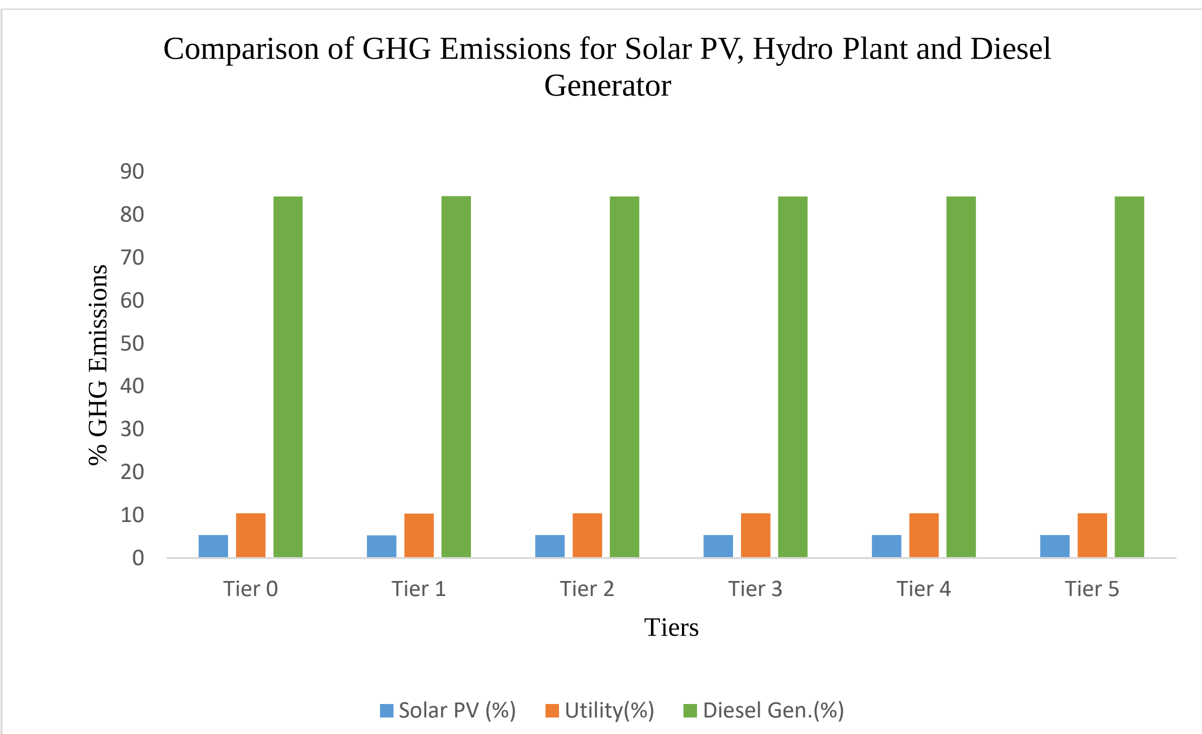

Figure 4.13: Percentage S, U and G GHG Emission

4.6.1 Summary on the Relationship Between Solar PVs, Grid Power and Diesel Generator Power Source.

(i) From Figure 4.13 it is observed that solar PVs have the least GHG emissions of averagely 5% compared to 11% of hydro power GHG emissions and 84% of diesel generator GHG emissions. This makes solar PVs a favorable consideration in terms of GHG emissions.

(ii) Solar photovoltaics systems are not 100% clean as most studies claim based on their lifecycle analysis. Throughout their life time they emit some components of greenhouse gases including the following: carbon, carbon dioxide, Sulphur oxides, particulate matter etc. as illustrated in Table 4.11.

4.7 Lifecycle Impact Analysis (LCIA) of Solar PV systems

The lifecycle impact analysis was done through a characterization factor to classify the environmental impacts of solar PVs into midpoint and endpoint impact categories/indicators. Midpoint categories only focus on a single environmental problem example climate change or acidification while endpoint indicators break the environmental impacts into three levels i.e. human health, ecosystem and social (resource scarcity) [44]. According to [46] the emission factor of PV systems also depends on the size of the system i.e. the Wp rating.

4.7.1 Classification of the Environmental Effects of solar Photovoltaic systems

The environmental effects were categorized into the following categories:

(I.) Midpoint Category

Global Warming

From the analysis in Table 4.11 carbon dioxide is one of the GHGs emitted in the solar PVs lifecycle. CO2 emissions is directly responsible for global warming effect and its effects is represented by 5.24 *10^-2 Kg CO2-eq/kWh [44]. The percentage relationship between the major components of solar PVs emissions is as shown in Figure 4.14.

(II.) Endpoint Categories

(A). Ecosystem Level

(i) Emission of trichlorofluoromethane (CFC-11) is responsible for the stratospheric ozone depletion, from the inventory analysis done and presented in Table 4.11 CFC-11 represents 2.5*10^-8 kg/kWh [44]. Ozone depletion has a direct negative effect on the ecosystem.

(ii) Considering solar PV farms, there is a lot of heat emitted from the solar panels which affects the thermal balance of the area hence affecting the ecosystem.

(iii) CFC availability in the LCIA of SET (solar energy technologies) and its direct attachment to ozone depletion causes adverse effects on plants, humans and environment.

(B). Health Level

Emission of NOx in solar PVs lifecycle account for 1.2*10^-4 kg NOx-eq/kWh and NOx respiratory exposure can trigger and exacerbate existing asthma symptoms [44]. NOx reacts with volatile organic compounds in the presence of sunlight to form ozone. Ozone can cause adverse effects such as damage to lung tissue and reduction in lung function mostly in susceptible populations (children, elderly, asthmatics). Ozone can be transported by wind currents and cause health impacts far from the original sources.

Presence of PM in the inventory analysis is an indicator that SET emit approximately about 0.2% throughout the lifecycle of the system compared to other GHGs and toxic gases. The relationship may seem small but it cannot be ignored because inhaling of PM and Exposure to such particles can affect both the lungs and heart. Numerous scientific studies have linked particle pollution exposure to a variety of problems, including: ... decreased lung function. increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing.

The ozone depletion which is caused by CFCs result in secondary production of an ozone layer near the ground (terrestrial ozone layer), which causes adverse effects on plants, humans and environment with increased number of bronchial diseases in human.

(C). Social Level

Accidental release of the toxic substances of solar cell modules to the soil and ground water poses a great danger to the environment and society. The solar technology industry through its enormous growth has also contributed to lifestyle improvement through creation of jobs

For large solar farms it may lead to displacement of people and loss of agriculturally productive land hence loss of live hood.

A summary of the main components of a solar photovoltaic systems emission together with their impact category is presented in Table 4.20. The relationship between the various emissions of the same is captured in Figure 4.14.

Table 4.20: Summary of Environmental Impact Indicators for Solar PVs Consumers

	Carbon Footprint and associated GHGs emissions for Various S Consumers-Lifecycle Analysis							
#	**TIER**		**0**	**1**	**2**	**3**	**4**	**5**
1	Solar PV size		3	3.5	60	300	1000	2400
2	Daily consumption (Wh)		12.9	15.05	258	1290	4300	10320
3	Annual consumption(kWh)		4.644	5.418	92.88	464.4	1548	3715.2
	Impact category unit for sc-Si [45]	**Impact Category**						
1	Kg .CO2-eq/kWh (Kg)	• Global warming	0.2433456	0.283903	4.866912	24.33456	81.1152	194.6765
2	Kg .CFC11-eq/kWh(Kg)	• Ozone depletion	1.13778E-07	1.33E-07	2.28E-06	1.14E-05	3.79E-05	9.1E-05
3	Kg .NOx-eq/kWh(Kg)	• Ozone formation • Human health • Terrestrial ecosystems	0.00055728	0.00065	0.011146	0.055728	0.18576	0.445824
4	Kg .PM2.5-eq/kWh(Kg)	PM formation	0.000571212	0.000666	0.011424	0.057121	0.190404	0.45697
5	Kg .SO2-eq/kWh(Kg)	• Terrestrial acidification	0.001147068	0.001338	0.022941	0.114707	0.382356	0.917654
6	KBq .co-eq/kWh(kBq)	• Ionizing radiation • Human health • Ecosystem	0.0206658	0.02411	0.413316	2.06658	6.8886	16.53264
	Total annual GHG Composition		**0.266287074**	**0.310668**	**5.325741**	**26.62871**	**88.76236**	**213.0297**
			12.97527262	**12.97527**	**12.97527**	**12.97527**	**12.97527**	**12.97527**

The percentage relationship between the major environmental impact indicators for the adopted levels of consumers of S is represented in Figure 4.14. Some of the GHG and toxic gases like: CFC, NOx, PM, and SO2 have an impact level of less than 1% but it cannot be ignored because it is quantifiable. Carbon dioxide emission for solar PV systems account for the largest GHG emission with 91.4% followed by ionizing radiation with7.8% of the main GHG and toxic gas emissions.

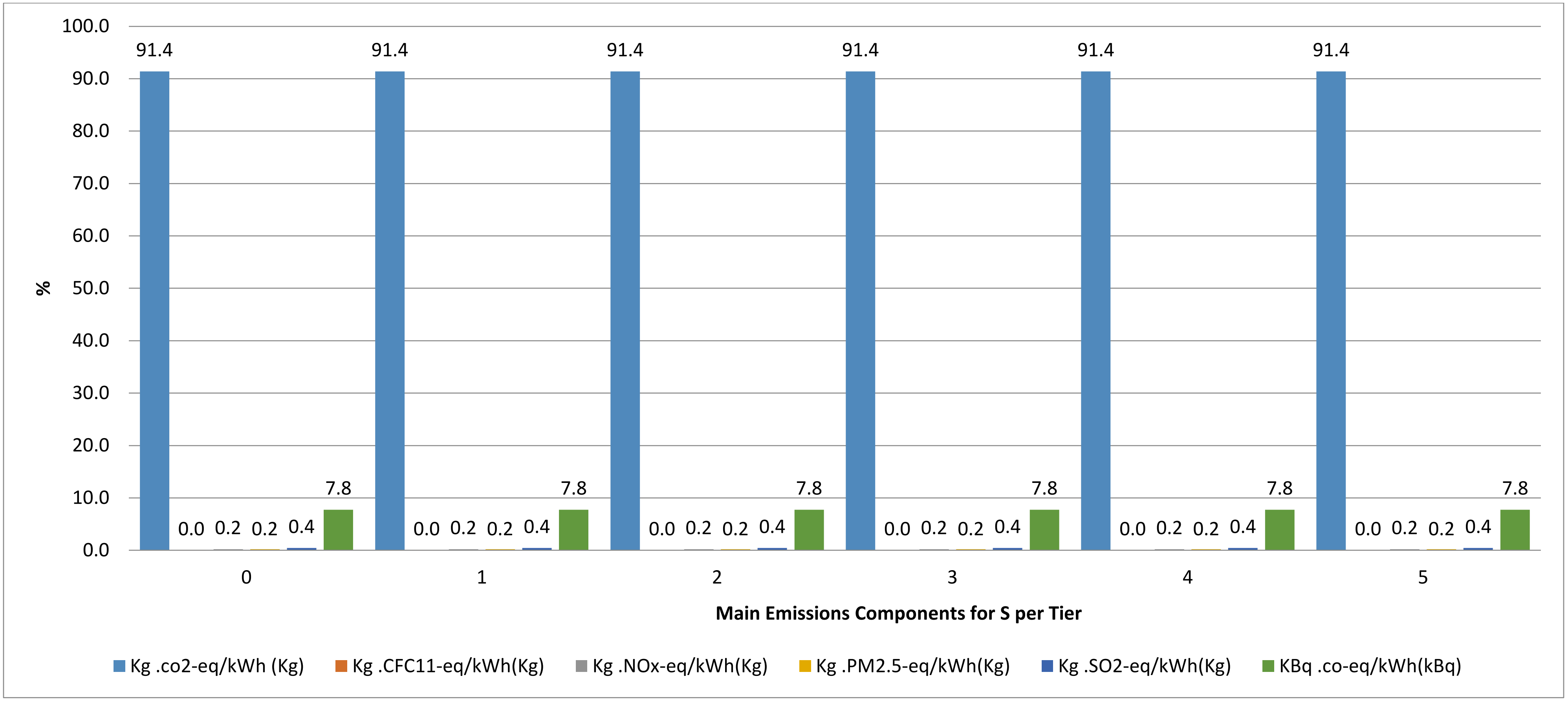

Figure 4.14: percentage relationship of major components of solar PVs emissions

4.8 Interpretation of the Results

Solar energy technologies (SET) have positive environmental impacts when compared to conventional energy (diesel) and Hydro power sources, for instance, reduction of the greenhouse gas emissions (CO2, N2O, CH4, etc.), and prevention of toxic gas emissions (SO2, particulates) as shown in Table 4.20 and interpreted in Figure 4.14. In addition, SETs can reduce transmission lines of electricity grids. Most of the GHG and toxic gases emissions for SET is during the manufacture, construction and transportation phase of their lifecycle, operation phase is almost emission free.

The percentage comparison of the carbon footprint shown in Figure places solar emits the least GHG with an average of 5% compared to an average of 11% of hydro power GHG emissions and 84% of diesel generators emission. This makes SET a better option for adoption compared to the other two sources of energy in terms of the environmental effects.

4.9 Disposal of Solar Photovoltaic Systems in Kenya

Waste disposal of solar PVs in Kenya is a time bomb considering the increased adoption of the system over the past decade following the government's policy of tax exemption on all solar panels and BOS. Lack of information on the appropriate and safe methods of disposal of the solar panels together with the BOS poses a great health hazard to the population. Global sales of off- grid solar devices reached 130 million between 2010 and 2017. In 2016, alone, 8.07 million off-grid solar systems were sold around the world, 3.83 million of them in Sub-Saharan Africa with an estimated 32% of all solar equipment sold in sub-Saharan Africa be sold in Kenya [42,43]

The Environmental Management and Co-ordination (E-Waste Management) Regulations, 2013 and the National E-Waste Management Strategy Revised Draft, April 2019 provides direction on regulations and policies for E-Waste management in Kenya. Much emphasis has only been put on ICT equipment like computers and their accessories and telecommunication devices like mobile phones.

Despite the aforementioned increase in use of solar PVs products in Kenya, nothing specific has been highlighted on the E-Waste management strategy about the safe disposal of specifically the solar panels but only the safe disposal of the BOS has been captured [41].

The key players in the E-waste guidelines include: the government/policy makers, private sector (manufacturers, distributors/ importers) and civil society (refurbishment centers, collectors, recyclers). In the Kenya's E-waste management situation, the informal sector has dominated the process.

4.9.1 The current developments for E-waste management in Kenya are as follows [41].

(i) **Separation of Waste at source**: This involves segregation of various categories of E-waste at the source.

(ii) **Collection:** The existing collection entities are established either individually or jointly or as registered society The established collection entities contract or sub contract the E-waste collectors normally known as ‘scavengers ‘to supply them with the waste.

(iii) **Transportation**: This involves the movement of the collected waste to the designated places or dump sites or recycling facilities for processing. Transportation of waste is carried out by licensed companies.

(iv) **Recycling**: In Kenya recycling involves both formal and informal recycling, hence there exists limited information on the volumes collected and processed. Companies licensed by NEMA as E-waste recyclers as in 2019 included the following: Waste Electrical and Electronic Equipment Centre (WEEE Centre), Sinomet Kenya, Sintmund Kenya and E-waste Initiative Kenya (Ewik).

(v) **Refurbishing**: this is carried out by licensed entrepreneurs and organized groups in order to increase the lifespan of products.

(vi) **E-waste take back**: Some manufacturers have introduced the take back programmes in the country but lack of consistency and awareness to the public poses a big challenge.

(vii) **Trans-boundary waste movement**: This involves movement of waste across foreign countries. Kenya is a signatory to Basel Convection 1994 on trans-boundary movement of waste and can therefore import and export waste.

4.9.2 Current Active E-Waste Recycling Initiatives in Kenya

Following the challenges associated with E-waste management, various stakeholder and groups have risen to collect, treat and properly dispose E-waste (Global Waste Management Outlook, UNEP,2015). In Kenya, several initiatives have been undertaken and these includes:

i) **The WEEE Centre**: It is a privately owned E-Waste management centre located in Nairobi and other major cities in Kenya with constant support from various local and international partners.

It deals with E-waste collection, dismantling and automated processing services. The valuable materials are sold to local recycling facilities for re-use. WEEE has partnered with international partners and this enables them to ship hazardous and non-valuable e-waste to international recyclers and smelters.

ii) **Safaricom Limited**: It's a telecommunication company in kenya and it has actively participated in the collection of used phones and other E-Waste and safe disposal of the same. It has partnered WEEE Centre to receive the collected waste for dismantling and further processing.

iii) **Sintmund Group**: This is a licensed company and operates as an advanced recycling facility for electrical and electronics waste

iv) **Sinomet Kenya Limited**: It deals with transportation, treatment/disposal and trans-boundary movement of E-waste. Sinomet has changed itself into a big trans-boundary mover of E-waste through its international recyclers and up-cyclers of E-waste while also maintaining close ties with its local scrapping partners.

v) **E-waste Initiative Kenya (Ewik):** This is an E-Waste management organization operated by a Kenyan based NGO operating specifically in the informal sector. It provides a safe disposal option across the country through their network

4.9.3 Possible Consequences of Poor E-Waste Handling in Kenya

Environmental Effects

The environmental effects may include the following: Air pollution especially when the E-Waste is burnt, accumulation of large dump sites especially for bio degradable equipment, toxicity and radioactive nature of E-Waste degrades the environment, blockage of water run-off channels, unpredictable weather conditions due to depletion of the o-zone layer etc.

Economic Effects

Poor E-Waste disposal causes the following direct and indirect economic effects: increased public spending on health care, complex investment on environmental remediation technologies, loss of resources that can be recycled for re-use, lost employment,

4.9.4 E-Waste Disposal Challenges in Kenya

After close analysis of the E-waste disposal policies and regulations in Kenya the following gaps were identified regarding solar photovoltaic systems:

(i) **Limited information and awareness:** Successful implementation of policies/regulations requires extensive outreach and awareness raising through training and knowledge transfer systems. This information is widely lacking to majority of the Kenyan population.

(ii) **Weak policies:** the policies and regulations laid down for E-Waste disposal lack solid follow up measures and strict penalties.

(iii) **Resources:** For effective implementation of the E-Waste policies and regulations the government (national and county) require intensive resources to set up collection centres across the country.

(iv) **Solar PVs disposal omission on the E-Waste management regulation 2013:** There is a definition gap on the classification of E-Waste. Solar PVs and its accessories is a wide area of interest on their disposal and should have been classified independently because of the current concerns.

4.10 Research Validation

The results were a clear indication that adoption of solar photovoltaic systems as a source of electrical power for the rural population in Kenya provide superior environmental and economic benefits compared to grid power source from hydro sources and diesel generator power sources. According to previous researches few works have considered combined Economic and Environmental effects analysis for solar PV. In [4] only the GHG (CO_2) for the LCIA and Energy Pay Back Time (EPBT) for the LCCA were analyzed. Other similar works include [12], [13] and [14] which did not consider the other parameters of Environment like the composition of the GHG and Cost. In this project, LCCA, LCIA and LCCA-LCIA approaches in the PV analysis have been done. The results obtained for the economic and environmental effects for the three sources of power in rural Kenya are presented in Table 4.8 and Appendix I, II, III and IV.

Environmental impacts were classified into midpoint and end point categories based on the multitier framework. The LCA of the environmental effects used the four stages (definition of scope, inventory analysis, LCIA and interpretation of results) to determine the environmental impacts of solar systems by comparing it to another RE (hydro power) and fossil fuels. The disposal mechanism of E-Waste available in Kenya were also discussed together with the challenges in solar photovoltaic disposal. Properly designed Solar PVs application provide higher economic benefits and enjoy minimum GHG and toxic gases emissions compared to hydro power and fossil fuels sources of energy

4.11 Chapter Conclusion

This chapter quantified the economic impacts of solar photovoltaic systems by LCC, PBP, ROI while the environmental impacts where quantified by the LCIA approach/ technique. The solar PV System LCC is 14.8% of the Diesel generator LCC and variable for the utility LCC while the ROI for solar PVs is above 20% across all the five Tiers of the Multi-Tier Framework. The highest PBP of Solar PVs is less than 7 years considering a lifetime of 25 years. The percentage GHG emissions for SET is 5% compared to grid power and diesel generator power sources at 11% and 84% respectively.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

This chapter gives a summary of the project conclusion and recommendations for future work.

5.1 Conclusion

The economic and environmental effects of solar photovoltaic systems were studied. In quantifying both the positive and negative economic and environmental effects the solar photovoltaic system were compared to the most applicable sources of electrical power in the Kenyan rural setup i.e. the grid power (hydro-power) and fossil fuels application on diesel generators. In the following paragraphs, a summary of the quantifiable economic and environmental impacts is presented.

Regarding all the studied systems (the photovoltaic systems, grid systems and the diesel generator systems), the systems were categorized to have the same nominal levels of consumers/capacity using a standard framework (The Multi-Tier Framework). The economic effects of the solar PVs were determined using the following Economic Tools: LCC, PBP and ROI as presented in Table 4.8 and 4.9 of the results. In Tier 1 the solar PVs have the minimum LCC of approximately $4.5 considering a 25-year life time in comparison to U and G with $347 and $30.5 respectively. This trend is similar for all the other Tiers which is an indicator that it is economically cheaper in terms of cost to use solar PV technology for power supply compared to grid and diesel generator power. The PBP of solar PV systems compared to diesel generator system is 3.7 years while when comparing PV to grid power supply it ranges between 3 months and approximately 7 years for large consumers in Tier 5, this is an acceptable duration to support adoption of SET. The ROI for solar PVs consumers across all the Tiers is above 20% compared with the two alternatives under this study. Considering the above mentioned economic impact measurement tools it is clear that solar PV Systems can be adopted as a favorable option as a source of electrical power for the Kenyan rural population.

Considering the environmental impacts of solar PVs, the same system and specifications were used in order to determine the GHG and toxic gases emissions. Most researches have been done on the GHG emission i.e. the equivalent carbon dioxide emission and the global warming or the carbon avoidance aspect, this research project expanded the emission aspect by classifying them into midpoint and endpoint impact categories/indicators. The various main components and contribution of the equivalent carbon dioxide emissions were identified as: CO_2 (91%), CFC at almost 0% though in terms of quantity (kg)the emissions are minimal, NOX (0.2%), SO2(0.4%), PM (0.2%) and kBq ((7.8%) as presented in Table 4.20 and Figure 4.13 of the results section. These components were further categorized into: Ecosystem, health and social levels in order to bring out their specific environmental impact contribution. From this environmental impact conclusion, it is clear that solar PVs are not emission free considering their lifecycle though when compared to the available energy alternatives solar PVs may provide a better option. Continuous improvement on the manufacturing processes/technologies may reduce the emissions further.

Waste disposal being one of the potential problems facing the solar PV systems end of life was discussed and the major challenges in the current Kenyan situation identified as the following: Limited information and awareness, Weak policies, Resources, Solar PVs disposal omission on the E-Waste management regulation 2013.

5.2 Recommendations

In this research the assumption made was that grid power source is only from Hydro-power, however in determining the ideal economic impacts, a collaboration with the relevant utility companies i.e. KENGEN, KETRACO and KPLC is required/ necessary in order to get the actual data especially on the lifecycle costing of grid power supply in reference to the Kenya energy mix. Further research(expansion) on all the available emissions from the solar photovoltaic systems can be done to determine all the components of the total emissions. Education, Training and Public Awareness on climate change issues receive minimal consideration in Kenya's formal education system. The level of awareness on climate change is low across the country, climate change issues can be incorporated in the education curriculum in order to increase awareness. This area can form a basis for further scientific research in order to regularly update available knowledge and build confidence in mainstreaming climate change information in decision making.

REFERENCES

[1] Nygaard, I., Hansen, U.E., Larsen, T.H., Palit, D., & Muchunko, C. (2018)" off-grid access to electricity innovation challenge". In accelerating the green energy revolution-perspectives on innovation challenges: DTU International energy report 2018 (pp47-54)

[2] Kenya Climate Innovation Centre" Kenya Solar PV Market Assessment"

[3] Onsomu, L., A.," SOCIO-Economic Impacts of Photovoltaic Solar Installation and Use: A Case Study of Borabu Division in Nyamira County "2013

[4] Vishakha Baharwani et al, "Life Cycle Analysis of Solar PV System: A Review" International Journal of Environmental Research and Development. ISSN 2249-3131 Volume 4, Number 2 (2014), pp. 183-190

[5] Azzopardi B and Mutale J. 2010. "Life cycle analysis for future photovoltaic systems using hybrid solar cells," Renewable and Sustainable Energy Reviews 14, no. 3 (April 2010): 1130-

[6] Nawaz I. and Tiwari GN. 2006. "Embodied energy analysis of photovoltaic (PV) system based on macro- and microlevel," Energy Policy 34, no. 17 (November 2006): 3144-3152.

[7] Sherwani AF, et al. 2010. "Life cycle assessment of solar PV based electricity generation systems: A review," Renewable and Sustainable Energy Reviews 14, no. 1 (January 2010): 540-544.

[8] Ito M, et al. 2009. "A Comparative LCA Study on Potential of Very-large Scale PV Systems in Gobi Desert," Institute of Electrical and Electronics Engineers, NY:IEEE.

[9] Levine MD and Aden NT. 2008. "Global Carbon Emissions in the Coming Decades: The Case of China," Annual Review of Environment and Resources, Vol. 33: 19-38 (November 2008).

[10] Dones, R., Heck, T., & Hirschberg, S. (2003) Greenhouse gas emissions from energy systems: Comparison and overview. PSI annual report.

[11] Gagnon, L., Belanger, C., & Uchiyama, Y. (2002) "Life-cycle assessment of electricity generation options: The status of research in year 2001," Energy Policy 30, 1267--1278

[12] Lenzen M, J. Munksgaard, 2002, "Energy and CO2 life-cycle analyses of wind turbines—review and applications", Renewable Energy 26, July 02 p339-362

[13] Fthenakis V and Alsema E. 2006. “Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs,” Progress in Photovoltaics 14, no. 3 (May 2006), 275–280.

[14] Pehnt, M. (2006) {Dynamic life cycle assessment (LCA) of renewable energy technologies}. Renewable Energy 31, 55--71.

[15] Abu-Rumman, A.K., Muslih,I., Barghash ,M.A., ”Life Cycle Costing Of PV Generation System “Journal of Applied Research on Industrial engineering. Vol 4,No.4(2017)PP252-258

[16] Carbinet S., Belbooms, Leornard” A lifecycle analysis (LCA) of photovoltaic panels: A review’ Renewable and Sustainable Energy Reviews 38 (2014) 717 – 753

[17] Mahmud M.A.P energies 2018, 11, 2346, Huda N, Farjana S.H and Lang C. , environmental impacts of solar photovoltaic “2018, energies

[18] H. C. Kim, et al. "Energy Payback and Life-Cycle CO2 Emissions of The BOS in An Optimized 3·5 MW PV Installation." Progress in Photovoltaics 14.2 (2006): 179-190. Environment Complete. Web.

[19] L., Lu, and Yang H.X. "Environmental Payback Time Analysis of A Roof-Mounted Building-Integrated Photovoltaic (BIPV) System In Hong Kong." Applied Energy 87. (n.d.): 3625-3631. ScienceDirect. Web.

[20] Knapp, K., and T. Jester. "Empirical Investigation of the Energy Payback Time for Photovoltaic Modules." Solar Energy -Phoenix Arizona Then New York- 71.3 (2001): 165-172. British Library Document Supply Centre inside Serials & Conference Proceedings. Web.

[21] V.M., Fthenakis, and Kim H.C. "Photovoltaics: Life-Cycle Analyses." Solar Energy 85. Progress in Solar Energy 1 (n.d.): 1609-1628. ScienceDirect. Web

[22] Energy & Petroleum Regulatory Authority, "Energy & Petroleum Regulatory Authority," 1 July 2018. [Online]. Available: www.epra.go.ke. [Accessed 16 June 2019].

[23] Hsu et al. “Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation” Journal of Industrial Ecology. Volume 16, Number S1 (2012), pp.S122-S133

[24] https://www.epra.go.ke/download/the-energy-act-2019

[25] https://www.epra.go.ke/services/petroleum/petroleum-prices/

[26] Nidah A. and Khaled A. (2019), "Techno-economic Comparison of Solar power tower system/photovoltaic electrical energy to small loads" Journal of Taibah University for Science, 13:1, 216-224, DOI:10 1080/16583655.2018.1556916.

[27]https://www.google.com/search?q=current+currency+exchange+rates+in+kenya&oq=c&aqs=chrome.1.69i59l2j69i60l4j5l2.2850j0j7&sourceid=chrome&ie=UTF-8, [Accessed 29 June 2020]

[28] https://globalsolaratlas.info/map

[29] http://www.leonics.com/support/article2_12j/articles2_12j_en.php

[30] Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity 3rd Edition. Report IEA-PVPS T12-08:2016.

[31] https:// Energypedia (5 June 2018). "Kenya Energy Situation". Energypedia.info. Retrieved 3 July 2020.

[32] Nugget D., Sovacool B.K, "Assessing Lifecycle Greenhouse Gas Emissions from Solar PV and Wind Energy: A Critical Meta-Survey", Energy Policy 65(2014) pp 229-244

[33] Shamal M.K, "Economic and environmental analysis of remote diesel generator with photovoltaic cogeneration", International Journal of Scientific and Research Publications, Volume 7, Issue 8, August 2017 533ISSN 2250-3153www.ijsrp.

[34] https://www.juancole.com/2013/05/funding-africas-largest.html

[35] A.D Marco, I. Petrosillo., T. Semeraro, M.R Persimani, R. Aredano, G. Zurlini, "The contribution of utility scale solar energy to the global climate regulation and its effects on local ecosystem services global ecological conservation 2 (2014)" pg. 324-337

[36] http://wds.iea.org/wds/pdf/CO2KWH_Methodology.pdf, Retrieved 30 July 2020

[37] https://timeforchange.org/what-is-a-carbon-footprint-definition, Retrieved 30 July 2020

[38] https://energy education .ca/encyclopedia/diesel generator emissions, Retrieved 30 July 2020

[39] Konrad, Reif (ed), "Diesel Motor Management Systems and Components". 2nd Edition. Springer Fachmedien, Wiesbaden, 2014, ISBN 978-3-658-06554-6. P.171

[40] https://en.wikipedia.org/wiki/diesel_exhaust ,Retrieved 3 July 2020.

[41] Ministry of Environment and Forestry, “National E-Waste Management Strategy Revised Draft”, April 2019

[42] World Bank/Dalberg, “The 2018 Off-Grid Solar Market Trends Report”, International Finance Corporation (2018)

[43]https://www.gogla.org/sites/default/files/resource_docs/global_offgrid_solar_market_report_h1_2019.pdf,retrieved

[44] Milousi M., Et al., “Evaluating the Environmental Performance of Solar Energy Systems Through a Combined Life Cycle Assessment and Cost Analysis”, Sustainability,2019, doi:10.3390/su11092539

[45] Pehl et al., “understanding the future emissions from low carbon power systems by integration of lifecycle assessment and integrated energy modeling, nature energy”, 2017, dol:10.1038/541560-017-0032-9.

[46] Gunerhan H., Et al, “Environmental Impacts of Solar Energy Systems”, Research gate,2009, PP 134

APPENDICES

Appendix I: Pass-through Charges, Taxes and Levies for October 2018

Parameter	Unit Of Measure	Applicable Rate
Fuel Cost Charge (FCC)	Ksh/kWh	2.50
Forex Adjustment (Forex)	Ksh/kWh	-0.077
Inflation Adjustment (Infla)	Ksh/kWh	0.1
Water Resource Management Authority(WARMA)	Ksh/kWh	0.0248
VAT	%	16%
ERC Levy	Ksh/kWh	0.03
REP Levy	%	5%

Appendix II: Total Cost per Unit (October 2018 Pass-through costs)-approved electricity tariffs

Parameter	Unit Of Measure	Applicable Rate	Dc 1	Dc 2	Sc 1	Sc 2
Energy Rate (A)	Ksh/kWh		10	15.8	10	15.6
Fuel Cost Charge (FCC) (B)	Ksh/kWh	2.5	2.5	2.5	2.5	2.5
Forex Adjustment (Forex) (C)	Ksh/kWh	-0.0768	-0.0768	-0.0768	-0.0768	-0.0768
Inflation Adjustment (Infla) (D)	Ksh/kWh	0.1	0.1	0.1	0.1	0.1
WARMA	Ksh/kWh	0.0248	0.0248	0.0248	0.0248	0.0248
VAT	%	16% of (A+B+C+D)	2.003712	2.931712	2.003712	2.899712
ERC Levy	Ksh/kWh	0.03	0.03	0.03	0.03	0.03
REP Levy	%	5% of (A)	0.5	0.79	0.5	0.78
Total Cost	Ksh/kWh		15.08171	22.09971	15.08171	21.85771
Old Tariff	Ksh/kWh		22.09971	22.09971	21.85771	21.85771

Appendix III: Off-Line Excel Carbon Footprint Calculator for Solar PV Consumers

Carbon Footprint/associated GHGs for Various S Consumers-Lifecycle Analysis							
#	**TIER**	**0**	**1**	**2**	**3**	**4**	**5**
1	Kg .co2-eq/kWh (Kg)	0.243	0.284	4.867	24.335	81.115	194.676
2	Kg .CFC11-eq/kWh(Kg)	0.000	0.000	0.000	0.000	0.000	0.000
3	Kg .NOx-eq/kWh(Kg)	0.001	0.001	0.011	0.056	0.186	0.446
4	Kg .PM2.5-eq/kWh(Kg)	0.001	0.001	0.011	0.057	0.190	0.457
5	Kg .SO2-eq/kWh(Kg)	0.001	0.001	0.023	0.115	0.382	0.918
6	KBq .co-eq/kWh(kBq)	0.021	0.024	0.413	2.067	6.889	16.533
	Total annual GHG Composition	0.266	0.311	5.326	26.629	88.762	213.030
	variance(%)	**12.97527262**	**12.97527**	**12.97527**	**12.97527**	**12.97527**	**12.97527**

Appendix IV: Off-Line Excel Carbon Footprint Calculator for Grid Consumers

Carbon Footprint for Various grid Consumers-Lifecycle Analysis							
#	**TIER**	**0**	**1**	**2**	**3**	**4**	**5**
1	**Solar PV size**	3	3.5	60	300	1000	2400
2	**Daily consumption (Wh)**	12.9	15.05	258	1290	4300	10320
3	**Annual consumption(kWh)**	4.644	5.418	92.88	464.4	1548	3715.2
4	**Co2 emission factor(g-eq/kWh)**	97	97	97	97	97	97
5	**Eq.co2 emission(g)-Daily(U)**	1.2513	1.45985	25.026	125.13	417.1	1001.04
6	**Annual Co2 emission(kg)-(U)**	0.450468	0.525546	9.00936	45.0468	150.156	360.3744

Appendix V: Off-Line Excel Carbon Footprint Calculator for Diesel Generators Power Consumers

GHG Composition for Diesel Generator consumers-Off-Line calculator							
#	Tier	0	1	2	3	4	5
1	Daily power Consumption(Wh)	12.9	15.05	258	1290	4300	10320
2	Annual consumption(kWh)	4.644	5.418	92.88	464.4	1548	3715.2
3	daily generator consumption(L)	0.003741	0.0044	0.07482	0.3741	1.247	2.9928
4	annual generator consumption(L)	1.34676	1.584	26.9352	134.676	448.92	1077.408
3	Co2 emission factor(Kg/L)	2.7	2.7	2.7	2.7	2.7	2.7
4	Eq.co2 emission(Kg)-daily	0.0101007	0.01188	0.202014	1.01007	3.3669	8.08056
5	Annual eq.Co2 emission(kg)	3.636252	4.2768	72.72504	363.6252	1212.084	2909.002
	Major GHG Components - G						
	Nitrogen	2.734461504	3.216154	54.68923	273.4462	911.4872	2187.569
	Oxygen	0.5454378	0.64152	10.90876	54.54378	181.8126	436.3502
	Carbon dioxide	0.258173892	0.303653	5.163478	25.81739	86.05796	206.5391
	water	0.094542552	0.111197	1.890851	9.454255	31.51418	75.63404
	carbon monoxide	0.001563588	0.001839	0.031272	0.156359	0.521196	1.250871
	Nitrogen Oxide	0.001563588	0.001839	0.031272	0.156359	0.521196	1.250871
	Hydro carbon	0.000181813	0.000214	0.003636	0.018181	0.060604	0.14545
	aldehyde	3.63625E-05	4.28E-05	0.000727	0.003636	0.012121	0.02909
	particulate matter	0.0002909	0.000342	0.005818	0.02909	0.096967	0.23272
	Total GHG Emission(Kg)-eq.co2	3.636252	4.2768	72.72504	363.6252	1212.084	2909.002
	Variance(%)	-2.44257E-14	0	1.95E-14	-1.6E-14	1.88E-14	-1.6E-14

Appendix VI: Off-Line Excel Carbon Footprint Calculator for Comparison of S, U& G Consumers

GHG Emission Comparison for Solar PVs, Hydro Power and Diesel Generators-Off-Line Excel Sheet							
#	Tier	0	1	2	3	4	5
1	Daily Power Consumption(Wh)	12.9	15.05	258	1290	4300	10320
2	Annual Power Consumption(kWh)	4.644	5.418	92.88	464.4	1548	3715.2
3	GHG Emission Factor(g/kWh)-S	49.9	49.9	49.9	49.9	49.9	49.9
4	Annual GHG Emissions(Kg)-S	0.231736	0.270358	4.634712	23.17356	77.2452	185.3885
5	GHG Emission Factor(g/kWh)-U	97	97	97	97	97	97
6	Annual GHG Emissions(Kg)- U	0.450468	0.525546	9.00936	45.0468	150.156	360.3744
7	Annual Gen.Consumption(L)-G	1.34676	1.584	26.9352	134.676	448.92	1077.408
8	GHG Emission factor(Kg/L)-G	2.7	2.7	2.7	2.7	2.7	2.7
9	Annual GHG Emissions(Kg)- G	3.636252	4.2768	72.72504	363.6252	1212.084	2909.002
8	GHG Emissions Ratio(S:U:G)	1:1.9:15.7	1:1.9:15.7	1:1.9:15.7	1:1.9:15.7	1:1.9:15.7	1:1.9:15.7
	GHG Emissions by Percentage						
	Tier	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
	Solar PV (%)	5.366168	5.329666	5.366168	5.366168	5.366168	5.366168
	Utility(%)	10.43123	10.36027	10.43123	10.43123	10.43123	10.43123
	Diesel Gen.(%)	84.2026	84.31006	84.2026	84.2026	84.2026	84.2026

Appendix VII: Turnitin Report

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Suggestion/Question	Answer	page
Modify the title to capture the multi-tier framework.	Replaced a case study of rural Kenya with using the Multi-Tier Framework	Cover Page
Suggested I modify the specific objectives (i) and (ii)	Replaced analyze and determine with “to perform.”	3,4
Table 3.1 Tier 0 was blank	Inserted negligible	13
Shift approved electricity tariffs to appendices	Table 3.2 and 3.3 were shifted to Appendix I and II.	77
Minimize much mathematical calculations on the report	Minimized mathematical calculations	Done