TECHNO-ECONOMIC ASSESSMENT OF GRID-TIE SOLAR PV SYSTEM IN KENYA

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DECLARATION

Student Declaration

I hereby do declare that this project is my original work and has not been submitted for the award of degree in another University.

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DEDICATION

I dedicate the research work to my dear mum, dad, and family members who gave me time and encouragement during the research period.

ABSTRACT

An increase in the cost of electricity in Kenya is partly due to the significant reliance on fossils fuels, which are unsustainable as well as environmentally unfriendly. In the electricity generation mix of 2854 MW in 2021, 26% was obtained from thermal (fuel) while solar contributed 2%. The adverse effects related to fossil fuel have resulted in the government and private investors exploring the abundant renewable energy source (solar) as an alternative, although at a slower pace. The purpose of this study was to increase the uptake of solar Photovoltaic (PV) technology in Kenya by providing crucial information to be considered by investors in solar PV technology. The main objective of the study was to fill the knowledge and contextual gap on the technical and economic analysis of the performance of the grid-tie solar (PV) systems in Kenya. Specific objectives were to evaluate and compare the monthly performance of simulated and measured energy generation of the PV system; to determine the performance of the technical and economic parameters of the case study PV system and compare to other design models and finally to analyse the benefits of the saved amount of carbon emission. The study evaluated a 54kWp system consisting of 216 solar PV modules, three(25kW) grid-tie inverters, nine (8kW) islanding inverters, and battery backup, installed on the rooftop of 'Daima Towers' in Eldoret, Kenya (0.516° N and 35.282° E). The system was monitored for one year in 2020. Primary data was collected by observation, survey, and inspection of the system as well as face-to-face interviews with the system engineer. Secondary data was obtained from the building's financial records and Kenya power (KPLC) electricity billing records. Simulation software (PVsyst 6.86) was used to analyse the input data that included component specification, Investments made, operation conditions, and meteorological site data. Meteorological site data were imported from the NASA-SSE database (1983-2005) using geographical coordinates input into the PVsyst meteorological data management platform. The measured yearly energy was 82 MWh compared to simulated energy of 87 MWh, an average difference of 6%, the high consistency reported verified that simulation results were reliable. The final yield (FY) was 1518 kWh/kWp and reference yield (RY) was 1943 kWh/kWp. Capacity utilization factor (CUF), performance ratio (PR) and PV penetration levels (PL) were 0.173, 0.78 and 0.170 respectively. Levelised cost of energy (LCOE) from solar was kshs. 12 / kWh compared to kshs. 22 / kWh on the grid imports. The system had return on investment (ROI)) of 103% with a simple payback period (S.P.B.P) of 12 years. Comparison to other possible design model shows that design with no battery storage would give the highest technical and economic performance. The saved carbon emission was 677 tons in the PV system lifetime which is equivalent to planting 564 mature trees. These analysis shows that the technical, economic and environmental benefits of grid-tie solar PV technology are worth the investment. The study recommends the use of real-time and accurate meteorological instruments and sub energy meters to improve on accuracy of these results.

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ABBREVIATIONS AND ACRONYMS

PV	Photovoltaic
MW	Mega Watts
MWh	Mega Watts hours
W/m^2	Webbs per meter square
SMEs	Small Medium Enterprise
NCC	National Control Center
KPLC	Kenya Power and Lighting Company
DC	Direct Current
AC	Alternating Current
Wp	Watt peak
MWp	Mega Watts peak
kWp	Kilo Watts peak
GHG	Greenhouse gases
SHS	Solar Home System
UNEP	United Nation Environmental Program
AY	Array Yield
E (DC)	DC Energy
E (AC)	AC Energy

P (PV)	PV array power rating capacity
RY	Reference Yield
RI	Reference Irradiance
AL	Array captured Losses
SL	System losses due to inverter
PR	Performance Ratio
CUF	Capital Utilization Factor
PL	Penetration Level
Pf	Power factor
PVsyst	Photovoltaic simulation software
NASA	National Aeronautics and Space Administration
SSE	Solar System Exploration
CO_2	Carbon dioxide
LCE	Life Cycle Emissions
STC	Standard Test Conditions
LCOE	Levelized Cost of Energy
GlobHor	Horizontal global irradiation
DiffHor	Horizontal diffuse irradiation
T_Amb	Temperature ambient.

GlobInc	Global incident in coll. plane
GlobEff	Effective Global, corr. for IAM and shadings
EArray	Effective energy at the output of the array
E_User	Energy supplied to the user
E_Solar	Energy from the sun
E_Grid	Energy injected into grid
EFrGrid	Energy from the grid

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CHAPTER 1: INTRODUCTION

1.1 Background of the Study

The background of this study can be examined from several perspective consisting of: Development of photovoltaic (PV) system in the world-global, Africa, Eastern Africa, and local-Kenyan perspective.

1.1.1 *World Solar Photovoltaic (PV) Development.*

The light from the sun can be converted to electricity in solar cells through the photovoltaic (PV) effect. Edmond Becquerel in Paris first discovered the PV effect in 1839 while experimenting with metal electrodes and electrolytes (Palz, 2011). Albert Einstein in 1904 further describe the phenomenon of PV effect that later earned him Nobel Prize award in 1921. The use of photovoltaic (PV) systems for electricity generation started in the mid-20th century and was for space technology like powering the satellites. In 1970s the establishment of PV production companies in America, Europe and parts of Asia resulted in commercial adaptation of solar PV electricity generation. In the 1980s a large-scale production and installation of PV modules was witnessed in terms of both kilo Watts and Mega Watts, which was partly due to more discoveries in increasing efficiency and lowering the costs of production of PV components.

In the twenty-first century, a rapid growth in solar PV technology was witnessed across the world. A continuous growth of the global solar PV installed capacity occurred from 2015 to 2019 with projection of reaching 1.4 terawatts by 2024 (Jaganmohan, 2021). This increase can be attributed to shift in global markets towards renewable and distributed energy technologies to mitigate the effects of climate change, while ensuring sustainable energy availability. Table 1.1 shows the global total solar PV capacity forecast 2015-2024.

Table 1.1: Global total solar PV capacity from 2015-2024

Year	**Capacity in Gigawatts**
2015	229.3
2016	306.5
2017	404.5
2018	509.3
2019	633.7
2024 (forecast)	1427.7

1.1.2 *Africa Solar PV Energy Development*

The start of solar PV technology in Africa started in 1972 when the French installed a solar PV in a village school in Niger, to operate an educational television (Palz, 2011). The 1970s brought the global issue of environment and energy as key important factors in world future development. The United Nation conference in Nairobi in 1981 came up with objective to promote environmentally friendly sources of energy as well as understanding environmental effect of energy production and use. One of the key strategies was to support research and development to harness renewable sources of energy in developing countries (United Nation Enviroment Programme, 1981). The outcome of this conference was the increase implementation of solar PV system in Africa from 1980s onward with most installations done being standalone PV system.

According to World Bank reports, Africa is distant behind the rest of the world in solar PV development despite having the highest potential as shown in Table 1.2.

Table 1.2: Potential and capacity of solar PV per region in 2018.

Region	*Solar PV potential (kWh/m2)*	*Installed Capacity (MW)*
Asia Pacific	4.06	282,046
Europe	3.39	124,730
North America	4.09	52,805
Latin America/Caribbean	4.48	9,558
Africa	4.49	4,163
Middle East	4.96	3,867

From Table 1.2, Africa and Middle East had the highest solar PV potential compared to other regions of the world but with lowest installed solar PV capacity. This shows that a lot of solar energy is untapped especially in Africa that has larger surface area compared to Middle East, which is smaller. Europe and Asia Pacific have highest installed solar PV despite their low solar PV potential. The clear gap between Africa countries high solar PV potential and its installed solar PV capacity is partly due to lack of policies, information, and capital investment to promote growth in the sector as compared to developed countries (The World Bank, 2020) . Given that more than 60% of Africa's rural homes have no electricity as per world bank report, the high solar potential offers a solution if commitment is made in harnessing solar energy. Governments in Kenya, Senegal, Egypt, and Morocco among other countries in Africa have shown firm commitment to developing renewable energy infrastructure. With the increase global pressure for countries to invest in sustainable energy sources, Africa is likely to address the energy poverty situation by harnessing solar and other renewable energy sources available.

Africa energy mix is gradually shifting from traditional thermal and hydropower to inclusion of other renewable sources like geothermal, solar and biomass. Solar PV panel and other components costs have fallen rapidly since 2010. The current cost standing at less than three USD / Watt peak and is still projected to go down further by 2025. The reduction in costs and the government policies favoring solar PV technology, there is significant growth and exponential in use of solar PV system.

The Report by International Energy Agency on the status of sub-Saharan Africa solar PV capacity 2017-2025, shows a significant growth in development of solar PV energy capacity (International Energy Agency, 2020). Table 1.3 shows the yearly additions of solar PV capacity 2017-2021 for Sub-Saharan Africa.

Table 1.3: PV installed capacity growth by year (Grid-tie PV system)

Year	PV installed capacity growth by Year (On-grid) in GW				
	South Africa	Other SSA	Kenya	Tanzania	Ethiopia
2017	0.29	0.21	0.01	0.00	0.00
2018	0.03	0.26	0.08	0.01	0.00
2019	0.03	0.25	0.01	0.00	0.00
2020	1.30	0.22	0.01	0.00	0.01
2021	0.18	0.67	0.09	0.00	0.00

The commissioning of large-scale solar PV plant in South Africa at the end of 2020 resulted to in growth of installed solar PV capacity by 1.3 GW against the initial estimate of 0.50. South Africa is leading the whole of Africa with installed capacity 4.17 GW solar PV, which is more than 70% of the current capacity in Africa (Bellini, 2021).

By 2021, Kenya had 0.09 GW for off grid installed solar PV compared to 0.07GW and 0.04 GW for Tanzania and Ethiopia respectively, while grid-tie system stood 0.17 GW, 0.01 and 0.01 for the three countries respectively (International Energy Agency, 2020). As South Africa is setting the pace for harnessing solar PV technology in Africa, Kenya is setting the pace for the Eastern Africa countries hence the success of solar PV technology in Kenya could influence the growth in other Eastern African countries.

1.1.3 *Solar Photovoltaic in Kenya*

The conference funded by UNEP on renewable energy and environment held in Nairobi in 1981 (United Nation Enviroment Programme, 1981) marked the start of solar photovoltaic electricity generation in Kenya. This conference attracted many renewable energy experts from all over the world to discuss the global progress of renewable energy and aroused a lot of interest among Kenyans and donor organizations in the country. This resulted to importation of solar PV panels and accessories for installation of solar home systems, mostly in the rural areas of Kenya. Kenya Investment Authority conducted a survey in 2005 that established the annual market for solar PV modules in Kenya was 500 kWp and was projected to grow annually by 15%. A government program initiated in 2005 to provide basic electricity to boarding schools and health centres in remote rural areas increased the annual installation demand for solar PV modules by 100 kWp in 2006 (Guyo, 2013).

Before 2017, most of solar PV systems in Kenya were installed in the rural areas as off grid systems. However, from 2017 this situation progressively change with grid-tie solar PV growing steadily from less than 10MW in previous years to 60MW after commissioning of Garissa power plant in 2018 and further an additional of 110 MW Eldoret solar plants which was commissioned at the end of 2021. This is attributed to the enactment of policies and government promoting an enabling environment in solar PV market.

Kenya currently has both the mix of off-grid and on-grid solar PV system accounting to 90MW and 170 MW respectively (International Energy Agency, 2020). The Least cost power development plan (LCPDP) 2020-2040 includes 50 committed power generation projects in Kenya with solar PV accounting for 404 MW of the 2838 MW committed power generation in the period (Presidential taskforce on the Review of Power purchase agreements, 2021). As of July 2021, Kenya had total installed electricity generation capacity of 2854 MW. From this 26% was obtained from thermal sources as shown in Table 1.4 (National Control Center-KPLC, 2021). According to the generation mix, it is evident that Kenya depends significantly on fossil fuel for electricity generation as compared to solar sources, which contributed 2%. This is ironical; given the fact that solar energy source is abundant in nature compared to fuel, which is imported into the country. This significantly contributes to high electricity costs and increase greenhouse gases emission.

Table 1.4: Analysis of Installed vs Dispatched Capacity for July 2021

2021 July Analysis of Installed Capacity vs Dispatched Capacity				
Technology	**Installed capacity**		**Dispatched Capacity**	
	MW	**% Share**	**MW**	**% Share**
Hydro	815	29	753	31
Geothermal	787	28	685	28
Thermal /diesel	756	26	635	26
Wind	436	15	263	11
Solar	60	2	45	2
UETCL	0	0	50	2
Total	**2854**	**100**	**2431**	**100**

Kenya had several rooftops and ground-mounted solar PV systems; most of these were less than ten MW peak and were distributed in nature with a few centralized generations. By the year 2020, the country had 2% of the total electricity generation mix coming from on-grid PV solar plants with centralized generation- Garissa plant contributing more than 80%, while distributed solar plants having less than 20% capacity. By end of 2021, Kenya had approximately 170 MW capacity of grid-tie solar PV system interconnected to the national grid with distributed generation contributing significantly, as shown in Table 1.5. This is a continuous growth in the grid-tie solar PV system as commercial entities, government and other investors are keen on promoting clean and sustainable sources of energy. Other commercial entities in the process of implementing grid tie solar PV system in Kenya includes East African breweries (EABL), Tatu City, Total Kenya, Wildflowers, Kapa Oil, Two rivers mall among others.

Table 1.5: Grid-tie PV System in Kenya

Name	**size MW**	**Year**	**Installation type**
Strathmore University	0.60	2016	Rooftop
K.Dharamshi & Co.Ltd	0.25	2017	Rooftop
Garissa solar plant	55.00	2018	Ground mounted
ICIPE	0.14	2018	Rooftop
ICIPE-Mbita Point	0.20	2018	Rooftop
Daima Towers, Eldoret	0.05	2018	Rooftop
London Distillers Ltd	1.00	2019	Rooftop
Garden City Mall	1.20	2020	Rooftop
Bidco Kenya Ltd	1.20	2020	Rooftop
Selenkei and Cedate	80.00	2021	Ground mounted
Others	30.00	-	Rooftop/ground

1.2 Statement of the Problem

The production of energy from a solar PV system is one of the most environmentally friendly methods of generating electricity. Globally, most countries are exploring and investing in solar PV systems due to their simplicity, sustainability, and environmental friendliness. This makes the PV system to be one of the fastest-growing areas of the renewable energy sector. Solar PV systems in Kenya are mounted either on rooftops or on the ground. Most of these PV systems are distributed in nature with limited capacity of around one MWp or less. Very few centralized generations exceeding 10MWp exist in the country.

A significant share of electricity in Kenya is still generated from fossil fuels. However, possible depletion of fossil fuel reserves and unstable price of oil are major concerns for high electricity costs in Kenya. Moreover, the increasing use of fossil fuels accounts for a significant portion of environmental pollution and greenhouse gas (GHG) emissions, which are major contributors to global-warming. In the total electricity generation mix of 2854 MW in 2021, 26% was obtained from thermal (fuel) while solar contributed only two percent despite its abundant availability source.

To overcome the problems associated with the generation of electricity from fossil fuels, the Kenyan government and private investors have embarked on exploring and investing in abundant renewable energy sources like solar. However, few African countries have contributed knowledge on solar PV system performance in comparison to the developed countries. The knowledge, contextual and operational gaps could be due to a lack of adequate information on the performance of the grid-tie solar PV systems and limited understanding of the global trends in energy access and management. This could have resulted in the slow uptake and investment in the solar PV energy in Kenya, hence the need for this study. This study will provide information on techno-economic performance of grid-tie solar for guiding investors and promote future investment. From this information, investors will make informed decision on PV technology investments.

1.3 Objectives of the Study

1.3.1 *Main Objective*

The main objective of this study was to fill the knowledge and contextual gap on the technical and economic analysis of the performance of the grid-tie solar Photovoltaic (PV) systems in Kenya.

1.3.2 *Specific objectives*

The specific objectives of this study were:

i. To compare the monthly performance of PVsyst simulated and actual energy Generation of the PV system.
ii. To evaluate the performance of the technical parameters of the PV system and compare case study to other possible PV design model using PVsyst simulation.
iii. To evaluate the performance of the economic parameters of the PV system and compare case study to other possible PV design model using PVsyst simulation.
iv. To analyze the benefits of the saved amount of carbon emission.

1.4 Justification and Significance of the Study

The world's need for energy in the 21st century is growing exponentially, and the adverse effect of climate change is becoming a norm each day. Reliance on fossil fuels to meet the ever-growing energy needs of the world is no longer sustainable. Fossil fuel sources of energy are highly linked to climate change, due to high greenhouse gases (GHG) emitted during combustion to release energy. As the world rushes to harness solar energy, which is abundant and renewable, the need for information on the performance of previously installed PV systems is critical in any decision making.

Few African countries have contributed information on solar PV system performance in comparison to developed countries. These have made investors to rely on the developed and other Asian country's information resulting in poor decision-making. Kenya is leading the rest of Eastern and Central Africa in the solar PV technology and need for the critical information is urgent in setting the pace. Government and private investors championing renewable and sustainable energy can utilize the information to increase the rate of investment in solar PV technology. This study was to fill the knowledge and contextual gap on the technical and economic analysis of the performance of the grid-tie solar Photovoltaic in Kenya. The study will provide required information, promote investment, and influence decision making in solar PV investment.

1.5 Scope of the Study

Kenya as a country is located along the equator making it viable in tapping solar energy. It has high insolation rates with an average of 5-7 peak sunshine hours (The equivalent number of 6 hours per day when solar irradiance averages 1,000 W/m^2) and receives average daily insolation of 4-6kWh/m^2. The scope of this research was limited to evaluation and analysis of a 54kWp PV system located in 'Daima Towers' Eldoret, Kenya. The study analyses the one-year period data-2020 and uses PVsyst simulation software for analysis and comparisons.

1.6 Assumptions, Limitations and Delimitations of the Study.

1.6.1 *Assumption*

The study assumes that the imported meteorological data is the true reflection of the current weather condition of the study location. It was also assumed that the total energy supplied from both solar PV and KPLC grid represented the actual energy demand of the building.

1.6.2 *Limitations of the Study*

Previous studies in Africa and Kenya in particular have not extensively address the technical and economic parameter performance of grid-tie solar PV system. This has resulted to less available data to compare with results of the findings of this study.

Financial constraints made it impossible to practically measure the meteorological data of the site. This study is limited to the actual measurements for year 2020 and simulation for the PV system lifetime.

1.6.3 *Delimitations of the study*

The study was conducted at Daima Towers building located at Latitude 0.516° N and Longitude 35.282° E, with Altitude at 2092 m in Eldoret, Kenya. A 54kW Solar PV system installed on the rooftop of the building was evaluated and studied for one year in 2020. Figure 1.1 shows the aerial view of Eldoret town and the Daima Tower building with installed PV system on rooftop.

Figure 1.1: Aerial view of Daima Towers in Eldoret town.

1.7 Chapters Overview

This study is arranged into five main chapters. Chapter 1 introduces the background of the study by examining the history and current solar PV system development for the global, regional, and local perspectives. Moreover, the chapter presents the problem statement, objectives, justifications and scope of the study. The next chapter will discuss the literature review of previous studies carried out in different locations on solar PV system. Chapter 2 will also cover previous studies on comparison of measured and simulated grid-tie PV system performance; analyze the studies on technical and economic performance of PV system before concluding the chapter with studies on benefits of saved amount of carbon when using solar PV system.

Chapter 3 presents the methodology employed in answering the objectives of the study. This chapter gives the data collection and detail evaluation of the 54kWp grid-tie PV system as the case study. The chapter make use of simulation software-PVsyst to evaluate and analyze the case study. PVsyst is also used to design other possible PV system that could be adopted in place of the case study for purpose of performance comparison. In Chapter 4, the 54-kWp grid-tie PV system is analyzed and discussed in terms of technical and economic parameters performance. Ultimately, Chapter 5 discusses the conclusions from the study and provides the recommendations arising from the study.

CHAPTER 2: LITERATURE REVIEW.

2.1 Introduction

This chapter reviews the previous study on solar PV system technology in global and Kenyan contexts. The chapter covers previous studies on PV system types, solar resource assessment, and PV system orientation and connection topologies. Furthermore, the chapter covers studies on comparison of measured and simulated grid-tie PV system performance, and analyzes studies on technical and economic performance of PV systems. In addition, it discusses the different PV system simulation software available on market and explains their pros and cons. Finally, the chapter concludes by analyzing studies on benefits of saved amount of carbon when using solar PV system.

2.2 Solar PV Systems.

A Photovoltaic system consists of one or several solar panels, an inverter and other electrical hardware that generate electricity from the sun energy (Photovoltaic system, 2020). Solar PV systems are of three main types: off-grid, grid-tied and hybrid types (Zipp, 2015), as follows in Table 2.1.

Table 2.1: Types of PV system.

PV Systems	**Description**
Off-Grid	Are standalone and serve loads isolated from main grid.
Grid-tie	PV system is integrated with main grid to supply the load, and cannot work without grid except in islanding mode with battery backup.
Hybrid	Incorporate other sources of energy to PV system like wind

PV systems are commonly used in small electronics gadgets like watch, torch, and calculators, in satellite applications as well as to provide electricity for domestic, commercial, and industrial applications among others.

2.3 Grid-Tie Solar PV Systems.

Grid-tie solar Photovoltaic (PV) refers to a PV system in which solar panels and related equipment are electrically connected to the load and mains electricity supply hence can feed electricity back to the grid (Zipp, 2015). These PV systems can be installed on the ground, rooftops of buildings or on the shades of parking lots. Grid-tie power plants can also be installed as solar plants for purpose of injecting all their produced power into the grid (Omran, 2010). The building blocks of a grid-connected photovoltaic system are shown in Figure 2.1. The system is mainly composed of a matrix of PV arrays, which converts the sunlight to DC power, and an inverter unit that converts the DC power to AC power. The generated AC power is injected into the grid or utilize by the local loads. In some cases, to improve the availability of the power generated by the PV system storage devices are used (TanFon, 2020).

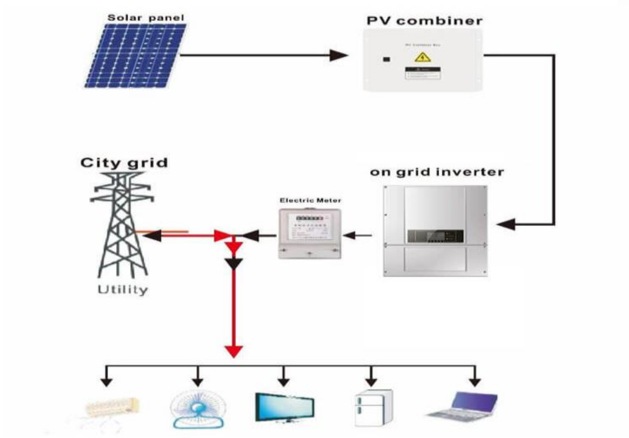


Figure 2.1: Grid-tie solar PV system (Source: TanFon, 2020)

2.4 The Solar Resource Assessment

The sun is the source of solar and all energy on the earth's surface. It is composed of a mixture of gases with a predominance of hydrogen gas. Hydrogen is converted to helium in a massive thermonuclear fusion reaction on the sun. Because of this reaction, the surface of the sun is maintained at a temperature of approximately 5527-degree Celsius. This energy is radiated away uniformly in all directions (Choi, 2021).

Before discovery of petroleum in mid nineteenth century diverted the global energy demand source to over reliance on fossil fuels, man depended for a long time on the sun for drying and heating. In one hour, the surface of earth is exposed to enough energy that can meet its energy needs from the sun for a whole year. The solar energy is radiated by to the earth surface during the rotation and revolution of the earth round the sun. This phenomenon makes the suns radiation reaching the earth's surface to vary as the earth moves around the sun. Due to this phenomenon, the parts of the earth nearest to the equator receive more solar energy than parts far from the equator.

The sun energy reaching the PV array on the earth surface have main beam, (direct radiation), the ground reflected beam (because of reflection of the direct beam from the earth surface) and the diffused beam (direct radiation affected by atmospheric absorption) as shown in the Figure 2.1. The figure shows that not all the radiation that is released by the sun will reach the solar PV array surface placed on the earth. Because of these phenomena, the orientation of the solar PV array is important for energy absorption. According to (Kalogirou, 2012) , the orientation of the solar PV array has two major parameters, the slope, and the azimuth. The slope is the angle of tilt with reference to the ground horizontal surface and the azimuth is the direction towards which the array surface face. When a solar PV array is installed south of the equator, azimuth is due north and when installed north of the equator, azimuth is due south. The azimuth can be due north or due south depending on the location on the earth's surface. At noon every day, the sunrays are perpendicular to the earth surface on the equator and give maximum radiation. Any other time of the day, the position of the sun is affected. This study will provide information on performance of PV system installed in Kenya with respect to slope and azimuth orientation of the panels. .

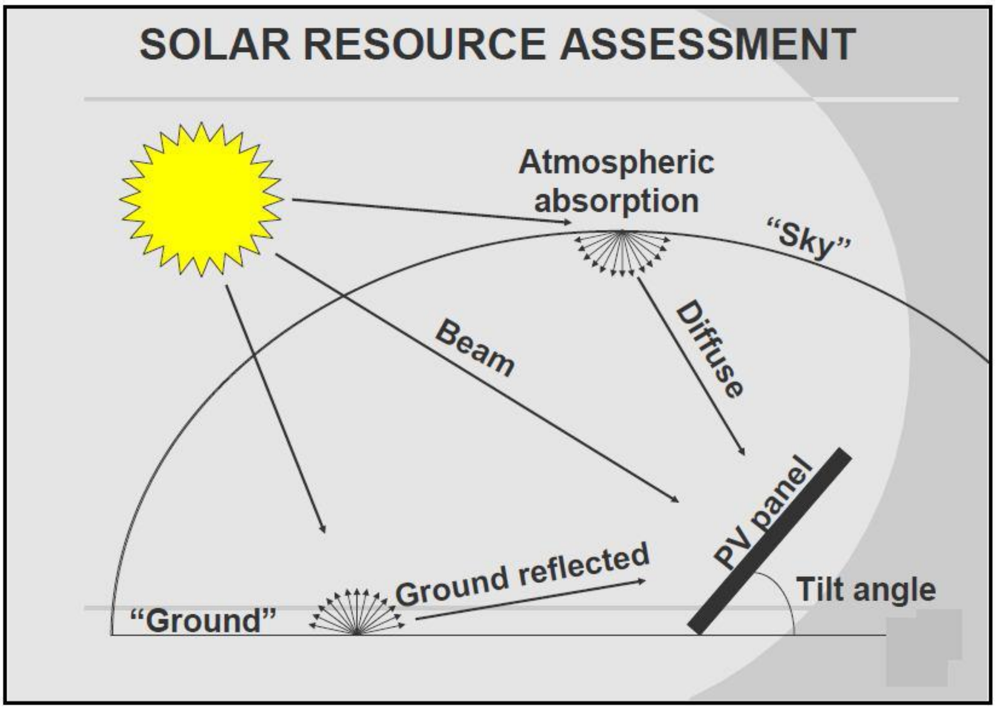


Figure 2.1: The Solar Insolation on an Array on the Earth Surface (Guyo, 2013)

2.5 Solar PV Fixed and Tracking Orientation

Optimization of the harness solar PV energy is among the most researched section in solar PV system installation. The PV panels' installation orientation is particularly important in ensuring high-energy yield. Various technology has evolved over time that are determined to increase the exposure period of solar modules to the sunrays reaching the earth surface. The PV system orientation is achieved by use of support structure for the PV modules.

2.5.1 *Fixed or Static Orientation*

The amount of solar radiation reaching the surface of PV module is close to linearly proportion to the energy production of a PV module. Hence, incident irradiation is the best method for optimizing energy output. To optimize the absorption of the sun radiation in clear skies, the PV panel normal to the plane, should point towards the sun in a way that the direct beam of solar is perpendicular to the surface of PV panel (Lave & Kleissl, 2011). Besides increasing solar conversion efficiency of the PV panel, energy output can be optimized by considering the daily atmospheric transmissivity variation at a given location as well as solar geometry. It is particularly important to know the optimum azimuth and tilt angles at which to place a fixed tilt panel on the ground or flat roof such that it is exposed to maximum irradiation. Fixed tilted orientation is the oldest and simplest design that is widely used due to the following reasons.

Fixed tilted PV panel mounting are simple to design, can withstand harsh environmental condition, are cheaper in costs and do not contribute to PV system losses as compared to PV system trackers that use energy during movements in tracking the sun position.

2.5.2 *Tracking PV system Orientation.*

Solar PV tracking system is used to increase the electricity energy production of the installed PV system by enabling the PV panels to follow the sun throughout the day (Marsh, 2022). The tracking system works in such a way as to minimize the incident angle by orienting the panels such that the sunrays strike them perpendicularly to their surface. Two main types of solar PV trackers are available in the market and includes dual-axis and single-axis trackers.

2.5.2.1 Single-Axis Trackers.

These trackers move the PV panels on one axis; they can be aligned with north and south orientation, which will allow the PV panels to move from east to west, thereby tracking the sun as it rises and sets. This will optimize the efficiency and increase energy yield of the PV system without having to install additional solar PV panels. Single-axis tracking is suitable in warm and dry weather conditions and are preferred to be installed on flat surface. In comparison to the fixed tilt orientation, single-axis orientation of PV panels can increase the PV system efficiency and ensure more energy yield that will compensate for additional costs. Large-scale PV installations usually prefers single-axis setups, due to their location on large plots of land without the limited space as in a commercial rooftop space.

2.5.2.2 Dual-Axis Trackers.

These trackers allow solar PV panels to move on two axes, they are usually aligned to both east-west and north-south. This type of PV tracking system uses sensors and algorithms to track the sun different location in position due to the revolution and rotation of the earth round the sun in a year. Dual-axis trackers are more expensive and not widely used by large-scale solar PV energy generators. Dual trackers are preferred in commercial properties –because of space constraints on rooftop of commercial buildings to install more solar panels. Dual-axis trackers have been observed to produce more energy as compared to both the fixed and single-axis orientation. The tracking system can produce up to more than 40% of energy than typical fixed panels; this can help businesses to produce more energy to complement energy from the grid in meeting energy demand of their operations in a small space.

2.5.3 *Active and Passive PV solar trackers.*

The single-axis and dual-axis solar PV system trackers can be of active or passive types. The active type is the most common and widely used, it has motor and mechanical gears, responsible for movement of the panels. In addition, they rely on the sensors, microprocessors to track the sun radiation. Active solar trackers are more accurate and efficient as compared to passive (Shukla, Awasthi, & Porwal, 2020). The passive solar trackers use low boiling point compressed fluids or certain typed of shape metal alloys that serve as actuators by using the principal of thermal expansion to track the sun, in place of motor drives. These trackers are less advanced in their makeup and function in comparison to active types.

2.6 Solar Photovoltaic Array Output

Solar PV array refers to a collection of solar panels that are connected to each other to give electric power. The array output is the power output of the solar PV array that will be delivered to the designed solar PV system. Normally the power that is delivered by the solar PV array is lower than its rated capacity because of the effect of the de-rating factors mainly due to temperature and irradiance.

2.7 Connection topologies of PV system

There are four main types of PV system connection topologies, which includes centralised, string, AC modules and multi-string topologies (Summers & Betz, 2012).

2.7.1 *Centralised topology.*

Centralised topology is the PV system connection where modules are connected in series to give strings; the strings are then connected parallel to each other to the input of one inverter that is ultimately connected to load or grid (Islam, Guo, & Zhu, 2014). Advantage of series connection allows for large output DC Voltage output while parallel string connection increases DC output power. Drawbacks of the centralised topology includes reduce efficiency due to diode conduction losses and centralised inverter that limits future expansion of the PV system. Figure shows the centralised topology PV connection.

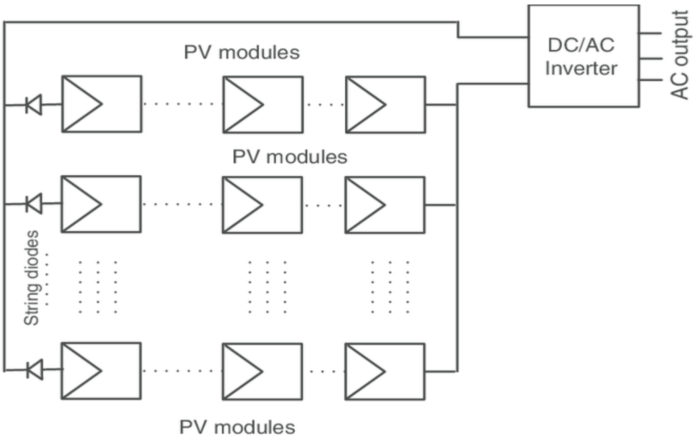


Figure 2.2: Centralize PV topology

2.7.2 *String Topology*

In this type of PV connection, the PV strings are connected to separate inverters with no diodes in the circuit. Boost converters can be added in the string to increase DC voltage to the required level (Summers & Betz, 2012). Figure shows the string topology of PV system.

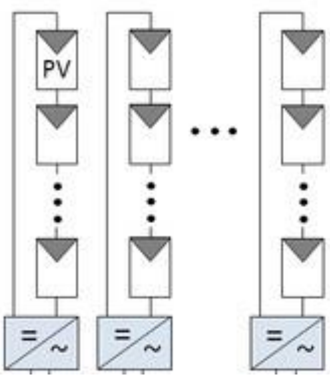


Figure 2.3: String PV Topology

String topology is widely used due to the following advantages.

More efficient than centralised topology as losses associated with diodes are not present as well as each string is independent.

Future PV system expansion is not limited as inverters and strings can easily be added.

2.7.3 *AC Modules*

In this type of PV connection, the solar panel modules are each connected to its own inverter. It is suitable for small PV systems.

2.7.4 *Multi-string PV Topology.*

Multi-string combines the centralised and string topology to increase the efficiency and reliability of the PV system. The strings are connected to common DC bus bar via boost converter and then to centralised inverter, which is, usually three phase. Multilevel inverters can be employed for large capacity PV systems. Advantages of this topology includes the advantages of the string topology and simplicity of centralised topology. However, they are limited to centralised inverter size hence suitable for large PV system where multilevel inverters are employed. Figure shows the multi-string connection topology

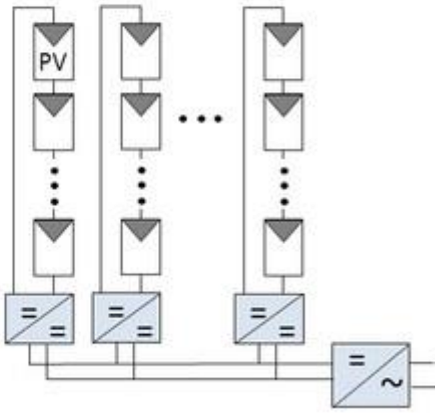


Figure 2.4: Multi-string PV Topology.

2.8 Solar PV System Simulation Software.

Simulation refers to a synthetic of the dynamics of real-world system over time. It is a technique used for modelling and investigating system performance (Sharma, Verma, & Singh, 2014). Both free and sold computer-based simulation tools are available in the market for designing and analysing the solar PV system. However, most of free software are limited in system design and simulation hence the reason most system designers and researchers prefer to purchase simulation tool. The most widely used solar PV simulation tool are as follows according to (Allam, 2017):

a) Homer Pro

This program originates from NREL-National Renewable Energy Laboratory in USA. It can model multiple energy sources and has simulation, optimization, and sensitivity analysis tool (Allam, 2017). It has wide database of weather data and PV components with option of importing more. The price is relative high compared to other programs. It is available for both academic and commercial purposes.

b) PV Planner

It is cloud based hence online tool with real-time data available resulting to high reliability. Its origin country is Slovakia from solar resource database provider SolarGIS (Allam, 2017). The program has three packages with the most expensive package allowing real time interaction with i-maps for accurate geographic locations. Although it has large database of weather and PV component, the need for high internet connectivity to use the program limits its use. The program price is high compared to others.

c) Solar Pro

Laplace Systems in Japan created this program. It offers minute-by-minute calculations making it more accurate. It offers an interactive 3D user interface that allows PV system visualization (Allam, 2017). It is bundle with wide range of weather and PV component data. Its price is relatively high but lower than Homer and PV Planner.

d) PVsyst

In Switzerland Mermoud and Villoz developed PVsyst simulation software (Mermoud & Villoz, 2012). It is widely accepted in the world as a standard for design and simulation of solar PV system. It was designed for students, academia's, engineers, and researchers use. It can simulate most parameters, which are required in designing PV system, and generates comprehensive reports on the performance. PVsyst has wide range of meteorological and PV component database with ability to import user defined or data from other sources. It is relatively cheap in price when compared to Solar Pro, PV Planner and Homer simulation programs.

e) Other Programs

Other commonly used PV system simulation software are RET Screen, SAM (System Advisor model) and PV F-CHART. These programs are available for free use but have limited design and simulation functionality.

2.9 Comparison of measured PV Yield and PVsyst Simulated Yield.

The accuracy of any simulated performance results for a PV system can be verified by comparison to the actual measured and analysed data using accurate measuring instruments (Mermoud & Villoz, 2012). Accuracy evaluation consists of two components, which includes the measurement accuracy and modelling accuracy. Measuring accuracy for meteorological data including solar irradiance requires very well calibrated instruments, which is rarely the case; however, measuring electrical parameters is more accurate although malfunction of the system might not be well documented. These in turn affects the simulated results in comparison to the actual yield results.

Modelling accuracy is brought about by PV modules specified due to the reliance on manufactures specifications in the software database. Other parameters like inverter values, wiring etc. that may be set at any value are not very significant to the accuracy of the simulation (Mermoud & Villoz, 2012). The accuracy of yield forecast in a PVsyst relies on the input meteorological data, operating conditions and PV module real behaviour with respect to the specified parameters.

PVsyst simulation accuracy can be improved by using on-site precise measuring instruments for meteorological and solar resource measurements (Boughamrane, 2016). However, due to costs and extended period required to obtain reliable meteorological data, most researchers rely on data from airports and other institutions that daily monitors the weather patterns and stores the data in their database for future references. World meteorological institutions relies on stationery and drifting buoys, satellites aircrafts, ships and land-based stations to collect weather information's (World Meteorological Organisation, 2015). The NASA database has derived monthly average for weather forecasting parameters, which are adopted to estimate PV system performance. These values do not differ much with the real measure values at a specified time during the study hence the possibility of similarity between measured and simulated results (Boughamrane, 2016) .

Long-term prediction of PV system performance requires complex approach on the technical and financial parameters behaviour. This can be due to assumptions made on weather, tariffs changes, grid response behaviour among other factors. However, the accuracy of the prediction can be increased by, inputting accurate data for technical and financial parameters during PV system modelling (Mabhoko, 2020). Accurate predictions are useful in meeting investor's expectation, influences decision-making and creates trust in the technology.

(BHATTI, 2016) In his comparison established that the simulated and actual data showed much consistency for the 4.83 kWp PV system installed at Malardalen University. The variation from the yearly actual PV production was found to be 6% in comparison to PVsyst simulations. The researcher identified that no previous study in Kenya had done the comparison of PVsyst simulation results to the actual results. This study could fill the gap by presenting and comparing the PV system performance results from actual measured to simulated results, in local Kenyan perspective.

2.10 Technical Parameters Performance Analysis of Grid-tie PV System.

According to (Bwawan, 2010) , Performance analysis can be determined by calculating different parameters describing energy quantities for the PV system and its components and comparing it with the standard. The parameters includes System yields, performance ratio, capacity utilization factor, system losses and penetration levels of PV system.

2.10.1 ***System Yield.***

System yield is divided into three types, which includes:

i) *Array Yield (AY)*- The AY can be calculated as the ratio of daily, monthly, or yearly energy output from a PV system array to the rated capacity of PV array power (Adaramola & Vasgas, 2015) It is given as shown in Equation (1):

$$\mathrm{AY} = \frac{\mathrm{EArray}}{\mathrm{P\ (PV)\ rated}} \qquad (1)$$

Where EArray is the DC energy output (kWh) from the PV array and P (PV) is the PV system peak rated capacity in kWp.

i) *Final Yield (FY)* – According to (Sharma & Chandel , 2013) the final yield can be calculated as the total AC energy output during a given period divided by the rated capacity of PV array power. And given as in Equation (2):

ii) $$\mathrm{FY} = \frac{\mathrm{E(AC)}}{\mathrm{P\ (PV)\ rated}} \qquad (2)$$

Where E (AC) is the AC energy output in kWh.

iii) *Reference Yield (RY)* - The reference yield can be determined as a total in-plane irradiance in array collector divided by the reference irradiance (RI) under standard temperature (1 kW/m^2). It is calculated as in Equation (3)

$$\mathrm{RY} = \frac{\mathrm{GlobInc}}{\mathrm{RI}} \qquad (3)$$

Where GlobInc is the Global incident in collector plane in kWh/m^2 and RI is the reference irradiance in kW/m^2.

iv) Energy losses

The PV array losses (AL) can be calculated as the following in Equation (4) (Wittkopf, Wittkopf, Valliappan, Liu, & Ang, 2012):

$$\mathrm{AL}=\mathrm{RY} - \mathrm{AY} \qquad (4)$$

System loss (SL) is caused by the inverter inefficiencies and is calculated as Equation 5:

$$\mathrm{SL}=\mathrm{AY} - \mathrm{FY} \qquad (5)$$

2.10.2 *Performance Ratio*

The Performance Ratio (PR) describes the quality of a PV solar system that is independent of capacity and location of system. PR describes the relationship between the real and estimated energy outputs of the PV system (Ayompe, Duffy, McCormack, & Conlon, 2011). Performance ratio is calculated as the ratio of the final energy yield of the PV system-FY to the reference yield-RY as in Equation 6, it is usually expressed in percentage.

$$\mathrm{PR} = \frac{\mathrm{FY}}{\mathrm{RY}} \qquad (6)$$

2.10.3 *Capacity Utilization Factor*

According to (Elhaji, Ndiaye, & Bah, 2016) the capacity utilization factor (CUF) is calculated as the ratio of real annual energy output by the PV system E (AC) to the amount of energy the PV system would generate if it is operated at full rated power for full day for a year, and is given as in Equation (7). CUF can be expressed in percentage.

$$\mathrm{CUF} = \frac{\mathrm{E(AC)}}{\mathrm{P(PV)\ rated} \times 8760} \qquad (7)$$

2.10.4 *PV Penetration Level (PL)*

The penetration level of installed PV systems can be defined as the ratio of total AC energy output of a PV system-E (AC) to the total energy supplied to user (E_User) and is given as in Equation 8.

$$\mathrm{PL} = \frac{\mathrm{E(AC)}}{\mathrm{E\_User}} \qquad (8)$$

The overall technical performance of any grid-tied PV system can be evaluated and compared with other systems.A study on technical assessment of 10 MW centralized grid-tied solar PV system in Uganda established that the FY, PR, and CUF were 1671 kWh/kWp/year, 75.8% and 19.1% respectively for technical parameters (Oloya , Gutu , & Adaramo, 2021). However, the study did not analyze the other parameters of the system yield and PV penetration levels that are also crucial in decision making on PV system investment, hence this study will bridge this gap.

2.11 Economic Parameters Performance of Grid-tie PV System.

Several important economic PV parameters need to be considered when making economic analysis on a PV system (Solar PV World Expo , 2020). These parameters includes Capital expenditure (CAPEX), Operating expenditure (OPEX), Levelized cost of energy (LCOE), electricity tariff, simple payback period (SPBP), return on investment (ROI).The CAPEX equals to the total summation of the panel modules costs, the inverters used, the cabling and other related accessories, mounting structures and labour and transport costs. The costs of installations can be expressed in Kenyan shillings or US dollar per Watt peak (Wp) installed and calculated using equation 9 as:

$$\text{Cost per Watt peak} = \frac{\text{CAPEX}}{\text{P(PV) rating in watts}} \qquad (9)$$

LCOE is calculated by dividing the total CAPEX and OPEX for period of 25 years by the useful energy produced by the system in kWh for the same period.

Simple payback period (SPBP) is the length of time required to recover the capital costs of an investment (Ibrik, 2020). It is used to analyse the feasibility of the project. If the payback period is lower than the project lifetime then the project is feasible, otherwise, it is not. SPBP can be calculated as in equation (10).

$$\text{SPBP} = \frac{\text{CAPEX}}{\text{Total savings /year}} \qquad (10)$$

Net Present Value refers to the difference between the present worth of cash inflow and present worth of cash outflow over given period. It is given by equation (11)

$$\text{NPV} = \text{Income cash flow} - \text{Outcome cash flow} \qquad (11)$$

Return on Investment (ROI) is an economic term used to explain the profitability of an investment. It compares the investment costs to how much you earned to evaluate its efficiency (Birken & Curry, 2021). ROI is given as in equation (12)

$$\text{ROI} = (\text{Net Profit} \div \text{cost of investment}) \times 100 \quad \text{ROI} = \frac{Net\ Profit}{\text{CAPEX}} \qquad (12)$$

Investors uses ROI to evaluate their portfolios as well as assessing any type of expenditure. Since ROI alone does not consider the period, it is important to calculate the annualised ROI as in equation (13)

Annualized ROI = ((1+ ROI) ^ (1/n) -1) ×100 (13)

Where n is number of years.

Conventionally an annual ROI of 5% or greater is considered as a better ROI for long-term investment ventures.

Findings on economic parameter performance of 10kWp grid-tie solar PV system in Strathmore University, Kenya were the LCOE was 26 Kshs / kWh and S.P.B.P was 9 years (Silva, Ronoh, & Ndegwa, 2013). The PV system was installed through debt financing of 15% per annum resulting to high LCOE, which is also depended on methods of financing. Given this study was conducted when PV components cost were relatively high, beside the fact that the study did not consider other economic parameters, this study could fill this gap and provide current information on PV system performance.

2.12 Greenhouse Gases Emission.

Greenhouse gases are chemical compounds in the earth's atmosphere that absorbs, and trap infrared radiation (heat) reflected from the earth surface. These gases are responsible for greenhouse effects that are responsible for climate change and global warming (US Energy Information Administration, 2021). Greenhouse gases appear naturally as well as created by human activities. Naturally occurring GHG are ozone layer and water vapour, which plays a significant role in maintaining the atmospheric climate balance. Ozone layer traps the harmful ultraviolet radiation from the sun and prevents it from reaching the earth. GHG from human activities that are responsible for global warming includes:

- Nitrous oxide (N_2O), Carbon dioxide (CO_2), and Methane (CH_4).

- Other gases: Sulfur hexafluoride (SF_6), Sulfur hexafluoride (SF_6), Hydro fluorocarbons (HFCs), Perfluorocarbons (PFCs) and Nitrogen tri fluoride (NF_3).

2.12.1 *LCE-Lifecycle Emissions for Different Energy Generation Technology*

Findings from study by World nuclear association (WNA, 2011) established that, it was evident in the older studies estimating solar photovoltaic lifecycle emission to be comparable to fossil fuel generation methods as shown in the Table 2.2. Solar PV, wind, biomass, hydroelectric, and nuclear had LCE intensities that are significantly lower than fossil fuel-based generation. Coal had the highest LCE while natural gas and oil were moderate.

Table 2.2: Life Cycle of GHG Emissions

Technology	**Mean**	**Low**	**High**
	Tonne CO2e/ GWh		
Lignite	1054	790	1372
Coal	888	756	1310
Oil	733	547	935
Natural Gas	499	362	891
Solar PV	85	13	731
Biomass	45	10	101
Nuclear	29	2	130
Hydro-electric	26	2	237
Wind	26	6	134

2.12.2 *Carbon Balance*

The Carbon Balance tool in PVsyst software allows estimating the saving in Carbon dioxide (CO_2) emissions expected for the PV installation. Reasoning behind this tool is that the generated electricity by the PV installation will replace the same amount of electricity in the existing grid. If the PV installation per kWh carbon footprint is smaller than the one for the grid electricity generation, there will be a net saving of CO_2 emissions from the PV system (Mermoud & Villoz, 2012). Thus, the total carbon balance for a PV installation is the difference between produced and saved CO_2 Emissions, and it depends on four key factors as in equation 14.

$$E\_Solar \times System\ lifetime \times Grid\ LCE - PV\ System\ LCE = Carbon\ Balance \quad (14)$$

a. *E_Solar :* The System Production, of the PV installation for one year as computed by the PVsyst simulation, although due to aging of PV, there is yearly decrease of 1%.

b. *System lifetime*- This refers to the PV system installation lifetime, given in years. It determines, together with E_Solar, the total amount of Energy that will be replaced by the PV installation.

c. *Grid LCE* – It represents the average amount of CO_2 emissions per energy unit for the Electricity produced by the grid and given in gCO_2 / kWh.

d. *PV System LCE* - It represents the total amount of CO_2 emissions from PV installation to decommissioning.

2.12.3 *Benefits of saved amount of Carbon dioxide emissions*

Greenhouse gases emitted in the atmosphere are major contributor of global warming as they have the effect of trapping the heat from sun in the earth's atmosphere. The result of the global warming are the adverse climatic conditions across the globe, which includes floods, droughts, and earthquakes among others, which are threat to world population. The GHG like CO_2, NO_2 and SO_2 are the leading cause of respiratory diseases and premature death. Trees are very important in absorbing CO_2 from the atmosphere.

One mature tree can absorb up to 40kg of CO2 in one year (Stancil, 2019). However, the high rate of CO_2 emissions when energy is produced from fuel and increase deforestation can never much afforestation. Therefore, the current approach of reducing carbon emission while meeting the energy demands of the industrializing world is crucial. There are three key impacts of reducing greenhouse gases emission in our environment (Hayes, 2020). These impacts affect the air quality, economic growth and slowed climate change.

a) Air Quality

Increase greenhouse gases emission affects land, water, and air quality of our surrounding. Air quality is certain to worsen according to Paris Agreement. The degradation of air quality will negatively affect our daily life and expose us to diseases associated with respiratory systems and other dreadful disease like cancer. Decreasing the amount of greenhouse gases emission has the effect of decreasing deaths related to air pollution and will ease pressure on health care facilities. Moreover, this in turn will ensure a healthy environment for the well-being of our bodies and our surrounding.

b) Economic Growth

The cost of generating electricity energy from fossil fuels is high in comparison renewable energy sources due to technology advancement. The return on investment for investing in renewable energy sources is more appealing as more investors and funding are being channeled to development of renewable and sustainable energy.

c) Slowed Climate Change

Climate Change is the main cause for severe droughts, flooding, earthquakes, and other environmental hazards. Reduction in greenhouse gases emission will ultimately reduce the climate change rate and all the devastating effects associated with it, which destroys property and organic life in the world.

2.13 Summary and Gaps in Previous Study

The previous study carried out by different authors provided limited information on the Techno-economic assessment of grid-tie solar PV system in Kenya and Africa as shown in the Table 2.3.

Table 2.3: Literature Review Summary

Authors	**Study / Findings**	**Gap**
Lave & Kleissl, 2011	The direct beam of solar should be perpendicular to the surface of PV panel for optimum yield.	Study was carried out in California, US but given the difference in climate condition with Africa, this study will compare both fixed and tracking orientation of PV panels in Kenya.
Mermoud & Villoz, 2012	The accuracy of any simulated performance results for a PV system can be verified by comparison to the actual measured results.	Limited information from Kenya to prove this case, hence this study will bridge this gap.
Stancil, 2019	Established that One mature tree can absorb up to 40kg of CO2 in one year	No comparison done on equivalent of trees to the saved CO2 by solar PV system

Oloya , Gutu , & Adaramo, 2021	A study on technical assessment of 10 MW centralized grid-tied solar PV system in Uganda, established that the FY, PR, and CUF were 1671 kWh/kWp/year, 75.8% and 19.1% respectively.	Study was limited to several technical parameters but not comprehensive.
Silva, Ronoh, & Ndegwa, 2013)	Findings on economic parameter performance of 10kWp grid-tie solar PV system in Strathmore University, Kenya were the LCOE was 26 Kshs / kWh and S.P.B.P was 9 years	Study was carried out when cost of PV systems were high as compared to current

CHAPTER 3: METHODOLOGIES

3.1 Introduction

This chapter presents the methodologies employed in meeting the objectives of this study. The research was conducted at 'The Daima Towers' in Eldoret town, Kenya (0.516° N, 35.282° E). A 54kWp grid tie solar PV system with battery backup installed on rooftop of the building, was evaluated and monitored for a period of one year (from January 2020 to December 2020). The technical and economic parameters of the solar PV system were collected by survey, observation, inspection, and interview with system engineer. The building's energy demand and supply from both solar PV system and KPLC grid were recorded in the daily, monthly, and yearly tables.

PVsyst computer-based PV simulation program was used to analyze the input parameters. The parameters included the PV system component specifications, meteorological data of the site and the system capital and operation costs. The software predicted solar PV system yields, performance of various technical and economic parameters. Moreover, the software predicted the estimated amount of Carbon dioxide emission that could be saved at the end of the PV system lifetime.

3.2 Case Study: Eldoret Daima Towers 54 kWp Grid-Tie Solar PV System

3.2.1 *Daima Towers Building*

Currently this is the tallest and largest building in the western region of Kenya, located at geographical coordinates 0.516° N, 35.282° E. The building is 26 stories tall with modern unique features including a swimming pool, restaurant, multi floor car park and expansive office spaces. The tower has full powered lighting system, CCTV surveillance, water storage with pumping and modern speed elevators that serves the different floors.

3.2.2 ***Building Power Supply and Demand***

The building was metered at 11KV by KPLC and served by one MVA ground mounted step-down transformer (11000/415V). The transformer, standby generator and switchgear equipment are all housed at the building basement floor. The building has maximum estimated energy demand of 1572 KWh per day and 574 MWh per year as per the estimated daily building consumption with 30% tenancy level at the time of study. The energy supply of the building, specifically the lighting system is complemented by 54-kWp grid tie solar PV system. KPLC grid supplies more than 80% of the energy demand of the building. Solar PV system are located on a special room at 26th floor and the rooftop of the building and supplies approximately 18% of the building energy demand.

3.2.3 ***Major Components of the Building Solar PV System***

The system consists of the following components, which are electrically interconnected to each other. They incudes 216 solar panels, 3 grid tie inverter, 9 smart inverter, back up battery, switchboard, combiner box, dc junction box, and control multi-cluster box and SMA meter.

3.2.3.1 Solar panels

The PV arrays are responsible for tapping the solar energy and converts it to DC energy. There are 216 solar PV modules distributed to three solar farms as shown in figure 3.1. Each farm has 72 panels and a 3-phase grid tie inverter. The panels are arranged into 12 strings of 18 solar PV modules in series. Each module has 265Wp power rating and 28V operating voltage. Each solar firm has four strings of 18 modules each that are connected to a three-phase grid tie inverter by 6mm^2 DC cables, with each string output estimated at 504 VDC. The connection topology used is that of multi-string and multi-level inverter that combines the advantages of string and centralized inverter topologies. These advantages include the increase efficiency and flexibility of the PV system. See Appendix A for detail technical specifications of the used solar PV module.

Figure 3.1: Installed Solar Panels on Rooftop of Daima Towers

3.2.3.2 Grid-tie Inverter.

Grid-tie inverters are special type of DC to AC converters that can automatically synchronize the output of the inverter to the national grid by matching the voltage, frequency, and phase sequence. This is the main component that converts solar direct current (DC) to Alternating Current (AC), which is utilized in the building or can be fed back to the grid. Figure 3.2 shows the sunny tri-power 25000tl inverter as installed. The system has three grid tie inverters that are rated 24KWp and voltage range of 390V-800V that are distributed to each of the three firms. The output of the three inverters is connected to one bus bar by $50mm^2$ core copper cable. See Appendix B for technical specification of the SMA tri-power inverter used. Advantages of this grid tie inverter are high efficiency of 98% with enormous design flexibility and compatibility due to high voltage range.

Figure 3.2: SMA Sunny Tri-Power 25000tl Inverter.

3.2.3.3 SMA Sunny Islanding Inverter.

These smart inverters convert AC to DC when solar energy is available, thereby charging the backup batteries. When solar energy is not available, energy from batteries is converted to AC and fed back to the load. The inverters allow the PV system to operate in off grid mode incase synchronization to main grid fails. The PV system is made of three clusters sets of the islanding inverter. Each set has three 8kwp sunny islanding inverters as shown in Figure 3.4. Each cluster is connected to 24 number of batteries.

Figure 3.3: Cluster of Sunny Islanding Inverters.

The Sunny Island temporarily stores self-generated power in the battery thus making it possible to use solar power around-the-clock. See Appendix C for detail technical specifications of islanding inverter used.

3.2.3.4 Battery Backup.

The battery backup is divided into 3 clusters, each with 24 batteries that are connected in series to give 48V as shown in figure 3.5. Each battery is rated 2v, 1000Ah and acts as back up to the system. The lead-acid batteries used have a lifespan of more than 20years making them useful for the estimated PV system lifetime of 25years.

Figure 3.4: Valve Regulated Lead-Acid OPzV Batteries.

Using 2V cells is an economic way to achieve a large storage capacity while keeping costs down. Perfect for use with high-powered systems to deliver the loads that are required, some characteristics of the OPzV cells includes very high-expected service life, high cycle stability, compatible and optimum space utilization.

3.2.3.5 *Other Components*

Other components used in the PV system includes the multi-cluster box, switchboard, home manager and solar meter. The components are used for logic control, switching, monitoring and energy measuring of solar PV yield, respectively.

3.2.4 ***Working Principle of the 54 kWp Grid tie solar system***

Energy from the sun is tapped using the solar PV arrays comprising of 216 PV modules located on the building's rooftop. The modules are equally distributed into three solar farms. The three solar farms output set are each connected to the grid-tie inverter rated

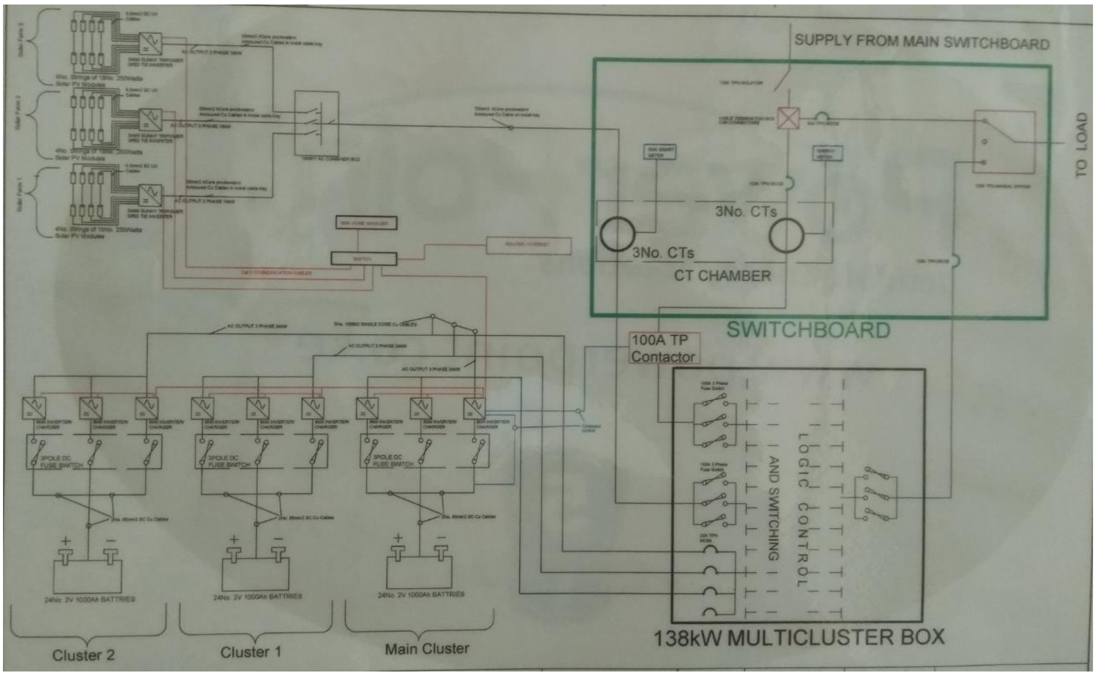


Figure 3.5: Grid-Tie Solar PV System Wiring Diagram as Build in Daima Towers

24 kWp. The inverters convert DC energy to AC energy, which are then connected to AC combiner junction box that gives the main AC output bus bar. The bus bar has 70mm^2 copper cable and is connected to the multi-cluster logic box via solar SMA meter. Figure 3.5 shows the wiring diagram of the system as build. The multi-cluster box logic circuit controls the output of the PV and battery systems before feeding the supply to the load. Priority is given to supply from solar PV output before grid supply is utilize.

3.3 Data Collection

The primary data of the PV system were collected by observation, inspection, survey, and interview with the system engineer. Secondary data were obtained from the building's financial records and KPLC electricity billing records. Data of interest were daily building consumption, solar PV production, energy imports from grid, and technical parameters of the system as well as financial costs of the system. Evaluation and continuous monitoring of 54-kWp grid-tie PV solar system for the year 2020 obtained the following data.

3.3.1 *Daily Building Consumption*

Since the building had tenancy level of 30%, there was likely low energy demand during the time of study that was anticipated to grow with time as more tenants move in. This data was collected by obtaining the power rating of energy consuming appliances, machines, and equipment within the building. Estimates were done for the expected number of hours the given appliance will be in use per day. The table 3.1 shows the maximum daily consumption of electricity energy in the building. The maximum demand was estimated at 1572 kWh per day and 574 MWh per year if the entire load was in use as projected. However, that is not normally the case. Therefore, clear picture of the building energy demand was obtained from energy meters, which gave the real time consumption. The actual energy demand was found to be 485 MWh for the year 2020. The energy demand was supplied from solar PV system and KPLC electricity grid at 82 MWh and 403 MWh respectively

Table 3.1: Daima Towers building energy demand.

	Appliance	**Number**	**Rating in watts**	**Daily use hours/day**	**Daily Energy watt hours**
1	Lamps	980	40	12	470400
2	TV/PCs/Switches/Electronics	450	100	10	450000
3	Domestic appliances	19	2000	3	152000
4	Fridges	10	0.8kwh/day	24	7992
6	Air Conditioners	21	400	24	201600
7.	Water pump	2	25000	2	100000
8	Elevator	3	20000	3	180000
9	Others		400	24	9600
Total Energy consumption in a day(Watt-hours)					1571592

3.3.2 *Technical Data of the System*

Technical data refers to the technical specification parameters of the solar PV system as installed in the building's rooftop. These data are important in evaluating the technical parameter performance of the PV system, which includes the system yield, performance ratio, Capital utilization factor, PV penetration levels and system losses. The data was collected by observation, survey and interview with system engineer and recorded as in Table 3.2.

Table 3.2: Technical Data of the PV System

Parameter	**Description**
System Capacity	54KWp
Number of panels	216
System area in meter squares	421 m^2
Year of installation	July 2018
PV Brand / Model No./ rating/ Type	Yingli/YL265c-30b/265Wp
Grid-tie inverter model/ number/ rating	SMA 25000tl/ 3/ 25KW
Sunny islanding inverter/number/rating	Sunny island 8.0h/9/8kw
Backup batteries/capacity/volts/number	OPzV/1130Ah/2V/72

3.3.3 *Financial Data*

This data represents the economic aspects of the solar PV system as was installed in the building. The system engineer shared with the researcher, the financial details including the investment costs, operation costs among others. These data are useful in assessing and evaluating the economic parameter performance of the case study PV system. These performance parameter as earlier mentioned are as follows: Levelized cost of energy (LCOE), electricity tariff, simple payback period (SPBP), and return on investment (ROI), the data collected was evaluated and summarized as in Table 3.3

Table 3.3: Financial Costs of the PV System

Direct Costs			
Item/description	Number of units	Cost per unit	Total (Kshs.)
PV module(YL 265-30b)	216	22,000	4,752,000
Support for modules	216	6,520	4,408,320
Inverter (sunny tri-power 25000tl)	3	333,400	1,000,200
Sunny Island battery Inverter	9	320,000	2,880,000
Batteries	72	116,875	8,415,000
Design/Studies/Analysis	1	1,000,000	1,000,000
Installation	Transport		540.000
	Accessories/fasteners		353,163
	Wiring		388,800
	Labor		2,000,000
Net Investment (CAPEX)		22,737,483	
Operation Costs/Maintenance			
Salaries		60,000/year	
Cleaning		36,000/year	
Provision for battery maintenance		45,000/year	
Total Operation costs(OPEX)		141,000/year	

Further to evaluating and recording data on technical and economic parameters of the system, the system was continuously monitored for one year (January-December 2020) and the data recorded in tables on daily, monthly, and yearly basis.

3.3.4 *Daily Hourly Energy Supply and Demand*

This data was monitored hourly for 24 hours on the solar and KPLC energy meters on 31 March 2020 as shown in Table 3.4. The difference between previous reading and current reading was recorded as the energy supply from the two sources, which included the grid (EFrGrid) and PV system (E_Solar). Since energy was not stored, the total energy demand (energy supplied to user- E_User) was taken as equal to the total energy supply as recorded in energy meters. This data was used in daily load profile analysis of the building as well as analysis of daily supply and demand patterns.

Table 3.4: Hourly Energy Supply and Demand for 31 March 2020.

Time	**Solar meter (kWh) reading**	**KPLC meter (kWh) reading**	**E_Solar kWh**	**EFrGrid kWh**	**E_User**
0:00	48215.07	968491	0.00	38	38.00
1:00	48215.07	968529	0.00	39	39.00
2:00	48215.09	968568	0.00	39	39.00
3:00	48264.40	968607	0.00	38	38.00
4:00	48325.58	968645	0.00	38	38.00
5:00	48413.28	969683	0.00	39	39.00
6:00	48461.03	968722	0.00	38	38.00
7:00	48467.31	968760	12.39	37	49.39
8:00	48478.70	968797	14.99	39	53.99
9:00	48492.69	968836	19.15	44	63.15
10:00	48510.34	968880	19.55	50	69.55
11:00	48527.11	968930	18.49	46	64.49
12:00	48545.60	968976	25.92	36	61.92
13:00	48571.52	969012	25.49	35	60.49
14:00	48597.01	969047	32.50	38	70.50
15:00	48629.51	969085	29.71	37	66.71
16:00	48659.22	969122	21.81	43	64.81
17:00	48681.03	969165	18.26	45	63.26
18:00	48699.29	969210	7.60	43	50.60
19:00	48706.89	969253	0.00	42	42.00
20:00	48706.89	969295	0.00	45	45.00

21:00	48706.89	969340	0.00	43	43.00
22:00	48706.89	969383	0.00	43	43.00
23:00	46706.89	969426	0.00	42	42.00
			245.86	977	1222.86

3.3.5 *Daily energy supply and demand*

Daily meter readings for both solar PV output and Imports from KPLC were recorded each day from 1st to 31st March 2020 and tabulated as shown in the Table 3.5.

Table 3.5: Daily Energy Supply and Demand for March 2020.

Day	**Solar meter (kWh) reading**	**KPLC meter (kWh) reading**	**E_Solar kWh**	**EFrGrid kWh**	**E_User**
1	41304.35	935957	238.40	689	927.4
2	41545.10	937031	240.75	1074	1314.75
3	41782.40	938165	237.30	1134	1371.3
4	42022.19	939442	239.79	1277	1516.79
5	42248.50	940658	226.31	1216	1442.31
6	42480.50	941757	232.00	1099	1331
7	42695.38	942841	214.88	1084	1298.88
8	42928.76	943739	233.38	898	1131.38
9	43173.57	944899	244.81	1160	1404.81
10	43412.08	946160	238.51	1261	1499.51
11	43658.78	947416	246.70	1256	1502.7
12	43894.23	948655	235.45	1239	1474.45
13	44121.69	949771	227.46	1116	1343.46
14	44361.66	950858	239.97	1087	1326.97
15	44614.76	951746	253.10	888	1141.1
16	44871.71	952951	256.95	1205	1461.95
17	45121.89	954262	250.18	1311	1561.18
18	45370.97	955463	249.08	1201	1450.08
19	45612.37	956719	241.40	1256	1497.4
20	45854.20	957910	241.83	1191	1432.83
21	46.090.48	958964	236.28	1064	1300.28

22	46335.34	959888	244.86	924	1168.86
23	46580.20	960912	239.87	1064	1303.87
24	46820.07	961963	233.89	1051	1284.89
25	47058.22	963138	238.15	1175	1413.15
26	47289.80	964345	231.58	1207	1438.58
27	47519.55	965320	229.75	975	1204.75
28	47743.70	966375	224.15	1055	1279.15
29	47979.32	967370	235.62	995	1230.62
30	48215.17	968451	235.85	1071	1316.85
31	48461.03	969428	245.86	977	1222.86
			7384.11	34200	41594.11

3.3.6 *Monthly energy supply and demand 2020*

The meter reading for both solar and grid supply was observed and recorded continuous from January to December of 2020. This data is important in comparing the actual measured system yields and energy demand of the building in comparison to the simulated results. The data was recorded by reading both the solar and KPLC meters on the end of every month in the year 2020 and tabulated as shown in Table 3.6

Table 3.6: Monthly Energy Supply and Demand for the Year 2020

Period	**Solar meter (kWh) reading**	**KPLC meter (kWh) reading**	**E_Solar kWh**	**EFrGrid kWh**	**E_User**
January	32473	902199	8401	29434	37835
February	39727	933270	7254	31071	38325
March	47111	967470	7384	34200	41584
April	51524	994866	4413	27396	31809
May	56020	1028842	4496	33976	38472
June	59083	1061111	3063	32269	35332
July	65982	1095622	6899	34511	41410
August	74185	1132038	8203	36416	44619
September	81569	1173168	8492	41130	49622
October	88953	1211594	7384	38426	45810
November	96408	1244482	7455	32888	40343
December	104994	1276329	8586	31847	40433
Totals			**82030**	**403564**	**485594**

3.3.7 *Monthly Grid Electricity Billing-KPLC.*

Table 3.7: Cost of Imported Electricity from Grid

Billing period	Energy in (kWh)	Average Pf	Energy costs, Total –Kshs	Levies & Taxes – Kshs	Total in kshs	Cost /kwh
Dec-20	31847	0.74	564010.15	241272.85	805283.00	25.30
Nov-20	32888	0.66	634999.00	236606.00	871605.00	26.50
Oct-20	38426	0.78	584166.55	276770.45	860937.00	22.40
Sep-20	41130	0.73	665550.68	272469.32	938020.00	22.80
Aug-20	36416	0.70	635136.05	242278.95	877415.00	24.10
Jul-20	34511	0.74	563787.31	220694.69	784482.00	22.70
Jun-20	32269	0.79	500401.13	199003.87	699405.00	21.70
May-20	33976	0.75	533826.55	203150.45	736977.00	21.70
Apr-20	27396	0.79	441212.34	172295.66	613508.00	22.40
Mar-20	34200	0.78	537855.51	198924.49	736780.00	21.50
Feb-20	31071	0.73	536262.21	203861.79	740124.00	23.80
Jan-20	29434	0.81	374984.75	172356.25	547341.00	18.60
	403564		**6572192.23**	**2639684.77**	**9211877.00**	

Average cost of energy imported from grid= Kshs. 22.80 per kWh.

Levies & taxes :

VAT, Warma Levy, Inflation Adjustment, Fuel Energy Cost, REP Levy, EPRA Levy and Forex Exchange Adjustment.

3.4 PVsyst simulation Methods

3.4.1 *Highlights*

PVsyst software was used to study the system short and long-term technical and economic performance. PVsyst is Computer based software package commonly used in designing, studying, analyzing, and sizing of various solar PV system application. The software has a wide range database containing meteorological data, solar PV system components data as well as tools used in the simulation. It also has the option of importing the various data from external sources or user defined sources, making it flexible. This software is applied when designing or studying DC-grid, Solar pumping, standalone and grid-tie (connected) solar energy applications as shown in Figure 3.6. Its extensive database for meteorological and solar energy components makes it conducive for this kind of study.

Full-featured study and analysis of a project.
- Accurate system yield computed using detailed hourly simulations,
- Different simulation variants can be performed and compared,
- Horizon shadings, and 3D tool for near shadings effects study,
- Detailed losses analysis,
- Economic evaluation performed with real component prices.

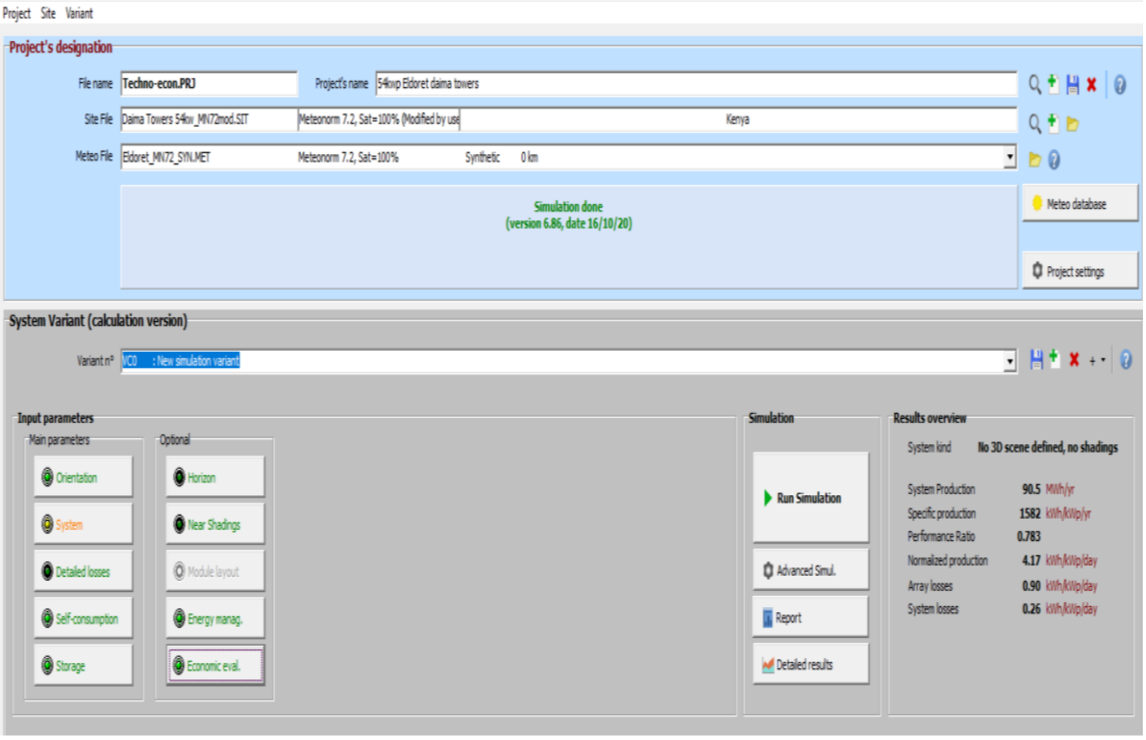
Figure 3.6: PVsyst Project Design Windows

The following computer program and operating system were used in study:

- Software version-PVsyst 6.86
- Windows version-Windows 10

3.4.2 *PVsyst simulation Step by Step Procedure.*

Launch the software and click the project design button then select a grid-connected option on the system section to reach the window in Figure 3.8.



File name: Techno-econ.PRJ
Project's name: 54kwp Eldoret daima towers
Site File: Daima Towers 54kw_MN72mod.SIT — Meteonorm 7.2, Sat=100% (Modified by use — Kenya
Meteo File: Eldoret_MN72_SYN.MET — Meteonorm 7.2, Sat=100% — Synthetic — 0 km

Simulation done
(version 6.86, date 16/10/20)

Variant n°: VC0 : New simulation variant

System kind	No 3D scene defined, no shadings	
System Production	90.5	MWh/yr
Specific production	1582	kWh/kWp/yr
Performance Ratio	0.783	
Normalized production	4.17	kWh/kWp/day
Array losses	0.90	kWh/kWp/day
System losses	0.26	kWh/kWp/day

Figure 3.7: System Variant Window

In this window, you are required to define your project name, file name and site data before proceeding to input other parameters. In this study the location and meteorological data of the site were obtained by using GPS coordinates of the site location and importing the meteorological data into the software from NASA SSE – database.

3.4.3 *Importing Meteorological data of the site to the PVsyst*

Secondary meteorological data was used in the simulation due to limited resources and time to measure the actual meteorological data of the site. In the PVsyst home screen, choose the databases icon to reach the window in the Figure 3.9. Click on geographical site and choose from the list if your site is available, otherwise proceed to import meteo data section. Click the ‘known format’ icon for data from NASA database or click ‘custom file’ for your own measured weather data saved in excel sheet. For this study NASA –SSE satellite monitored weather data was selected. By clicking the ‘known format’, you will be redirected to the next window where you will select the NASA-SSE database. The program will prompt you to input geographical coordinates of the study site.

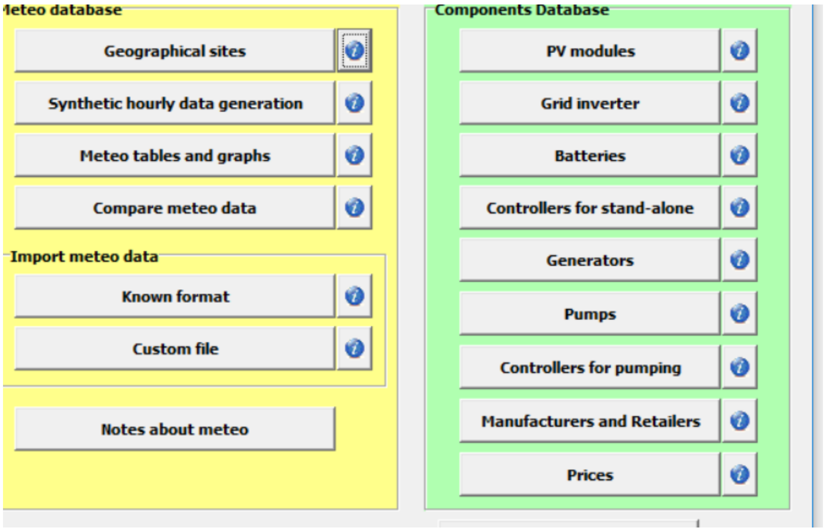


Figure 3.8: Meteo Database Windows.

Once these input data were added and ‘Enter’ key pressed, meteorological data of the site was generated, downloaded and saved in the software database. Once this is done, the window in Figure 3.8 is closed. Go back to project design windows as in the Figure 3.7. From meteo database icon, select the imported meteo data for the site.

It should be noted that the probability distribution of the system production forecast for different years is mainly dependent on the meteo data used for the simulation and depends on the type and source of meteorological data.

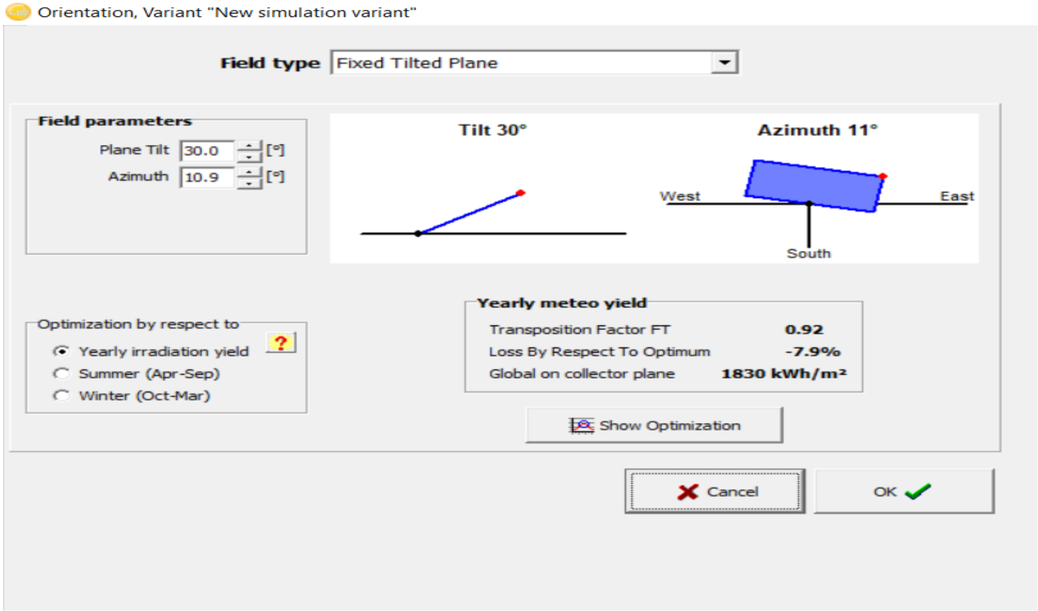
3.4.4 *System Variant definition in PVsyst*

Two types of system parameters need to be defined in the project; they include main and optional parameters.

3.4.4.1 Main parameters.

These were the major parameters in the system that defines the technical input. They included system orientation, system parameters, detailed losses, self-consumption, and storage information.

a) ***Orientation***-In this field we define the inclination and azimuth angle depending on the installation of our solar panels. After measuring the PV modules installation using a set of 2 measuring instrument (Protractor and meter rule), orientation was defined as in the Figure 3.9.



Orientation, Variant "New simulation variant"

Field type Fixed Tilted Plane

Field parameters
Plane Tilt 30.0 [°]
Azimuth 10.9 [°]

Optimization by respect to
● Yearly irradiation yield
○ Summer (Apr-Sep)
○ Winter (Oct-Mar)

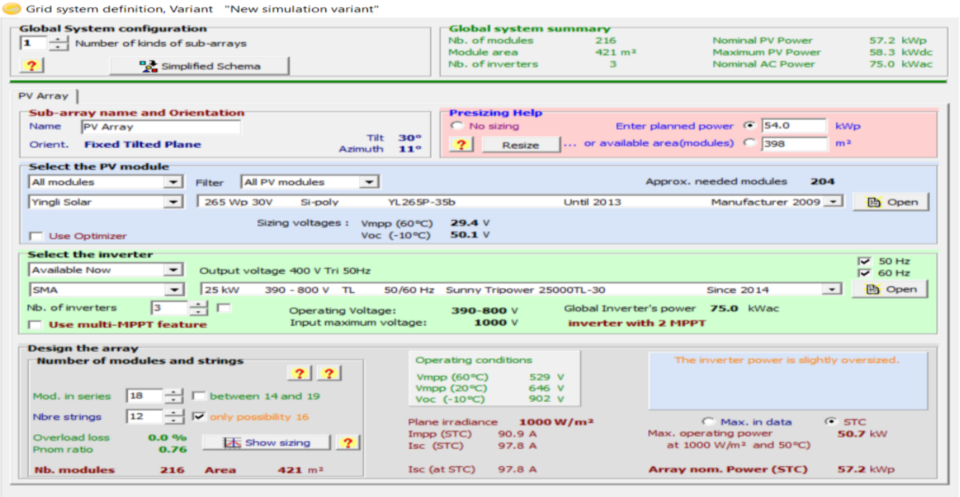
Yearly meteo yield

Transposition Factor FT	**0.92**
Loss By Respect To Optimum	**-7.9%**
Global on collector plane	**1830 kWh/m²**

Figure 3.9: Orientation Variant

b) ***System***- In this section, the main parameters of the system are defined according to specifications as installed. The main data in this section is the technical details of the PV modules, Inverters as connected and installed in the system.

First, we define the capacity of the system in study at 54kwp and area at 421m2 for purpose of sizing the system. The next section is selection of PV module from the extensive database of components. The PV module in our case is Si-Poly-crystalline type with model YL265P-35b with an efficiency at STC of 13.6%. Afterward we select the inverter used in the system (Sunny Tri-power -25000tl-30). Once the model of the component is selected the rest of the details are automatically loaded from simulation program database as shown in the Figure 3.10. PV array design in the program was done by defining the number of modules in series and the number of strings used. Design for inverter in the simulation program involved defining inverter numbers, size, and manufacturer as used in the PV system.


Grid system definition, Variant "New simulation variant"

Global System configuration
1 Number of kinds of sub-arrays

Global system summary
Nb. of modules 216
Module area 421 m²
Nb. of inverters 3
Nominal PV Power 57.2 kWp
Maximum PV Power 58.3 kWdc
Nominal AC Power 75.0 kWac

PV Array

Sub-array name and Orientation
Name: PV Array
Orient.: **Fixed Tilted Plane**
Tilt **30°**
Azimuth **11°**

Presizing Help
○ No sizing
Enter planned power ● 54.0 kWp
... or available area(modules) ○ 398 m²

Select the PV module
All modules
Filter: All PV modules
Approx. needed modules **204**
Yingli Solar
265 Wp 30V Si-poly YL265P-35b Until 2013 Manufacturer 2009
Sizing voltages : Vmpp (60°C) **29.4** V
Voc (-10°C) **50.1** V
☐ Use Optimizer

Select the inverter
Available Now
Output voltage 400 V Tri 50Hz
☑ 50 Hz
☑ 60 Hz
SMA
25 kW 390 - 800 V TL 50/60 Hz Sunny Tripower 25000TL-30 Since 2014
Nb. of inverters 3 ☐
Operating Voltage: **390-800** V
Input maximum voltage: **1000** V
Global Inverter's power **75.0** kWac
☐ **Use multi-MPPT feature**
inverter with 2 MPPT

Design the array
Number of modules and strings
Mod. in series 18 ☐ between 14 and 19
Nbre strings 12 ☑ only possibility 16
Overload loss 0.0 %
Pnom ratio 0.76
Nb. modules 216 Area 421 m²

Operating conditions
Vmpp (60°C) 529 V
Vmpp (20°C) 646 V
Voc (-10°C) 902 V
Plane irradiance **1000 W/m²**
Impp (STC) 90.9 A
Isc (STC) 97.8 A
Isc (at STC) 97.8 A

The inverter power is slightly oversized.

○ Max. in data ● STC
Max. operating power at 1000 W/m² and 50°C) **50.7** kW
Array nom. Power (STC) 57.2 kWp

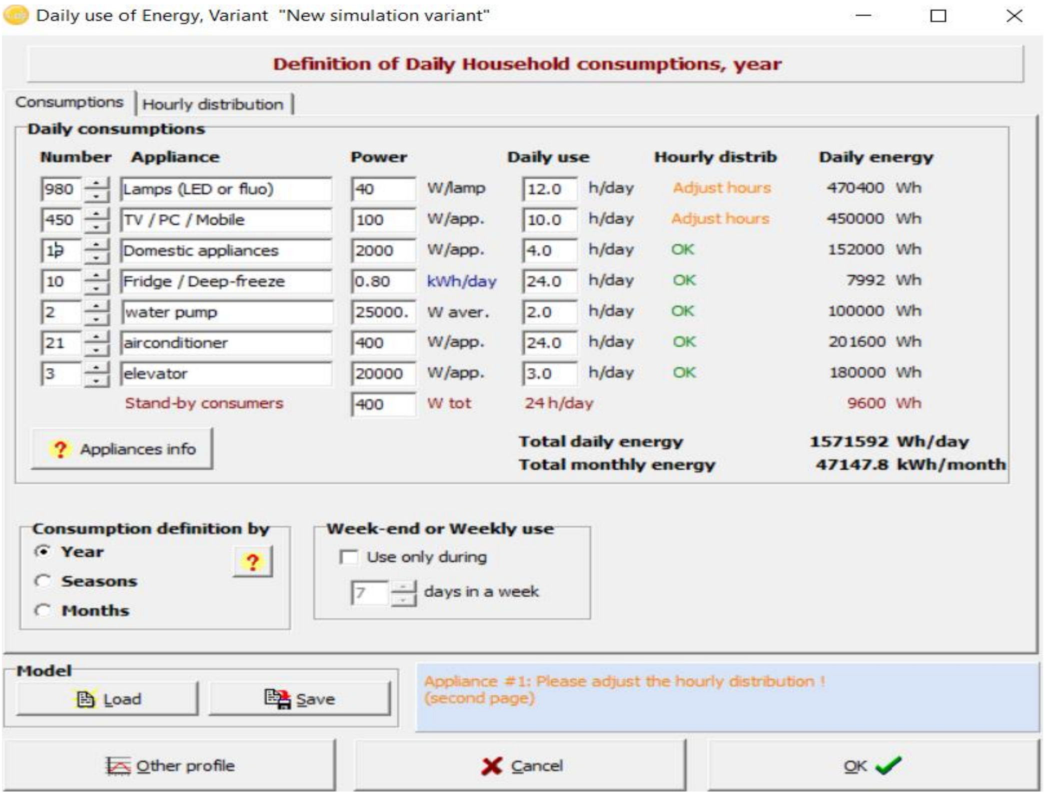
Figure 3.10: Grid System Definition Variant.

c) **Detailed losses**

In this section, the default software set up was used, because the solar panels were installed on top of the rooftop of the tallest building in the site location. There are zero shadings from trees or other buildings, which would interfere with solar PV panel exposure to sunlight.

d) **Self-Consumption**

This was defined based on tenants and common areas served by the building energy supply. Total energy consumption per day was estimated at 1572 KWh per day and 574 MWh per year based on building load requirement. Figure 3.11 shows the energy estimated self-consumption load.



Daily use of Energy, Variant "New simulation variant"

Definition of Daily Household consumptions, year

Daily consumptions

Number	Appliance	Power		Daily use		Hourly distrib	Daily energy
980	Lamps (LED or fluo)	40	W/lamp	12.0	h/day	Adjust hours	470400 Wh
450	TV / PC / Mobile	100	W/app.	10.0	h/day	Adjust hours	450000 Wh
19	Domestic appliances	2000	W/app.	4.0	h/day	OK	152000 Wh
10	Fridge / Deep-freeze	0.80	kWh/day	24.0	h/day	OK	7992 Wh
2	water pump	25000.	W aver.	2.0	h/day	OK	100000 Wh
21	airconditioner	400	W/app.	24.0	h/day	OK	201600 Wh
3	elevator	20000	W/app.	3.0	h/day	OK	180000 Wh
	Stand-by consumers	400	W tot	24 h/day			9600 Wh

Total daily energy **1571592 Wh/day**
Total monthly energy **47147.8 kWh/month**

Consumption definition by
● **Year**
○ **Seasons**
○ **Months**

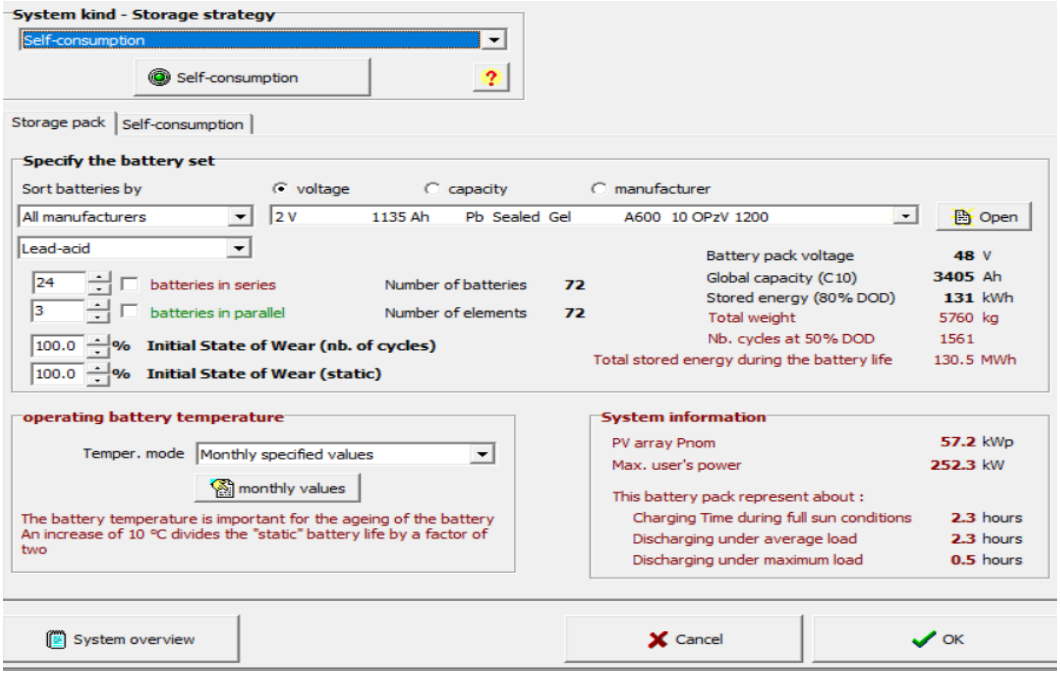
Week-end or Weekly use
☐ Use only during
7 days in a week

Appliance #1: Please adjust the hourly distribution !
(second page)

Figure 3.11: Daily Building Consumption in PVsyst

e) Storage

The sunny islanding inverter and three cluster of battery banks are the main components responsible for storage of the backup power during sunlight hours. The batteries are then discharged when solar energy is unavailable. The storage parameters were defined as follows in the Figure 3.12. In the storage windows, parameters related to battery storage are all defined, including the number and connection type. The exact battery type is selected from the extensive database of solar storage batteries available on PVsyst component database.



System kind - Storage strategy: Self-consumption

Specify the battery set

Sort batteries by ● voltage ○ capacity ○ manufacturer

All manufacturers

Lead-acid

2 V 1135 Ah Pb Sealed Gel A600 10 OPzV 1200

24 ☐ batteries in series — Number of batteries 72

3 ☐ batteries in parallel — Number of elements 72

100.0 % **Initial State of Wear (nb. of cycles)**

100.0 % **Initial State of Wear (static)**

Battery pack voltage	**48** V
Global capacity (C10)	**3405** Ah
Stored energy (80% DOD)	**131** kWh
Total weight	5760 kg
Nb. cycles at 50% DOD	1561
Total stored energy during the battery life	130.5 MWh

operating battery temperature

Temper. mode: Monthly specified values

The battery temperature is important for the ageing of the battery An increase of 10 °C divides the "static" battery life by a factor of two

System information

PV array Pnom	**57.2** kWp
Max. user's power	**252.3** kW
This battery pack represent about :	
Charging Time during full sun conditions	**2.3** hours
Discharging under average load	**2.3** hours
Discharging under maximum load	**0.5** hours

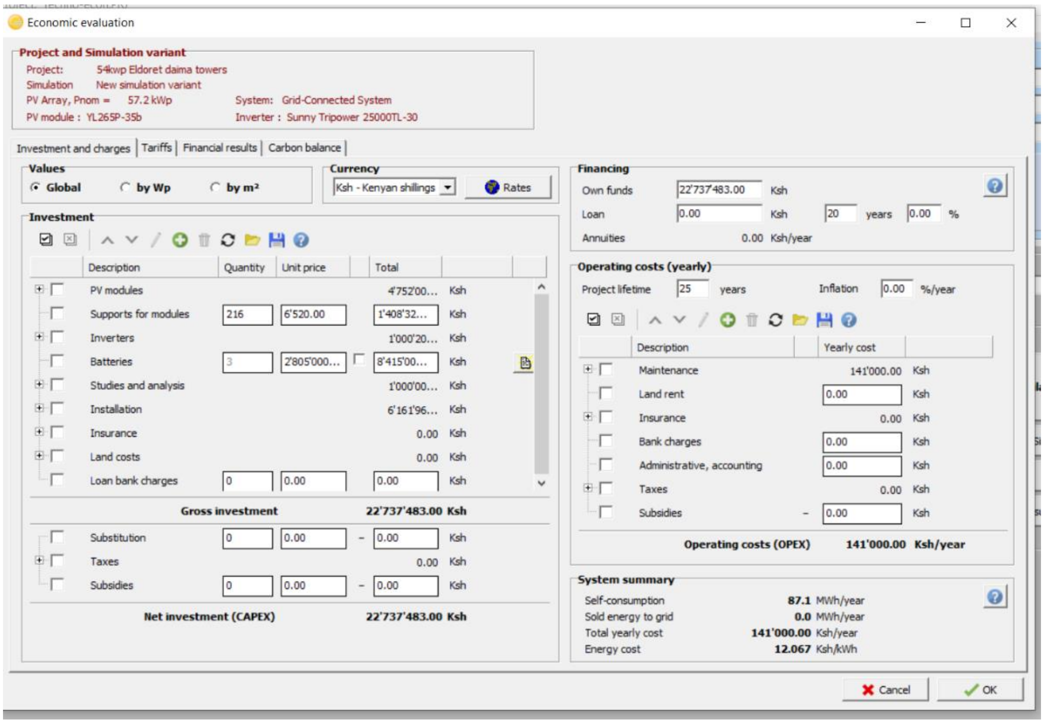
Figure 3.12: Storage Management Windows in PVsyst.

There are three cluster of batteries: one master and two slave, each cluster has 24 batteries connected in series to make 48V, which is connected, to sunny islanding inverter.

After the main parameters of the system design, the simulation is run by clicking ‘Run Simulation’ button to obtain results as well as activate optional parameters.

3.4.4.2 Optional Input Parameters-Economic evaluation

It has four active sections, namely: Horizon, near shading, energy management and economic evaluation part. The first three sections are left in default set up while the economic evaluation section is defined as follows as per the collected financial data from the system. The total capital cost (CAPEX) of the system was approximated at Kshs. 22,737,483 while operating cost (OPEX) at kshs.141000 per year. Source of fund was financed directly by shareholders of the building. Figure 3.13 shows the input parameters for economic evaluation.



Project and Simulation variant
Project: 54kwp Eldoret daima towers
Simulation New simulation variant
PV Array, Pnom = 57.2 kWp
System: Grid-Connected System
PV module : YL265P-35b
Inverter : Sunny Tripower 25000TL-30

Values
● Global ○ by Wp ○ by m²

Currency
Ksh - Kenyan shillings

Investment

Description	Quantity	Unit price	Total	
☐ PV modules			4'752'00...	Ksh
☐ Supports for modules	216	6'520.00	1'408'32...	Ksh
☐ Inverters			1'000'20...	Ksh
☐ Batteries	3	2'805'000... ☐	8'415'00...	Ksh
☐ Studies and analysis			1'000'00...	Ksh
☐ Installation			6'161'96...	Ksh
☐ Insurance			0.00	Ksh
☐ Land costs			0.00	Ksh
☐ Loan bank charges	0	0.00	0.00	Ksh
Gross investment			**22'737'483.00**	**Ksh**
☐ Substitution	0	0.00	- 0.00	Ksh
☐ Taxes			0.00	Ksh
☐ Subsidies	0	0.00	- 0.00	Ksh
Net investment (CAPEX)			**22'737'483.00**	**Ksh**

Financing
Own funds 22'737'483.00 Ksh
Loan 0.00 Ksh 20 years 0.00 %
Annuities 0.00 Ksh/year

Operating costs (yearly)
Project lifetime 25 years
Inflation 0.00 %/year

Description		Yearly cost	
☐ Maintenance		141'000.00	Ksh
☐ Land rent		0.00	Ksh
☐ Insurance		0.00	Ksh
☐ Bank charges		0.00	Ksh
☐ Administrative, accounting		0.00	Ksh
☐ Taxes		0.00	Ksh
☐ Subsidies	-	0.00	Ksh
Operating costs (OPEX)		**141'000.00**	**Ksh/year**

System summary

Self-consumption	**87.1**	MWh/year
Sold energy to grid	**0.0**	MWh/year
Total yearly cost	**141'000.00**	Ksh/year
Energy cost	**12.067**	Ksh/kWh

Figure 3.13: Economic Evaluation.in PVsyst

3.4.5 ***Analysis and Results Simulation.***

Following successful definition of economic and technical parameters of the case study PV system the final simulation was run. Technical and economic performance results were obtained in form of reports, which gave the short-term analysis for the whole year from January to December and longtime analysis for the system lifetime of 25 years. The software also calculates and gives the estimate amount of carbon that will be saved, which otherwise would have been released to atmosphere if the given electricity generated by solar PV were imported from grid.

3.5 Comparison of Case Study PV System Design to Other Possible Designs Scenarios.

Further to the evaluation of the technical and economic parameters of the case study PV system, other possible design scenario were also analyzed and compared to case study. PVsyst software was used to model different PV system design for the same capacity and location as the current installed system. The three scenarios were simulated as follows.

3.5.1 *Scenario 1- 54kwp PV System with Tilt Orientation and no Battery Storage.*

The current PV system has battery backup that offers less than two hours backup of solar energy. A PVsyst simulation was carried out for the system without battery backup to determine the performance of the technical and economic parameters in comparison to the PV system under investigation. This study was to establish impact of having battery storage on grid-tie PV system. The investigation was conducted by editing the previous simulation as follows:

Open the saved 54kWp grid-tie solar PV system and proceed to system variant definition window (main window). In the main parameter section, click the storage button to obtain the storage management window shown in Figure 3.12. In the storage strategy window, select no storage in place of self-consumption. This selection removes the window that requires battery storage component definitions. Then click ok to save the set up in the window.

In optional parameter section, click the economic evaluation button to go to window in Figure 3.13. In the window, remove all the costs element related to battery storage and click ok to save the window and return to main window. Finally click the ‘Run Simulation’ button to simulate the technical and economic performance for the 54-kWp grid tie PV system without battery storage.

3.5.2 *Scenario 2- 54 kWp Grid-Tie PV System with Dual-Axis Tracker and Battery Backup.*

This study was done to determine the effect of having solar PV trackers on the technical and economic parameter performance of PV system. PVsyst simulation for a 54-kWp PV system on the same location was done by editing the case study simulation set-up as follows:

Open the saved case study simulation set-up on the PVsyst software and proceed to system variant window. On the main parameter section, select the ‘Orientation’ button to obtain the window in Figure 3.9. In the window, replace ‘fixed tilted plane’ with ‘tracking two axes’.

On optional parameter in the system variant window, select click ‘economic evaluation’ button to reach window in Figure 3.13. In this window, adjust the coast of the modules from kshs. 6,520, which fixed support structure cost to kshs. 25,000, which is the cost of solar tracker fittings for one solar panel. Click ok to exit the window and return to ‘system variant definition’ window. In the same window run the simulation for the technical and economic parameter performance of the PV system for scenario 2 by clicking ‘Run Simulation’ button.

3.5.3 *Scenario 3- 54kwp Grid Tie PV System with Dual Axis Tracker and No Battery Storage.*

The study in this scenario was to determine the PV system performance when solar PV trackers are used and battery storage eliminated. For scenario 3, PVsyst simulation was done by editing the case study simulation set-up as follows:

To adjust the PV system orientation from fixed tilted orientation to dual-axis tracker orientation follow the same steps as in scenario 2, also adjust the economic evaluation windows as in scenario 2. In addition, follow the steps in scenario 1 to adjust the case study simulation set up from one with battery storage to PV system with no battery storage, also adjust economic evaluation window as in scenario 1. Click 'ok' and return to 'system variant definition' window to run the simulation by clicking 'Run Simulation' button to obtain the technical and economic performance analysis.

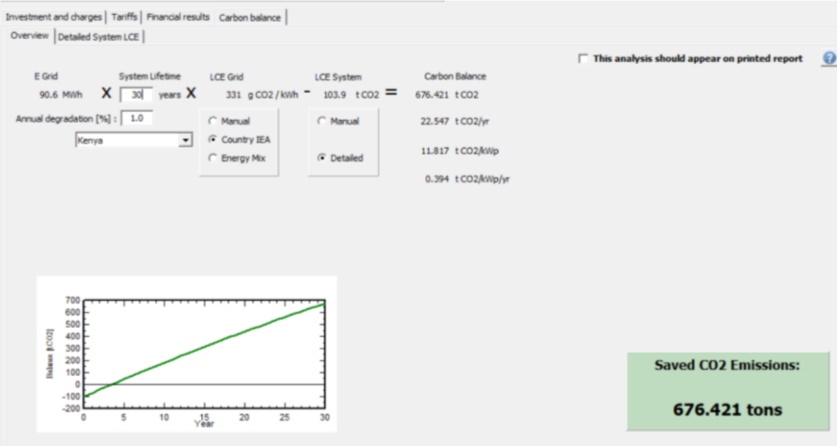
3.6 Carbon Balance

In PVsyst, carbon balance can be estimated by finding the saving in Carbon dioxide (CO_2) emissions expected for the PV installation. Reasoning behind this tool is that the generated electricity by the PV installation will replace the same amount of electricity in the existing grid. The calculations were done using equation 14 in Chapter 2 as follows.

$$E\_Solar \times System\ lifetime \times Grid\ LCE - PV\ System\ LCE = Carbon\ Balance$$

Taking into account annual PV system depreciation rate of 1% per annum.

The Carbon balance in the PVsyst is defined in the optional parameter section by clicking the 'Carbon balance' button and inputing the equation 14 values as shown in the Figure 3.14. Then run the entire simulation again to obtain the results.



E Grid 90.6 MWh X System Lifetime 30 years X LCE Grid 331 g CO2 / kWh - LCE System 103.9 t CO2 = Carbon Balance 676.421 t CO2

Annual degradation [%] : 1.0

Kenya

LCE Grid: ○ Manual ● Country IEA ○ Energy Mix

LCE System: ○ Manual ● Detailed

22.547 t CO2/yr

11.817 t CO2/kWp

0.394 t CO2/kWp/yr

Saved CO2 Emissions:

676.421 tons

Figure 3.14: Saved amount of Carbon emissions.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the research findings obtained from the methodologies employed in the study. PVsyst software and Microsoft excel tools were used to analyze the data. This chapter presents the comparison of actual measured energy yield of the solar PV system to the expected energy from PVsyst software. It was done to verify whether the simulated results for both long and short term were reliable in the study.

In addition, the chapter gives the technical and economic performance results of the case study of the 54-kWp PV system. The results of the analysis on the system yields, performance ratio, penetration factor, capital utilization factor, SPBP, ROI among others is presented in the technical and economic analysis section. The use of PVsyst and Microsoft excel tools ensures the results are presented in simple and verifiable means that answers the objective/ questions of the study.

4.2 Summary of Yield Results from PVsyst Simulation.

Following the successful simulation of the PVsyst design set up of the case study, various results were obtained for the performance of both technical parameters. The results were in report format. These results among others included the system yield of the PV system as well as the electricity that will be supplied from the grid to meet the builds energy demand. The outcome of the simulation yield results was as shown in the Table 4.1.

Table 4.1: PVsyst Simulation of Energy Yields

Month	**GlobInc kWh/m^2**	**EArray MWh**	**E_Solar MWh**	**EFrGrid MWh**	**E_User MWh**
January	218.7	10.16	9.52	31.96	41.48
February	183.3	8.52	7.95	29.52	37.47
March	181.0	8.59	8.05	33.43	41.48
April	142.2	6.84	6.48	33.66	40.14
May	125.7	6.08	5.79	35.69	41.48
June	107.6	5.25	5.01	35.13	40.14
July	104.8	5.14	4.92	36.56	41.48
August	120.0	5.93	5.68	35.81	41.48
September	157.6	7.56	7.13	33.01	40.14
October	186.8	8.86	8.31	33.17	41.48
November	190.8	8.97	8.38	31.77	40.14
December	225.4	10.55	9.84	31.65	41.48
Year -2020	**1943.9**	**92.46**	**87.06**	**401.36**	**488.42**

4.3 Comparison of Measured Energy to Expected Energy from Simulation

This comparison was done to verify whether we could rely on PVsyst simulated results in analysis of the PV system. Figure 4.1 shows the chart comparison of expected energy to actual measured energy. Refer to Table 3.6 for measured solar PV generation and Table 4.1 for simulated expected energy (E_Solar). The comparison of measured energy to expected (simulated) for the month of January to June 2020, showed slight difference between the two with expected energy slightly high for the month of January to March and higher for April to June.

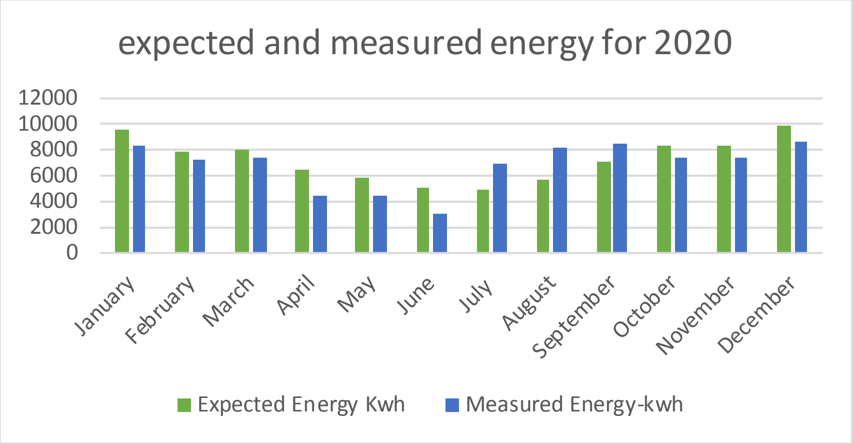


Figure 4.1: Expected vs Measured Energy for 54kWp PV System

For the months of July to September 2020, the expected energy was slightly lower than measured energy, while the months of October to December the expected energy was slightly higher than the actual measured energy. The mean difference between the actual measured and the expected energy yield for the year 2020 was calculated as follows:

Mean expected results= 87054 / 12 = 7254.50kWh

Mean measured results= 82030 / 12 = 6833.83kWh

Mean difference=7255 - 6834 = 421 kWh

Average difference percent = 421 / 6834 × 100 = 6%

The comparisons of simulation and measurements showing slight differences between them, the average difference being 6%. The difference between the expected energy yields as predicated by the software compared to measured energy can be attributed to three possible reasons. The first reason could be lack of regular maintenance as expected resulting to dust accumulation on panels hence decreasing energy yield. Secondly, it could be due to the use of historical meteorological data in software simulation of results that slightly vary from the actual weather conditions in the study site. Other reasons could be related to the accuracy of measuring equipment used as well as system losses that could have been captured differently by software simulation in comparison to the actual measured energy. The slight difference between actual measured and simulated energy yield can be decrease further if the probable causes are address by, strict schedule maintenance of panels, contacts, terminals etc., to increase the PV system efficiency. In addition, use of recent actual measured meteorological data input to the PVsyst software will improve on accuracy of the results although at a cost. Due to the slight difference between actual and simulated energy yields, the results of this investigation using the PVsyst simulation software were considered when expected calculation were analysed.

4.4 Electricity Energy Demand and Supply of the Building

The quantity of energy demanded (E_User) refers to the amount of energy consumed for a particular period. Quantity of energy supplied (E_Solar and EFrGrid) refers to the flow of energy to the market from different generating sources to meet the energy demand. The quantity is usually measured in kilowatt-hours (kWh).

4.4.1 *Daily Energy Demand and Supply of the Building.*

The data from continuous 24 hours monitoring of the building hourly energy demand and supply were analysed. From the data, it was observed that, the building energy demand was served by supply from both solar PV system generation and imports from KPLC grid, on 31st March 2020 as shown in figure 4.2.

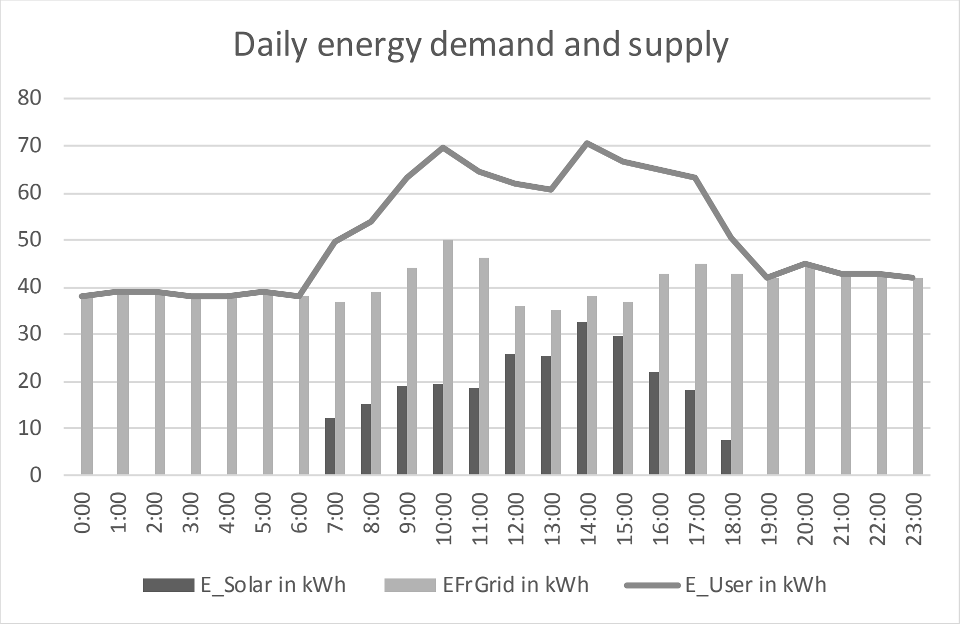


Figure 4.2: Daily Energy Demand and Supply Graph for the Building.

From the daily demand curve, it was observed that the highest consumption of energy occurs during the day when the sunlight is available. This can be attributed to the fact that the building experience increase human activities due to high commercial activities during the day. Most electronics like personal computers, television and electrical machines like elevators, air conditioners among others were more active during the day. During the night equipment active were bulb-lights and few electrical equipment, resulting to lower energy demand as observed. The solar energy generated during the day was given priority by the intelligent grid tie inverters before grid imports supply hence maximum utilization of generated solar electricity. The solar electricity generation is high during the day with the peak at around 1400hours, during this period the building energy demand is met with both solar and grid electricity. There is significant decrease in import of electricity from the grid due to use of solar electricity to partly meet the building energy demand. During night hours, the energy demand is supplied purely from the grid. The battery backup was estimated to offer backup supply of less than two hours that was practically not viable as it contributed to decrease PV system efficiency. However, the backup ensured a steady supply of intermittent solar energy during the day.

4.4.2 *Monthly Energy Demand and Supply of the Building –March 2020.*

The daily electricity energy supply and consumption for the building that was recorded from 1st March to 31st March of 2020 was analysed and presented as in Figure 4.3. The graphs shows that there is low energy demand during weekends and increase energy demand during weekdays. The reason behind this is likely to be the commercial nature of the building whereby most human activities are active during weekdays while in weekends most people are at home, hence low energy demand in the building. Solar electricity generation remains slightly constant most days of the month. The energy demand from the building was served by supply from both solar and imports from grid.

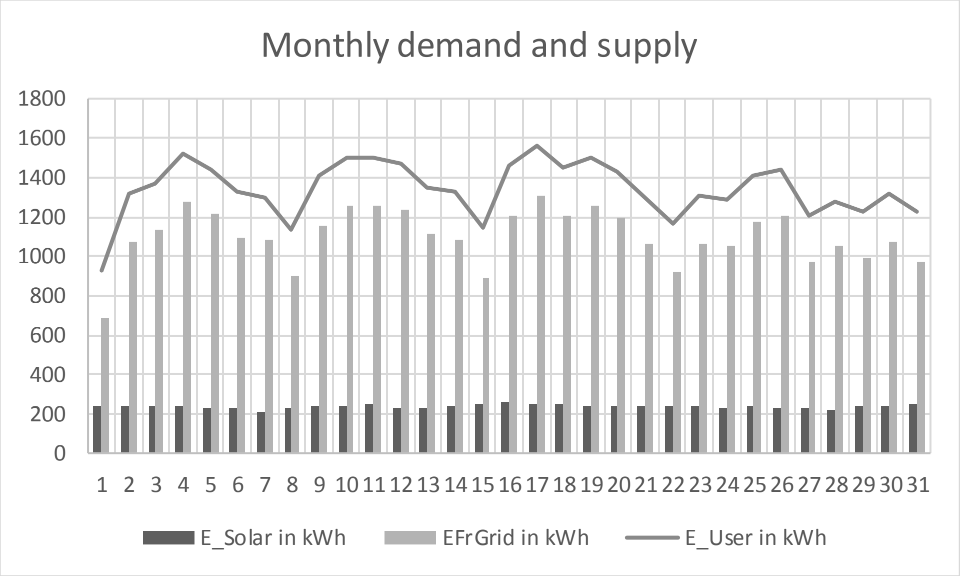


Figure 4.3: Monthly Energy Demand and Supply to the Building.

From the graph, a big percentage of power supply in the reference month comes from KPLC grid while slightly less than 20% is supplied from solar PV system. Since solar energy is slightly constant, the changes in electricity demand is proportional to the changes in KPLC grid electricity supply. The energy demand in the last days of the reference month was observed to drop with probable cause being the increase in covid-19 cases in Kenya during the last days of March 2021. Tuesdays to Thursdays were observed to be the days with high-energy demand compared to Mondays and Fridays during weekdays.

The generated solar energy remains slightly constant as the weather conditions in the month of March remained somehow the same. The 16th to 18th of March 2020 had slightly high solar energy generation as compared to other days of the month.

4.4.3 *Yearly Energy Demand and Supply for the Building - 2020*

The energy demand for the year 2020 was analysed from data recorded on energy supply from both solar and KPLC grid. The peak energy demand was on the month of September while the month of April experience low energy demand as shown in Figure 4.4.

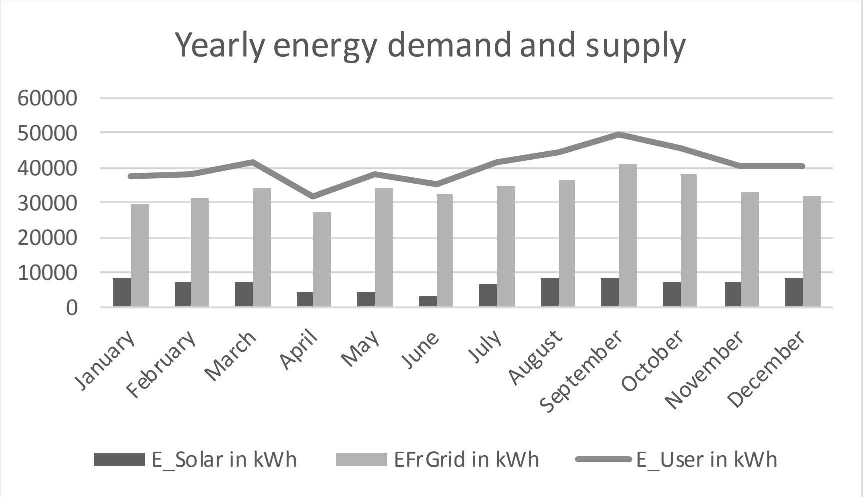


Figure 4.4: Yearly Energy Demand and Supply.

The energy demand for the building slightly increased from January to March 2020 before dropping on the month of April and steadily increasing from May to September same year. Slight decrease in demand from September to December 2020 was observed.

The changes in energy demand are linked to the movement of tenants in and out of the building due to relocation of their businesses. The main reason for sharp drop in the energy demand on the month of April was the onset of Covid-19 in Kenya during the month of March when cases increased exponentially, resulting to declaration of lock down in the entire country. As Kenyans adopted to the new normal during the month of May onward, the energy demand of the building steadily increased to the month of September. The energy supply from both solar and grid electricity remains relative to each other depending on the energy demand. The supply from grid was dependable and readily available to supplement solar electricity generation.

4.5 Technical Performance Analysis of Grid-tie PV System.

The 54kwp Daima Towers grid tie PV system was analyzed in terms of electrical performance. The main investigated parameters included the system yield, system losses, performance ratio, and penetration level and capital utilization factor. These parameters were analyzed from the technical data collected on the PV system, which included energy yields and installation parameters. A comparison between case study and other possible PV system design of same capacity and location for the technical parameter was done.

4.5.1 *System Yield.*

System yield is divided into three types, which includes array yield, final yield, and reference yields.

Reference Yield (RY) - The reference yield can be determined as a total in-plane irradiance in array collector divided by the reference irradiance (RI) under standard temperature (1 kW/m^2). It is calculated as in Equation (3) in Chapter 2.

$$RY = \frac{1943.9}{1} = 1943.9 \text{ kWh/kWp/year}$$

Array Yield (AY) - This the ratio of daily, monthly or yearly direct current DC energy output from a PV array to the rated PV array power and is given by the equation 1-Chapter 2. Maximum array PV power output was found by multiplying each module power rating times their number = 265W × 216= 57.2kW.

$$AY = \frac{92420}{57.2} = 1615.73 \text{ kWh/kWp/year.}$$

Final Yield (FY) – According to (Sharma & Chandel , 2013) the final yield can be calculated as the total AC energy output during a given period divided by the rated capacity of PV array power, and given as in Equation (2) – Chapter 2:

$$FYa = \frac{82030}{57.2} = 1433.58 \text{ kWh/kWp/year for the actual measurement}$$

$$FYs = \frac{87064}{57.2} = 1522.10 \text{ KWh/kWp/year for simulated results.}$$

4.5.2 **Performance Ratio**

It is the ratio of the final energy yield of the PV system to the reference yield. It represents energy available after losses have been deducted when converting generated DC to useful AC energy as in equation 6- Chapter 2.

$$PRa = \frac{1433.58}{1943.9} = 0.737 \qquad PRs = \frac{1522}{1944} = 0.782$$

Where PRa is performance ratio for actual measure yields for the year while PRs is simulated performance ratio. Figure 4.5 illustrates the monthly performance ratio for PV system as simulated in PVsyst.

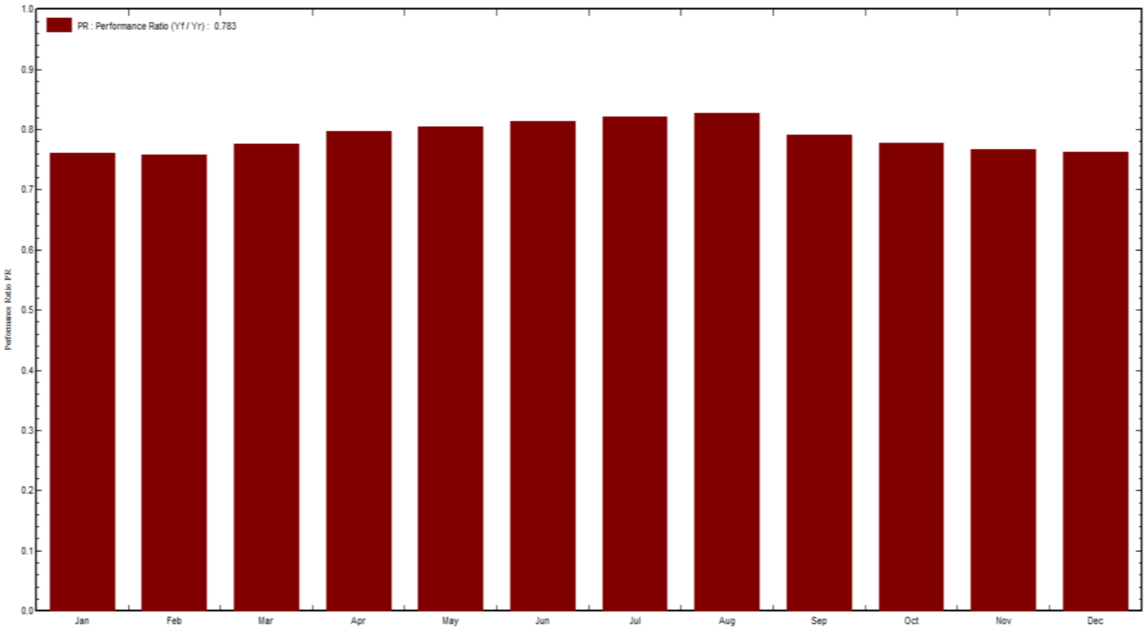


Figure 4.5: Monthly Performance Ratio of the PV System.

The system performance ratio is estimated at an average of 74% and 78% for actual and simulated results. This is a good indication on the viability of the project.

4.5.3 *Capacity Utilization Factor*

The capacity utilization factor (CUF) is calculated as the ratio of annual energy output by the PV system to the amount of energy the PV system would generate if it were operated at full rated power for full day for a year. It is given as in Equation (7)-Chapter 2.

$$\mathrm{CUFa} = \frac{82030}{54\times8760} = 0.173 \qquad \mathrm{CUFs} = \frac{87064}{54\times8760} = 0.184$$

Given that, CUFa and CUFs are actual and simulated parameters, respectively.

4.5.4 *PV Penetration Level (PL)*

The penetration level of installed PV systems can be defined as the ratio of total AC energy output of a PV system-E (AC) to the total energy supplied to user (E_User) and is given as in Equation 8- Chapter 2.

$$\text{PLa} = \frac{82030}{485000} = 0.170 \qquad \text{PLs} = \frac{87064}{490064} = 0.178 \tag{8}$$

4.5.5 *Energy Losses*

The array captured losses (AL) due to PV array losses can be calculated as per Equation (4) in Chapter 2:

ALa=1943.9 – 1615.73 = 328.17 kWh/kWp/year

System loss (SL) is caused by the inverter inefficiencies and is calculated as Equation 5 in Chapter 2.

SLa=1615.73 – 1433.58 = 182.15 kWh/kWp/year

Total actual losses of the PV system are 328.17 + 182.15 = 510.32 kWh/kWp/year

Where ALa and SLa are as per the actual measured yields.

4.3.6 Normalized Productions (per installed kwp) from PVsyst

Normalized productions are defined as standardized variables for assessing the PV system performance. The variables are Lc- the Collection losses or the PV array capture losses (AL), Ls is the system loss (SL) and the Yf is the produced useful energy (FY). In Figure 4.6, it was observed that normalized power is 57.2kWp while system loss is 0.26kWh/kWp/day. Energy supplied to the user is 4.17 kWh/kWp/day and. Collection loss (PV-array losses) is 0.9 kWh/kWp/day. These results were obtained from the simulation.

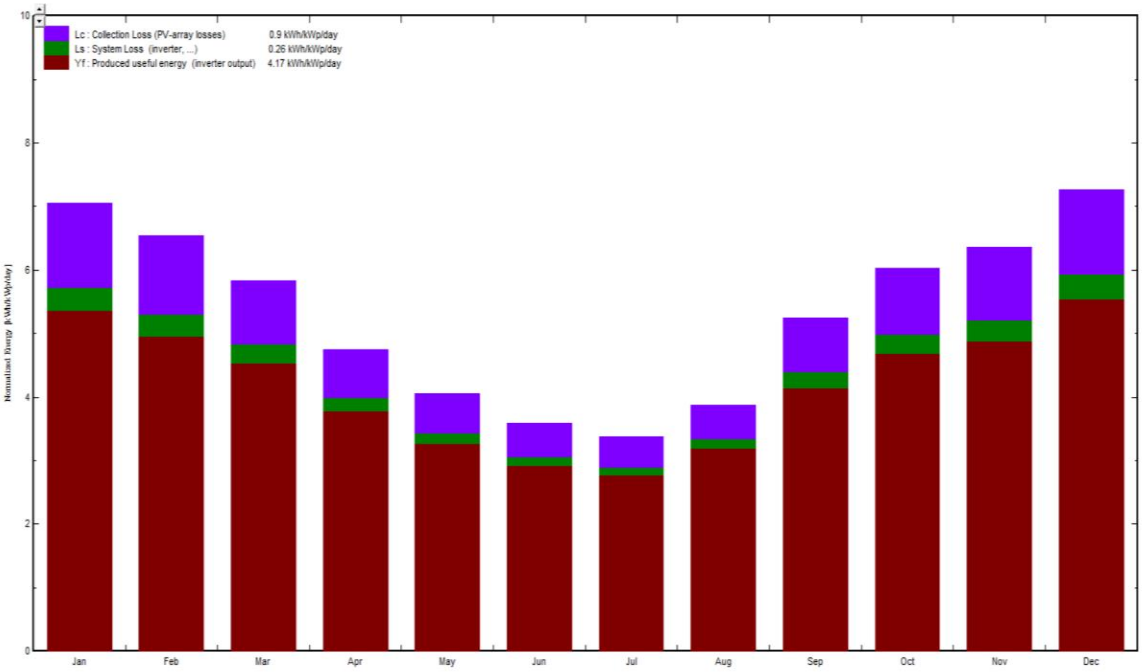


Figure 4.6: Normalized Productions.

When converted to yearly the following are obtained:

FY=4.17 × 365=1522kWh/kWp/year

SLs=0.26 × 365=94.9 kWh/kWp/year

ALs=0.9 × 365=328.5 kWh/kWp/year

Total simulated losses of the PV system= 328.5 + 94.9=423.4 kWh/kWp/year

From Figure 4.6 it can observed that the system performed well in the months of January to April and September to December while there was low generation from May to August.This is mainly attributed to rainy seasons during the month of May to August which experience less sunny days.

4.5.6 *Comparison of Actual to Simulated Technical Parameter Results*

Table 4.2 shows the summary comparison of technical parameter performance between the actual and simulated results.

Table 4.2: Actual vs Simulated Parameter Performance

Parameter	**Actual performance**	**Simulated performance**	**% diff**
Reference yield (RY) kWh/kWp/year	1944	1944	0
Array yield (AY) kWh/kWp/year	1616	1616	0
Final yield (FY) kWh/kWp/year	1434	1522	6
PR in %	73.7	78.2	4.5
CUF %	17.3	18.4	1.1
PL %	14.3	15.2	0.9
Total losses - kWh/kWp/year	510.32	423.4	17.0

From this Table 4.2, it is evident that there is slight difference between simulated and actual PV system technical parameter performance except for energy losses. This could be due to lack of regular maintenance or mismatch in meteorological data for actual and simulated values.

4.5.7 *System Loss flow chart*

Figure 4.7 shows the dstribution of losses as well as summary of consumption and generation by PV system. All the energy generated from PV system as simulated (87MWh/year is consumed locally) while 401 MWh is imported annually from the grid.

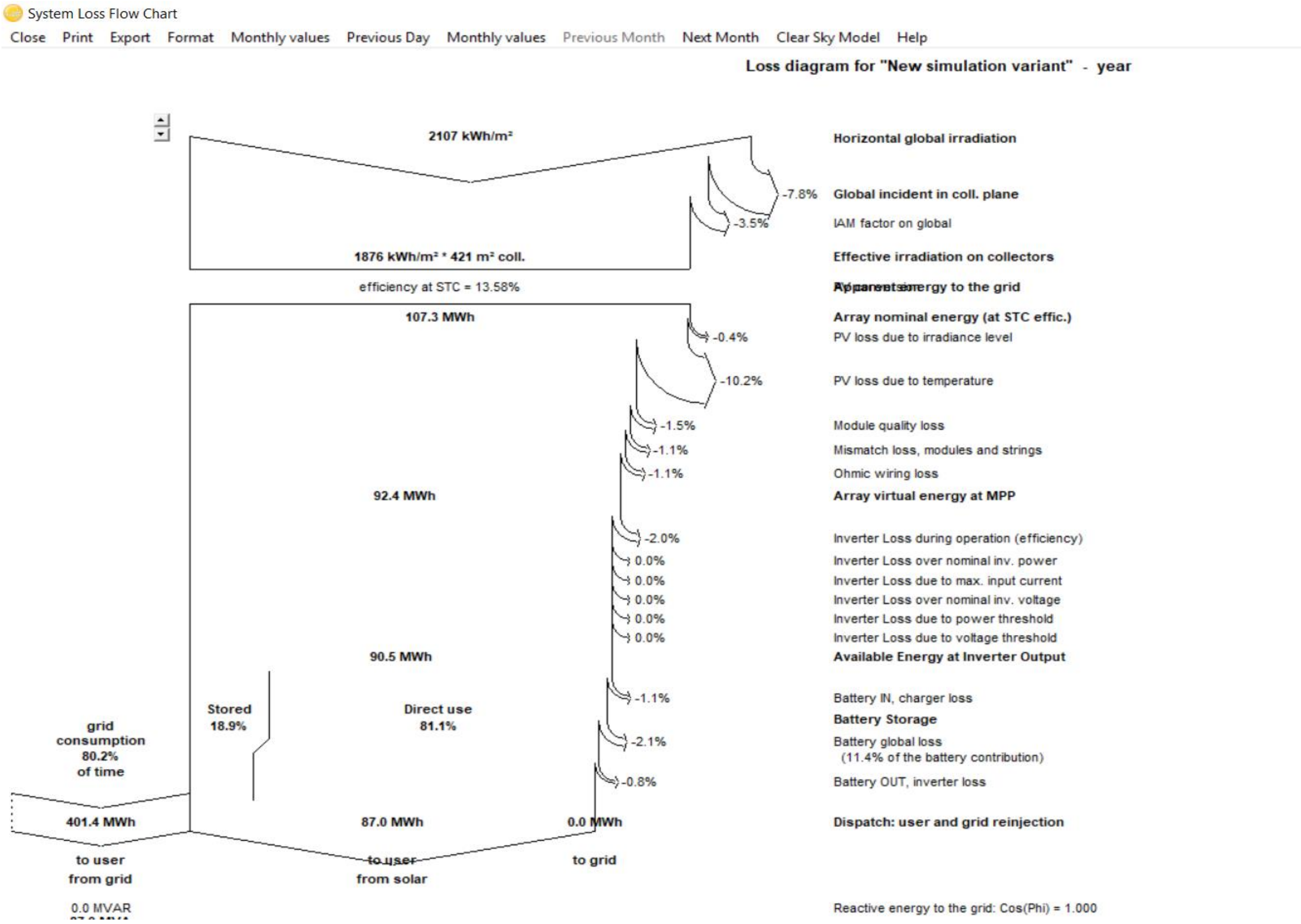


Figure 4.7: System loss flow chart

We can deduce that the effect of battery in the system is negligible as demand for solar energy which is given priority is more than supply hence larger percent imports from grid. The horizontal global irradiance was 2107 kWh/m2 while effective irradiation on collector stand at 1876 kWh/m^2. Effective irradiation was converted to energy with panel surface area of 421m^2 at panel efficiency of 13.58% at STC to give output DC energy of 107.3 MWh. The energy is further lossed due to temperature, irradiance level, module quality and wiring to give array virtual energy at maximum power point at 92.4 MWh. More losses from the inverter and backup battery charging and discharging result to final yield energy which is transferred to the load to be 87 MWh.

4.5.8 *Comparison of case study technical parameter performance to other possible design for 54-kWp PV system.*

Comparison was done between the case study and three other different possible design for the PV system. The rooftop space occupied by the PV system was full in capacity and no space for additional of solar panels. However, while maintaining same system capacity it was verified using PVsyst simulation, that improvement on technical and economic performance of the PV system could be achieved by adopting different design model. The case study technical parameter performance in comparison to the three other possible design scenario was analyzed as in the Table 4.3

Table 4.3: Case Study Technical Performance Comparison to Other Design

Parameter	**Case Study**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Energy output /year in MWh	87	90	122	130
Reference Yield kWh/kWp/yr	1944	1944	2866	2866
Array Yield in kWh/kWp/yr	1616	1616	2461	2461
Final Yield - kWh/kWp/yr	1522	1667	2259	2407
Penetration level	14.3	15.7	21.3	22.6
CUF in %	18.4	19.0	25.8	27.5
PR in %	78.2	85.8	78.8	84.0

According to the simulation analysis of the case study and the three different design scenarios, it was observed that the case study had the lowest technical parameters performance in comparison to the other design model. The array yield and reference yield for case study and scenario 1 were the same at and 1616 and 1944 respectively, due to the fixed tilted plane orientation that was used in both the designs. In case of scenario 2 and scenario 3, the reference and array yield increased to 2866 and 2461 respectively, because of the adoption of dual axis tracking system in place of fixed tilted orientation. The case study had the lowest energy yield of 87MWh due to use of fixed tilted orientation and battery storage, while scenario 3 design had the highest energy yield of 130MWh due to use of dual axis tracking orientation and exemption of battery storage. Scenario 3 had the highest PV system penetration level and CUF at 22.6% and 27.5% respectively in comparison to other possible design. Scenario 1 had the highest performance ratio of 85.8% while case study had the lowest performance ratio at 78.2% as compared to other design scenarios.

Grid-tie PV system design without battery storage was observed to offer high technical parameter performance as compared to systems with battery storage. The main reason for this was found to be the fact that the PV energy generated was partly lost in charging and discharging of batteries. The study established that for grid tie PV system that is supplying energy, which is less than the building demand, does not need storage system, as chances of having excess energy for storage are less. Furthermore, it was observed that for areas with limited installation space of PV system, use of solar PV system trackers could significantly improve the technical parameter performance of the PV system.

4.6 Economic Performance Analysis of Grid-Tie PV System.

The economic performance of the PV system was evaluated by considering the financial costs in Table 3.3 of Chapter 3 and simulated results of the PVsyst. These parameters includes Capital expenditure (CAPEX), Operating expenditure (OPEX), Cost per Watt peak, Levelized cost of energy (LCOE), electricity tariff, simple payback period (SPBP), return on investment (ROI), Net present values and yearly net profit.

4.6.1 *PV System Cost Per Watt Peak*

Cost per Watt peak was as given in equation 9- Chapter 2 and equals

Cost per Watt peak= $\frac{22,737,483}{57200}$ = kshs. 397 / Wp

4.6.2 *Levelized Cost of Energy*

LCOE is calculated by dividing the total CAPEX and OPEX for period of 25 years by the useful energy produced by the system in kWh for the same period.

Cost of produced energy = sum of costs over lifetime / total energy produced over lifetime. Given that, the effective lifetime of the PV system is capped at 25years when maximum efficient operation is expected.

Operation costs for 25years =141000*25=3,525,000

Capital investment =22,737,483

Sum of cost over lifetime=22,737,483+3,525,000=26,262,483

Total energy over lifetime=87.1*25=2177.5MWh

Hence, LCOE =26,262,483/2177500= 12.0

=12.0 Ksh/kWh

4.6.3 *Simple Payback Period (SPBP)*

Simple Payback Period (SPBP) is another technique can be used to analyse the project feasibility and it can be defined as the length of time required to recover the capital cost or the (LCC) of an investment. The project is feasible if the SPBP is lower than the project lifetime, otherwise it is not (Ibrik, 2020). The SPBP can be estimated as from equation 10 in Chapter 2:

$$\mathrm{SPBP} = \frac{\mathrm{CAPEX}}{\mathrm{Total\ savings\ /year}}$$

CAPEX= Kshs.22, 737, 483

Total savings/ year equals the amount of money that would be paid to KPLC if the energy was imported minus the operating cost per year.

Since 87.1 MWh were saved at cost of 22.8 Ksh/kWh (refer to Table 3.7 in Chapter 3) with operating cost of Ksh.141000 per year. Total saving/year = 87.1 ×1000×22.8 - 141000= 1,844,880.

Hence $\mathrm{SPBP} = \frac{22737483}{1844880}$ = 12.3 years.

Since the SPBP is less than the PV system lifetime of 25 years, this PV system is feasible.

4.6.4 *Net Present Value*

Net present value (NPV) or present worth was calculated as a difference between the present worth of cash inflows and the present worth of cash outflows over a given period. The function simply requires cash flow input (NCF) from all years of operation of the solar system, and cash flow output including capital investment, maintenance, and replacement cost as a negative amount. Figure 4.7 shows Cumulative Cash flow of the system.

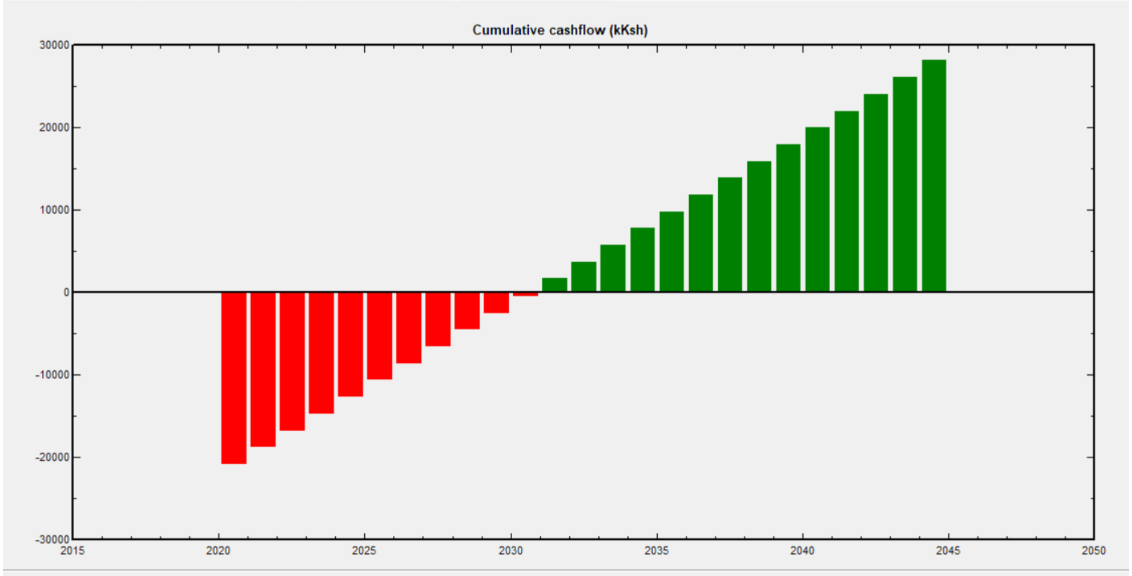


Figure 4.7: Net Present Value Chart

Because the net present value is positive, it means the project is feasible.

4.6.5 ***Return on Investment (ROI)***

ROI is expressed as a percentage and calculated by dividing an investment net profit or loss by its initial cost for the system lifetime refer to equation 12 in Chapter 2.

Net profit per year = (Grid tariff – solar LCOE) x E_solar = (22.8-12.0) ×87100= Ksh.940680.

Net Profit After 25 years = 940680 x 25 = Ksh.23, 517,000

CAPEX=22,737,483. Hence ROI $= \frac{23517000}{22737483}$ = 1.034 which is 103.4%.

Annualized ROI = ((1+ ROI) ^ (1/n) -1) ×100 as given in equation 13 of Chapter 2, since n= 25 years:

Annualized ROI = ((1+ 1.03) ^ (1/25) -1) ×100 = 2.87%

This is quite below the best-accepted annualized ROI of 5% per annum for long-term investment. Despite, the low annualize ROI, the benefits of PV system in environment and reducing the cost of electricity outweigh the low ROI. ROI can be increased further by ensuring the best design approach for PV system. See Appendix E for detail economic results as simulated in PVsyst.

4.6.6 *Comparison of Case Study Economic Parameter Performance to Other Possible Design for 54 KWp PV System Design.*

Analysis for economic parameters of the case study and the other three other possible PV system design were carried out using PVsyst simulation. The economic parameter performance of the case study was compared to the other possible design model as shown in the Table 4.4.

Table 4.4: Case Study Economic Parameters Performance Vs Other Possible Design

Parameter	**Case Study**	**Scenario 1**	**Scenario 2**	**Scenario 3**
CAPEX	22,737,483	11,442,483	26,729,163	18,314,163
OPEX	141,000	96,000	141,000	96,000
Watt peak cost Ksh/Wp	397	200	467	320
LCOE Ksh/kWh	12.1	6.1	9.9	6.4
S.P.B.P in years	12.3	6.0	10.1	6.6
ROI %	103.4	314.2	147.9	277.7
Annualized ROI %	2.87	5.85	3.68	5.46

The case study was found to have lowest return on investment due to high operating costs and high capital investment of which estimated 50% was due to battery storage and related components. Since the solar PV penetration factor for the building standards at 15%, it means there is no excess energy from PV system that requires being stored as the demand for energy supplied from solar PV is four times less than demanding. As the occupancy in the building increases so will energy demand, hence there will be no need for storage of energy. The storage components and related circuit contributes to loss of more than 3 MWh of energy produced resulting to decrease system efficiency.

For scenario 2, using dual axis tracker in place of tilted orientation will results to increase in final energy yield from 87MWh to 122MWh, an increase of 40% more energy. However, solar trackers are expensive than fixed structures hence an increase in capital cost by 17.5% in comparison to the built PV system. The operating costs remain the same due to availability of battery storage while ROI increased to 147% from 103%, an increase of 44%. Use of solar PV tracker can be used as an alternative to increasing solar PV panel due to space constraints. Use of solar PV tracker slightly will improve the economic and technical performance of the solar PV system in the building.

For scenario 3, solar PV trackers are used in place of fixed orientation and battery storage and related component are removed from the design, hence the circuit becomes simple. The capital and operating costs are reduced by 19.5% and 32% respectively. The energy yield is increased from 87MWh to 130MWh as compared to the current built PV system. SPBP will decrease from 12.3 years to 6.6 years while ROI increases from 103% to 277%. LCOE will be 6.4 Ksh/kWh as compared to 12.0 Ksh/kWh currently, hence making the system more economical than previous PV system with battery storage.

For the scenario 1, if the battery storage components were to be removed from the PV system while retaining fixed tilted orientation, capital cost would be reduced by approximately 50% while operating costs will decrease by 32%. The useful energy yield will increase slightly to 90MWh from current 87MWh. The technical and economic performance of the PV system is significantly improved, and the circuit is simplified due to absence of battery storage components. The LCOE will decrease from kshs. 12 to kshs 6.1 with SPBP decreasing from 12.3 years to 6 years. The ROI increased from 103% to the highest of 314% in comparison to other possible design.

This shows that the best solar PV system to be adopted by investors on rooftop of buildings where there is space constraints and energy demand is high than supply should be fixed orientation with no backup storage, which has annualized ROI of 5.85% or scenario with dual tracker and without battery storage, which has annualized ROI of 5.46%. Both scenario 1 and 3 are above the best-recommended annualized ROI of 5%. This design is simple and easy to build and maintain while ensuring cheap electricity, short SPBP and high ROI.

4.7 Benefits of Saved CO_2 Emissions

Given that a PV modules have a lifespan of 30 years with the first 25 years being the years with optimum energy yield, carbon balance is estimated for 30 years. Appendix H shows the detailed simulated results of the saved CO_2 emmisions for 30 years. The PV System LCE is contributed by the PV modules, transportations, support structures, and inverters during installations, operations and when decommissioning. The PVsyst program estimated the saved amount of carbon at 676.4 tons. Given that, it is estimated that one mature tree can absorb up to 40kg of CO2 in one year (Stancil, 2019). Therefore, this would be equivalent to having planted 564 mature trees. This will contribute to improved air quality, ensure clean environment and contributing in slowing climate change in the world. The benefits that can be obtain will address economic growth by preventing channelling of funds to health crisis, severe environmental hazard among others.

4.8 Summary of Results in Comparison to other Works

The results from this study has bridge the information gaps for the local Kenyan perspective in comparison to previous study as shown in Table 4.5 below.

Table 4.5: Results Findings Comparison to other Works

Authors	**Study / Findings**	**Findings from this study**
Lave & Kleissl, 2011	The direct beam of solar should be perpendicular to the surface of PV panel for optimum yield.	The study has compared both fixed and PV trackers orientation performance in Kenya and agrees with findings from Lave and Kleissl
Mermoud & Villoz, 2012	The accuracy of any simulated performance results for a PV system can be verified by comparison to the actual measured results.	The study verified that PVsyst software can be used to predict both short and long term PV system performance in Kenya, with acceptable variation from the actual..
Stancil, 2019	Established that One mature tree can absorb up to 40kg of CO2 in one year	The study establish that use of PV system in Kenya to generate energy can mitigate GHG emissions hence equivalent to planting trees.

Oloya , Gutu , & Adaramo, 2021	A study on technical assessment of 10 MW centralized grid-tied solar PV system in Uganda, established that the FY, PR, and CUF were 1671 kWh/kWp/year, 75.8% and 19.1% respectively.	In comparison to grid tie solar PV system technical parameter performance, the study has shown little variation with study results from Uganda hence these results can be relied upon in East Africa region.
Silva, Ronoh, & Ndegwa, 2013)	Findings on economic parameter performance of 10kWp grid-tie solar PV system in Strathmore University, Kenya were the LCOE was 26 Kshs / kWh and S.P.B.P was 9 years	This study established that kWh cost of energy from solar PV has significantly reduced from previous kshs 26 to current Kshs 12- Kshs 6 depending on solar PV system design

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS.

5.1 Summary

The study investigated the PV system for a period of one year in 2020 and the energy yield for the period were recorded. PVsyst software was used to calculate the expected energy for the year 2020 by using the observed system parameters input to the software. These parameters include the PV system panels' orientation, meteorological data of the site, system technical properties and financial expenses. Results of the comparison of the measured energy to the simulated (expected) for year 2020 shows a slight difference of 6%. From these results, it was verified that PVsyst simulation software could be relied upon for both short-term and long-term analysis of the grid-tie PV system. A comparison of different PV system design model that could be possible on the same building were analyzed.

Investigation in the technical parameter performance of the system showed that the actual performance for system yield were array yield (AY) at 1616 kWh/kWp/year, reference yield (RY) at 1943 kWh/kWp/year, and final yield at 1434 kWh/ kWp /year. Performance ratio, capital utilization factor and PV penetration level for the year 2020 were 78%, 17.3% and 17% respectively. Moreover, there was no notable system disturbance because of integrating PV system to grid energy supply. Comparison of case study to other possible design model of the PV system showed that the design model with solar trackers and no battery storage would have optimum technical parameter performance.

An evaluation of economic parameters of the PV system was done to establish the financial performance of the PV system. The parameters include the initial capital invested, yearly operating costs of the PV system, Watt peak cost of the system, LCOE, S.P.B.P and ROI. The economic parameters were further investigated in comparison to other possible PV system in the building. The results of the investigation showed for the current system design, the capital and operating costs of the system stood at Kshs. 22,737,483 and kshs. 141,000 per year respectively. Watt peak (Wp) cost, LCOE, S.P.B.P, ROI of the system were Kshs. 397, Kshs. 12 / kWh, 12 years and 103% respectively considering 25 years of the active system lifetime. The results shows that other possible design models had more ROI as compared to the current installations. Grid-tie PV system without battery storage or with PV trackers offers high annualized ROI than other system design.

To investigate the environmental benefit of using solar PV energy to complement energy imports from the grid the amount of saved carbon dioxide was estimated using PVsyst software simulation. The results shows that approximately 676.4 tonnes of CO2 emissions would be saved by using the PV system for its whole lifetime of 30 years. This is equivalent to planting 564 trees in the study site. The benefits included, improved air quality of the surrounding, contribution of the system to slowing the rate of climate change as well as economic development because of the saved money that could have been used in paying for expensive grid energy. The results on saved carbon dioxide emissions shows that grid-tie solar would contribute in reducing greenhouse gases emission, thereby mitigating global warming.

5.2 Conclusions

The purpose of this study was to increase the uptake of solar Photovoltaic (PV) technology in Kenya. The study assessed the technical and economic parameters performance of grid-tie solar PV system in Kenya. The findings obtained from this study would provide crucial information in decision making by investors and other stakeholders in solar energy development. This would increase solar PV penetration in Kenya and increase environmental responsibility awareness to players in the energy sector. The following are conclusions that can be drawn from the study.

1. The comparison of actual measured to the simulated yields, showed a small difference of 6% for the year 2020. This result verifies that PV system simulation software can be used to study performance of a PV system with minimum variation from the actual system performance. In the feasibility study phase of a PV system, it is important to make use of effective PV simulation software tools available in market to achieve a design model that would give optimum performance of the system. Lack of information on the best PV system design model for a particular location can result to high capital investment with poor performance in economic and technical parameters of the PV system.
2. Technical performance of a grid-tie PV system can be calculated by considering the various parameters describing energy quantities. These parameters provide information to investors on PV system performance in given locations, regardless of the solar plant size. A comparison can easily be done for different grid-tie PV system design models ,using simulation software and design with optimum technical performance be identified for investment. The case study design model was found to provide positive feedback for system designers in terms of technical parameter performance. However, case study comparison of the technical parameter performance to other possible design model showed that optimum technical performance would have been achieved for design with solar tracker and no battery storage.

3. The economic aspects of a PV system investment are normally considered before the actual investment. In order to come up with the best investment plan it is important to do a background check on expected results once the investment is made. For the case study, the results provides positive feedback to investors on the economic performance of the PV system. However, comparison of case study results to other possible design models showed that grid-tie PV system with tilt orientation and no battery storage tends to have optimum economic parameters performance than system with batteries. Since battery storage and related components significantly contribute to initial investment cost, decision on whether to have them in the PV system should be critical for system designers.
4. Finally, the environmental benefit of saved amount of carbon emissions in a PV system is worth the investment. Installing solar PV system is like planting trees that plays an important role in carbon dioxide absorption and improving air quality. One solar panel of 265W operated for 1 years will save 110.6 kg of carbon emissions. This will ultimately contribute in fight against climate change, improve air quality and reduce health issues related to environmental pollutions.
5. The constraints in this study were lack of precise whether measuring instrument, hence the study relied on NASA-SSE database (1983-2005) data for meteorological site data. The analysis for this study PV system were limited to actual data obtained from inspection, observation, interview with system engineer and energy meters available on site due to unsuccessful installation of PV monitoring and data acquisition system.

5.3 Recommendations

This study analysed the technical and economic parameters performance of grid-tie solar PV system. However, in the study several limitations can be addressed by increase of resources and research period. This study recommends the following to improve more on the knowledge and contextual gap on the technical and economic analysis of grid-tie PV system in Kenya:

1. Accuracy of the measured and simulated techno-economic performance assessment can be improved further by ensuring regular schedule maintenance of the system to minimize system losses for measured energy yield. Simulated results can be improved further by using real time measured meteorological data input and accurate technical and economic parameters.
2. To obtain more accurate technical parameters, it is advisable to use sub-meters in various electric load points within the building to ascertain more accurate electricity demand and supply. Use of data loggers to obtain exact solar energy yield for the PV system is recommended as this study relied on data from solar energy meter. Similar study should be repeated on grid-tie PV system on other parts of the Kenya territory, specifically in areas with different climatic conditions like Kisumu and Lodwar. The results obtain can be compared with this study and analysis done to give investors a clear picture on the best region to invest in grid-tie PV system in Kenya.
3. The study relied on one-year estimate of the PV system and PVsyst software simulation for long-term analysis. However, a detail analysis of operating costs for five or more years should be done, and averages obtain. This will ensure all

costs of running the system are captured more accurately, hence more accurate economic results. The study recommends that investors in similar PV system, should take due diligence and compare various PV system design models to ensure high ROI without compromising technical parameters.

4. Use of air monitoring equipment of the building surrounding could help in checking the air quality of the surrounding and detecting any changes on environment in future as uptake for solar PV system grows in Eldoret town.

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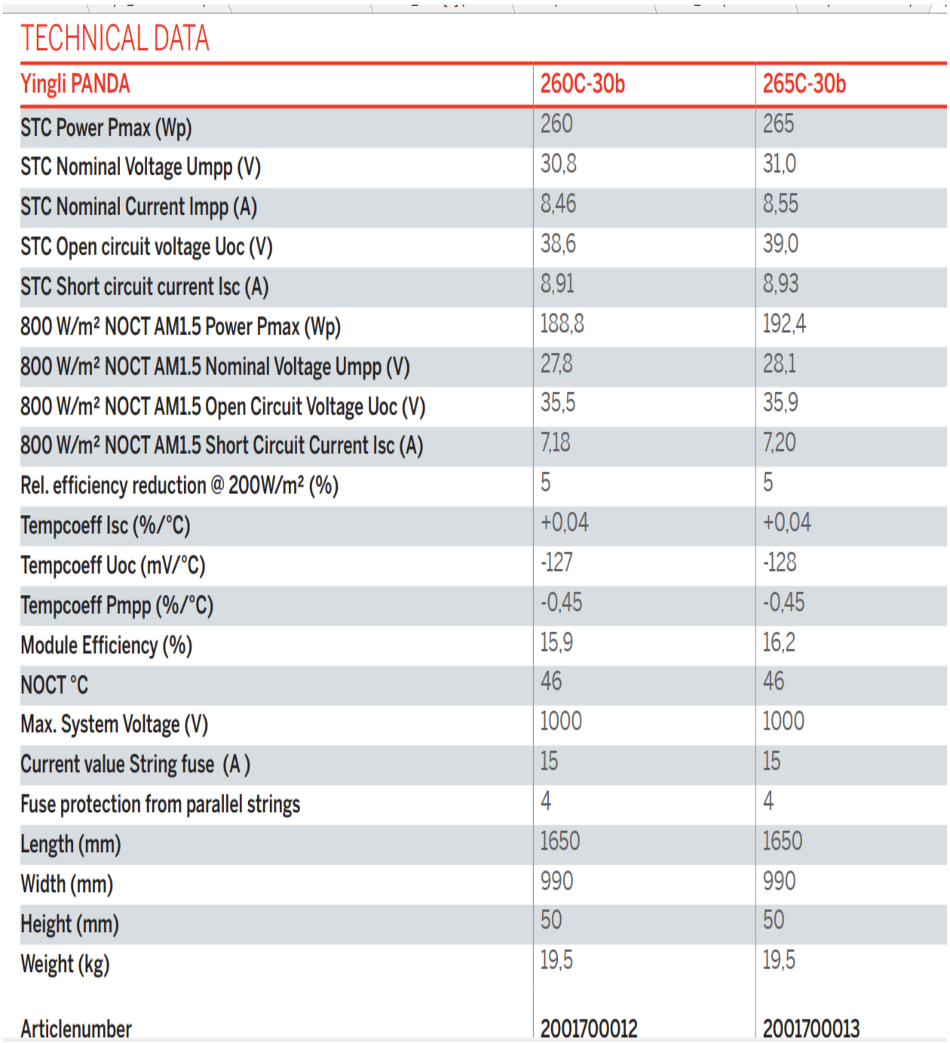
APPENDICES

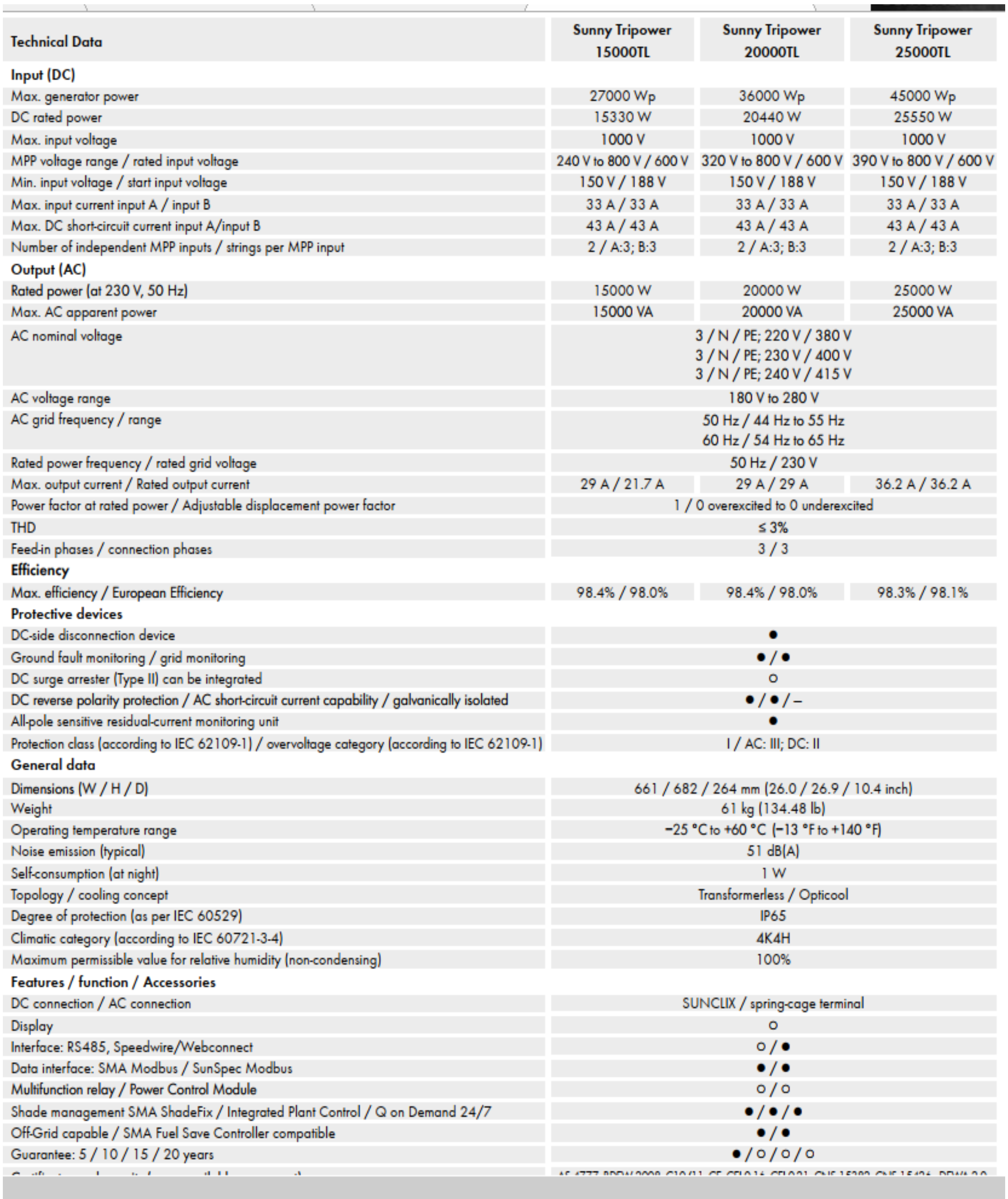
Appendix A: Technical specification of solar module



TECHNICAL DATA

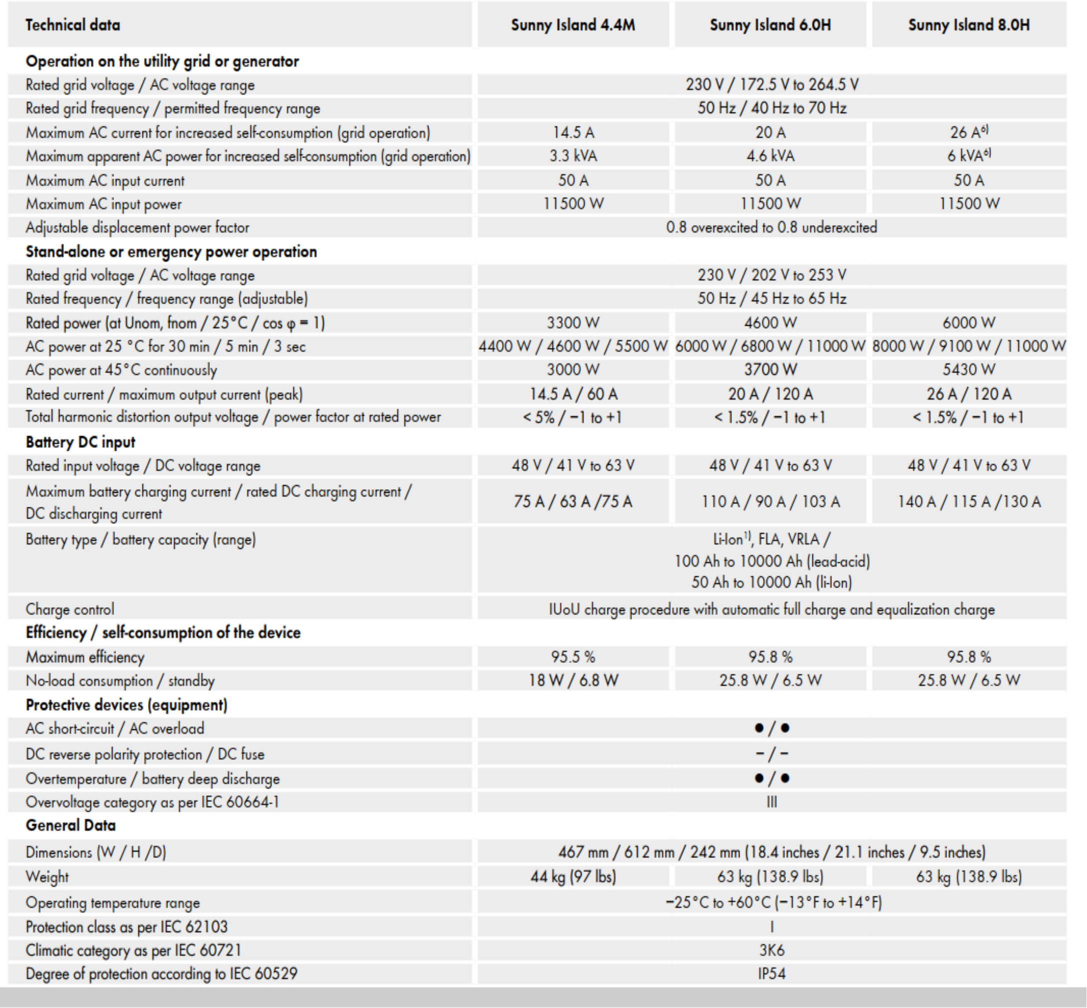
Yingli PANDA	260C-30b	265C-30b
STC Power Pmax (Wp)	260	265
STC Nominal Voltage Umpp (V)	30,8	31,0
STC Nominal Current Impp (A)	8,46	8,55
STC Open circuit voltage Uoc (V)	38,6	39,0
STC Short circuit current Isc (A)	8,91	8,93
800 W/m² NOCT AM1.5 Power Pmax (Wp)	188,8	192,4
800 W/m² NOCT AM1.5 Nominal Voltage Umpp (V)	27,8	28,1
800 W/m² NOCT AM1.5 Open Circuit Voltage Uoc (V)	35,5	35,9
800 W/m² NOCT AM1.5 Short Circuit Current Isc (A)	7,18	7,20
Rel. efficiency reduction @ 200W/m² (%)	5	5
Tempcoeff Isc (%/°C)	+0,04	+0,04
Tempcoeff Uoc (mV/°C)	-127	-128
Tempcoeff Pmpp (%/°C)	-0,45	-0,45
Module Efficiency (%)	15,9	16,2
NOCT °C	46	46
Max. System Voltage (V)	1000	1000
Current value String fuse (A)	15	15
Fuse protection from parallel strings	4	4
Length (mm)	1650	1650
Width (mm)	990	990
Height (mm)	50	50
Weight (kg)	19,5	19,5
Articlenumber	2001700012	2001700013

Appendix B :Technical specification of Grid tie Inverter



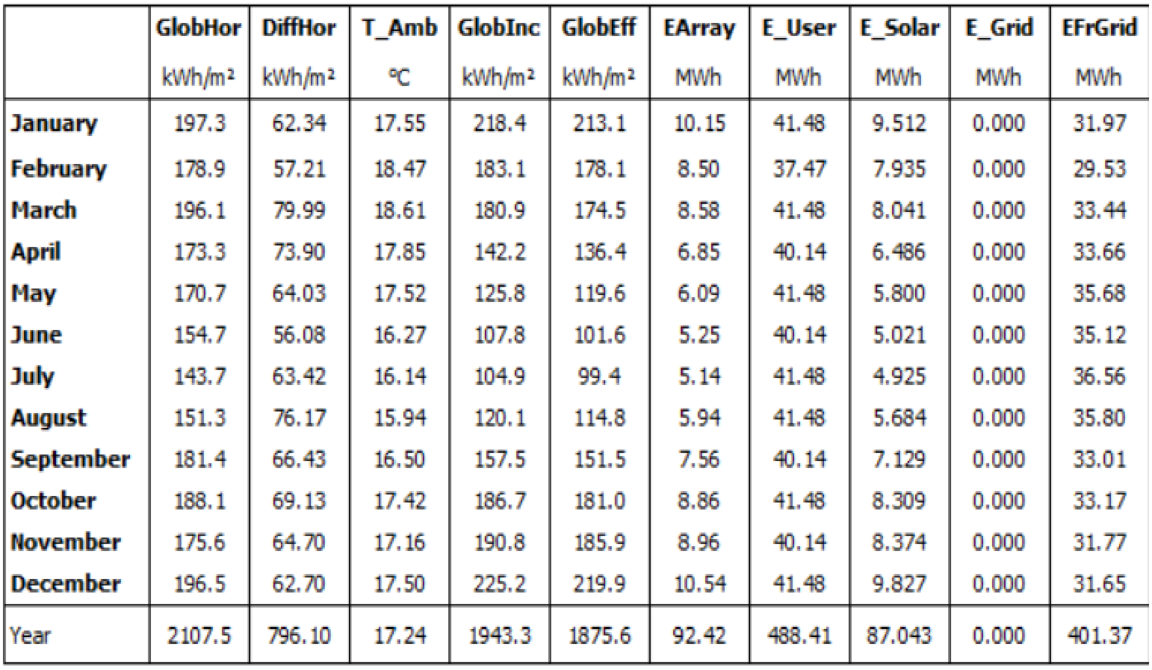
Technical Data	**Sunny Tripower 15000TL**	**Sunny Tripower 20000TL**	**Sunny Tripower 25000TL**
Input (DC)			
Max. generator power	27000 Wp	36000 Wp	45000 Wp
DC rated power	15330 W	20440 W	25550 W
Max. input voltage	1000 V	1000 V	1000 V
MPP voltage range / rated input voltage	240 V to 800 V / 600 V	320 V to 800 V / 600 V	390 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	33 A / 33 A	33 A / 33 A	33 A / 33 A
Max. DC short-circuit current input A/input B	43 A / 43 A	43 A / 43 A	43 A / 43 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3	2 / A:3; B:3	2 / A:3; B:3
Output (AC)			
Rated power (at 230 V, 50 Hz)	15000 W	20000 W	25000 W
Max. AC apparent power	15000 VA	20000 VA	25000 VA
AC nominal voltage	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V		
AC voltage range	180 V to 280 V		
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz		
Rated power frequency / rated grid voltage	50 Hz / 230 V		
Max. output current / Rated output current	29 A / 21.7 A	29 A / 29 A	36.2 A / 36.2 A
Power factor at rated power / Adjustable displacement power factor	1 / 0 overexcited to 0 underexcited		
THD	≤ 3%		
Feed-in phases / connection phases	3 / 3		
Efficiency			
Max. efficiency / European Efficiency	98.4% / 98.0%	98.4% / 98.0%	98.3% / 98.1%
Protective devices			
DC-side disconnection device	●		
Ground fault monitoring / grid monitoring	● / ●		
DC surge arrester (Type II) can be integrated	○		
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / –		
All-pole sensitive residual-current monitoring unit	●		
Protection class (according to IEC 62109-1) / overvoltage category (according to IEC 62109-1)	I / AC: III; DC: II		
General data			
Dimensions (W / H / D)	661 / 682 / 264 mm (26.0 / 26.9 / 10.4 inch)		
Weight	61 kg (134.48 lb)		
Operating temperature range	−25 °C to +60 °C (−13 °F to +140 °F)		
Noise emission (typical)	51 dB(A)		
Self-consumption (at night)	1 W		
Topology / cooling concept	Transformerless / Opticool		
Degree of protection (as per IEC 60529)	IP65		
Climatic category (according to IEC 60721-3-4)	4K4H		
Maximum permissible value for relative humidity (non-condensing)	100%		
Features / function / Accessories			
DC connection / AC connection	SUNCLIX / spring-cage terminal		
Display	○		
Interface: RS485, Speedwire/Webconnect	○ / ●		
Data interface: SMA Modbus / SunSpec Modbus	● / ●		
Multifunction relay / Power Control Module	○ / ○		
Shade management SMA ShadeFix / Integrated Plant Control / Q on Demand 24/7	● / ● / ●		
Off-Grid capable / SMA Fuel Save Controller compatible	● / ●		
Guarantee: 5 / 10 / 15 / 20 years	● / ○ / ○ / ○		

Appendix C :Technical specification of sunny islanding Inverter



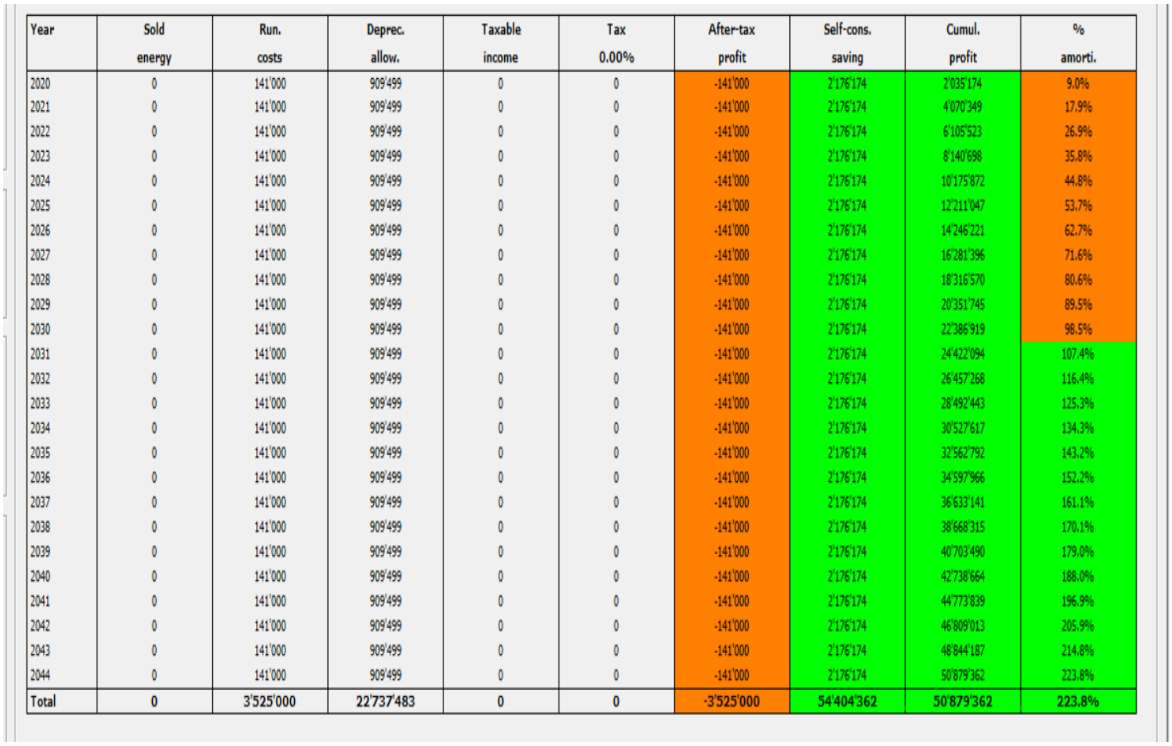
Technical data	**Sunny Island 4.4M**	**Sunny Island 6.0H**	**Sunny Island 8.0H**
Operation on the utility grid or generator			
Rated grid voltage / AC voltage range	230 V / 172.5 V to 264.5 V		
Rated grid frequency / permitted frequency range	50 Hz / 40 Hz to 70 Hz		
Maximum AC current for increased self-consumption (grid operation)	14.5 A	20 A	26 A[6]
Maximum apparent AC power for increased self-consumption (grid operation)	3.3 kVA	4.6 kVA	6 kVA[6]
Maximum AC input current	50 A	50 A	50 A
Maximum AC input power	11500 W	11500 W	11500 W
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited		
Stand-alone or emergency power operation			
Rated grid voltage / AC voltage range	230 V / 202 V to 253 V		
Rated frequency / frequency range (adjustable)	50 Hz / 45 Hz to 65 Hz		
Rated power (at Unom, fnom / 25 °C / cos φ = 1)	3300 W	4600 W	6000 W
AC power at 25 °C for 30 min / 5 min / 3 sec	4400 W / 4600 W / 5500 W	6000 W / 6800 W / 11000 W	8000 W / 9100 W / 11000 W
AC power at 45 °C continuously	3000 W	3700 W	5430 W
Rated current / maximum output current (peak)	14.5 A / 60 A	20 A / 120 A	26 A / 120 A
Total harmonic distortion output voltage / power factor at rated power	< 5% / −1 to +1	< 1.5% / −1 to +1	< 1.5% / −1 to +1
Battery DC input			
Rated input voltage / DC voltage range	48 V / 41 V to 63 V	48 V / 41 V to 63 V	48 V / 41 V to 63 V
Maximum battery charging current / rated DC charging current / DC discharging current	75 A / 63 A /75 A	110 A / 90 A / 103 A	140 A / 115 A /130 A
Battery type / battery capacity (range)	Li-Ion[1], FLA, VRLA / 100 Ah to 10000 Ah (lead-acid) 50 Ah to 10000 Ah (li-Ion)		
Charge control	IUoU charge procedure with automatic full charge and equalization charge		
Efficiency / self-consumption of the device			
Maximum efficiency	95.5 %	95.8 %	95.8 %
No-load consumption / standby	18 W / 6.8 W	25.8 W / 6.5 W	25.8 W / 6.5 W
Protective devices (equipment)			
AC short-circuit / AC overload	● / ●		
DC reverse polarity protection / DC fuse	– / –		
Overtemperature / battery deep discharge	● / ●		
Overvoltage category as per IEC 60664-1	III		
General Data			
Dimensions (W / H /D)	467 mm / 612 mm / 242 mm (18.4 inches / 21.1 inches / 9.5 inches)		
Weight	44 kg (97 lbs)	63 kg (138.9 lbs)	63 kg (138.9 lbs)
Operating temperature range	−25 °C to +60 °C (−13 °F to +14 °F)		
Protection class as per IEC 62103	I		
Climatic category as per IEC 60721	3K6		
Degree of protection according to IEC 60529	IP54		

Appendix D : System yields



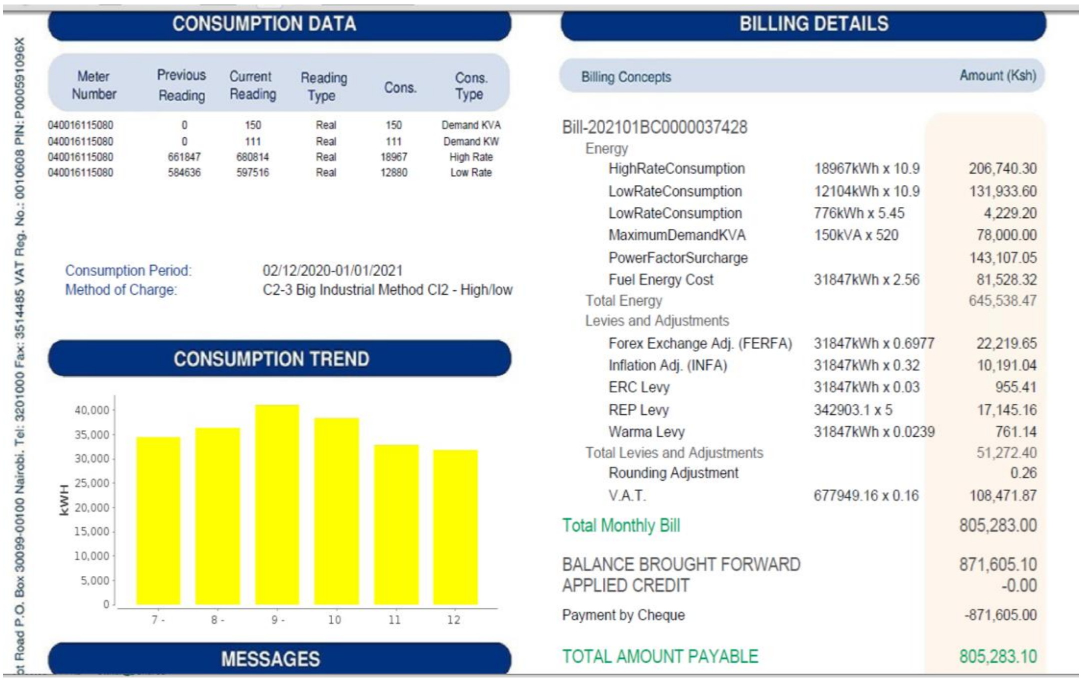
	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_User	E_Solar	E_Grid	EFrGrid
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	MWh	MWh	MWh
January	197.3	62.34	17.55	218.4	213.1	10.15	41.48	9.512	0.000	31.97
February	178.9	57.21	18.47	183.1	178.1	8.50	37.47	7.935	0.000	29.53
March	196.1	79.99	18.61	180.9	174.5	8.58	41.48	8.041	0.000	33.44
April	173.3	73.90	17.85	142.2	136.4	6.85	40.14	6.486	0.000	33.66
May	170.7	64.03	17.52	125.8	119.6	6.09	41.48	5.800	0.000	35.68
June	154.7	56.08	16.27	107.8	101.6	5.25	40.14	5.021	0.000	35.12
July	143.7	63.42	16.14	104.9	99.4	5.14	41.48	4.925	0.000	36.56
August	151.3	76.17	15.94	120.1	114.8	5.94	41.48	5.684	0.000	35.80
September	181.4	66.43	16.50	157.5	151.5	7.56	40.14	7.129	0.000	33.01
October	188.1	69.13	17.42	186.7	181.0	8.86	41.48	8.309	0.000	33.17
November	175.6	64.70	17.16	190.8	185.9	8.96	40.14	8.374	0.000	31.77
December	196.5	62.70	17.50	225.2	219.9	10.54	41.48	9.827	0.000	31.65
Year	2107.5	796.10	17.24	1943.3	1875.6	92.42	488.41	87.043	0.000	401.37

Appendix E :Detailed economic results



Year	Sold energy	Run. costs	Deprec. allow.	Taxable income	Tax 0.00%	After-tax profit	Self-cons. saving	Cumul. profit	% amorti.
2020	0	141'000	909'499	0	0	-141'000	2'176'174	2'035'174	9.0%
2021	0	141'000	909'499	0	0	-141'000	2'176'174	4'070'349	17.9%
2022	0	141'000	909'499	0	0	-141'000	2'176'174	6'105'523	26.9%
2023	0	141'000	909'499	0	0	-141'000	2'176'174	8'140'698	35.8%
2024	0	141'000	909'499	0	0	-141'000	2'176'174	10'175'872	44.8%
2025	0	141'000	909'499	0	0	-141'000	2'176'174	12'211'047	53.7%
2026	0	141'000	909'499	0	0	-141'000	2'176'174	14'246'221	62.7%
2027	0	141'000	909'499	0	0	-141'000	2'176'174	16'281'396	71.6%
2028	0	141'000	909'499	0	0	-141'000	2'176'174	18'316'570	80.6%
2029	0	141'000	909'499	0	0	-141'000	2'176'174	20'351'745	89.5%
2030	0	141'000	909'499	0	0	-141'000	2'176'174	22'386'919	98.5%
2031	0	141'000	909'499	0	0	-141'000	2'176'174	24'422'094	107.4%
2032	0	141'000	909'499	0	0	-141'000	2'176'174	26'457'268	116.4%
2033	0	141'000	909'499	0	0	-141'000	2'176'174	28'492'443	125.3%
2034	0	141'000	909'499	0	0	-141'000	2'176'174	30'527'617	134.3%
2035	0	141'000	909'499	0	0	-141'000	2'176'174	32'562'792	143.2%
2036	0	141'000	909'499	0	0	-141'000	2'176'174	34'597'966	152.2%
2037	0	141'000	909'499	0	0	-141'000	2'176'174	36'633'141	161.1%
2038	0	141'000	909'499	0	0	-141'000	2'176'174	38'668'315	170.1%
2039	0	141'000	909'499	0	0	-141'000	2'176'174	40'703'490	179.0%
2040	0	141'000	909'499	0	0	-141'000	2'176'174	42'738'664	188.0%
2041	0	141'000	909'499	0	0	-141'000	2'176'174	44'773'839	196.9%
2042	0	141'000	909'499	0	0	-141'000	2'176'174	46'809'013	205.9%
2043	0	141'000	909'499	0	0	-141'000	2'176'174	48'844'187	214.8%
2044	0	141'000	909'499	0	0	-141'000	2'176'174	50'879'362	223.8%
Total	0	3'525'000	22'737'483	0	0	-3'525'000	54'404'362	50'879'362	223.8%

Appendix G: KPLC Monthly bill for December 2020



pt Road P.O. Box 30099-00100 Nairobi. Tel: 3201000 Fax: 3514485 VAT Reg. No.: 0010608 PIN:P000591096X

CONSUMPTION DATA

Meter Number	Previous Reading	Current Reading	Reading Type	Cons.	Cons. Type
040016115080	0	150	Real	150	Demand KVA
040016115080	0	111	Real	111	Demand KW
040016115080	661847	680814	Real	18967	High Rate
040016115080	584636	597516	Real	12880	Low Rate

Consumption Period: 02/12/2020-01/01/2021
Method of Charge: C2-3 Big Industrial Method CI2 - High/low

CONSUMPTION TREND

MESSAGES

BILLING DETAILS

Billing Concepts		Amount (Ksh)
Bill-202101BC0000037428		
Energy		
HighRateConsumption	18967kWh x 10.9	206,740.30
LowRateConsumption	12104kWh x 10.9	131,933.60
LowRateConsumption	776kWh x 5.45	4,229.20
MaximumDemandKVA	150kVA x 520	78,000.00
PowerFactorSurcharge		143,107.05
Fuel Energy Cost	31847kWh x 2.56	81,528.32
Total Energy		645,538.47
Levies and Adjustments		
Forex Exchange Adj. (FERFA)	31847kWh x 0.6977	22,219.65
Inflation Adj. (INFA)	31847kWh x 0.32	10,191.04
ERC Levy	31847kWh x 0.03	955.41
REP Levy	342903.1 x 5	17,145.16
Warma Levy	31847kWh x 0.0239	761.14
Total Levies and Adjustments		51,272.40
Rounding Adjustment		0.26
V.A.T.	677949.16 x 0.16	108,471.87
Total Monthly Bill		805,283.00
BALANCE BROUGHT FORWARD		871,605.10
APPLIED CREDIT		-0.00
Payment by Cheque		-871,605.00
TOTAL AMOUNT PAYABLE		805,283.10

Appendix H: CO_2 Emissions Balance.

Produced Emissions	**Total:**	**103.92 tCO2**		
	Source:	Detailed calculation from table below		
Replaced Emissions	**Total:**	**899.4 tCO2**		
	System production:	90.57 MWh/yr	Lifetime:	30 years
			Annual Degradation:	1.0 %
	Grid Lifecycle Emissions:	331 gCO2/kWh		
	Source:	IEA List	Country:	Kenya
CO2 Emission Balance	**Total:**	**676.4 tCO2**		

System Lifecycle Emissions Details:

Item	Modules	Transport1	Supports	Inverters
LCE	1713 kgCO2/kWp	35.0 gCO2/km	2.21 kgCO2/kg	349 kgCO2/units
Quantity	57.2 kWp	350 km	2160 kg	3.00 units
Subtotal [kgCO2]	98036	68.8	4769	1047