# THE UNIVERSITY OF NAIROBI

## FACULTY OF ENGINEERING

### DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

# Effectiveness of Vertically Mounted Solar Panels on Buildings - A Case Study of Radisson Blu Hotel

**By**

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# DECLARATION

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Title of the work:

| |
|---|
| EFFECTIVENESS OF VERTICALLY MOUNTED SOLAR PANELS-A CASE STUDY OF |
| RADISSON BLU HOTEL, NAIROBI |
| |

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This Project Report is submitted with our approval as University Supervisors:

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Prof. Cyrus Wekesa

University of Eldoret

Signature: ……………… Date: 17/06/2022…

# DEDICATION

I dedicate this project to my parents Mr. and Mrs. Kiboi and my siblings and friends for their continued support throughout this research project.

ACKNOWLEDGEMENT

Many thanks to God for the opportunity to undertake this research project to completion. For the gift of life and good health.

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# ABSTRACT

Solar energy is a renewable energy source that can help reduce a hotel's energy demand. Hotels being some of the largest energy consumers in Kenya can incorporate solar to save on energy costs. This research suggests the use of vertically mounted solar panels on building walls, especially tall buildings as the wall area is generally larger than the roof area. This is considered an element of Building Integrated Photovoltaic where a building's structure is used to produce power. The aim of this research was to establish how effective and feasible are vertical, wall-mounted PV panels in the case of Radisson Blu Hotel located in Nairobi, Kenya. An experimental model was set up to evaluate and determine the output and efficiency of vertically mounted solar panels (VMSP). The results obtained were compared with the traditional horizontal models. The results were also compared to the current guest energy use to determine the savings expected. With this experimental setup, savings of USD 52.28 and a payback period of 7 years with a return on investment of 14% can be realized. The payback period and Return on Investment (ROI) can be improved by using higher power-rated panels and increasing the number of modules. Recommendations for further research and studies were also suggested. Overall, hotels and buildings in general in Kenya should take advantage of the good climate and incorporate solar in their list of energy sources in order to maximize its benefits. With this, they can gain a competitive edge over their peers by saving on energy costs and being labeled as green buildings.

*Keywords:* Vertically Mounted Solar Panels (VSMP), Building Integrated Photovoltaic (BIPV), Adaptive Photovoltaic Technology

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# ACRONYMS AND ABBREVIATIONS

VMSP- Vertically mounted solar panel

PV- Photovoltaic

DC- Direct current

AC- Alternating current

CBD- Central business district

BIPV- Building integrated photovoltaic

UV- Ultra violet

HVAC- Heating ventilation and air conditioning

RO- Reverse osmosis

ICT- Information communication technology

COVID- Corona virus disease

LPG- Liquefied petroleum gas

EPP- Emergency power supplier

GDP- Gross domestic product

USD- United states dollar

KWh- Kilowatt hour

MW- Megawatt

SDG- Sustainable development goals

UNHABITAT- United Nations human settlement program

KW- Kilowatt

LEED- Leadership in energy and environmental design

Toe- Tonnes of oil equivalent

Kgoe- Kilogram of oil equivalent

PBP- Payback period

ROI- Return on investment

NPV- Net present value

IRR- Internal rate of return

# CHAPTER ONE: INTRODUCTION

## 1.1 Background

With growing populations and urbanization, most energy demand is concentrated in cities and urban areas. Sustainability of this energy demand requires that it be fulfilled using reliable, non-polluting and abundant sources of energy. According to Hernandez [1], solar power is available in most parts of the world, is renewable and does not emit greenhouse gases.

Solar power features considerably low energy densities, thereby requiring a larger area to produce a significant amount of energy. Urban areas such as Nairobi are heavily populated, making land a scarce and expensive resource. Traditional installations have placed solar panels on the roofs of buildings. These urban areas and cities are characterized by tall buildings, where the wall area is larger compared to the roof area [2]. As such, building facades offer an attractive alternative for such installations.

Vertical solar panels may receive less solar radiation than roofs and horizontal surfaces and are affected by the compact nature of urban areas [3], but the façade features a larger area than roof area. For instance, a building with 4 floors has 4 times façade area compared to the roof area. With the decreasing cost of PV panels in the recent years [4], these installations will become more popular. A building could also have both wall mounted and roof top PVs in order to maximize on the output.

Research conducted in Queensland suggests that PV system presents an effective way to reduce a building's electricity bill thereby reducing carbon emissions. The research shows that a 6kW PV installation can cover 61% of the electricity demand, thereby saving about 90% in electricity bills and reducing the building's carbon emissions by 95% [5].

PV panels require a high capital cost. This has caused slow market penetration [6-8] thus warranting approaches to combine the PV generation with building installation strategies along with feasibility studies of micro-grid systems. This has resulted in building integrated photovoltaic systems (BIPV), where electricity generation is integrated into a building's structure.

Façade mounted are not as effective as horizontal mounted owing to the difference in solar insolation or irradiance. This however has not prevented the exploration of this design. Scholars have conducted research on how to increase their output by using adaptive technologies. Solar tracking mechanisms and software are used to improve and maximize the use of daylight to increase electricity generation thereby increasing efficiency of wall mounted PV [9].

As Kenya's population and economy grows, so does the energy demand. The government's effort to make Kenya a middle income country by 2030 has not been without challenges. Kenya is heavily reliant on hydropower and there is not enough investment in power generation. Companies in Kenya experience outages translating to an average loss of USD 63,000 in a month. These outages cause downtimes causing a 7.1% decrease in sales for the companies [10]. Electricity is distributed by the Kenya Power Company. During outages, power is supplied from emergency power suppliers (EPPs) installed by individual companies and institutions. EPPs include diesel powered generators.

Kenya's economy is really advanced compared to other East African countries. It mainly relies on agriculture which accounts for about 24% of the entire GDP. Table1.1 shows some of the leading socio-economic indicators. Life expectancy has been included in the table because depending on the form of energy used, health can be impacted and therefore affecting the number of years a person lives [11, 12].

Table 1.1: Kenya's Socio-Economic Indicators [11]

| **Socio–Economic Indicator** | **Unit** | **2015** | **2016** | **2017** | **2018** | **2019** |
|---|---|---|---|---|---|---|
| Population | Million | 47.9 | 49.1 | 50.2 | 51.4 | 52.6 |
| GDP | USD(billion) | 64.0 | 69.2 | 79.0 | 87.8 | 95.5 |
| GDP per capita | USD | 1336.9 | 1410.5 | 1572.3 | 1708.0 | 1816.6 |
| GDP growth rate | % | 5.7 | 5.9 | 4.7 | 6.3 | 5.4 |
| Electricity consumption | GWh | 9514.6 | 10057.7 | 10359.9 | 11182.0 | 11620.7 |
| Petroleum consumption | 000 tonnes | 5489.4 | 5999.0 | 6347.7 | 6114.4 | 6439.6 |
| Total energy consumption | 000Toe | 7826.4 | 8.53.2 | 8410.1 | 8702.3 | 8854.0 |
| Energy consumption per capita | Kgoe | 298.0 | 422.0 | 501.0 | 436.0 | 259.0 |
| Life expectancy at birth | Years | 64.80 | 65.39 | 65.91 | 66.34 | 66.44 |

Kenya's power generating plan stands at 2929MW as at 2019. Geothermal proportion has risen from 14.8% in 2013 to 28% in 2019. This led to a reduction in dependency on hydropower. The 4.65MW addition is from off- grid plants [13, 14]. From Table1.2, it is noted that renewable energy only contributes to 74% of Kenya's energy mix. There are plans to improve and expand the current energy mix with an addition of 5000+ MW.

Table 1.2: Kenya's Energy Mix as of December 2019 [15]

| **Energy source** | Hydropower | Geothermal | Wind | Solar | Biomass | Non-renewable | TOTAL |
|---|---|---|---|---|---|---|---|
| **MW** | 837 | 823 | 336 | 95 | 88 | 750 | 2929 |
| **% Contribution** | 29 | 28 | 11 | 3 | 3 | 26 | 100 |

## 1.2 Problem Statement

Solar panels offer a great alternative source of 'clean' energy. They can be used to generate either thermal or electrical energy. With the decreasing solar panel prices and increasing fossil fuel costs, more establishments are embracing this technology. Even with the adoption of this technology, it needs to be effective and efficient, making both practical and economic sense.

While previous installations feature horizontal mountings, emerging issues such as rising population, scarcity of land and increased energy demand have warranted exploration of other installations. City hotels and buildings in general need to re-consider their energy sources so as to better position themselves in the market.

Vertically mounted or façade mounted solar panels is an installation that hotels and buildings in general can use to increase and diversify their energy sources. This installation is not affected by scarcity of land as no additional space is required to set up the panels. While solar PV technology is not new in Kenya, where it has found use in water pumping solutions and powering rural communities, its potential in urban areas has not been fully explored. There exists little to no research on how VMSP would perform in Kenya.

This research recommends use of VMSP as an alternative or additional source of energy, thereby maximizing the sun's potential while meeting a hotel's energy demand.

## 1.3 Research Objectives

### 1.3.1 Main Objective

To determine technical performance and economic viability of vertically mounted solar panels.

### 1.3.2 Specific Objectives

i) To review vertically mounted solar panels.
ii) To configure an experimental set-up for the analysis.
iii) To analyse technical performance of VMSP as compared to horizontally mounted panels.
iv) To perform economic evaluation of VMSP.

## 1.4 Research Questions

i) What are the current hotel energy sources and energy demand?
ii) What research has previously been done on VMSP?
iii) Are vertically mounted solar panels feasible?
iv) What are the cost- benefit impacts of vertically mounted solar panels in comparison to roof top installed solar panels?

## 1.5 Justification of the Study

The building sector is one of the most energy consuming sector- about 40% of total electricity generated in the East African region according to UNHABITAT. Majority of this energy is used in heating, cooling and ventilation and lighting when the building is operational. The amount of energy consumed in a building is directly linked to the building design, materials used to build it and the needs of the occupants [16].

The hospitality industry is a major sector in Kenya's economy. As such, it plays a big part in contributing to the overall country's energy use. Energy consumption in the hospitality industry has been on the rise as is noted in Figure 1.2.

One of Kenya's vision 2030's macro and economic pillars is the business tourism sector. As such, the Kenyan hospitality industry is growing at a fast rate. Tourist arrivals are anticipated to grow at about 6.9% compounded yearly. This translates to about 2.06 million tourists expected in 2022 from up 1.47 million arrivals in the year 2017 [17]. Development of new hotel properties and refurbishment of existing ones indicates confidence in Kenya’s economic growth despite the global COVID-19 pandemic.

These developments translate to higher energy demands. Vertically mounted solar PVs present an opportunity to ensure reliability on power systems by managing power outages and boosting hotel business by saving on energy costs and attracting more guests. A hotel with VSMP can also serve as an educational tool for young students wanting to venture into renewable energy careers.

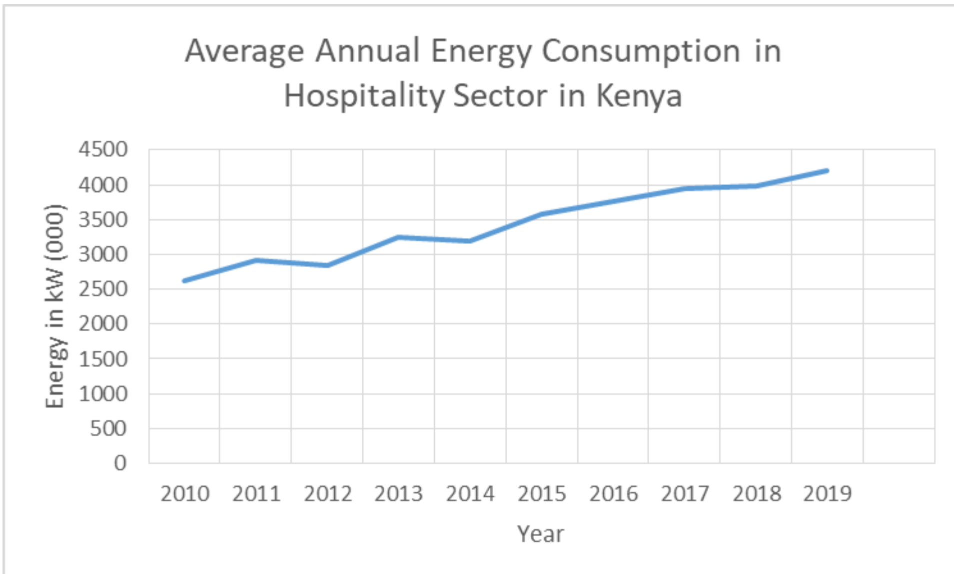



Figure 1.1: Annual Energy Consumption in Kenya's Hospitality Sector [18]

## 1.6 Scope of the Study

The research has assessed the technical and economic impacts, both positive and negative, resulting from use of VMSP in place of or in addition to the regular rooftop or horizontally mounted systems. The study was based on the Radisson Blu hotel located in Nairobi, Upper Hill, with the experimental set up at the University of Nairobi. These two facilities are in the same geographical location hence the weather and climatic conditions in these two areas are the same. Therefore, the panels are expected to have similar performance if they were actually mounted on the hotel’s façade.

### 1.7 Project Report Organization

Chapter One discusses solar energy and why it is important to adopt its use. It also focuses on the purpose of this research and the need to adopt VMSP. Chapter Two discusses solar PV basic concepts and the existing or traditional model of horizontally mounted solar panels. It also reviews previous research work done and seeks to identify the gaps in these researches. Chapter Three discusses how the research was carried out, methods of data collection and analysis. Chapter Four presents the data collected and its analysis. Chapter Five describes the conclusions arrived from the research, contribution made by this research and gives recommendations for further studies.

# CHAPTER TWO: LITERATURE REVIEW

This chapter reviewed the types of PV panels in the market and their characteristics. A review of previous studies and their contribution has been done. An existing gap in Kenya was also identified.

## 2.1 Basic Concepts

The basic component of a photovoltaic (PV) system are the cells which convert energy from the sun to electrical energy. Their efficiency ranges from 10-23% [19]. Some of the most commonly used PV technologies are amorphous silicon (a-si), mono-crystalline silicon (m-si), copper-indium-diselenide (CIS), poly-crystalline silicon (P-si) and cadmium-telluride (CdTe). The cells when connected, form PV modules. Modules when connected form a PV array. Figure 2.1 gives a comparison of the different types of technologies used.

| Characteristic | Monocrystalline | Polycrystalline | Amorphous (thin film) |
|---|---|---|---|
| Composition | Single crystal | Many crystals | Thin silicon layers |
| Color | Black | Blue | Multiple |
| Efficiency | 17 - 23% | 10 – 14% | 5 – 6% |
| Lifetime | 23 - 30 years | 20 – 25 years | 15 – 20 years |
| Manufacturing process | Complicated | Easier | Complicated |
| Cost | Expensive | Cheaper | Expensive |
| Temperature tolerance | 0 – 5% | -15 - +5% | -3 - +3% |

Figure 2.1: Characteristics of Different PV Technologies [20]

In addition to the modules, other components are needed to complete the PV system. These components are the charge controller, battery, and inverter and safety devices.

a) **Charge Controller.** Its purpose is to regulate flow of electricity from the module to the battery to the load. It ensures that the battery remains fully charged. When the system is in use, it allows flows of electricity from the system to the load. When the energy demands are high, it stops the flow of electricity to the load until the battery is sufficiently charged [21].

b) **Battery.** This is a storage device. It stores the power for use at night when the panels are not producing any power or during the day when they are not producing enough power. Batteries are installed depending on the size of the system and its requirements [21].

c) **Inverter.** This is a device that converts DC to AC. These, like the batteries are installed depending on the system needs. They monitor the performance of the PV system, optimize voltage thereby ensuring that the system attains its maximum power point (MPP). Inverters also function as safety devices by protecting the system from faults [22].

PV systems are commonly mounted on buildings flat surfaces, particularly rooftops. This provides opportunities for mini- grid and off-grid systems [23, 24]. These opportunities can be explored either in the design phase or in cases of retrofit of an existing building. According to Ceron et al research, [25] nearly 50% of BIPV systems are based off of rooftop installations. However, their performance and efficiency could be affected by elements such as the angle of tilt of the PV modules, availability of solar radiation, module's surface temperature, and space between the module rows among others.

BIPVs offer several advantages such as they function to improve the building's appearance and aesthetics while providing power at the same time. Operation hours, in the case of office buildings coincide with peak power production hours and they do not require additional land use, a commodity that is now scarce and expensive especially in the CBD.

## 2.2 Review of Previous Work

### 2.2.1 Methods of Integrating PV into a Building

There are various ways in which PVs can be integrated into a building. The panels can either be placed on top or ingegrated with the facade and roof system of a building.

i) Sloped glazing. Tilted walls, greenhouses, sunspaces, sloped glazing and atriums are examples of sloped glazing configuration. They consist of semi- transparent glazing componenets with aluminium frames containing plastic glazing or tinted, laminated glass units. They mostly offer daylighting solutions for buildings. PV panels are much less transparent than regular glass threfore, proper design should be done to optimize daylighting solutions. Figure 2.2 shows the solar office in Doxford International Park, Sunderland, where this configuration has been applied [26].

Figure 2.2: Atrium PV Panels in the Solar Office of Doxford International Park, Sunderland, UK [26]

ii) Vertical panels. These are similar in construction as the sloped glazing. However, power output is reduced due to their vertical orientation. Curtain walls  present an opportunity for a wide range of PV panels to be used because they typically contain opaque areas where non- tranparent panels can be used. Semi- transparent PV panels may be used in the curtain wall where daylighting is the main objective. Compromises between density of the PV panels, overheating and glare are necessary in this configuration. Figure 2.3 and 2.4 show instances where vertical panels have been employed.

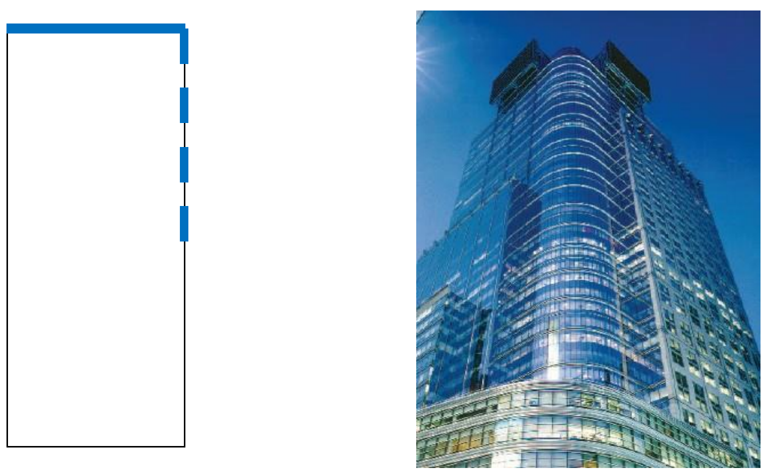


Figure 2.3: Times Square, New York [26]

Figure 2.4: APS Office Facility in California [26]

iii) PV panels on inclined walls. This system presents better efficiency since the panels are tilted at an angle. This however may bring about some complexity in the building's design and self-shading to some extent. Most commercially available PV panel types can be employed in this design. This configuration has been applied at the university of North Umbria in the UK and Kyocera Cooperation Building in Japan as in Figure 2.5 [26].

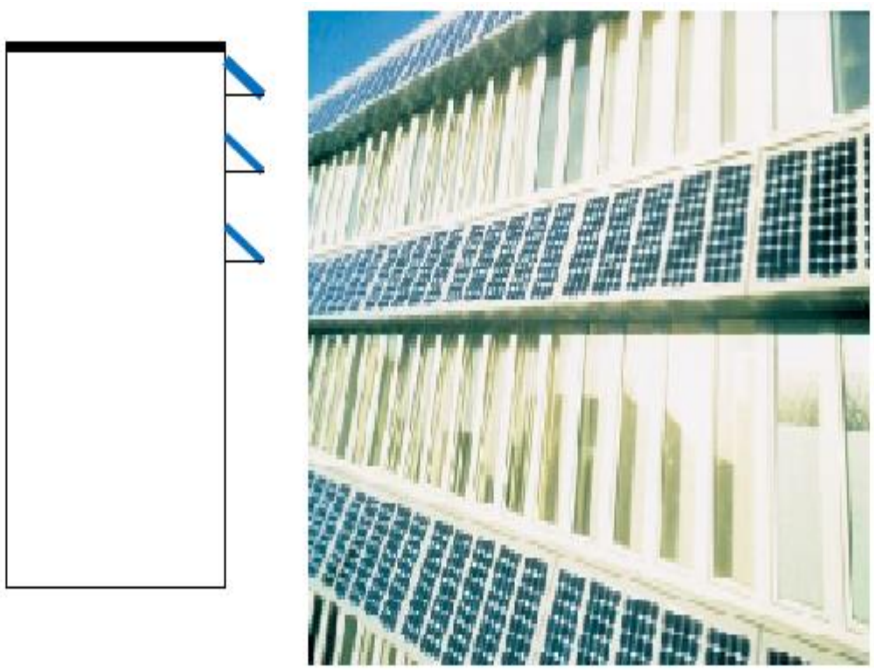


Figure 2.5: Inclined PV Panels at the University of North Umbria, UK, Installed in 1994 [26]

iv) Fixed sunshades. This system has been applied in the Samsung C&T Corporation building in Seoul, Korea. Details of the study are discussed later in this chapter. It is applicable where glare reduction is required but leads to loss of daylight. Effiency is improved due to the tilt. The shading elements easily accomodate PV laminates since they are oriented toward the sun, have rear ventilation that helps in temperature moderation and have a flat surface. As can be noted in Figure 2.6, 2.7 and 2.8, the panels are secured to the building using metal frames. This makes construction easier as that would have been the construction if sunshades were to be placed on the building walls. This configuration presents a challenge where shading can come from adjacent buildings or self-shading can occ ur.

Figure 2.6: Samsung Commercial Office Building in Seoul, Korea [26]

Figure 2.7: Fixed Sunshades in the SUVA Building, Switzerland Built in 1993[26]

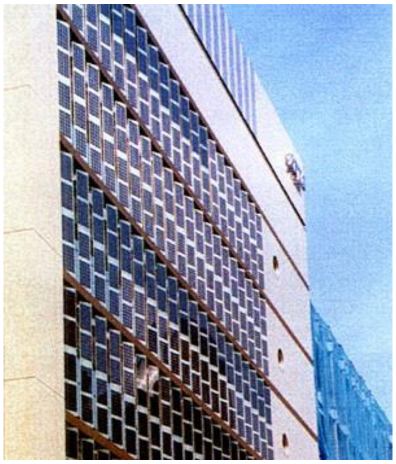


Figure 2.8: Solar Wings in an Office Building in Switzerland with Fixed BIPV Louvres [26]

v) Movable sunshades. Figure 2.9 shows this configuration which combines benefits of fixed sunshades and improved efficiency since the tilt angle and orientation of the panels can be adjusted either mechanically or electrically. This however requires more capital investment but with a greater efficiency.

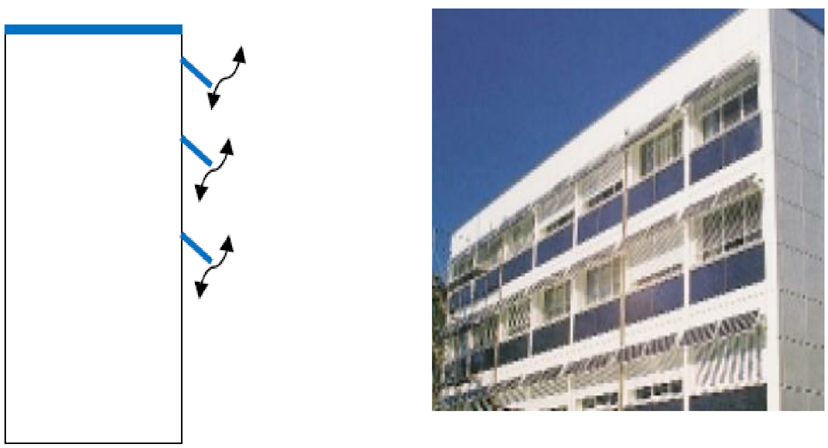


Figure 2.9: Moveable Sunshades in a Commercial Office Building in Switzerland [26]

For this research, the fixed sunshade configuration model was used. The panels were placed in vertical orientation and tilted at angles of 14̊ and 30̊. Where capital is not constrained, the movable sunshades are recommended as they have added benefits of maximizing on the solar radiation as well as remote control using BMS.

### 2.2.2 Samsung C&T Corporation Buildings in Korea

This study was conducted by T. Hwang et al [8]. The study's objective was to set up and develop a PV generator. In the research, different solutions were sought to attain maximum energy production by varying the direction and inclination of the PV installation. In addition, studies on the results of varying installation distance, D, to module length, L, ratio were done. PV panels were installed on the different building facades after which calculations made depending on the orientation of the walls.

***Direction:*** In the research, high efficiency monocrystalline silicon PV were installed at an inclination of 90˚on four walls facing the north-west (NW), the north-east (NE), the south-west (SW) and the south-east (SE) using a D/L ratio of 2. Due to Korea's geographical location, maximum electric energy is produced in the months of April and May. It then starts decreasing from July and reaches its lowest in December. The study concludes that the PV installed on the southwest and southeast facing walls perform better in terms on electricity generation compared to those installed on the northeast and northwest facing walls, throughout the year [8].

***Angle of inclination:*** This is a characteristic of the maximum total annual irradiance on the PV panels. The panels are attached to the southwest and southeast facing walls with varying vertical and horizontal angles as can be seen from Table 2.1. Results are represented in the form of graphs as shown in Figures 2.1 and 2.2. Latitude, longitude and weather conditions affect the curves. It is noted that maximum solar insolation is harvested from the southwest and southeast facing walls at a horizontal inclination of 60˚ or vertical inclination less than 15˚. Again, a larger D/L ratio will cause more solar insolation upon the panels [8].

Table 2.1: Various Horizontal and Vertical Angles with Varying D/L Ratio [8]

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Horizontally inclined angles | 0˚ | 15˚ | 30˚ | 45˚ | 60˚ | 75˚ | 90˚ |
| D/L ratio | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | ∞ |
| Vertically inclined angles | 0˚ | 15˚ | 30˚ | 45˚ | 60˚ | 75˚ | 90˚ |
| D/L ratio | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | ∞ |

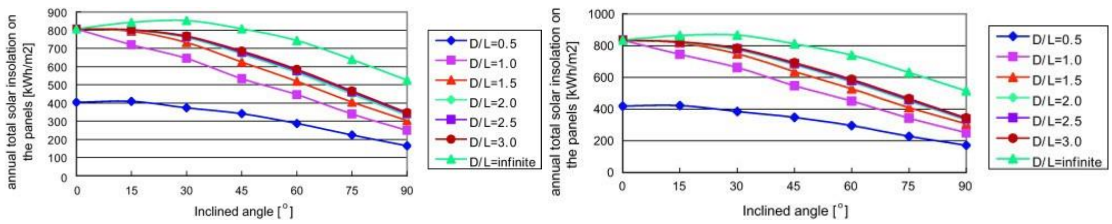



Figure 2.10: Total Annual Solar Insolation with Vertically Inclined Angles (a)Southeast Facing wall (b)Southwest Facing Wall [8]

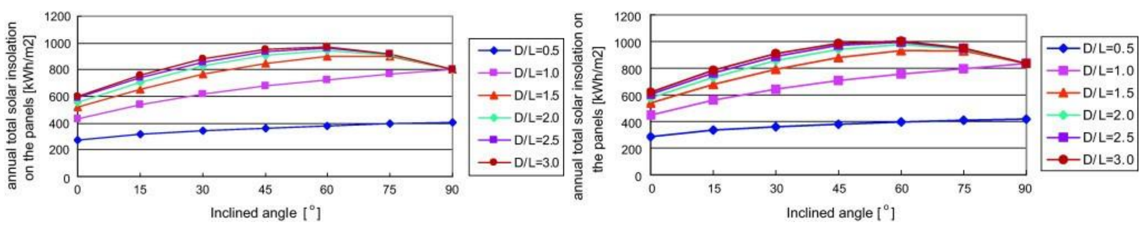



Figure 2.11: Total Annual Solar Insolation with Horizontally Inclined Angles (a)Southeast Facing Wall (b)Southwest Facing Wall [8]

### 2.2.3 Commercial buildings in Vietnam

A comprehensive and detailed study of the façade system is lacking but a proposal of the same is available. The proposal discusses the general design process, choosing the façade wall, software and appropriate solar panels. [27]

Commercial buildings in Vietnam can use 2 kinds of PV panels.

i) Thin film PV cladding. This is great for canopies, facades, skylights as well as curtain walls. These have advantages such as they are not affected by temperature hence do not need ventilation for optimum operation, they can operate at greater efficiency at non-optimal angles and can operate even at 10% sunlight which means they operate for longer hours over the year thus producing a higher energy yield [28].
ii) Crystalline PV cladding. These are ideal to seek maximum energy production. This type of cladding has similar mechanical properties to architectural glass that is used in construction. Its benefit is that it used for energy generation with an efficiency of up to 16% [29].

***Façade PV walls:*** The walls of buildings act as mediator or buffer between the internal and external environment. PV façade design involves integrating solar panels into the envelope of a building. Some of the ones suitable for Vietnam are:

i) PV curtain wall. This is a continuous building envelope with non-structural outer walls (Figure 2.3 a). It is useful where a building requires thermal insulation, protection from various weather conditions, reducing noise from the outside and meeting part of the building's energy demand. The PV is integrated in the building's outer thin layer therefore, where they are used, it is important that the initial PV design caters for energy needs relating to visual and thermal comfort.

ii) Glazed façade PV. Glazed PV laminates used in rooftop installations are usually made using crystalline (transparent) silicon cells where space between the cells has been adjusted. They can also be made with thin film which has laser-cut grooves. These present a sieve like design within the glazed panels as illustrated in Figure 2.3(b). In commercial buildings, they will, together with extruded aluminum frames, typically be in the envelope system. They also find use as skylights. Glazed PV panels can be used in place of transparent glass, with proper electrical wire passages construct. This arrangement provides an opportunity to control solar and daylight solar when they replace external louvers thereby giving the building a unique and interesting architectural appearance. These glazed PV panels ordinarily put together glass-glass photovoltaic laminates whose ability to transmit light can be adjusted thereby stimulating design of light and shadow which plays an important part in balancing energy requirements of the building.

iii) Rain screen façade PV. This set up consists of an installation that carries the load, a cladding panel and an air gap. During summer time, heat is dissipated as a result of the air gap that is naturally ventilated as a result of the top and bottom openings. A cooling effect on the wall is achieved through this installation thereby improving efficiency and effectiveness of the modules (Figure 2.3 c).

iv) PV accessories. These include balconies, shading systems, outdoor partitions, parapets among others. Shading is most commonly used to control indoor micro climate. Shading devices are of various types: external, interposed or internal, roof or façade, vertical, horizontal, fixed or tracking (manual or electrical), movable screen or panels, curtain or blind, consisting of special elements (selective glass, prismatic glass, solar thin-film). In these accessories, PVs are laminated to make use of shadow function so as to produce energy (Figure 2.3 d).



(a) PV Curtain Wall (b) Glazed Façade PV (c) Rain Screen Façade PV

(d) PV Accessories

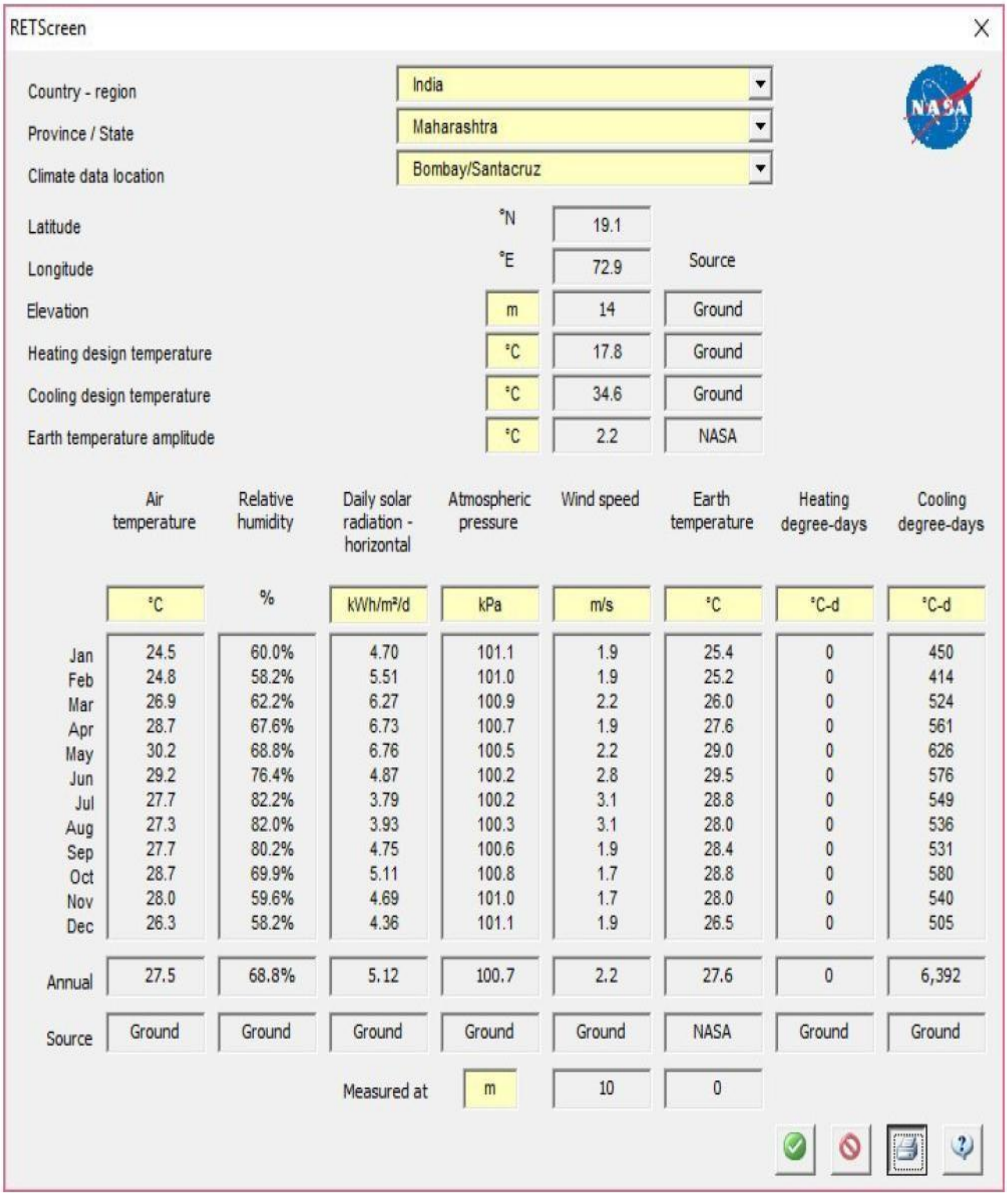
Figure 2.12: Types of PV Facade Walls [30]

### 2.2.4 High Rise Buildings in Mumbai, India

India is generally known for its dense population especially in urban areas. Mumbai is one such densely populated city in India. Urbanization has led to growth in high rise buildings in this city. These buildings are high energy consumers and hence are a source of GHG emissions as they currently use power generated from fossil fuels. With an increase in these buildings, demand for energy has also risen. India is also blessed with abundant sunshine thereby presenting an opportunity to exploit solar energy. Use of façade solar PVs on high rise buildings of India also saves on land resource as it is densely populated [31].

A software, RET Screen 4, from Canada [32] is applied to evaluate the performance of solar or any other source of renewable energy for a certain location as in Figure 2.4. The software can be used to evaluate the comparative output of CdTe and monocrystalline technologies applied to the facades of Mumbai's high rise buildings.

Various high rise buildings were analyzed to establish façade capacity and generation. The results show potential for realizing substantial savings in electricity cost and a reduction of GHG emissions [31].


RETScreen

| | | | |
|---|---|---|---|
| Country - region | | India | |
| Province / State | | Maharashtra | |
| Climate data location | | Bombay/Santacruz | |
| Latitude | °N | 19.1 | |
| Longitude | °E | 72.9 | Source |
| Elevation | m | 14 | Ground |
| Heating design temperature | °C | 17.8 | Ground |
| Cooling design temperature | °C | 34.6 | Ground |
| Earth temperature amplitude | °C | 2.2 | NASA |

| | Air temperature | Relative humidity | Daily solar radiation - horizontal | Atmospheric pressure | Wind speed | Earth temperature | Heating degree-days | Cooling degree-days |
|---|---|---|---|---|---|---|---|---|
| | °C | % | kWh/m²/d | kPa | m/s | °C | °C-d | °C-d |
| Jan | 24.5 | 60.0% | 4.70 | 101.1 | 1.9 | 25.4 | 0 | 450 |
| Feb | 24.8 | 58.2% | 5.51 | 101.0 | 1.9 | 25.2 | 0 | 414 |
| Mar | 26.9 | 62.2% | 6.27 | 100.9 | 2.2 | 26.0 | 0 | 524 |
| Apr | 28.7 | 67.6% | 6.73 | 100.7 | 1.9 | 27.6 | 0 | 561 |
| May | 30.2 | 68.8% | 6.76 | 100.5 | 2.2 | 29.0 | 0 | 626 |
| Jun | 29.2 | 76.4% | 4.87 | 100.2 | 2.8 | 29.5 | 0 | 576 |
| Jul | 27.7 | 82.2% | 3.79 | 100.2 | 3.1 | 28.8 | 0 | 549 |
| Aug | 27.3 | 82.0% | 3.93 | 100.3 | 3.1 | 28.0 | 0 | 536 |
| Sep | 27.7 | 80.2% | 4.75 | 100.6 | 1.9 | 28.4 | 0 | 531 |
| Oct | 28.7 | 69.9% | 5.11 | 100.8 | 1.7 | 28.8 | 0 | 580 |
| Nov | 28.0 | 59.6% | 4.69 | 101.0 | 1.7 | 28.0 | 0 | 540 |
| Dec | 26.3 | 58.2% | 4.36 | 101.1 | 1.9 | 26.5 | 0 | 505 |
| Annual | 27.5 | 68.8% | 5.12 | 100.7 | 2.2 | 27.6 | 0 | 6,392 |
| Source | Ground | Ground | Ground | Ground | Ground | NASA | Ground | Ground |
| | | | Measured at | m | 10 | 0 | | |

Figure 2.13: Mumbai Ambient-RETScreen4 [32]

### 2.2.5 Adaptive Photovoltaic Facades

As mentioned in Chapter One, façade installations are not as effective as rooftop installations. Therefore, adaptive characteristics are needed to improve the solar PV's performance. An adaptive PV system addresses effects of shading and features a solar tracking system integrated in the façade thereby reaping the benefits of both. Solar tracking can improve a PV's output between 30-40% in a year compared to the fixed-tilt module counterpart or up to 70% when compared to horizontal installations [33]. Solar trackers could be single axis or dual axis. Dual axis trackers are however not easily incorporated in BIPV installations. These trackers can function with sun sensors or without sun sensors.

***Case studies on adaptive photovoltaic facades***

As early as 1986, discussions on how to convert buildings into energy producers were ongoing. Emerging issues from the discussion were on building aesthetics. The public utilities building of Aachen (Germany) was the first building to take up this challenge. Here, solar cells were embedded into the insulation glass creating a semi-transparent multifunctional façade. The building was completed in 1991 [34]. Initial adaptive installations were applied using louvers/ shutters integrated with PV that could track either on a daily or periodic basis. These systems can be set up vertically or horizontally and are operated by linear actuators. This system has been applied at Riverhouse, One Rockefeller Park (New York), a residential high rise building that is LEED gold certified [35]. The building was established in 2009.

International BauAustellung (IBA)'s The Soft House in Hamburg Germany (Figure 2.6) consists of a 4 row housing unit [36]. This building's distinguishing feature is the adaptive façade with a two axis solar tracking feature. Pliable, spring like composite boards reinforced with fiber bend to optimize solar angle of thin film flexible PVs. Winch rotation enables daily east, west sun tracking thereby ensuring optimum solar harvesting. A Building Management System (BMS) is used for daily or seasonal adaptive PV façade adjustments.

Figure 2.14: IBA's The Soft House [36]

Another example of solar façade applications is the town hall in Freiburg  Breisgau, Germany. With an area of 26115m², the PV's output is 220kWp. It features staggered vertically projecting modules with a height of 3.5m, 60cm width and weighing 100kg with PV cells and great thermal insulation [37].

## 2.3 Research Gap

Previous research has mostly been conducted in European, Asian and American locations with no significant research in Africa. These continents do not receive good solar radiation compared to Africa. This has however not limited the research process and actual implementation of VSMP. The research done in most of these areas has also not been implemented as in the case of India and Vietnam.

Currently there isn't any available research on VMSP or BIPV in Kenya hence the need for this research. Kenya in located at the equator region and hence receives a good amount of solar insolation throughout the year. This project has identified that gap and seeks to explore the feasibility and performance of VMSP in Nairobi, Kenya using the Radisson Blu Hotel as a case study. This report seeks to bridge the gap between available theories and practical applications.

### 2.4 Benefits and Drawbacks of VSMP

VSMP present a number of benefits as compared to their horizontal counterparts.

i) It saves on land, an already scarce resource.

ii) Reduces on the environmetal impact where excavation needs to be done on the ground for installation.

iii) Apart from power generation, they offer insulation to a building thereby saving on energy costs.

iv) They improve the aesthetics of a building.

v) A building with VMSP can be used for educational purposes, aiding in research studies.

vi) It is good for business as clients and customers are more drawn to buildings that are environmentally concious.

They are however not without some drawbacks as follows:

i) Initial investment cost may be high depending on the complexity of the installation.

ii) Shading losses may be high depending on the proximity of nearby buildings thereby reducing efficiency and power output.

iii) Some dirt and dust may settle on the panels. It may be difficult to clean them due to the design of the installation thereby reducing power output and efficiency.

### 2.5 Chapter Conclusion

From review of the previous work done, it was established that there exists a research gap especially in Kenya. Other countries have realized the potential that solar energy has and have explored various ways of maximizing its potential. It is time that Kenya also invests in this research, maximizing on its ideal location (equator) and reaping its benefits. Being a developing country, a lot of projects on infrastructure are ongoing and in the planning stages, meaning many buildings and structures are expected to be developed. This research has sought to explore the feasibility of vertical installations in Nairobi, Kenya. With support from the government, this concept can be applied to achieve vision 2030 as a country.

# CHAPTER THREE: METHODOLOGY

## 3.1 Review of Previous Methods

### 3.1.1 Samsung C&T Corporation Buildings in Korea

Monocrystalline PV panels were installed in facades facing southeast, southwest, northeast and northwest. The D/L ratio and inclination angles, both horizontal and vertical were used to determine maximum energy output. From this experiment, it was observed that maximum solar insolation from the south side facing walls can be achieved with $60^{\circ}$ horizontal angle of inclination or a vertical inclination angles below $15^{\circ}$. Also, larger D/L ratios can harvest more sunlight but is however not proportional to the energy generated since the power generation area is reduced [8].

### 3.1.2 Commercial Buildings in Vietnam

Since this was a proposal [27], guidelines were proposed, using software, to fully understand and reap the benefits of façade mounted solar panels.

i) Designing the wall-mounted PV prototype. This stage involves choosing a suitable prototype wall for the panels as discussed in the types of façade PV walls suitable for Vietnam climate, in Chapter Two. Civil engineers and architects are required to give their input.

ii) Facade PV simulation. In this stage, simulators are used to deduce the energy output from the system. Data required as input will be, rated solar power of the panels, number of panels, number of micro-inverters and their power rating, environmental conditions such as shading and sun hours. Output will be the energy yield either daily, monthly or annually. Micro inverters are recommended instead of the string type in order to maximize output from each panel.

iii) Building energy simulation. This last step is to determine overall efficiency of the PV panels with the system integrated with other mechanical and electrical aspects of the building.

The steps and recommended software are summarized in Table 3.1.

Table 3.1: Outlined Steps with Proposed Software for Each Step [28]

| **Step** | **Proposed Software** |
|---|---|
| Selection of façade PV prototype | Autodesk 3D [38]<br>Google Sketchup [39]<br>Rhinoceros 3D [40] |
| Simulation of façade PV system | PVSites [41] |
| Simulation of building's energy demand | EnergyPlus [42]<br>Edge [43] |

### 3.1.3 High Rise Buildings in Mumbai, India

The RETScreen 4 software was used in this research to determine the façade PV output for buildings in Mumbai. It was also used to compare outputs from different types of PV panels. From Figure 3.1, area occupied by the panels is determined by type of panels to be used. It is also noted that thin film panels require more area compared to crystalline panels for every MW produced. It is also noted that CdTe gives overall higher annual output for every MW installed as compared to the monocrystalline technology. Annual output is dependent on orientation of solar panels, building's geographical location, tilt angle, shading and type of PV panels used. For a lower incident angle, the output of VMSP could be higher than rooftop installations [31].

Results from analysis of various buildings in Mumbai, India is summarized in Figure 3.2. The average cost of electricity was taken as USD 0.12 per kWh. This was used in calculation of the expected savings.

### 3.1.4 Adaptive photovoltaic facades

This research as discussed in section 2.2.5, suggests use of adaptive technologies to improve the efficiency of wall mounted panels. It involves balancing shading and daylight through a smart device mounted on the façade such as solar tracking devices. A BMS is also used for remote control and adjustment of the panels depending on the required needs and changing weather patterns.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Photovoltaic** | | | | | | |
| Type | | | mono-Si | | CdTe | |
| Power capacity | kW | | 1,000.00 | | 1,000.00 | |
| Manufacturer | | Canadian Solar | | | First Solar | |
| Model | | mono-Si - CS6X-300M - MaxPowe | | | CdTe - FS-390W | |
| Efficiency | % | | 15.6% | | 12.5% | |
| Nominal operating cell temp. | °C | | 45 | | 46 | |
| Temperature coefficient | % / °C | | 0.40% | | 0.24% | |
| Solar collector area | m² | | 6,398 | | 8,000 | |
| Control method | | MPPT | | | MPPT | |
| Miscellaneous losses | % | | 7.0% | | 7.0% | |
| **Inverter** | | | | | | |
| Efficiency | % | | 96.0% | | 96.0% | |
| Capacity | kW | | 1000.0 | | 1000.0 | |
| Miscellaneous losses | % | | 0.0% | | 0.0% | |
| **Resource assessment** | | | | | | |
| Solar tracking mode | | | Fixed | Fixed | Fixed | Fixed |
| Slope ° | | | 65.0 | 90.0 | 65.0 | 90.0 |
| Azimuth ° | | | 0.0 | 0.0 | 0.0 | 0.0 |

| Month | Daily solar radiation - horizontal | Daily solar radiation - tilted | Electricity exported to grid | Electricity exported to grid | Electricity exported to grid | Electricity exported to grid |
|---|---|---|---|---|---|---|
| | kWh/m²/d | kWh/m²/d | MWh | MWh | MWh | MWh |
| January | 4.70 | 5.61 | 142.43 | 115.31 | 147.23 | 118.19 |
| February | 5.51 | 5.76 | 132.34 | 101.27 | 136.70 | 103.51 |
| March | 6.27 | 5.21 | 132.45 | 89.13 | 136.85 | 90.91 |
| April | 6.73 | 4.27 | 105.82 | 58.81 | 109.07 | 59.69 |
| May | 6.76 | 3.47 | 89.41 | 47.46 | 91.89 | 47.96 |
| June | 4.87 | 2.62 | 66.18 | 43.42 | 67.74 | 43.88 |
| July | 3.79 | 2.29 | 60.56 | 41.08 | 61.64 | 41.35 |
| August | 3.93 | 2.58 | 67.90 | 43.73 | 69.19 | 44.07 |
| September | 4.75 | 3.58 | 89.47 | 59.09 | 91.88 | 60.02 |
| October | 5.11 | 4.87 | 122.86 | 91.00 | 127.36 | 93.34 |
| November | 4.69 | 5.49 | 133.32 | 107.57 | 138.52 | 110.78 |
| December | 4.36 | 5.40 | 136.00 | 111.81 | 141.00 | 115.00 |
| **Annual** | **5.12** | **4.25** | **1,278.74** | **909.67** | **1,319.07** | **928.72** |

Figure 3.1: Comparison between Monocrystalline and Thin-Film (CdTe) PV for Mumbai, India [31]

## 3.2 Proposed Method

### 3.2.1 Problem Design

The problem formulation was based on a solar PV trainer. Technical data on the type of solar panel used was collected from the name plate. The panels were placed vertically at various tilt angles facing East and West directions. Data from these set ups was collected. The panels were also placed in horizontal orientation and data collected from this configuration. The data was analyzed using available software to give results.

| High-rise Building Name | Building Ht. Mtr. | Solar PV Facade Surface Area Sq. Mtr. | Solar PV Capacity Proposed KWp | Annual Generation MWh with vertical CdTe modules | Annual Generation MWh with tilt $65^0$ CdTe modules | Annual Savings Million INR with tilt $65^0$ CdTe modules | Net annual GHG emission reduction tCO2 |
|---|---|---|---|---|---|---|---|
| World One | 442 | 53040 | 6630 | 6152.64 | 8745.434 | 78.00927 | 8735.025 |
| Omkar 1973 | 320 | 64000 | 8000 | 7424 | 10552.56 | 94.12883 | 10540 |
| Minerva | 307 | 30700 | 3837.5 | 3561.2 | 5061.931 | 45.15242 | 5055.906 |
| Sky Suites | 291 | 29100 | 3637.5 | 3375.6 | 4798.117 | 42.7992 | 4792.406 |
| Sky Forest | 281 | 28100 | 3512.5 | 3259.6 | 4633.233 | 41.32844 | 4627.719 |
| KUL Couture | 275 | 13750 | 1718.75 | 1595 | 2267.152 | 20.22299 | 2264.453 |
| Orchid Hts. | 274 | 32880 | 4110 | 3814.08 | 5421.378 | 48.35869 | 5414.925 |
| The Park | 268 | 134000 | 16750 | 15544 | 22094.42 | 197.0822 | 22068.13 |
| One Avighna | 266 | 26600 | 3325 | 3085.6 | 4385.908 | 39.1223 | 4380.688 |
| Nathani Hts. | 262 | 26200 | 3275 | 3039.2 | 4319.954 | 38.53399 | 4314.813 |
| The Imperial | 256 | 30720 | 3840 | 3563.52 | 5065.229 | 45.18184 | 5059.2 |
| Ahuja Twrs. | 248 | 24800 | 3100 | 2876.8 | 4089.117 | 36.47492 | 4084.25 |

Figure 3.2: Solar PV Facade Proposed Capacity & Generation for High-rise Buildings in Mumbai, India [31]

### 3.2.2 Site Assessment

The first step was to determine the suitability of solar walls for the proposed location which is Radisson Blu hotel Nairobi, Upper hill. The hotel already has solar panels on the rooftop which are used for pre-heating water. Roof top location may sometimes have limitations of inadequate space, roof mounted structures such as chimneys, vents, air handling units and type of roofing material used. Where these limitations are present, wall mounted or ground mounted solar panels are used. A site assessment is necessary so as to maximize the energy output of the system [44]. Early site assessments and evaluation present economic benefits such as better cost estimation and optimized financial incentives in cases where rebates are available. They can determine how much energy production is expected thereby increasing customer confidence and satisfaction. It also eases the whole planning process. Few of the elements to consider when assessing a site include:

a) Sun hours
b) Shade analysis
c) Tilt angle

These factors are further discussed:

a) Sun hours

It is necessary to establish how much irradiation will be required in order to produce a given amount of power. This parameter helps determine for how long an area receives maximum sunlight [44].

Generally, Kenya receives substantial amounts of sunshine throughout the year with January being the hottest month and August receiving the lowest amount of sunshine (Figure 3.3). Time between sunrise and sunset does not differ much in Kenya due to the proximity to the equator. During the 'summer', the sun moves to the North slightly and during 'winter' it moves to the south slightly [46]. The intensity of sunlight changes through the day so the amount of energy received is summed up. The total is analyzed to determine the how long the sun would have to shine at 1000W/m² in order to provide the same amount of energy.

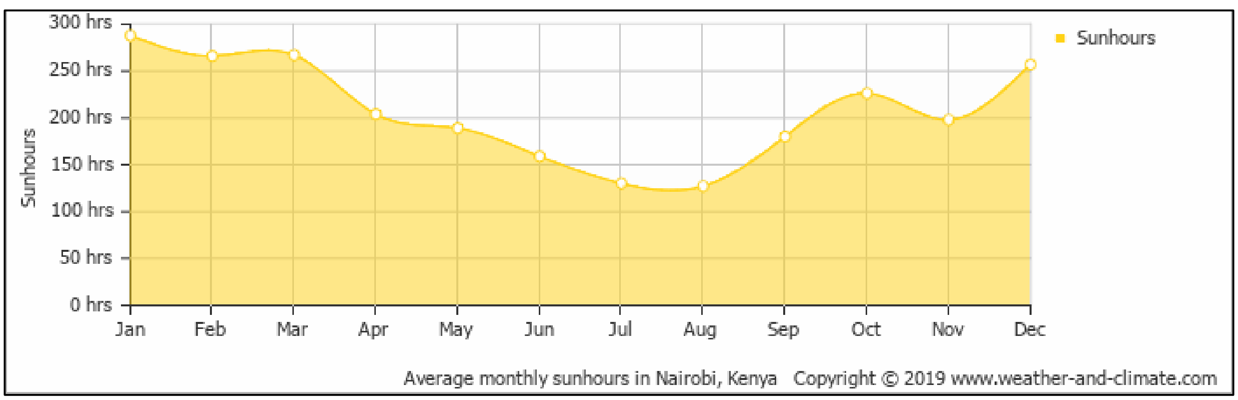



Figure 3.3: Nairobi Sun Hours [45]

b) Shade Analysis

PV arrays should ideally be installed in locations without shading. However, this is not always the case as most grid connected systems are mostly found in urban areas which are heavily built.

Shading reduces a PV module's output considerably and should therefore be avoided as much as possible. A shadow cast on a solar panel has a much greater effect on the energy yield than in the case of solar thermal systems. Shading can result from the system itself or from nearby objects [44].

i) Temporary Shading

This is caused by objects such as leaves, snow, bird droppings and other type of dirt that may cover the PV modules. The effects of these is usually reduced when the system is cleaned by rainwater so long as the system is tilted to about 12 degrees. The higher the tilt angle, the faster and easier the system gets clean. Therefore, by increasing the tilt angle during installation, this type of shading can be reduced significantly. Regular cleaning of the system also helps to curb this problem thereby increasing the solar yield. Cleaning can be done using plain water and a soft sponge. Losses due to soiling can be assumed to be between 2% to 5% which is generally considered acceptable [47, 48]. An advantage of VMSP is that the effects of this type of shading are minimal or none.

ii) Shading Resulting from the Location

This mostly comes from the surroundings such as buildings and trees. During the time of installation, shading from trees and shrubs may not be present but may develop over the years due to growth of vegetation. Cables may also cast a small but effective moving shadow [44].

iii) Shading Resulting from the Building

These present direct shadows coming from protruding facades, chimneys, satellite dishes, antennae, roof protrusions as well as lighting conductors. This type of shading should be taken into account when designing how the modules will be wired in order to minimize their impact [44].

iv) Direct Shading

This can result in high energy losses. If an object is very close to the modules, the shadow cast will be very dark. This then prevents maximum diffuse light from reaching the modules. This shadow reduces the energy incident to the cells by about 60% to 80% [43]. The further the shading object is, the lighter the shadow cast on the module hence the less the losses [44].

v) Self-Shading

This may be caused by solar module arrangement. It however, can be minimized through optimum spacing of the modules and the tilt angle [44].

c) Tilt Angle

This is the angle setting that is required for the panels to get maximum irradiation. As earlier discussed in section 3.1.4, the tilt angle for the vertically mounted panels can be improved by using adaptive technologies [32].

#### 3.2.2.1 Radisson Blu Hotel

Radisson Blu Hotel Nairobi began its operation in Kenya in the year 2015. The hotel is one of the high end 5 star rated hotels in Kenya and is located on Elgon Road, Upper Hill Nairobi. The hotel is a modern stylish city hotel with a unique and sophisticated design. It features a bar, restaurants, business class lounge, elegant guestrooms, inimitable event spaces, Spa and health facilities like gym and a heated swimming pool. The hotel caters for both local and international business travelers with maximum tranquility and comfort at all times.

The hotel sits on 35,470m$^2$ and has 271 guest rooms and 13 meeting rooms. Its design as seen in Figure 3.4 makes it a good candidate for this study. It offers large façade wall area both on the front and the back. The hotel is also located in an area with few surrounding buildings and tall trees hence minimizing effects that would be brought about by shading.

The hotel consists of HVAC systems, lights, kitchen equipment, laundry machines, RO plant, boilers, pumps, gym equipment, ICT and office equipment as the categories of energy consuming facilities. The hotel was operating 24/7 pre- COVID.

The facility is supplied with four main sources of energy; the utility grid, solar thermal energy, LPG gas for food preparation and diesel that is used to fuel 2 Standby generators and 3 steam boilers. The overall energy consumption at the hotel was found to average at 596,733kWh every month translating to 6,836,797kWh annually. This results to an energy expense of about USD. 70,267.64 every month translating to USD. 843,211.72 annually [50].

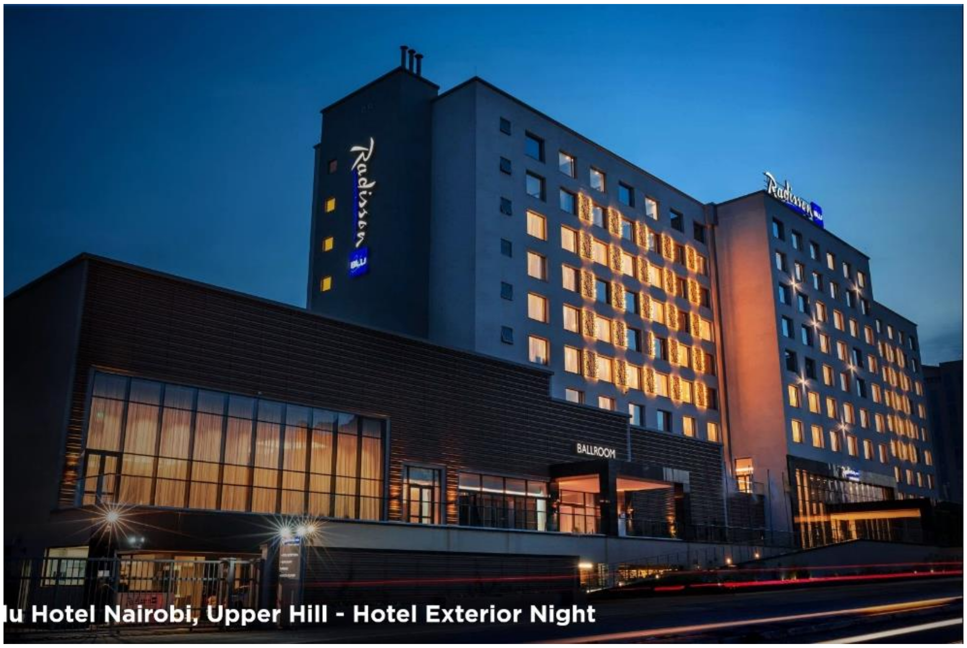



Figure 3.4: Radisson Blu Hotel Nairobi, Upperhill [49]

### 3.2.3 Solar Panel Data

Technical data on the solar panel used in the research is as in Table 3.2. There were 2 modules with the same characteristics and specifications.

Figure 3.5: Solar Panel Technical Data

| | |
|---|---|
| Maximum power Pmax | 115Wp |
| Voltage at maximum power Vmp | 17.7V |
| Current at maximum power Imp | 6.5A |
| Open circuit voltage Voc | 21.6V |
| Short circuit current Isc | 6.96A |
| Tolerance | ±5% |
| Model | PM 0115 |
| Manufacturer | PHOTON |
| Area | 1.87m² |

### 3.2.4 Energy Calculations

This section outlines the formulae used to determine the power input, output and efficiency of the panels. In addition, it gives methods used to evaluate the economic viability of VMSP.

a) Irradiation

Modelling and simulation for solar irradiation could be obtained starting from the mathematical formula for extraterrestrial radiation. Though most models consider extraterrestrial radiation to be constant, [45], extraterrestrial radiation in a specific area can be calculated using Equation 3.1,

$$G_{\circ} = \frac{24}{\pi}.S.\left[1 + 0.33.cos\left(\frac{2\pi.n}{365}\right)\right].(cos\emptyset.cos\delta.sin\omega_s + \omega_s.sin\varphi.sin\delta)[W/m^2] \qquad (3.1)$$

Where, S is the solar constant, n is number of days in the year, Ø is latitude of the area in study, δ is the declination of the earth, ω is the solar angle.

The atmosphere has some considerable influence on the radiation. The mass of air, m, identifies the path taken by the sun's rays through the atmosphere to sea level. It would be noted that m=0 if there was no atmosphere. The sun travels the shortest distance at the equatorial region where the sun is in the zenith, meaning that m=1. For various zenith angles, the air mass can be calculated using Equation 3.2:

$$m = \frac{1}{cos\theta_z} \qquad (3.2)$$

This formula gives an indication of the decrease in radiation in the north and south hemispheres compared to the equatorial region.

b) PV Output Power

This is dependent on hours of insolation and shading factors. It can be determined by Equation 3.3.

$$solar\ panel\ watts * average\ hours\ of\ sunlight * 75\% = daily\ watt\ hours \qquad (3.3)$$

75% is a derating factor introduced to take care of losses from factors that would affect efficiency of the panels as discussed later in this section.

c) PV Efficiency

The basic efficiency formula is given by Equation 3.4.

$$\eta = \left(\frac{P_{max}}{Area}\right)\frac{}{1000} * 100\% \qquad (3.4)$$

Where, η is efficiency, $P_{max}$ is PV panel's peak power in watts, $Area$ is length x width of the PV panel in square meters, under standard test conditions.

STC, Standard Test Conditions, refers to the set criteria for testing solar panels. The conditions are

i) Solar cell temperature at 25°C
ii) Solar irradiance at 1000 watts/sq.m
iii) Air mass at 1.5

The efficiency of solar cells is not yet good but the ability for a solar cell to produce power is great. Efficiency is affected by a number of factors such as:

i) Direction which the panels are facing: The direction affects the short circuit current. If the direction is not in line with the azimuth angle, then overall power output is reduced.

ii) Tilt angle of the panels: Tilt angle corresponds to the latitude of the earth. Nairobi is located at latitude -1.28333 and longitude 36.81667. [51]

iii) Irradiance on the panels: The higher the irradiance, the more the power output.

iv) Temperature: As the temperature increases, current increases and voltage decreases.

v) Shading: Shading caused by objects, dirt and dust decreases the overall efficiency of the solar panels. Vertically mounted panels will work better if there are no neighboring tall buildings on the wall which they are to be mounted. The panels should also be kept clean. An advantage of vertically mounted solar panels over the horizontally mounted ones is that the vertical ones are easier to keep clean as dust and dirt does not easily settle on them.

vi) Load: Load calculation is compulsory before the solar panels are installed. For stand-alone or off- grid systems especially, to properly size the batteries. Load affects the system's reliability. The system is not supposed to consume more power than its capacity. If it does, then the output of the system soon becomes zero and the efficiency becomes zero. Efficiency therefore reduces when we use the system beyond its capacity.

### 3.2.4 Experimental Set Up

The PV Trainer Kit, Figure 3.5, was used for this research. It was set up at The University of Nairobi, Electrical Machines Lab and consists of the following components:

a) PV panels consisting of 2 independent modules made of crystal silicon and a supporting structure.
b) Solar radiation sensor for measuring solar incident radiation.
c) Charge controller for optimizing power flow involving the PV panels, battery and inverter.
d) Battery for power storage.
e) Inverter for converting electrical variables at the battery and PV output from DC to AC.
f) Voltmeter for voltage measurement.
g) Ammeter for current measurement.
h) Remote control system with PC to display and record various parameters.
i) Sun tracker that can move the panel along 2 axes in order to optimize exposure to the sun.


Figure 3.6: PV Trainer Kit

### 3.2.5 Financial Analysis

Financial analysis of the project was done using Payback period (PBP), Return on investment (ROI), Net present value (NPV) and Internal Rate of Return (IRR). These tools were used in assessing the economic implication or benefits of the project.

Payback period refers to the amount of time it takes to recover the initial capital cost investment of a particular project. In other words, it is how long a project will take to break even. The shorter the payback period, the more attractive the investment is. Payback period will be determined using Equation 3.5.

$$Payback\ Period\ (PBP) = \frac{Capital\ Investment}{Annual\ Financial\ Saving} \quad (3.5)$$

The return on investment is a profitability measure to evaluate performance of a project. It is expressed as a percentage and will be calculated using Equation 3.6

$$Return\ on\ Investment = \frac{Annual\ Financial\ Savings}{Total\ amount\ of\ Investment} = \frac{1}{PBP}$$

(3.6)

Net present value is the value of the difference between your present cash inflows and present cash outflows over a given period of time. It is a financial appraisal tool used to assess the financial viability of a project. It was used to assess the profitability of the VSMP as it uses the time value of money. A positive NPV is a good indication of the viability of the project while a negative NPV is likely to result in a loss. Equation 3.7 was used to calculate the NPV. IRR is when NPV of cash flows is equal to zero.

$$\sum_{n=1}^{11} \frac{Annual\ savings}{(1+r)^t} - Initial\ cost\ of\ investment \quad (3.7)$$

### 3.3 Conceptual Framework

This research is focused on exploring feasibility of VMSP in trying to solve problems of lack of adequate previous research, high energy demand, scarcity of land and unreliable grid connected power supply. The approcah taken was to assess the site, set up the PV trainer kit and collect data. The data collected was analysed and recommendations were made.In this study, the independent variables were the number of PV modules used, angle of tilt of the modules, orientation of the modules and amount of solar radiation. These will affect the dependent variable which is the output of the modules as illustrated in Figure 3.6.

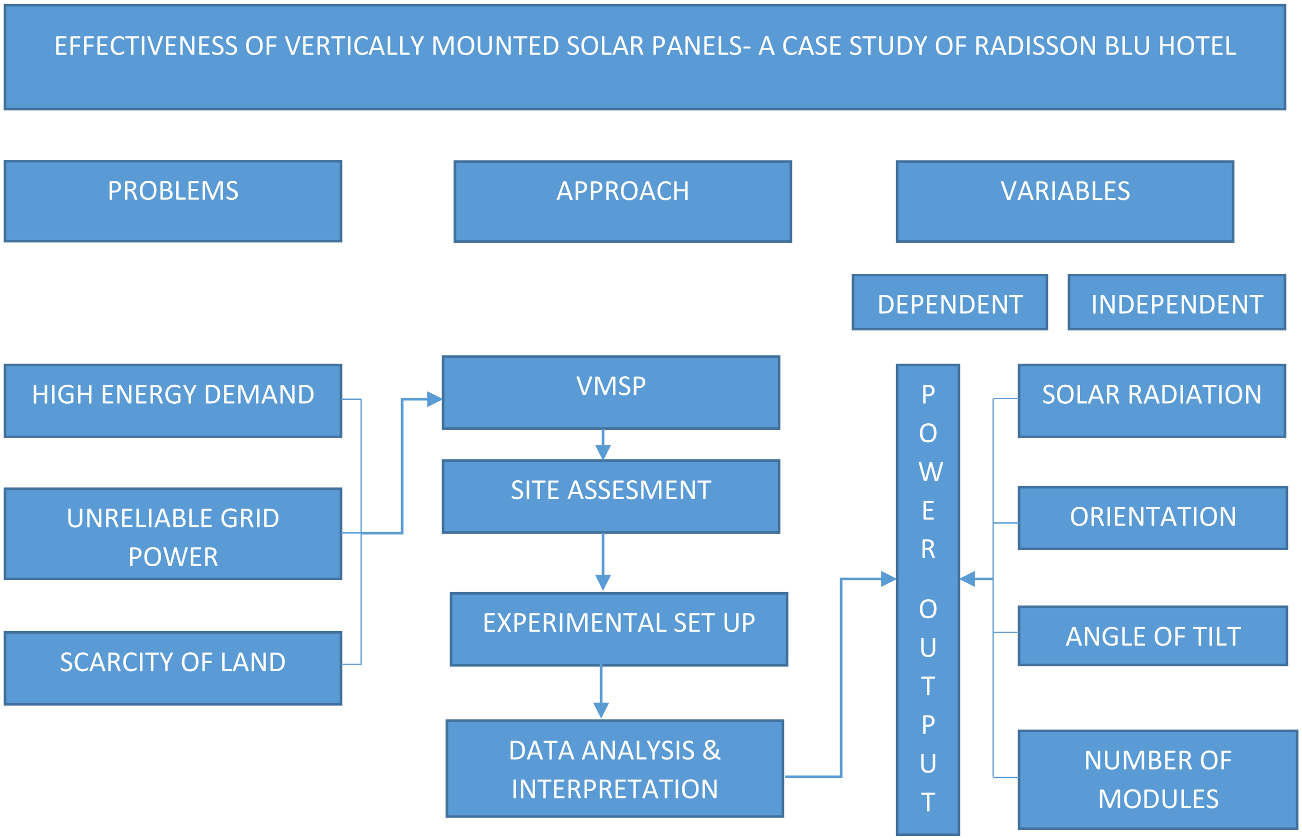



Figure 3.7: Conceptual Framework

### 3.4 Assumption

The hotel is located in Upperhill area while the experimental set-up was done at the University of Nairobi located in Nairobi town center. It was assumed that the results obtained form the set-up would be the same as if the modules were actually monted on the hotel as they are in the same geographical area.

### 3.5 Chapter Conclusion

This chapter reviewed methods used in previous researches and highlights their findings. It also explains the approach that was used to perform this research, including the experimental set-up and financial appraisal methods. A review of the subject building, Radisson Blu Hotel has also been done to evaluate the performance of the panels on this building's walls. The conceptual framework indicates the variables that would affect energy production and efficiency of the VMSP.

# CHAPTER FOUR: RESULTS, ANALYSIS AND DISCUSSION

This chapter presents the data collected, analysis and results to inform the conclusions and recommendations. Graphs were drawn to give a representation of the gathered data on amount of solar radiation received, voltage, current and power produced by the panels. This was analyzed for various tilt angles and orientations. Values obtained from the vertical installations were compared to those obtained from the horizontal installation. Power demand for a single guest room was evaluated. The ability for the vertical and horizontal installations to meet this power demand was evaluated. The economic viability of the vertical installation was also determined using, Net Present Value, Payback Period and Return on Investment.

## 4.1 Site assessment data

A site assessment, using the RETScreen software, was done by gathering climatic data for the Hotel's location. From Figure 4.1, it is noted that daily solar radiation- horizontal ranges from 3.75-6.66kWh/m²/day and that Kenya is in the warm-humid zone.

| | | | |
|---|---|---|---|
| Country | | Kenya | |
| Province/State | | | |
| Climate data location | See map | Nairobi/Dagoretti | |
| Latitude | ˚N | -1.3 | |
| Longitude | ˚E | 36.8 | **Source** |
| Climate zone | 3A | Warm - Humid | Ground+NASA |
| Elevation | m | 1,798 | Ground |
| Heating design temperature | °C | 10.6 | Ground |
| Cooling design temperature | °C | 28.5 | Ground |
| Earth temperature amplitude | °C | 13.5 | NASA |

| Month | Air temperature | Relative humidity | Precipitation | Daily solar radiation - horizontal | Atmospheric pressure | Wind speed | Earth temperature | Heating degree-days 18 °C | Cooling degree-days 10 °C |
|---|---|---|---|---|---|---|---|---|---|
| | °C | % | mm | kWh/m²/d | kPa | m/s | °C | °C-d | °C-d |
| January | 18.0 | 60.0% | 52.70 | 6.54 | 84.3 | 4.5 | 20.7 | 0 | 248 |
| February | 18.8 | 56.0% | 33.60 | 6.66 | 84.3 | 4.5 | 22.2 | 0 | 246 |
| March | 19.4 | 61.5% | 78.74 | 6.38 | 84.3 | 4.5 | 22.4 | 0 | 291 |
| April | 19.2 | 71.0% | 135.30 | 5.32 | 84.4 | 4.0 | 21.1 | 0 | 276 |
| May | 17.8 | 73.0% | 99.82 | 4.66 | 84.5 | 3.5 | 19.6 | 6 | 242 |
| June | 16.3 | 72.5% | 31.50 | 4.26 | 84.6 | 2.9 | 19.1 | 51 | 189 |
| July | 15.6 | 73.0% | 25.11 | 3.75 | 84.6 | 3.0 | 19.2 | 74 | 174 |
| August | 15.9 | 70.5% | 29.76 | 4.00 | 84.6 | 3.4 | 20.3 | 65 | 183 |
| September | 17.3 | 63.5% | 26.70 | 5.35 | 84.5 | 4.0 | 22.0 | 21 | 219 |
| October | 18.5 | 62.5% | 63.24 | 5.63 | 84.4 | 4.5 | 22.1 | 0 | 264 |
| November | 18.4 | 70.5% | 111.30 | 5.27 | 84.4 | 4.7 | 20.7 | 0 | 252 |
| December | 18.1 | 66.0% | 76.57 | 6.06 | 84.4 | 4.7 | 20.3 | 0 | 251 |
| **Annual** | **17.8** | **66.7%** | **764.34** | **5.32** | **84.4** | **4.0** | **20.8** | **218** | **2,835** |
| **Source** | Ground | Ground | NASA | Ground | Ground | NASA | NASA | Ground | Ground |
| Measured at | | | | | m | 10 | 0 | | |

Figure 4.1: Site Assessment Data for Radisson Blu Hotel, Nairobi

Figure 4.2 illustrates, the daily solar insolation by month. Kenya receives high solar insolation in the early months of the year and then decreases mid-year, between June and August and rises again from September to December. This shows that Kenya generally receives an almost consistent radiation. The air temperature also range between 10°c to 18°c throughout the year indicating that there are no extreme variations in the weather patterns.

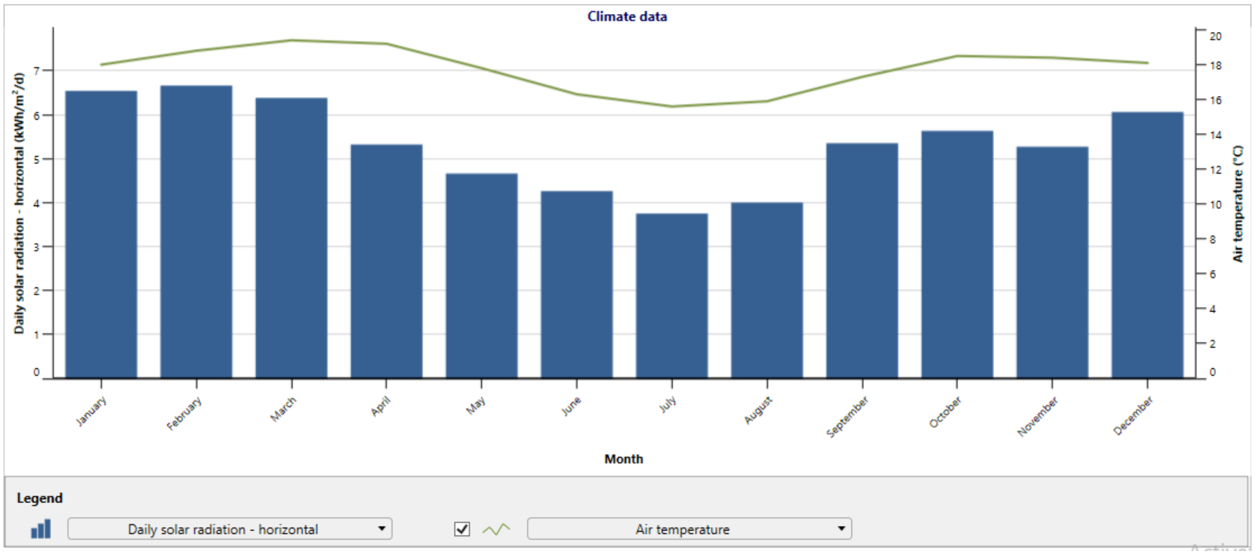



Figure 4.2: Nairobi's Climatic Data

**Calculation of Solar Irradiance**

From equation 3.1,

$$G_{o} = \frac{24}{\pi}.1366.\left[1 + 0.033.cos\left(\frac{2\pi.52}{365}\right)\right].(\cos(1.28333).cos23.45.sin25.32 + 25.32.\sin(1.28333).sin23.45)[W/m^2]$$

$$= 4231W/m^2$$

$$= 4.2kWh/m^2$$

This calculation was done for 21st February 2022 which is the 52nd day of the year 2022, at a solar angle of 25.32°, earth inclination of 23.45° using a solar constant of 1366W/m². Since Kenya is located at the equatorial region, the solar angle and earth inclination do not differ much. From previous researches and studies, the average daily insolation for Kenya is 3-7 kWh/m² per month and 4-6kWh/m² per day. The value is within the daily range.

### 4.2 Horizontally mounted solar panels

The trainer was set up horizontally for an average of 6 hours per day, for 3 days. Data collected was represented in tabular and graph forms as in the following sections.

#### 4.2.1 Case 1: 21st March 2022

On this day, the results obtained were as in Table 4.1 and Figures 4.3, 4.4 and 4.5. Total power output was 88.3W. Radiation was at its peak at 1970W at 1230hrs.

Table 4.1: Horizontal Mounting Output for 21st march 2022

| Date | 21/3/22 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy | Radiation | Efficiency | V1 | i1 | P1 | Time |
| 617 | 1155 | 2 | 19.31 | 1.32 | 25.5 | 0930hrs |
| 734 | 1374 | 1 | 19.34 | 0.56 | 4.8 | 1000hrs |
| 851 | 1593 | 0 | 19.04 | 0.23 | 4.5 | 1030hrs |
| 905 | 1694 | 0 | 18.87 | 0.35 | 6.6 | 1100hrs |
| 992 | 1856 | 0 | 18.97 | 0.23 | 4.4 | 1130hrs |
| 734 | 1374 | 1 | 19.34 | 0.56 | 10.8 | 1200hrs |
| 1052 | 1970 | 0 | 18.7 | 0.21 | 3.8 | 1230hrs |
| 969 | 1814 | 0 | 18.65 | 0.26 | 4.9 | 1300hrs |
| 940 | 1759 | 0 | 18.65 | 0.12 | 2.2 | 1330hrs |
| 941 | 1761 | 0 | 18.63 | 0.26 | 4.9 | 1400hrs |
| 811 | 1518 | 0 | 18.82 | 0.18 | 3.3 | 1430hrs |
| 642 | 1209 | 0 | 18.67 | 0.18 | 3.3 | 1530hrs |
| 163 | 305 | 2 | 17.97 | 0.26 | 4.7 | 1600hrs |
| 110 | 207 | 2 | 17.51 | 0.26 | 4.6 | 1630hrs |
| TOTAL | | | | | 88.3 | |

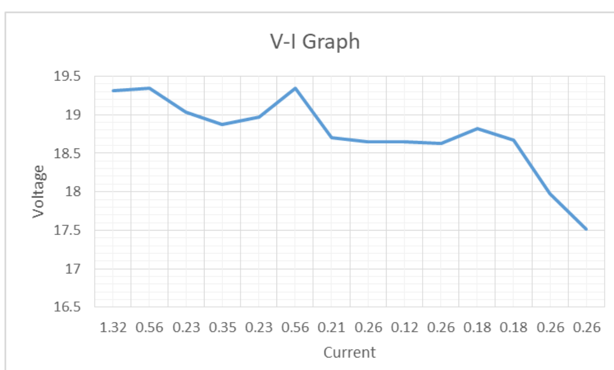



Figure 4.3: V-I Graph (21st March 2022)

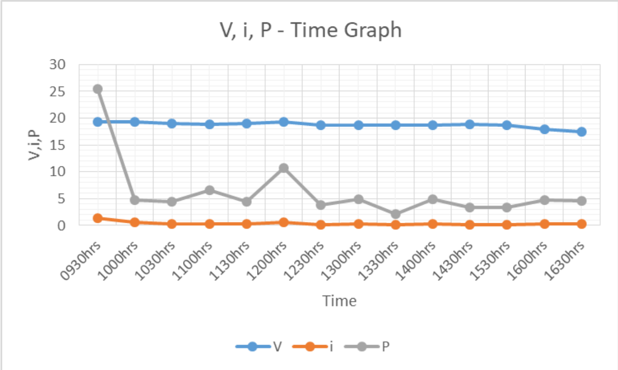



Figure 4.4: V,i,P-Time Graph (21st March 2022)

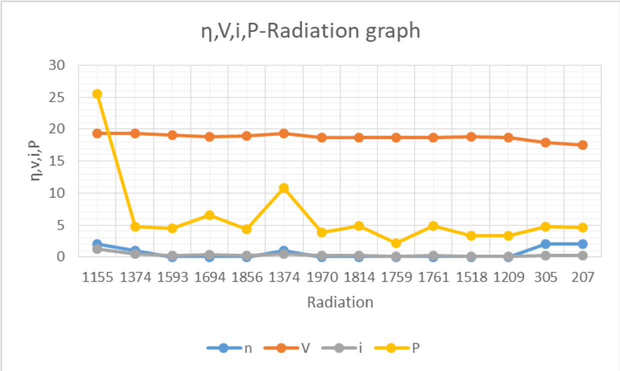



Figure 4.5: η,V,i,P-Radiation Graph (21st March 2022)

From the V-I graph, it is noted that when voltage decreased, current also decreased. In the second graph, voltage, current and power all decreased as the the day progressed into evening.

### 4.2.2 Case 2: 22nd March 2022

From Table 4.2, total power output was 382.2W. Radiation was highest at 1300hrs at 1986W.

Table 4.2: Horizontal Mounting Output (22nd March 2022)

| Date | 22/3/22 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy | Radiation | Efficiency | V1 | i1 | P1 | Time |
| 159 | 298 | 10 | 17.93 | 0.7 | 30.5 | 0900hrs |
| 692 | 1296 | 2 | 19.95 | 1.2 | 24 | 0930hrs |
| 673 | 1260 | 8 | 12.13 | 8.76 | 106.3 | 1000hrs |
| 784 | 1467 | 6 | 17.48 | 4.72 | 82.5 | 1030hrs |
| 326 | 609 | 3 | 17.3 | 1.23 | 21.3 | 1100hrs |
| 1013 | 1896 | 1 | 19.07 | 1.09 | 20.7 | 1200hrs |
| 1061 | 1986 | 1 | 18.82 | 0.79 | 14.9 | 1300hrs |
| 156 | 293 | 4 | 15.85 | 0.76 | 12.1 | 1330hrs |
| 218 | 408 | 3 | 17.21 | 0.82 | 14.1 | 1400hrs |
| 164 | 306 | 2 | 17.33 | 0.32 | 5.6 | 1430hrs |
| 513 | 960 | 2 | 18.24 | 0.91 | 16.6 | 1500hrs |
| 681 | 1275 | 1 | 18.75 | 0.91 | 17 | 1530hrs |
| 513 | 960 | 2 | 18.24 | 0.91 | 16.6 | 1600hrs |
| TOTAL | | | | | 382.2 | |

Figures 4.6, 4.7 and 4.8 illustrate the behaviour of voltage, current and radiation during this day.

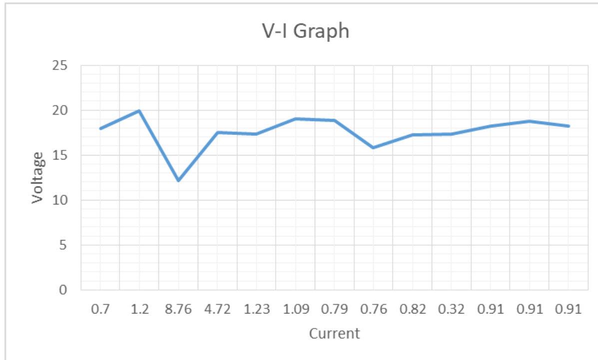



Figure 4.6: V-i Graph (22nd March 2022)

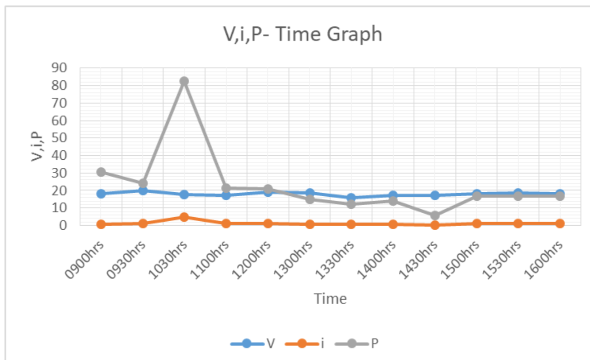



Figure 4.7: V,i,P-Time Graph (22nd March 2022)

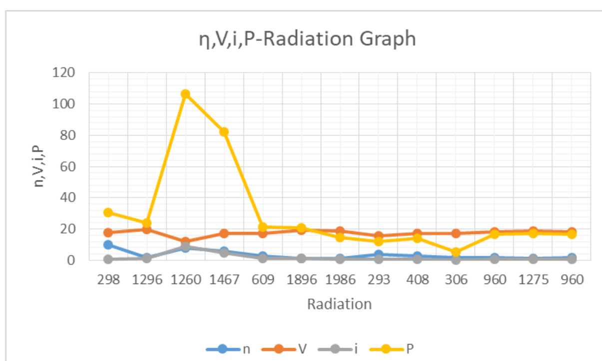



Figure 4.8: η,V,i,P-Radiation Graph (22nd March 2022)

### 4.2.3 Case 3: 30th March 2022

The total power output from this day was 561.4W. Radiation was highest at 1300hrs at 2110W. Efficiency increases upto 1130hrs then starts to decrease up to 1600hrs. The data was tabulated in Table 4.3 and graphs as in Figures 4.9, 4.10 and 4.11 drawn.

Table 4.3: Horizontal Mounting Output (30th March 2022)

| Date | 30/3/2022 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy | Radiation | Efficiency | V1 | i1 | P1 | Time |
| 859 | 1607 | 3 | 18.51 | 3.14 | 58.1 | 1000hrs |
| 948 | 1774 | 7 | 18.14 | 6.53 | 118.5 | 1030hrs |
| 192 | 360 | 12 | 13.5 | 3.11 | 41.9 | 1100hrs |
| 192 | 360 | 12 | 13.6 | 3.16 | 43 | 1130hrs |
| 894 | 1673 | 3 | 18.14 | 3.13 | 56.9 | 1200hrs |
| 849 | 1589 | 4 | 18.68 | 3.16 | 59.1 | 1230hrs |
| 1127 | 2110 | 2 | 18.97 | 2.4 | 45.6 | 1300hrs |
| 1054 | 1974 | 2 | 19.43 | 1.79 | 34.7 | 1330hrs |
| 195 | 366 | 7 | 15.94 | 1.58 | 25.2 | 1400hrs |
| 769 | 1439 | 1 | 19.19 | 1.08 | 20.8 | 1430hrs |
| 769 | 1439 | 1 | 19.19 | 1 | 19.1 | 1500hrs |
| 616 | 1154 | 2 | 19.02 | 1.05 | 20.1 | 1530hrs |
| 502 | 940 | 2 | 19.04 | 0.97 | 18.4 | 1600hrs |
| TOTAL | | | | | 561.4 | |

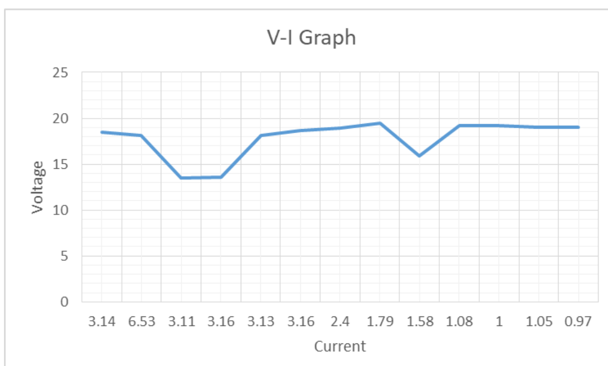



Figure 4.9: V-i Graph (March 30th 2022)

From the three days, it is noted that for horizontal mounting, the output is almost consistent through out the day. The graphs show consistency in Voltage- current, Power, efficiency and radiation. Highest power output was recorded on 30th March. The high power outputs can be attributed to the fact that the panel is laying flat therefore receives almost constant radiation through out the day.

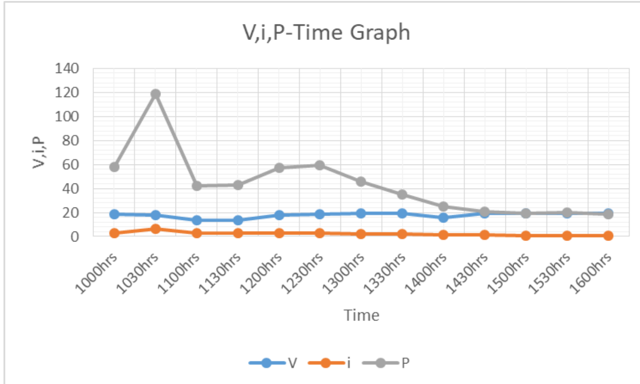



Figure 4.10: V,i,P-Time Graph (30th March 2022)

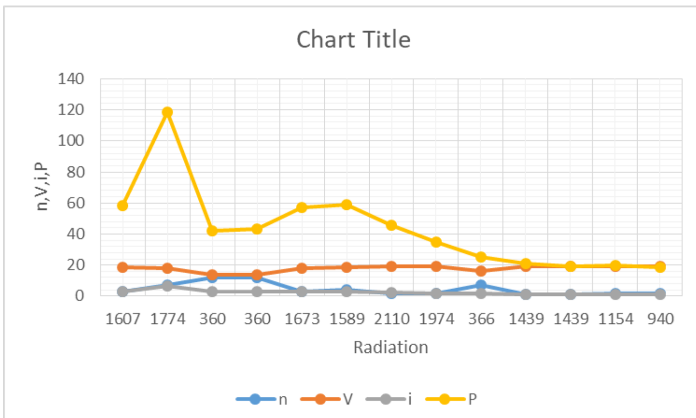



Figure 4.11: η,V,i,P-Radiation Graph (30th March 2022)

### 4.3 Vertically mounted solar panels

Data was collected from East and West orientations different tilt angles of 14°, 30° and 45° for different days. The following sections discuss in detail each of the different set-ups.

#### 4.3.1 Case 1: Orientation of 84̊ East at a Tilt angle of 14̊

In this first scenario, the panels were mounted facing 84̊  East at a tilt angle of 14̊. Data was collected for six and a half hours and recorded in Table 4.4. From the graph interpretation in Figures 4.12, 4.13 and 4.14, it is observed that voltage, current and power all decrease as the day progresses. The radiation which falls on the panels also decreases with as the day progresses. Efficiency decreases during the morning hours then increases around midday when the sun is at its peak between 1330hours and 1430hours then decreases up to zero towards late afternoon. The total power output form the panels on this particular day was 194.4W. This is from two modules of 115W rated power each.

Table 4.4: Vertical Mounting Output (21st February 2022)

| Date | 21/2/2022 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy W/m² | Radiation W | Efficiency % | V1 | i1 | P1 (W) | Time |
| 723 | 1353 | 3 | 18.24 | 2.08 | 37.9 | 1000hrs |
| 676 | 1266 | 2 | 18.29 | 1.38 | 25.2 | 1030hrs |
| 589 | 1103 | 2 | 18.11 | 1.29 | 23.2 | 1100hrs |
| 539 | 1010 | 2 | 18.12 | 0.88 | 15.9 | 1130hrs |
| 420 | 786 | 2 | 17.48 | 0.94 | 16.4 | 1200hrs |
| 323 | 605 | 3 | 16.68 | 0.97 | 16.1 | 1230hrs |
| 275 | 514 | 3 | 16.19 | 1 | 16.1 | 1300hrs |
| 151 | 282 | 5 | 15.16 | 0.88 | 13.4 | 1330hrs |
| 147 | 274 | 5 | 14.53 | 0.94 | 13.6 | 1400hrs |
| 190 | 190 | 5 | 12.99 | 0.76 | 9.9 | 1430hrs |
| 21 | 38 | 0 | 12.48 | 0 | 0 | 1500hrs |
| 87 | 163 | 4 | 12.65 | 0.53 | 6.7 | 1530hrs |
| 46 | 86 | 0 | 12.4 | 0 | 0 | 1600hrs |
| 21 | 38 | 0 | 12.33 | 0 | 0 | 1630hrs |
| TOTAL | | | | | 194.4 | 6.5hrs |

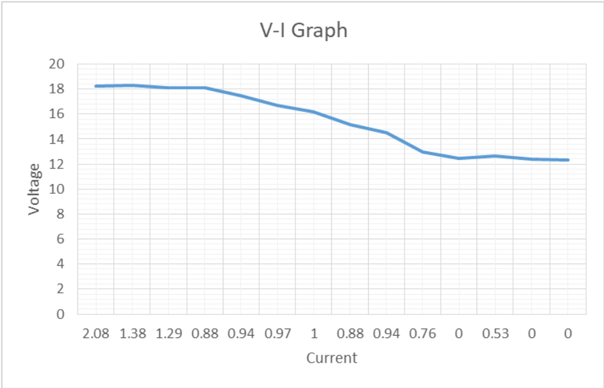



Figure 4.12: V-i Graph (21st February 2022)

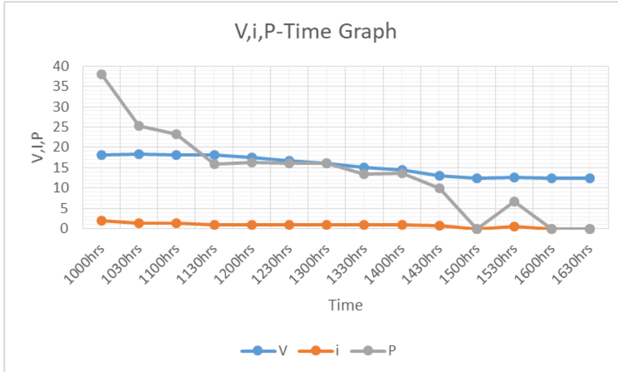



Figure 4.13: V,i,P-Time Graph (21st February 2022)

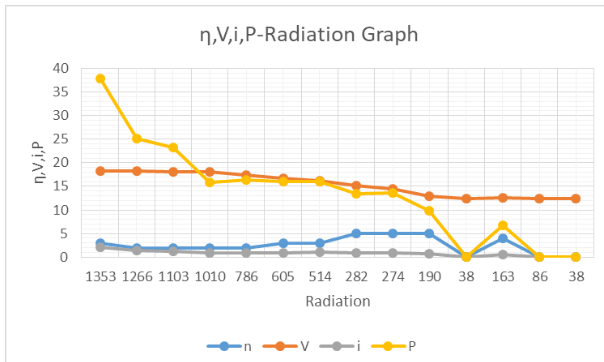



Figure 4.14: n,V,i,P-Radiation Graph (21st February 2022)

### 4.3.2 Case 2: Orientation of 278̊w at a Tilt Angle of 14̊

For this day, the trainer was set at 278̊ West and tilted at 14̊. Data collected is as in Table 4.5.

The set up was operational for 7 1/2 hours giving a total output of 129.7W. Power output was at its highest in the morning at 27.2W decreasing to zero by late afternoon. Radiation increased steadily reaching its maximum at 1330hrs at 744W then decreasing after that. Its is also observed that both voltage and current had a increasing trend up until 1230hours after which they started to decrease till 1630hours. This data was plotted on graphs in Figures 4.15, 4.16 and 4.17.

Table 4.5: Vertical Mounting Output (22nd February 2022)

| Date | 22/2/22 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy | Radiation W | Efficiency % | V1 | i1 | P1 (W) | Time |
| 82 | 153 | 18 | 13.06 | 2.08 | 27.2 | 0900hrs |
| 65 | 123 | 13 | 13.16 | 1.23 | 16.2 | 0930hrs |
| 123 | 230 | 6 | 15.85 | 0.91 | 14.4 | 1000hrs |
| 143 | 267 | 4 | 16.5 | 0.67 | 11.1 | 1030hrs |
| 136 | 254 | 4 | 16.02 | 0.59 | 9.4 | 1100hrs |
| 123 | 230 | 4 | 15.67 | 0.62 | 9.6 | 1130hrs |
| 91 | 170 | 5 | 14.82 | 0.56 | 8.2 | 1200hrs |
| 251 | 470 | 2 | 17.33 | 0.5 | 8.6 | 1230hrs |
| 183 | 342 | 2 | 16.33 | 0.47 | 7.7 | 1300hrs |
| 398 | 744 | 1 | 18.07 | 0.47 | 8.5 | 1330hrs |
| 152 | 285 | 3 | 15.8 | 0.56 | 8.8 | 1400hrs |
| 0 | 0 | 0 | 12.79 | 0 | 0 | 1430hrs |
| 0 | 0 | 0 | 12.74 | 0 | 0 | 1500hrs |
| 0 | 0 | 0 | 12.82 | 0 | 0 | 1530hrs |
| 0 | 0 | 0 | 12.72 | 0 | 0 | 1600hrs |
| 0 | 0 | 0 | 12.74 | 0 | 0 | 1630hrs |
| TOTAL | | | | | 129.7 | 7.5hrs |

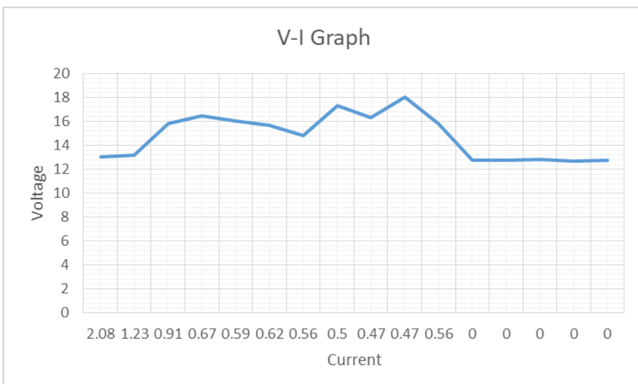



Figure 4.15: V-i Graph (22nd February 2022)

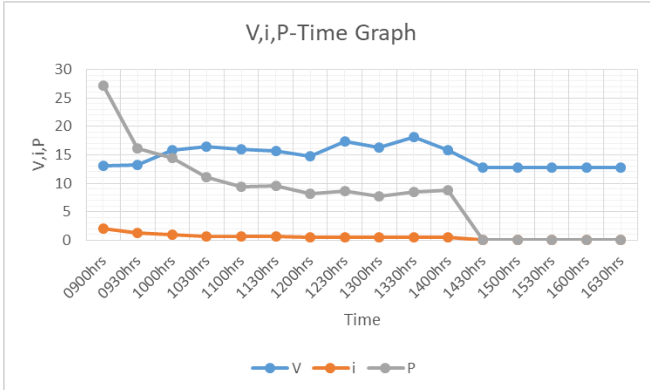



Figure 4.16: V,i,P-Time Graph (22nd February 2022)

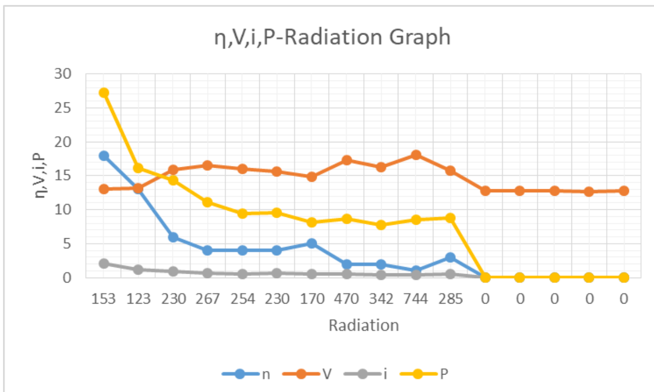



Figure 4.17: n,V,i,P-Radiation Graph (22nd February 2022)

### 4.3.3 Case 3: Orientation of 90° East at 30° Tilt Angle

On this day, data was gathered for 5 1/2 hours and tabulated in Table 4.6. This was then interpreted using graphs as in Figures 4.18, 4.19 and 4.20. Total power output was 87.8W. Radiation increased from 413W at 0900hrs to 1570W at 1030hrours then deacreased till end of day. Voltage, current and power had a decreasing trend up until midday where they rose and started decreasing after that. Efficiency also decreased as the day progressed from 4% at 0900hours to 1% at 1400hours then increased to 2% at 1430hours.

Table 4.6: Vertical Mounting Output (23rd February 2022)

| Date | 23/2/22 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy W/m² | Radiation W | Efficiency % | V1 | i1 | P1 (W) | Time |
| 219 | 413 | 4 | 18.41 | 0.91 | 15.6 | 0900hrs |
| 351 | 659 | 2 | 18.21 | 0.73 | 11.4 | 0930hrs |
| 477 | 936 | 1 | 19.34 | 0.5 | 10.1 | 1000hrs |
| 845 | 1571 | 0 | 19.17 | 0.38 | 7.9 | 1030hrs |
| 256 | 470 | 1 | 17.48 | 0.38 | 7.2 | 1130hrs |
| 565 | 1011 | 1 | 19.31 | 0.5 | 9.3 | 1200hrs |
| 461 | 863 | 1 | 17.52 | 0.32 | 5.3 | 1230hrs |
| 232 | 426 | 1 | 19.92 | 0.38 | 7.4 | 1300hrs |
| 164 | 578 | 1 | 18.21 | 0.44 | 8 | 1400hrs |
| 177 | 306 | 2 | 17.33 | 0.32 | 5.6 | 1430hrs |
| TOTAL | | | | | 87.8 | 5.5hrs |

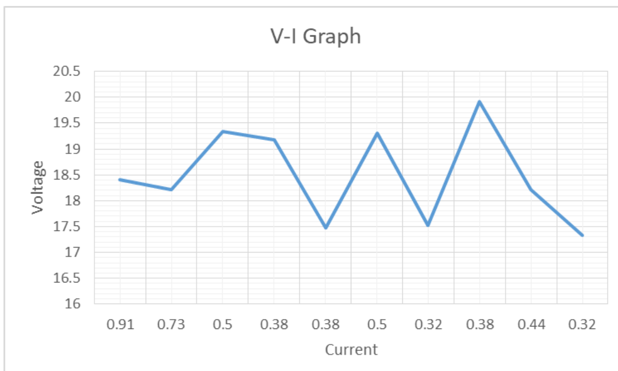



Figure 4. 18: V-i Graph (23rd February 2022)

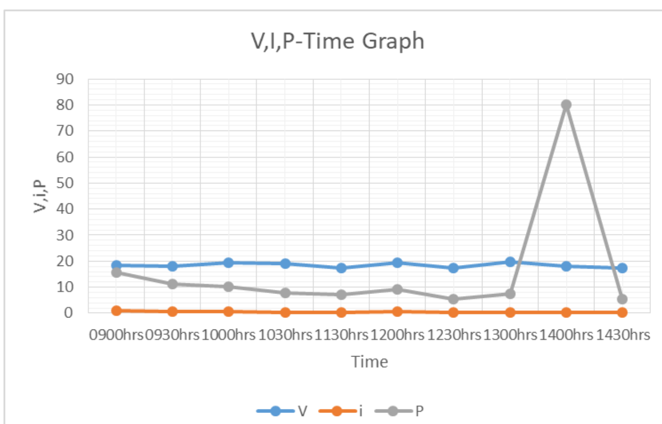



Figure 4.19: V,i,P-Time (23rd February 2022)

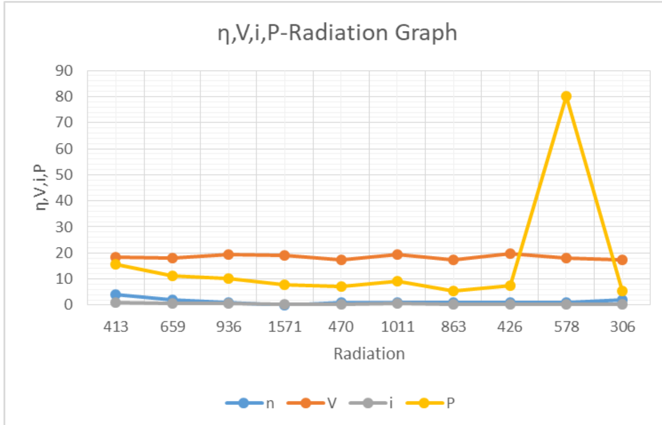



Figure 4.20: η,V,i,P-Radiation Graph (23rd February 2022)

### 4.3.4 Case 4: Orientation of 270° W at a Tilt Angle of 30°

Data collected for this configuration was tabulated in Table 4.8 and graphs in Figures Efficiency was highest at 5% at 1000hrs in the morning then decreased as the day progressed. A total of 59.9W was produced on this day. Power output generally decreased through out the day. The same trend was observed for both voltage and current in Figure 4.21 as power is a product of both. Figures 4.22 and 4.23 illustrate the behaviour of efficiency, radiation, voltage and current over time.

Table 4.7: Vertical Mounting Output (24th February 2022)

| Date | 24/2/22 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy W/m² | Radiation W | Efficiency % | V1 | i1 | P1 (W) | Time |
| 144 | 271 | 5 | 17.82 | 0.7 | 12.5 | 1000hrs |
| 156 | 293 | 3 | 17.95 | 0.41 | 7.4 | 1030hrs |
| 175 | 327 | 3 | 18.12 | 0.5 | 9 | 1100hrs |
| 202 | 379 | 1 | 18.34 | 0.29 | 5.4 | 1130hrs |
| 127 | 238 | 1 | 17.73 | 0.12 | 2.1 | 1200hrs |
| 169 | 316 | 1 | 17.95 | 0.26 | 4.7 | 1230hrs |
| 255 | 477 | 1 | 18.87 | 0.18 | 3.3 | 1300hrs |
| 180 | 337 | 1 | 18.36 | 0.21 | 3.8 | 1330hrs |
| 305 | 570 | 1 | 19.07 | 0.26 | 5 | 1400hrs |
| 205 | 384 | 1 | 18.53 | 0.23 | 1.3 | 1430hrs |
| 127 | 238 | 1 | 17.68 | 0.18 | 3.1 | 1530hrs |
| 63 | 117 | 2 | 15.85 | 0.15 | 2.3 | 1600hrs |
| TOTAL | | | | | 59.9 | 6hrs |

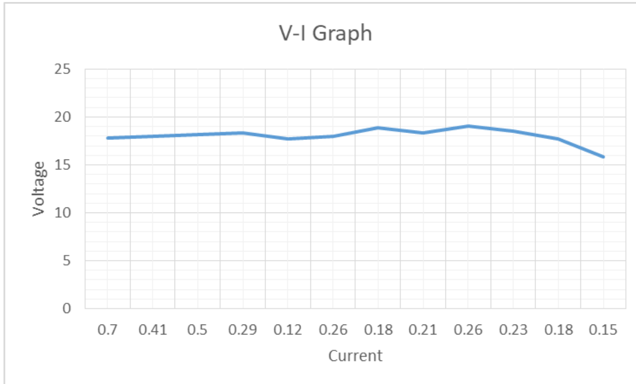



Figure 4.21: V-i Graph (24th February 2022)

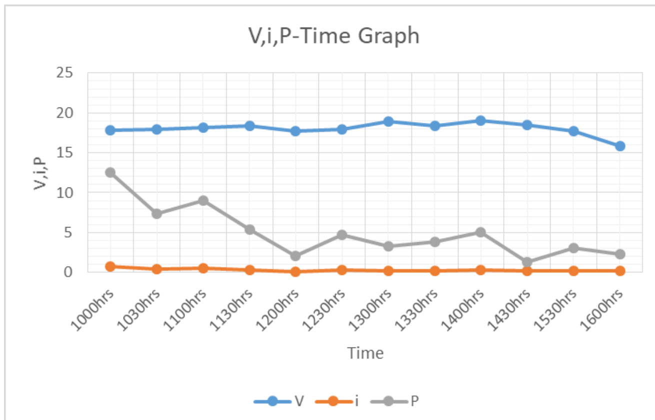



Figure 4.22: V,i,P-time (24th February 2022)

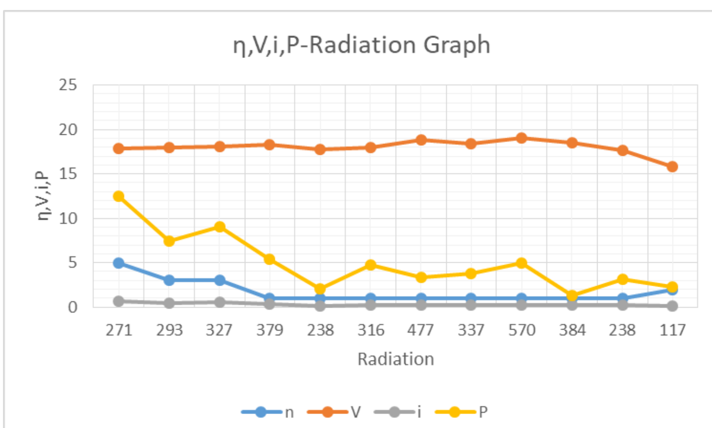



Figure 4.23: n,V,i,P-Radiation Graph (24th February 2022)

### 4.3.5 Case 5: Orientation of 90° East at a Tilt Angle of 45°

On this day, data was tabulated in Table 4.9. radiation was highest at 1000hrs then decreased till 1630hours. Data was collected for a total of 7 1/2 hours. Power output was highest at 0900hrs, at 10.1W then continued to decrease up to zero by 1630hrs giving a total of 36W. Both current and voltage followed the same trend as power output as is noted in Figures 4.24, 4.25 and 4.26.

Table 4.8: Vertical Mounting Output (28th February 2022)

| Date | 28/2/22 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy | Radiation W | Efficiency % | V1 | i1 | P1 (W) | Time |
| 948 | 1774 | 1 | 19.21 | 0.53 | 10.1 | 0900hrs |
| 954 | 1755 | 0 | 19.34 | 0.23 | 4.5 | 0930hrs |
| 1034 | 1935 | 0 | 17.41 | 0.8 | 2.8 | 1000hrs |
| 971 | 1818 | 0 | 19.29 | 0.18 | 3.4 | 1100hrs |
| 857 | 1603 | 0 | 19.46 | 0 | 0 | 1200hrs |
| 784 | 1467 | 0 | 19.21 | 0.23 | 4.5 | 1230hrs |
| 532 | 997 | 0 | 18.97 | 0.23 | 4.4 | 1300hrs |
| 529 | 991 | 0 | 18.99 | 0 | 0 | 1330hrs |
| 358 | 669 | 0 | 17.82 | 0.12 | 2.1 | 1400hrs |
| 372 | 696 | 0 | 18.87 | 0 | 0 | 1430hrs |
| 250 | 467 | 1 | 18.4 | 0.23 | 4.2 | 1500hrs |
| 94 | 176 | 0 | 17.4 | 0 | 0 | 1530hrs |
| 112 | 210 | 0 | 17.6 | 0 | 0 | 1600hrs |
| 71 | 134 | 0 | 15.97 | 0 | 0 | 1630hrs |
| TOTAL | | | | | 36 | 7.5hrs |

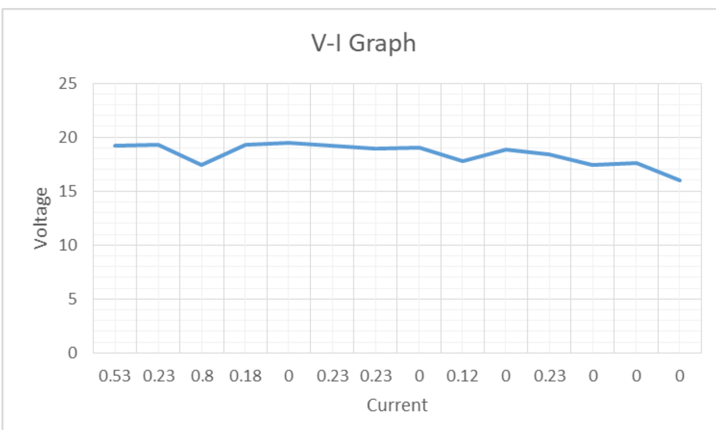



Figure 4.24: V-i Graph (28th February 2022)

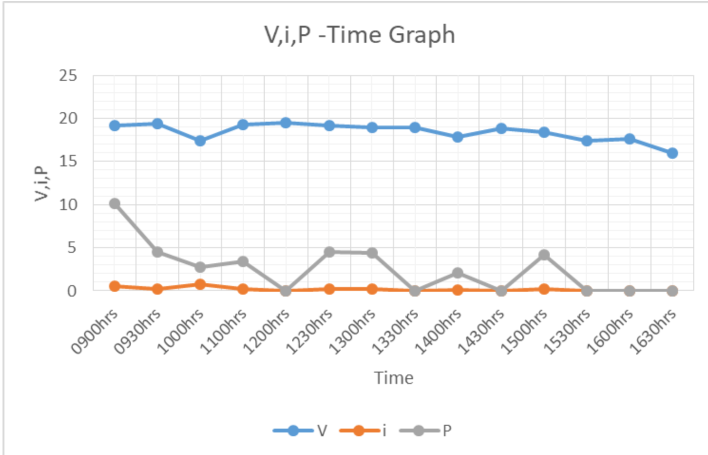



Figure 4.25: V,i,P-time (28th February 2022)

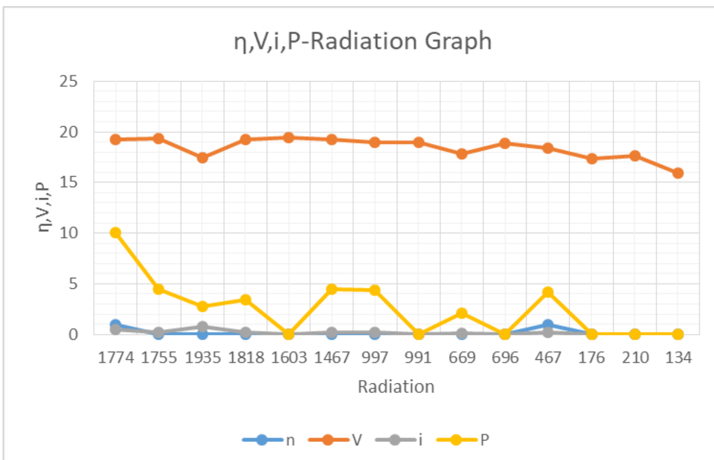



Figure 4.26: n,V,i,P-Radiation Graph (28th February 2022)

### 4.3.6 Case 6: Orientation of 270̊ West at a Tilt Angle of 45̊

In this case, power was at 4.9W at 0930hrs, then decreased to zero at midday and rose reaching its highest ,41.6W, at 1330hrs then dcreased till 1630 hours. Total power output was 86.8W on this day. Radiation was highest, 1803W, at 1430hrs then decreased towards the end of the day. This information was recorded on Table 4.10 and illustrated in Figures 4.27, 4.28 and 4.29.

From the graphs and tables, total power output for the East orientations is 318.2W while that from the western orientations was 276.4W. This suggested that East facing building walls would perform better in terms of power output. However, the difference between the two is not so large and hence westward facing walls would also give a considerable output. This is explained by Nairobi's equatorial location where time between sunrise and sunset does not differ much.

Table 4.9: Vertical Mounting Output (1st March 2022)

| Date | 1/3/2022 | | | | | |
|---|---|---|---|---|---|---|
| Solar energy W/m² | Radiation W | Efficiency % | V1 | i1 | P1 (W) | Time |
| 149 | 280 | 2 | 18.58 | 0.26 | 4.9 | 0930hrs |
| 246 | 461 | 1 | 18.85 | 0.23 | 4.4 | 1030hrs |
| 149 | 278 | 0 | 17.8 | 0 | 0 | 1130hrs |
| 794 | 1487 | 0 | 19.56 | 0 | 0 | 1230hrs |
| 509 | 953 | 1 | 19.17 | 0.35 | 6.7 | 1300hrs |
| 300 | 561 | 7 | 13.01 | 3.19 | 41.6 | 1330hrs |
| 963 | 1803 | 1 | 19.09 | 0.53 | 10.1 | 1430hrs |
| 176 | 329 | 3 | 16.58 | 0.67 | 11.2 | 1600hrs |
| 82 | 154 | 5 | 13.4 | 0.59 | 7.9 | 1630hrs |
| TOTAL | | | | | 86.8 | 7hrs |

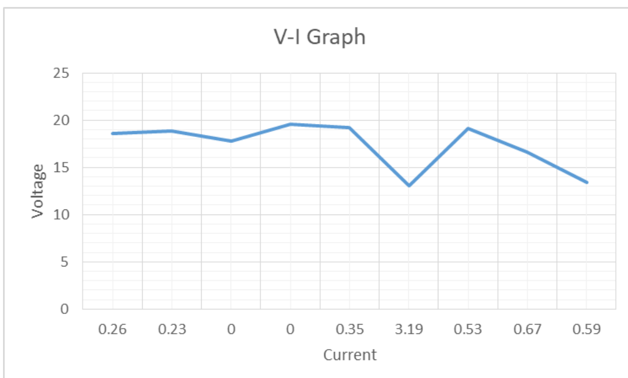



Figure 4.27: V-i Graph (1st March 2022)

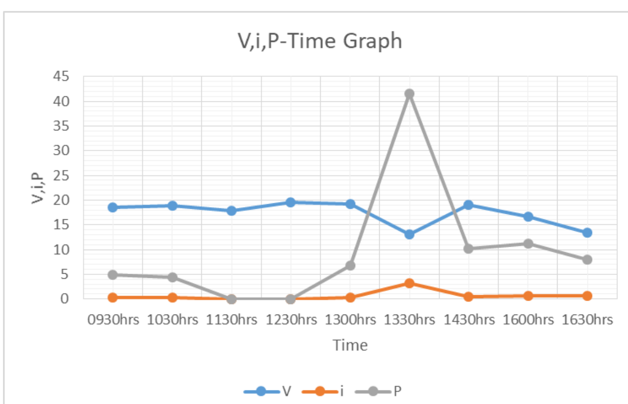



Figure 4.28: V,i,P-time (1st March 2022)

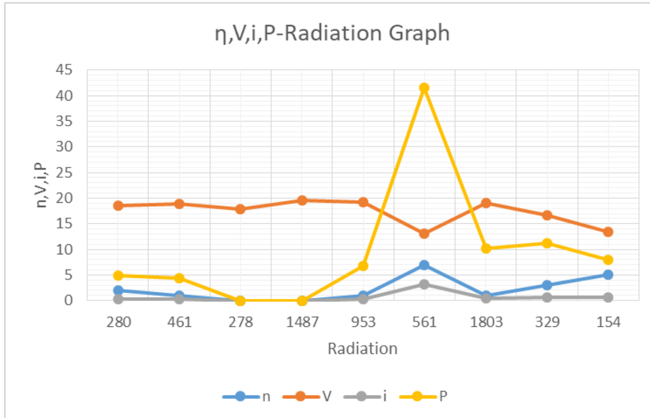



Figure 4.29: n,V,i,P-Radiation Graph (1st March 2022)

## 4.4 Comparison Between Vertical and Horizontal Mounted Panels

From Sections 4.2 and 4.3, it is noted that horizontally mounted panels will give consistent output as compared to vertically mounted panels. This can be attributed to the fact that vertically mounted panels face one particular direction, yet the earth is rotating 24/7.

### 4.4.1 Average Power Output

Average power output from the three days of horizontal mounting will be given by:

$$\frac{88.3 + 382.2 + 561.4}{3}$$

$$= 343.97W$$

$$343.97W * 6Hours * 0.75$$

$$= 1.5kWh$$

Average power output from the first three days from vertical mounting will be given by:

$$\frac{194.4 + 129.7 + 159.8}{3}$$

$$= 161.3W$$

$$161.3W * 6Hours * 0.75$$

$$= 0.726kWh$$

The horizontal installation gives a higher average power output as expected. It is higher than the vertical installation by about 0.8kWh. The value 0.75 is taken a sthe derating factor to take care of losses.

### 4.4.2 Radiation

A comparison was made between horizontal and vertical radiations received on 21st March 2022 and 21st February 2022 respectively. This represented comparison between East facing installation and horizontal mounting. The results are as in Table 4.11 and Figure 4.30.

Table 4.10: Horizontal and East Facing Vertical Radiation Values

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal | 1155 | 1374 | 1593 | 1694 | 1856 | 1374 | 1970 | 1814 | 1759 | 1761 | 1518 | 1209 | 305 | 207 |
| Vertical | 1353 | 1266 | 1103 | 1010 | 786 | 605 | 514 | 282 | 274 | 190 | 38 | 163 | 86 | 38 |

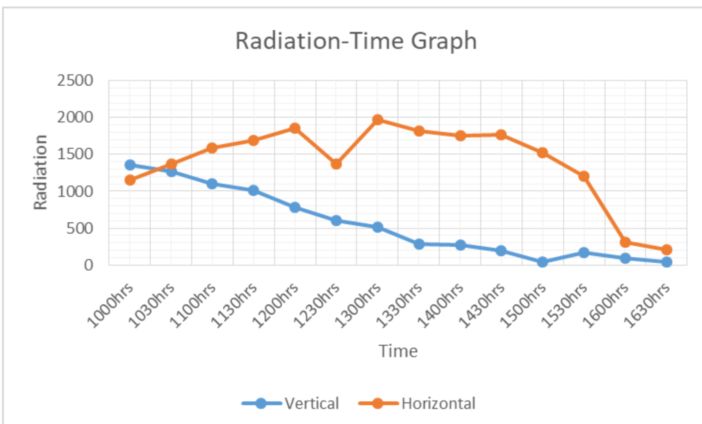



Figure 4.30: East Facing Vertical and Horizontal Radiation-Time Graph

Comparison was also made between westward facing mounting and the horizontal mounting for 22nd February 2022 and 22nd March 2022 respectively. The results are tabulated in Table 4.12 and represented using a graph in Figure 4.31.

Table 4.11: Horizontal and West Facing Vertical Radiation Values

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal | 298 | 1296 | 1260 | 1467 | 609 | 1896 | 1986 | 293 | 408 | 306 | 960 | 1275 | 960 | |
| Vertical | 153 | 123 | 230 | 267 | 254 | 230 | 170 | 470 | 342 | 744 | 285 | 0 | 0 | 0 |

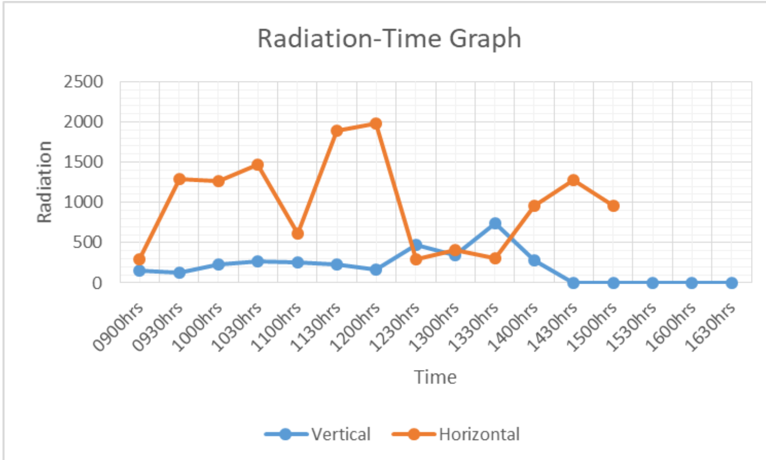



Figure 4.31: West Facing Vertical and Horizontal Radiation-Time Graph

From the graphs, it is noted that the horizontal mounting receives much greater radiation through out the day as compared to the vertical mounting in both East and West directions. Amount of radiation in both cases decreases towards late afternoon.

### 4.5 Calculation of panel efficiency

From equation 3.4, efiiciency is calculated as:

$$\eta = \left(\frac{115}{1.87}\right)\frac{}{1000} * 100\%$$

$$= 6.14\%$$

This is below range for the polycrystalline as per Figure 2.1. It can be attributed to the age of the panels as they were about 8 years old by the time of the experiment. Efficiency decreases with age of the modules.

### 4.6 Calculation of payback period

From Equation 3.5, payback period takes into account the initial capital investment and the expected finacial savings. To calculate the capital investment required, solar panel prices of models similar to what was used in the experiment were compared from Chloride Exide website, a local company dealing with solar panels and their accessories. Table 4.13 gives a summary of expected investment cost in US dollars.

Table 4.12: Estimated Costs

| | ITEM | COST(USD) |
|---|---|---|
| 1. | Solar panel 150W, multi crystalline, 24VDC | 170.90 |
| 2. | Inverter 150W, 24VDC | 15 |
| 3. | Battery 150Ah, 12V | 103.50 |
| 4. | Labor and accessories | 100 |
| | TOTAL | 389.40 |

Power demand for a standard room was calculated by adding up the power rating of all the equipment found in a room. These equipment as listed in Table 4.14 are necessary to enhance guest comfort and experience.

Table 4.13: Standard Guest Room Appliances

| Appliance | Power rating (kW) | No of units | Total kW |
|---|---|---|---|
| IP23 LED | 0.01 | 5 | 0.05 |
| GU9 LED | 0.01 | 3 | 0.03 |
| TV Set | 0.12 | 1 | 0.12 |
| Electric Kettle | 0.8 | 1 | 0.8 |
| CFL Lamps | 0.02 | 4 | 0.08 |
| Refrigerator | 0.15 | 1 | 0.15 |
| Iron Box | 1.6 | 1 | 1.6 |
| TOTAL | | | 2.83 |

From the energy audit report of the hotel [50], the average room consumption was found to be 0.2kW. It was asumed that this room is in use for an average of 6 hours. Therefore, power used for 6 hours will be given by,

$$0.2kW * 6hours = 1.2kWh$$

The hotel is under class C12 under Kenya Power billing tarrifs. Cost of a kWh for this tariff in the month of February 2022 was USD 0.1642 therefore cost of running the room was,

$$1.2kWh * 0.1642USD = 0.197USD$$

For the month of February, total cost will be,

$$0.197USD * 28days = 5.52USD$$

For the year,

$$5.52USD * 12months = 66.21USD$$

The savings that would be achieved with VMSP would be,

Using 21st February as the study point, power output from data collected was 194.4W. This was for a time of 6.5hours. Output therefore will be,

$$194.4 * 6.5 * 0.75 = 947.7watthours$$

Expected savings will therefore be,

$$0.9477kWh * 0.1642USD * 28days * 12months$$

$$= 52.29USD$$

Therefore,

$$Payback\ Period\ (PBP) = \frac{389.40}{52.29} \qquad = 7\ years$$

This should be noted that this is from a 230W rated power installation with 194.4W output as used in the experiment. Panels of higher output will greatly reduce on the payback period.

$$Return\ on\ Investment = \frac{Annual\ Financial\ Savings}{Total\ amount\ of\ Investment} = \frac{1}{PBP}$$

$$= \frac{1}{7} = 0.14 = 14\%$$

A return on investment of 14% is expected for the installation, taking into account the payback period. From research on the ‘potential and economic analysis of grid-connected solar PV power in Kenya’, the average ROI is given as 18.23% with a maximum of 25.4% and a minimum of 11.4% hence 14% is within range [52].

### 4.7 Calculation of NPV and IRR

From Equation 3.7, the net present value can be calculated using the excel application. Time was taken to be 11 years as it was estimated that, that is when the performance of the panels would begin deteriorating. Most panels have a lifetime of about 25 to 30 years but start to drop in effeciency by the 10th year depending on the factors such as weather conditions and maintenace.

A market value of 7% was used as it it the current prevailing market value according to the Central Bank of Kenya (CBK). Figure 4.32 illustrates the computation done.

| IRR computation with Excel IRR Function & Verification with NPV calculation | | | | |
|---|---|---|---|---|
| Year | Date | Cash Flows | Present Value of cashflows discounted @ **7.00%** | **A** |
| Year 0 | Year 0 | -389.40 | 389.40 | |
| Year 1 | Year 1 | 52 | 48.87 | Discounted from Year1 to Year0 |
| Year 2 | Year 2 | 52 | 45.67 | Discounted from Year2 to Year0 |
| Year 3 | Year 3 | 52 | 42.68 | Discounted from Year3 to Year0 |
| Year 4 | Year 4 | 52 | 39.89 | Discounted from Year4 to Year0 |
| Year 5 | Year 5 | 52 | 37.28 | Discounted from Year5 to Year0 |
| Year 6 | Year 6 | 52 | 34.84 | Discounted from Year6 to Year0 |
| Year 7 | Year 7 | 52 | 32.56 | Discounted from Year7 to Year0 |
| Year 8 | Year 8 | 52 | 30.43 | Discounted from Year8 to Year0 |
| Year 9 | Year 9 | 52 | 28.44 | Discounted from Year9 to Year0 |
| Year 10 | Year 10 | 52 | 26.58 | Discounted from Year10 to Year0 |
| Year 11 | Year 11 | 52 | 24.84 | Discounted from Year11 to Year0 |
| Total negative cash flows or outflows | | 0 | 392.11 | |
| Total positive cash flows or inflows | | 261 | 392.11 | |
| Sum of positive and negative discounted cash flows | | | **2.71** | ***<=Net Present Value (NPV)*** |
| **Internal Rate of Return (IRR)** | | ***7.14%*** | *This is equivalent to the discount rate which makes the NPV of cash flows Zero as above* | |

Figure 4.32: NPV Excel Computation

The above computation gives a positive NPV and an IRR of 7.14% indicating that it is a project that promises good returns.

## 4.8 Chapter Conclusion

In this chapter, results obtained from the experiment were analyzed quantitatively and comparisons made. Graphs have been drawn to better illustrate the results obtained. The results obtained were successfully able to validate the previous researches done that results obtained from horizontal mounting are better compared to the vertical installation. This has been validated by the Radiation-Time graphs and average power output comparison. The vertical installation is able to provide savings amounting to USD 52.29. It is established that the proposed installation is viable as evidenced by the payback period of 7 years and return on investment of 14%.

# CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion

From this research, it is noted that Kenya generally receives a good amount of solar insolation, from the solar irradiance computation of 4.2kWh/m². This then validates that solar energy is indeed a reliable source of energy for Kenya. Companies, institutions, homes and other establishments should therefore consider investing more in solar power harvesting. The government should also offer its support by giving incentives to accelerate achievement of vision 2030.

From the power input calculation, it is noted that a two module, 230W multi crystalline installation is able to provide at least 1kWh which is useful in powering some of the equipment in the guest room. It is suggested that if more panels or panels of a higher power rating were used, they would power the whole room effectively. This would solve the problem of power outages disrupting guests' comfort which is bad for business. A 6.14% efficiency for the panels is sufficient as most multi crystalline panels have their efficiency rated between 10-14%. The difference could be attributed to the fact that efficiency reduces with age since the set up used for the experiment was about 8 years old at the time.

A payback period of 7 years and a return on investment of 14% means that it is a worthy investment considering the savings that will be achieved within that period. The NPV of USD 2.71 is a positive indication on the viability of the project. These values can be improved with better installations and larger PV arrays. Vertically mounted solar panels would work well in the Kenyan climate. They can be mounted in both the east and west facing walls. The output between the two directions does not differ much. The output may not be as great as that of horizontal mounting but would work well to boost the current supply. Adoption of adaptive technologies would work well to improve the performance of these installations. The initial capital investment will be high but greater savings will be realized in the long run.

## 5.2 Recommendation

This research recommends VMSP on Nairobi's hotel buildings. It has been proven that it is viable and has the potential to generate enough energy to power buildings. It will help hotels and buildings in general to save on energy costs.

Further research should be done in these areas to improve on the findings of this research:

i) Taking into account at what height of the building the panels will be mounted as this could improve on the output of the panels. In this research, the data was collected at the ground level which presents a lot of shading from nearby objects hence affecting the output.

ii) Further research could be done on use of adaptive technologies and the cost implications for Kenyan buildings. This research only considered panels mounted at fixed angles with no provision for adjustments.

iii) More research can be done on the performance of the various technologies of solar panels, such as thin-film type, available in the market. This research only used the multi-crystalline PV type.

## 5.3 Contribution

This research has conducted a feasibility study on the effectiveness of vertically mounted solar panels based on results obtained from an experimental study. It has taken advantage of the fact that Kenya is located at the equatorial region and receives consistent irradiation throughout the year. The effectiveness of this installation has been established from the technical and financial appraisals. The study was not extensive enough due to certain limitations therfore, reccomendations for further work have been suggested in order to improve the research.

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# APPENDIX

## Appendix A: Solar Panel Data Sheet

### Photon PM0115

Photovoltaic Module Family
Model: PM0110 / PM0115

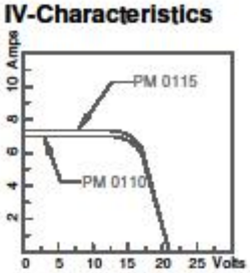
The module picture above is only indicative and may not depict the actual module

| Model | PM0110 | PM0115 |
|---|---|---|
| **Electrical parameters** | | |
| **Nominal Power – Pmax (Watts)** | **110** | **115** |
| Voltage at Maximum Power – Vmp (Volts) | 17.7 | 17.7 |
| Current at Maximum Power – Imp (Amps) | 6.2 | 6.5 |
| Open Circuit Voltage – Voc (Volts) | 21.6 | 21.6 |
| Short Circuit Current – Isc (Amps) | 7.0 | 7.3 |
| Maximum System Voltage | 1000 VDC | |
| Temperature Coefficient - Voc | -0.074 V / °C | |
| Temperature Coefficient - Isc | +2.80 mA / °C | |
| Solar Cells per Module - Units | 36 | |
| Parent Solar Cell Size - mm | 156 Sq. Multi Crystalline | |
| **Mechanical Details** | | |
| Dimensions – L x W x T mm | 1325 x 655 x 34 | |
| Weight – Kgs | 10.5 | |
| Mounting Holes Pitch (Y) – mm | 900 | |
| Mounting Holes Pitch (X) – mm | 611 | |
| Area – Sq. Mtrs | 0.87 | |

- Measurement Tolerance on Electrical Parameters ± 5%.
- All specified parameters are at STC 25°C cell, 100mW / cm² irradiance and AM 1.5.
- Specifications subject to change without prior notice due to product up gradations.

**Certifications:** IEC 61215 / IEC 61730-1 / IEC 61730-2 & TUV Safety Class II

### IV-Characteristics

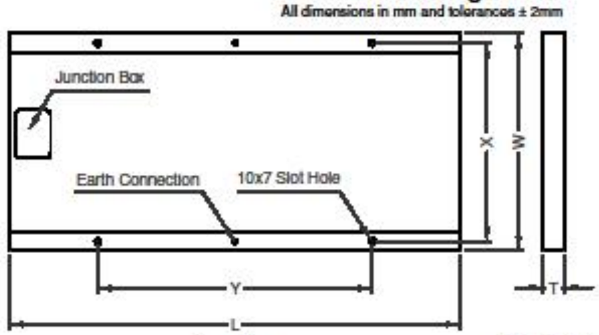



### Junction Box – JB5

97 x 94 x 29 mm
Four Terminals
Two 10A Diodes

### Mounting Details

All dimensions in mm and tolerances ± 2mm

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## Appendix B: Similarity Index Report

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**File name:** Teresia_Draft_May_2022_II.pdf (3.59M)
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ORIGINALITY REPORT

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**Appendix C: Examiner's Comments**

SUMMARY OF COMMENTS RAISED BY THE EXAMINER AND THEIR CORRECTIONS

| No | COMMENTS RAISED BY EXAMINER | CORRECTIONS |
|---|---|---|
| 1. | At what horizontal tilt angle do the solar panels have maximum efficiency? | A general rule is that the tilt angle should be set to the geographical latitude for optimum energy production. Nairobi is located at 1.2388º which means the panels will be set up at almost 180º so that they are perpendicular to the sun's rays. This has been addressed in Section 3.2.4 on efficiency. |
| 2. | Why is the ROI of 14% sound? | From research on the 'potential and economic analysis of grid-connected solar PV power in Kenya', the average ROI is given as 18.23% with a maximum of 25.4% and a minimum of 11.4% hence 14% is within range. This has been addressed in Section 4.6 with the above reference. |
| 3. | More data needs to be collected. | The data collected during that period is indicative of what we would expect throughout the year since Kenya's climate does not differ much. Again, different weather patterns were experienced during that period with rainy and sunny days. This is explained in Section 3.2.2 and Figure 3.3. |

## Appendix C: IEEE Conference Paper

2022 IEEE PES/IAS PowerAfrica

# Effectiveness of Vertically Mounted Solar Panels on Buildings - A Case Study of Radisson Blu Hotel, Nairobi

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*Abstract*-**Solar energy is a renewable energy source that can help reduce a hotel's energy demand. At present most Kenyan hotels depend on petroleum products as their main energy source. The concept of wall-mounted solar panels is still quite new. This research seeks to study the effectiveness of vertically mounted solar panels on hotel buildings (Radisson Blu Hotel, Nairobi Upperhill) based on economic and technical benefits. It discusses the results of an experimental study based on simulation and actual site measurements using proposed tools and software. Technical details of the solar PV trainer will be used for this study. The concept and results of this study can be applied to other buildings in general.**

*Index terms-* **Vertically Mounted Solar Panels (VMSP), Building Integrated Photovoltaic (BIPV), Adaptive Photovoltaic Technology**

## I. INTRODUCTION

The sun is a powerful energy source capable of meeting the earth's current and anticipated energy requirements. In many instances, solar PV panels are mounted on the roofs of hotels. Wall-mounted PV panels are applied in cases where there is limited space on the roof or where roofs are structurally damaged and cannot hold the PVs. Also, in instances where roof areas are not accessible, the panels can be mounted on the walls. They also make a building aesthetically pleasing. Again, for high-rise buildings, the wall area is usually larger than the rooftop area [1]. A building could also have both wall-mounted and rooftop PVs to maximize the output. Research conducted in Queensland suggests that PV system presents an effective way to reduce a building's electricity bill thereby reducing carbon emissions. The research shows that a 6kW PV installation can cover 61% of the electricity demand, thereby saving about 90% in electricity bills and reducing the building's carbon emissions by 95% [2]. PV panels require a high capital cost. This has caused slow market penetration [3-5] thus warranting approaches to combine the PV generation with building installation strategies along with feasibility studies of micro-grid systems. This has resulted in building integrated photovoltaic systems (BIPV). Façade mounted is not as effective as horizontal mounted due to the difference in solar insolation or irradiance. This however has not prevented the exploration of this design. Scholars have researched how to increase their output by using adaptive technologies. Solar tracking mechanisms and software are used to improve and maximize the use of daylight to increase electricity generation thereby increasing the efficiency of wall-mounted PV [6].

*Contribution:* Currently there are no Vertically Mounted Solar Panels (VMSP) in Kenya hence the need for exploration. Kenya is located in the equator region and hence receives a good amount of solar insolation throughout the year. This paper has identified that gap and seeks to explore the possibility and performance of VMSP in Nairobi, Kenya using the Radisson Blu Hotel as a case study.

*Paper Organization*: The paper consists of five chapters. Chapter one discusses solar energy and why it is important to adopt its use. It also focuses on the purpose of this research and the need to adopt VMSP. Chapter two reviews horizontal installations and previous research work done and seeks to identify the gaps in these researches. Chapter three discusses how the research was carried out, and the methods of data collection and analysis. Chapter 4 discusses the results obtained from the experiment and analyzes them. Chapter 5 concludes the project and gives recommendations from the experimental study.

## II. LITERATURE REVIEW

The basic component of a photovoltaic (PV) system are the cells that convert energy from the sun to electrical energy. Their efficiency ranges from 10-to 23% [7]. Some of the most commonly used PV technologies are amorphous silicon (a-si), mono-crystalline silicon (m-si), and polycrystalline silicon (P-si). The cells when connected, form PV modules. The modules when mounted to a building, provide opportunities for mini-grid and off-grid systems. According to Ceron et al, [8] nearly 50% of BIPV systems are based off of rooftop installations. However, their performance and efficiency could be affected by elements such as the angle of tilt of the PV modules, availability of solar radiation, module's surface temperature, and space between the module rows among others.

### A. *Samsung C&T Corporation buildings in Korea*

This study was done by T. Hwang et al [5]. The study's objective was to set up and develop a PV generator. In the research, different solutions were sought to attain maximum energy production by varying the direction and inclination of the PV installation. PV panels were installed on the different building facades after which calculations were made depending on the orientation of the walls. Due to Korea's geographical location, maximum electric energy is produced in April and May. It then starts decreasing from July and reaches its lowest in December. The study concludes that the PV installed on the

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southwest and southeast facing walls perform better in terms of electricity generation compared to those installed on the northeast and northwest facing walls, throughout the year [6].

### B. *Commercial building in Vietnam*

Vietnam has a huge potential to harness solar energy to meet its current demands. It has a year-round average direct normal radiation of 4-5.2kWh/m² per day for most parts of the country. The solar power potential is estimated at 56,000MW and this has been acknowledged by the government through the approval of more than 70 solar projects [9]. A comprehensive and detailed study of the façade system is lacking but a proposal of the same is available. The proposal discusses the general design process, choosing the façade wall, software, and appropriate solar panels [9]. The paper also suggests the use of thin-film technology for the panels due to benefits such as simple manufacturing process, light weight, flexible simple material handling pro, cess and lower material consumption. Micro-inverter configuration was recommended to have AC-DC conversion and maximum power point tracking (MPPT) performed on individual solar panels. This is to reduce efficiency losses due to shading brought about by neighboring buildings, trees, or the facade itself.

### C. *High Rise Buildings in Mumbai, India*

India is generally known for its dense population, especially in urban areas. Mumbai is one such densely populated city in India. Urbanization has led to growth in high-rise buildings in this city. These buildings are high energy consumers and hence are a source of GHG emissions as they currently use power generated from fossil fuels. With an increase in these buildings, energy demand has also risen. India is also blessed with abundant sunshine thereby presenting an opportunity to exploit solar energy. The use of façade solar PVshigh-rise rise buildings in India also saves on land resources as it is densely populated [10]. A software, RETScreen, [11] is applied to evaluate the performance of solar on these buildings. The software can be used to evaluate the comparative output of CdTe and monocrystalline technologies applied to the facades of Mumbai's high-rise buildings. Various high-rise buildings were analyzed to establish façade capacity and generation. The results show potential for realizing substantial savings in electricity cost and a reduction of GHG emissions [10].

### D. *Adaptive Photovoltaic Facades*

An adaptive PV system addresses the effects of shading and features a solar tracking system integrated into the façade thereby reaping the benefits of both. Solar tracking can improve a PV's output between 30-40% in a year compared to the fixed-tilt module counterpart or up to 70% when compared to horizontal installations [12]. Solar trackers could be single-axis or dual-axis. Dual-axis trackers are however not easily incorporated into BIPV installations. These trackers can function with or without sun sensors. The public utility building of Aachen (Germany) is an example where this technology is used [13]. Initial adaptive installations were applied using louvers/ shutters integrated with PV that could track either on a daily or periodic basis. These systems can be set up vertically or horizontally and are operated by linear actuators. This system has been applied at Riverhouse, One Rockefeller Park (New York), a residential high-rise building that is LEED gold certified [14]. International BauAustellung (IBA)'s The Soft House in Hamburg Germany (figure 1) consists of a 4-row housing unit [15]. This building's distinguishing feature is the adaptive façade with a two-axis solar tracking feature. A building management system (BMS) is used for daily or seasonal adaptive PV façade adjustments.

Figure 1: IBA's The Soft House [15]

Other examples of solar façade applications include the town hall in Freiburg im Breisgau, Germany.

## III. METHODOLOGY

### *A. Review of Previous Methods*

*Samsung C&T Corporation Buildings in Korea:* Monocrystalline PV panels were installed in facades facing southeast, southwest, northeast, and northwest. The D/L ratio and inclination angles, both horizontal and vertical were used to determine maximum energy output. From this experiment, it is observed that maximum solar insolation from the south side facing walls can be achieved with a 60̊ horizontal angle of inclination or a vertical inclination angle below 15̊. Also, larger D/L ratios can harvest more sunlight but are however not proportional to the energy generated since the power generation area is reduced [5].

*Commercial Buildings in Vietnam:* Since this was a proposal, [9] guidelines were proposed using software to fully understand and reap the benefits of façade mounted solar panels. The following steps were proposed:

i) *Designing the Wall Mounted PV Prototype*: This stage involves choosing a suitable prototype wall for the panels. Proposed software are Autodesk 3D, Google Sketchup, and Rhinoceros 3D.
ii) *Facade PV Simulation*: In this stage, simulators are used to deduce the energy output from the system. Data required as input will be rated solar power of the panels, number of panels, number of micro-inverters and their power rating, and environmental conditions such as shading and sun hours. The output will be the energy yield either daily, monthly, or annually. The proposed software for this exercise is PVSites.
iii) *Building Energy Simulation*: This last step is to determine the efficiency of the PV panels. The proposed software for this exercise is EnergyPlus and Edge.

*High-rise buildings in Mumbai, India:* The RETScreen 4 software was used in this research to determine the façade PV output for buildings in Mumbai. The area occupied by the panels is determined by the type of panels to be used. The annual output is dependent on the orientation of solar panels, the building's geographical location, tilt angle, shading, and

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type of PV panels used. For a lower incident angle, the output of VMSP could be higher than rooftop installations [10].

*Adaptive photovoltaic facades:* This research suggests the use of adaptive technologies to improve the efficiency of wall-mounted panels. This involves balancing shading and daylight through a smart device mounted on the facade.

### *A. Design Methods*

**i) Site Assessment**

The first step is to determine the suitability of solar walls for the proposed location which is Radisson Blu Hotel Nairobi, Upper hill. A site assessment is necessary to maximize the energy output of the system [16]. Elements to consider when assessing a site are discussed in the following section;

**Sun hours**. It is necessary to establish how much irradiation will be required to produce a given amount of power. This parameter will enable us to know for how long the area receives maximum sunlight. [16]

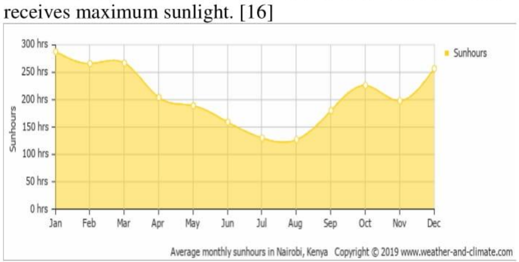


Figure 2: Nairobi Sun Hours [17]

Generally, Kenya receives substantial amounts of sunshine throughout the year with January being the hottest month and August receiving the lowest amount of sunshine (figure 2). The time between sunrise and sunset does not differ much in Kenya due to the proximity to the equator. The intensity of sunlight changes through the day so the amount of energy received is summed up. The total is analyzed to determine how long the sun would have to shine at 1000W/m² to provide the same amount of energy.

**Shade Analysis:** Most buildings are mostly found in urban areas which are heavily built causing shading to nearby buildings. Shading reduces a PV module's output considerably. Shading can result from the system itself or from nearby objects [16].

**Tilt Angle:** This is the angle setting that is required for the panels to get maximum irradiation. As earlier mentioned, the tilt angle for the vertically mounted panels can be improved by using adaptive technologies [11].

**ii) Solar Panel Data**

The technical data of the PV trainer used in the experiment is as follows.

Table 1: Technical Data on the Solar Panels

| | |
|---|---|
| Maximum power, Pmax | 115Wp |
| Voltage at maximum power, Vmp | 17.7V |
| Current at maximum power, Imp | 6.5A |
| Open circuit voltage, Voc | 21.6V |
| Short circuit current, Isc | 6.96A |
| Tolerance | ±5% |
| PV module model | PM 0115 |
| Manufacturer | PHOTON |

**iii) Experimental Set-Up**

The PV trainer, Figure 3, was used for this research. It consists of the following components:

a) PV panels consisting of 2 independent modules made of crystal silicon and a supporting structure.
b) Solar radiation sensor for measuring solar incident radiation.
c) Charge controller for optimizing power flow involving the PV panels, battery, and inverter.
d) Battery for power storage.
e) Inverter for converting electrical variables at the battery and PV output from DC to AC.
f) Voltmeter for voltage measurement.
g) Ammeter for current measurement.
h) Remote control system with PC to display and record various parameters.
i) Sun tracker that can move the panel along 2 axes to optimize exposure to the sun.

Figure 3: Solar PV trainer

## IV. RESULTS AND ANALYSIS

This section demonstrates the results achieved with the vertically set PV trainer. The panels were tilted at 14° facing 84° East and 278° West. Figures 4 and 5 show the voltage- current and power- time graphs respectively when the panels are facing East. It is noted that power output from the panels decreases with time. In Figures 6 and 7, the same is noted. However, power output from the Westside is less than the East as the sun sets on that side.

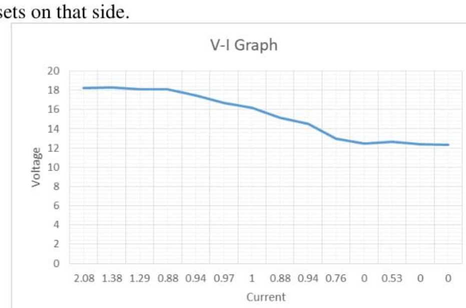


Figure 4: Voltage–Current graph at 14° tilt angle facing 84° East

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Figure 5: Power–time graph at 14° tilt angle facing 84° East

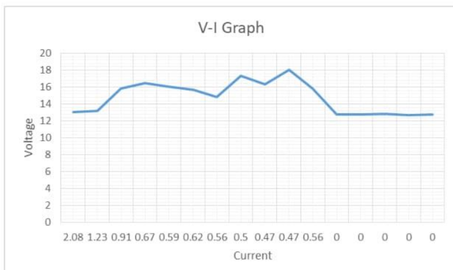

Figure 6: Voltage–Current graph at 14° tilt angle facing 278° West

Figure 7: Power–Time graph at 14° tilt angle facing 278° West

**i) Energy Analysis**

In this section, the power input, output, and efficiency of the panels is calculated as well as determining if VMSP are economically viable.

*Solar Irradiation*

Modeling and simulation for solar irradiation could be obtained starting from the mathematical formula for extraterrestrial radiation. Though most models consider extraterrestrial radiation to be constant, [32], extraterrestrial radiation in a specific area can be calculated using equation 1,

$$G_{\circ} = \frac{24}{\pi}.S.\left[1 + 0.033.cos\left(\frac{2\pi.n}{365}\right)\right].(cos\emptyset.cos\delta.sin\omega_s + \omega_s.sin\emptyset.sin\delta)[W/m^2] \quad [1]$$

Where S is the solar constant, n is the days' number in the year, Ø is the latitude of the area in study, δ is the declination of the earth, and ω is the solar angle.

$$G_{\circ} = \frac{24}{\pi}.1366.\left[1 + 0.033.cos\left(\frac{2\pi.52}{365}\right)\right].(\cos(1.28333).cos23.45.sin84 + 84.\sin(1.28333).sin23.45)[W/m^2]$$

$$= 4231W/m^2 \ = 4.2kWh/m^2$$

This calculation was done for 21st February 2022 which is the 52nd day of the year 2022, at a solar angle of 25.32°, earth inclination of 23.45° using a solar constant of 1366W/m².

The average daily insolation for Nairobi is 3-7 kWh/m². The value obtained is within range.

*PV Output*

This is dependent on hours of insolation and shading factors.

$solar\ panel\ watts * average\ hours\ of\ sunlight * 75\% = daily\ watt\ hours$ [2]

75% is a factor introduced to take care of losses from factors that would affect the efficiency of the panels.

Figure 8 shows data collected on 21st February 2022 for panels mounted vertically at 14° tilt angle. The total power output P1 for that day was 194.4W.

| Date | 21/2/2022 | | | | | | |
|---|---|---|---|---|---|---|---|
| Solar energy | Radiation | V1 | i1 | P1 (W) | Time | Direction | Tilt angle |
| 723 | 1353 | 18.24 | 2.08 | 37.9 | 1000hrs | 84° East | 14° |
| 676 | 1266 | 18.29 | 1.38 | 25.2 | 1030hrs | | |
| 589 | 1103 | 18.11 | 1.29 | 23.2 | 1100hrs | | |
| 539 | 1010 | 18.12 | 0.88 | 15.9 | 1130hrs | | |
| 420 | 786 | 17.48 | 0.94 | 16.4 | 1200hrs | | |
| 323 | 605 | 16.68 | 0.97 | 16.1 | 1230hrs | | |
| 275 | 514 | 16.19 | 1 | 16.1 | 1300hrs | | |
| 151 | 282 | 15.16 | 0.88 | 13.4 | 1330hrs | | |
| 147 | 274 | 14.53 | 0.94 | 13.6 | 1400hrs | | |
| 190 | 190 | 12.99 | 0.76 | 9.9 | 1430hrs | | |
| 21 | 38 | 12.48 | 0 | 0 | 1500hrs | | |
| 87 | 163 | 12.65 | 0.53 | 6.7 | 1530hrs | | |
| 46 | 86 | 12.4 | 0 | 0 | 1600hrs | | |
| 21 | 38 | 12.33 | 0 | 0 | 1630hrs | | |
| | | | | 194.4 | | | |

Figure 8: Data collected for vertical mounting

Power output will be given by,

$194.4W * 6.5hrs * 0.75 = 947.7Wh = 0.947kWh$

Table 2: Appliances in a guest room

| Appliance | Power rating (kW) | No of units | Total kW |
|---|---|---|---|
| IP23 LED | 0.01 | 5 | 0.05 |
| GU9 LED | 0.01 | 3 | 0.03 |
| TV Set | 0.12 | 1 | 0.12 |
| Electric Kettle | 0.8 | 1 | 0.8 |
| CFL Lamps | 0.02 | 4 | 0.08 |
| Refrigerator | 0.15 | 1 | 0.15 |
| Iron Box | 1.6 | 1 | 1.6 |
| TOTAL | | | 2.83 |

From the energy audit conducted at the hotel in 2018, the average room consumption was found to be 0.2kW per room. These panels are therefore able to meet the room demand.

*PV efficiency*

The basic efficiency formula is

$$\eta = \left(\frac{P_{max}}{Area}\right)\frac{}{1000} * 100\% \quad [3]$$

Where η is efficiency, $P_{max}$ is the PV panel's peak power in watts, $Area$ is the length x width of the PV panel in square meters, 1000 = standard test condition (STC) irradiance (watts/square meters) STC refers to the set criteria for testing solar panels. The conditions are; Solar cell temperature at 25°C, solar irradiance at 1000 watts/sq.m, and Air mass at 1.5.

From Equation 3,

$$\eta = \left(\frac{115}{1.87}\right)\frac{}{1000} * 100\%$$

*=6.14%*

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This is not too far from the average daily efficiency recorded by the PV trainer which ranges from 0-6%

*Calculation of Payback Period*

Power currently being used for 6 hours will be:

$$1.2kW * 6 = 1.2kWh$$

The hotel is under class C12 under Kenya Power billing tariffs. The cost of a kWh for this tariff in February 2022 was USD 0.1642. therefore the cost of running the room was,

$$1.2kWh * 0.1642usd = 0.197usd$$

For February, the total cost will be,

$$0.197ksh * 28days = 5.517usd$$

For the year,

$$5.517usd * 12months = 66.21usd$$

Table 2 shows the approximate costs of the components that will be required for the installation. This data is collected from the Chloride Exide website. A local solar products vendor.

Table 2: Initial Capital Cost

| | ITEM | COST(USD) |
|---|---|---|
| 1. | Solar panel 150W, multi-crystalline, 24VDC | 170.90 |
| 2. | Inverter 150W, 24VDC | 15 |
| 3. | Battery 150Ah, 12V | 103.50 |
| 4. | Labor and accessories | 100 |
| | TOTAL | 389.40 |

*Expected Annual Savings*

PV output from earlier calculation was 947.7Wh for 6 hours

Demand savings will be

*0.9477kwh*0.1642*28days*a*12months= 52.29ksh*

Therefore,

$$Payback\ Period\ (PBP) = \frac{389.40}{52.029} \quad = 7years$$

This should be noted that this is from a 230W rated power installation with 194.4W output as used in the experiment. Panels of higher output will greatly reduce the payback period.

$$Return\ on\ Investment = \frac{Annual\ Financial\ Savings}{Total\ amount\ of\ Investment} = \frac{1}{PBP}$$

$$\frac{1}{7} = 0.14 = 14\%$$

## V. CONCLUSION

From this research, it is noted that Kenya generally receives a good amount of solar insolation, from the solar irradiation computation. This then suggests that solar energy can be a reliable source of energy for Kenya and companies and homes should consider investing more in solar power harvesting. From the power output calculation, it is noted that a 230W multi-crystalline panel can provide at least 1kWh which is useful in powering some of the equipment in a guest room. It also suggests that if more panels or panels of a higher power rating were used, they would power a guest room effectively. This would solve the problem of power outages disrupting guests' comfort which is bad for business. A 6% efficiency for the panels is sufficient as most multi-crystalline panels have their efficiency rated between 10-14%. The difference could be attributed to the fact that efficiency reduces with age. A payback period of 7 years and a return on investment of 14% means that it is a worthy investment considering the savings that will be achieved within that period. Vertically mounted solar panels would work well in the Kenyan climate. They can be mounted on both the east and west-facing walls. The output may not be as great as that of horizontal mounting but would work well to boost the current supply. The initial capital investment will be high but greater savings will be realized in the long run.

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